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Wear and Friction Torque in thrust ball and roller bearings lubricated with "Windmill Gear Oils"

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Abstract

The power losses generated in power transmissions have attracted a considerable attention in recent times. The energy sources are no longer widely available as formerly, so the reduction of energy consumption with increased efficiency is increasingly required. Having in mind the optimization of the natural resources, the use of biodegradable products has grown significantly in recent years.

Aiming to achieve an higher environmental compatibility and lower power losses, test and validation of the lubricants is needed.

In this work three lubricant oils were considered, one has a mineral base, other has a PAO base and the third has an ester base. For these three lubricants several tests were performed and their tribological behaviour was evaluated and compared. The tests were performed with thrust ball bearings (TBB) and thrust roller bearings (TRB), with various operating conditions in elastohydrodynamic lubrication regime (boundary, mixed and full film).

The post-testing evaluation of the bearing consisted in weighing the rolling bearing before and after test and to evaluate their mass loss during the test. The bearing raceways and the rolling elements surfaces were analysed using a microscope to detect surface failures. The surface evolution was also evaluated through surface roughness measurements and topographies. Lubricant samples were collect after each test and were analysed through Analytical and Direct Reading Ferrography.

The mass loss results indicated that the TBB bearings lubricated with ESTER oil have higher mass loss than the TBB lubricated with MINERAL oil and this one higher mass loss than the TBB lubricated with PAO oil.

The total friction torque measurements to each type of rolling bearing (TBB and TRB), lubricated with the different oils and different operating conditions indicated that for the case of the test performed whith standard rolling bearings (20 rollers and 21 balls), there aren't significant differences whatever the lubricant tested. In the tests with modified TRB (10 rollers), the total friction torque presents similar values for the case of the lubricants PAO and ESTER and slightly higher in the case of the MINERAL oil. However, in the case of the modified TBB (7 balls), the total friction torque also present similar values for the case of the lubricants PAO and ESTER but slightly lower in the case of the MINERAL oil.

The analyses of the wear particles (Analytical Ferrography and Direct Reading Ferrography), also indicates higher particle concentration for the case of the ESTER oil, followed by the MINERAL oil and finally the PAO oil, whatever the rolling bearing type and operating conditions considered.

Resumo

As perdas de potência geradas nas transmissões mecânicas têm suscitado uma preocupação crescente. Isto deve-se ao facto de as fontes de energia já não estarem disponíveis em abundância, o que faz com que a diminuição do consumo energético com o aumento da eficiência seja cada vez mais necessária. Ainda no sentido de tentar optimizar a utilização dos recursos naturais, a procura de produtos biodegradáveis tem crescido significativamente.

Para aferir se um lubrificante apresenta maior compatibilidade com o ambiente e se conduz a uma diminuição da perda de potência, é necessária a realização de testes para comprovar tal eficiência.

Neste trabalho foi realizada a avaliação tribológica de três lubrificantes, os quais são formulados com diferentes óleos base (MINERAL, PAO e ESTER). Os testes foram realizados com TRB e com TBB, em diversas condições de funcionamento e em lubrificação elastohidrodinâmica (filme limite, misto e completo).

O procedimento adoptado para avaliação tribológica dos lubrificantes consiste em contabilizar a perda de massa (através das pesagens efectuadas antes e depois do ensaio), na observação das superfícies das pistas e dos elementos rolantes ao microscópio (Micrografia), na utilização do rugosímetro para obter a topografia das superfícies bem como os perfis de rugosidade e, por fim, na análise das partículas de desgaste (Ferrografia Analítica e Ferrografia de Leitura Directa).

Para os rolamentos axiais de esferas, os resultados das pesagens indicaram que os rolamentos lubrificados com o óleo ESTER apresentam maior perda de massa relativamente aos rolamentos lubrificados com o óleo MINERAL e este maior perda de massa que os rolamentos lubrificados com o óleo PAO.

As medições do momento de atrito total para cada tipo de rolamento (TRB ou TBB), lubrificados com os três tipos de óleos e em diferentes condições de funcionamento indicaram que para o caso dos ensaios com os rolamentos completos (20 rolos e 21 esferas), não existem diferenças significativas qualquer que seja o lubrificante testado. Nos ensaios onde se utilizaram rolamentos axiais de rolos modificados (10 rolos), o momento de atrito total apresenta valores similares para o caso dos lubrificantes PAO e ESTER e ligeiramente superior no caso do óleo MINERAL. No entanto, no caso dos ensaios com rolamentos axiais de esferas modificados (7 esferas), o momento de atrito total também apresenta valores similares para o caso dos lubrificantes PAO e ESTER mas ligeiramente inferior no caso do óleo MINERAL.

A análise das partículas de desgaste (Ferrografia Analítica e Ferrografia de Leitura Directa), também indica uma maior concentração de partículas de desgaste

para o caso do óleo ESTER seguido do óleo MINERAL e por fim o óleo PAO, independentemente do tipo de rolamento e das condições de funcionamento.

Keywords

Thrust ball bearings
Thrust roller bearings
Power losses
Film thickness
Friction coefficient
Friction torque
Pitting
Micropitting
Biodegradable oils
Non-toxic lubricants

Palavras chave

Rolamento axial de esferas
Rolamento axial de rolos
Perda de potência
Espessura de filme
Coeficiente de atrito
Momento de atrito
Pitting
Micropitting
Coeficiente de atrito
Óleo biodegradável
Oléos não toxicos

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Nomenclature

Symbol	Units	Designation
a	$[m]$	Hertz half-width
$CPUC$	$[/]$	Ferrometric index for the concentration of wear particles
d	$[mm]$	Inside diameter
D	$[mm]$	Outside diameter
D_L	$[/]$	Ferrometric index for the amount of large particles
dm	$[mm]$	Bearing mean diameter
D_S	$[/]$	Ferrometric index for the amount of small particles
$E*$	$[Pa]$	Equivalent Young modulos
Fn	$[N]$	Axial load
F_{R0}	$[N]$	Axial load per roller (20 rollers)
F_R	$[N]$	Axial load per roller (10 rollers)
F_{B0}	$[N]$	Axial load per ball (21 balls)
F_B	$[N]$	Axial load per ball (7 balls)
G	$[/]$	Dimensionless of the material parameter in contact EHD isothermic, smooth and Newtonian
g	$[m/s^2]$	Aceleration of gravity
G_{rr}	$[/]$	Sliding friction variable
G_{sl}	$[/]$	Sliding friction variable
h_o	$[m]$	Lubricant film thickness at contact centre
h_{0T}	$[m]$	Corrected lubricant film thickness
i_{rw}	$[/]$	The number of ball rows
$ISUC$	$[/]$	Ferrometric index for the severity of wear large particles
K_{ball}	$[/]$	Ball bearing related constant
K_{roller}	$[/]$	Roller bearing related constant
K_{rs}	$[/]$	The replenishment/starvation constant
Kz	$[/]$	Geometry constant
M_{drag}	$[N.mm]$	Friction torque of drag losses
M_{exp}	$[N.mm]$	Friction torque (experimental)
M_{seal}	$[N.mm]$	Friction torque of seals
M_{sl}	$[N.mm]$	Sliding friction torque
M_{total}	$[N.mm]$	Friction torque
M_{rr}	$[N.mm]$	Rolling friction torque
n	$[rpm]$	Rotational speed
p_o	$[Pa]$	Contac pessure (Hertz)
Q_i	$[N]$	Load per rolling element
$R1$	$[/]$	Geometry constants for rolling friction torque

Symbol	Units	Designation
R_eq	$[mm]$	Equivalent curvature radius
Rx	$[m]$	Radius of curvature in the direction of rolling
Ry	$[m]$	Radius of curvature in the direction perpendicular to the direction of rolling
s	[/]	Piezoviscosity parameter
$S1$	[/]	Geometry constants for sliding friction torque
Sa	$[\mu m]$	Arithmetic average deviation
Sp	$[\mu m]$	Surface maximum height
St	$[\mu m]$	Surface total height
Sv	$[\mu m]$	Maximum depth of surface
t	[/]	Piezoviscosity parameter
U	[/]	Dimensionless speed parameter in contact EHD isothermic, smooth and Newtonian
VM	[/]	Variableas a function of the oil level
W	[/]	Dimensionless of the load parameter in contact EHD isothermic, smooth and Newtonian
α	$[Pa^{-1}]$	Coefficient of piezoviscosity
Δ	[/]	Specific film thickness
η	$[mPa.s]$	Lubricant dynamic viscosity
θ_{lab}	[°C]	Room temperature
θ_{oil}	[°C]	Oil bath temperature
θ_{oil-l}	[°C]	Temperature stabilization
μ_{bl}	[/]	Boundary friction coefficient (essentially dependent of the additives)
μ_{EHD}	[/]	friction coefficient in full film conditions
μ_{sl}	[/]	Sliding friction coefficient
ν	$[cSt]$	Lubricant kinematic viscosity
ρ	$[Kg/m^3]$	Specific weight
σ	$[m]$	Composed roughness
τ	$[N/mm^2]$	Shear stress of lubricant
ϕ_{bl}	[/]	Weighting factor for the sliding friction coefficient
ϕ_{ish}	[/]	Inlet shear heating factor
ϕ_{rs}	[/]	Kinematic replenishment/starvation reduction factor

1. Introduction

Nowadays the economic interests impose the need to evaluate the efficiency of lubricated mechanisms (mechanical parts). The behaviour of the lubricants under the operating conditions of the mechanism must be known in order to predict the mechanism efficiency. So, it is necessary to develop methods and procedures to evaluate and compare the behaviour and performance of different lubricants.

The aim of this study is to analyse the influence of "Windmill gear oils" formulation on thrust ball and roller bearing performance.

To achieve this aim a Four-Ball machine was used ("Four-Ball Machine", Cameron - Plint, ref[a] E82/7752) in order to measure the wear and friction torque in bearings (see Annex A.1).

A new bearing house was developed, incorporating a torque transducer and several thermocouples. This assembly is monted on the Four-Ball Machine and allows the measurement of the friction torque and the operating temperature simultaneously for the desired combination of speed and load.

This thesis is the result of a large amount of experimental work with the purpose of evaluate the three selected lubricants. It presents the experimental tests performed, the test equipment used, the test procedures and the analyses of the results.

With the measurements made during each test, it is possible to evaluate the tribological performance of each lubricant through the wear produced on the bearing components (raceways, rolling elements and cage) and the degradation of the lubricant. This evaluation was made through the analysis of micrographs of the bearing raceways and of the rolling elements surfaces, topographies of the surfaces and the analysis of wear particles existing in the oil samples collected (Analytical Ferrography and Direct Reading Ferrography).

1.1. Aim and thesis outline

The work here reported is the result of the experimental and numerical work accomplished for the course of Mechanical Engineering Master's Degree under the Project and Mechanical Construction branch. The project was realized at CETRIB

(Tribology and Industrial Maintenance Unit of INEGI). The main aim of this work was to analyse the influence of "Windmill gear oils" formulation on thrust ball and roller bearing performance.

2. Lubrication and Lubricants

2.1. Introduction

The main purpose of using lubricants is to reduce friction and wear between two surfaces in relative motion. Thus, it can be said that, any substance - solid, liquid or gas - interposed between two surfaces aiming to make easier their relative slip, is a potential lubricant. However, other features are often required from the lubricants, such as a good separation of the surfaces and a good evacuation of the heat generated in the contact. Some of these characteristics are inherent, such as a low shear strength and good thermal conductivity, while others are related to surfaces, ie, protecting them against corrosion even in the absence of movement [8].

The need to full fill these basic requirements restricts the number of efficient lubricants to a limited number of base materials, either animal, vegetable, mineral or synthetic. Another factor that has been growing significantly in recent years, that further restricts the choice of a lubricant, is the environmental concern, which is leading to the development of new environmental friendly lubricants.

Moreover, in elastohydrodynamic contacts, the lubricant flows through the contact for a very short period of time of about *1 ms*, having a shock pressure of about *1 GPa* or higher, being submitted to shear rates that can reach $10^{-7}s^{-1}$ and temperature rises above *100 ^{o}C*. [2] These conditions, characterized by high and fast variations in pressure and temperature inside the contact, justify the change of the lubricant properties inside the contact, that are observed experimentally and theoretically determined [2]. Such operating conditions make the work of characterizing the physical, chemical, rheological and tribological behaviour of the lubricant within the contact even harder.

In this chapter it is intend to make a brief description of the main characteristics, specifications and properties of general lubricants as well as the description of the oils used in this work.

2.2. Lubricating oils

The base oils can be classified according to their origin;

Vegetable and animal oils - The vegetable and animal oils were certainly the first lubricants to be used. These lubricants have several advantages over mineral oils, eg, the high viscosity, high lubricity, low evaporation rate and rapid biodegradability, this last aspect being, maybe, the most important. Unfortunately, these vegetable oils oxidise quickly, having low resistance to high temperatures. The lubricants requirements have been increasing continuously, thus the use of animal and vegetable oils has been largely replaced by mineral and synthetic based products.

Mineral oils - Obtained from the distillation of crude petroleum, these oils can be distinguished by their chemical composition and may be paraffinic, naphthenic and aromatic. The aromatic fraction is usually undesirable and can be found in small proportions. Therefore, these aromatic fractions are the least used in lubrication, while the paraffinic and naphthenic based oils are widely used due to their low cost and reasonable performance.

Synthetic oils - Synthetic lubricants are obtained by synthesis of light hydrocarbons with the inclusion of some non-petroleum organic elements. These lubricants have some benefits, such as increased oil longevity and better heat resistance, having however, a higher cost. Synthetic oils include mainly four types: the synthetic hydrocarbons, the polyglycols, the organic esters and phosphate esters.

Some chemical agents can be added to these base oils, commonly called additives, which give the oil certain properties after finished. Some additives provide them useful new properties, that do not exist originally in oils while others can only improve their natural properties. [2]

2.3. Greases

A grease is the "dispersion of a thickening agent in a lubricating oil"

The thickeners can be of two types:

Soaps - Aluminum, Barium, Calcium, Lithium, Sodium and Strontium.

No soap - Organic clays, Polyureas, Inorganic compounds.

2.4. Solid Lubricants

A solid lubricant is a film of solid material composed of organic or inorganic compounds that is interposed between the surfaces to be lubricated.

Inorganic solid lubricants

Solid gelatinous;

Mixtures of soft solids;

Coverings and chemical reaction with the surface.

Organic solid lubricants

Soaps, waxes and fats;

Polymer films.

2.5. Gaseous Lubricants

The lubrication with gas is analogous in many aspects to lubrication with liquid. Although both are viscous fluids, they differ in two very important physical properties: the viscosity of gases is much smaller and the compressibility is much higher. Thus, the load capacity and film thickness in the contact are much lower when using a gaseous lubricant. [2]

The gaseous lubricants used for this purpose are air, steam, industrial gases, etc..

2.6. Physical properties of lubricating oils

2.6.1. Viscosity

To mathematically describe the behaviour of a lubricating oil, their physical and rheological characteristics should be well known. Probably the most important property of a lubricating oil is its viscosity. This property reflects the degree of internal friction or the resistance which a fluid offers to slip, thus becoming a dominant factor in power losses of mechanical components as bearings and gears.

By definition the viscosity of the fluid is the resistance imposed by the internal slip of the fluid molecules over each other.

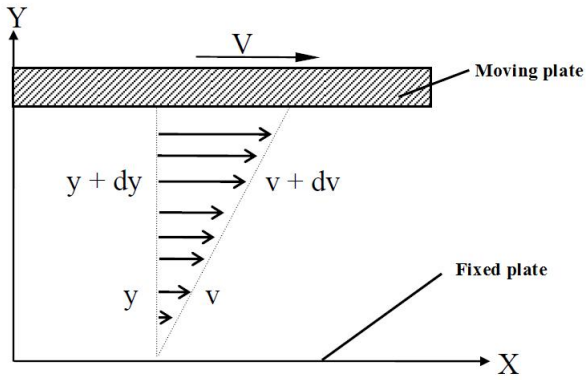


Figure 2.1.: Laminar flow of a fluid.

Newton's law of viscous flow establishes that the linear shear stress within a fluid is proportional to the variation of the fluid speed with the height between the plates surface y, ie,

$$\tau = \sigma_{xy} = \eta \frac{dv}{dy} \tag{2.1}$$

where η is a proportional constant defined by absolute viscosity (dynamic viscosity). The viscosity η is therefore a measure of internal resistance of friction of the fluid and the derivative $\frac{du}{dy}$ is the variation of the fluid speed with the height and can be referred to as shear rate or speed gradient. Assuming that the shear rate is constant, we have:

$$\frac{dv}{dy} = \frac{V}{h} \tag{2.2}$$

where,

$$\tau = \sigma_{xy} = \eta \frac{V}{h} \tag{2.3}$$

The unit of dynamic viscosity, also called absolute viscosity, is measured in Pascal Second (Pa.s) in the International System and is equivalent to $N.s/m^2$.

The kinematic viscosity (ν), which is inversely proportional to the density of the fluid (ρ), is obtained when the flow of fluid is caused by the gravity. Thus, the expression $\nu = \frac{\eta}{\rho}$ gives the kinematic viscosity in m^2/s, being common to represent the result in mm^2/s which corresponds exactly to cSt (centistokes), which is the unit most commonly used.

To better understand the above and check the remaining properties of a lubricating oil see references [2, 8].

2.6.1.1. Termoviscosity

Represents the variation of viscosity with temperature,

- **Law of Cameron** (Cameron's equation is simple but is only valid for small variations in temperature);
- **Norm ASTM D314**;
- **Vogel's Law**.

The viscosity of the most usual mineral and synthetic oils decreases when the temperature increases.

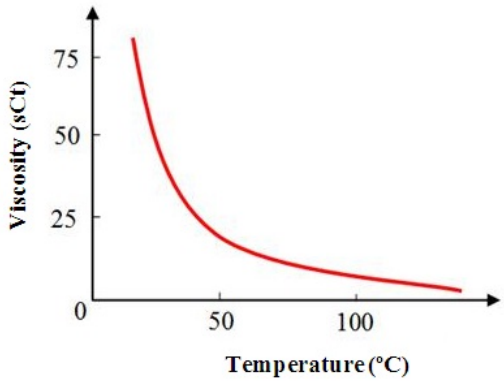


Figure 2.2.: Paraffinic mineral oil (ISO VG 32).

As an example, in the proximity of 20 ° C the viscosity decreases about:

- 2,5% for water;
- 10% to 15% for oil.

The method used in this work to determine the kinematic viscosity of the oils to be tested was the **ASTM D314** standard:

$$\log\left(\log(\nu + c)\right) = n - m \cdot \log(\theta) \tag{2.4}$$

where ν represents the kinematic viscosity (cSt), θ represents the temperature in Kelvin and $c = 0,7\ cSt$.

The parameters $\boldsymbol{m}$ and $\boldsymbol{n}$ are lubricant dependent and given by:

$$m = \frac{\log\left(\frac{log(\nu_0+c)}{log(\nu_1+c)}\right)}{\log\left(\frac{log(\theta_1)}{log(\theta_0)}\right)} \tag{2.5}$$

$$n = \log\left(\log(\nu_i + c)\right) + m \cdot log(\theta_i) \tag{2.6}$$

where $\boldsymbol{i}$ can represent the values $\boldsymbol{0}$ or $\boldsymbol{1}$, respectively the reference temperatures 40°C and 100°C between which the ASTM D341 standard can be applied.

2.6.1.2. Viscosity Index

The viscosity index is the need to specify how the various types of oils are influence by temperature variation. The method most used was proposed by Dan and Davis in 1929. These authors classified all known lubricants at that time, in different categories according to the value of its kinematic viscosity (SUS) at 210 °F (98.8 °C). Among all the oils with the same viscosity at 210 °F they have retained the two oils that had the lowest and highest viscosity at 100 °F (37.8 °C) .

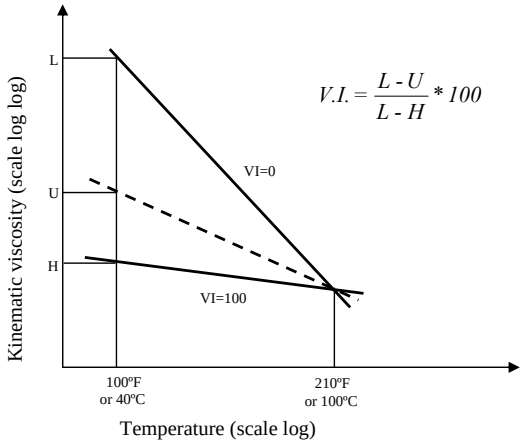


Figure 2.3.: Viscosity Index.

2.6.1.3. Piezoviscosity

Represents the variation of viscosity with pressure. The lubricants viscosity rises considerably with the increase of pressure. This is a very important fact since the lubricants can be submitted to very high contact pressures as it happens within the bearings and gears.

Barus [9] propose the following law, valid for a certain reference temperature:

$$\eta_s = \eta_0 \cdot e^{\alpha \cdot p} \tag{2.7}$$

where η_s represents the lubricants viscosity at the pressure p, η_0 represents the viscosity at atmospheric pressure and reference temperature θ_0 and α represents

the piezoviscosity coefficient, characteristic of each lubricant. This coefficient can be related to the kinematic viscosity using the Law of Gold:

$$\alpha = s\nu^t \times 10^{-9} \quad [Pa^{-1}] \tag{2.8}$$

where s and t are lubricant dependent constants [5]:

Table 2.1.: Lubricant dependent constants [5].

Pressure (GPa)	Constants s and t	Base oil type		
		MINERAL	**PAO**	**ESTER**
0.2	s	9.904	7.382	6.605
	t	0.1390	0.1335	0.1360
0,6	s	8.097	7.008	5.897
	t	0.1534	0.0984	0.1174

2.6.2. Density

Density (ρ) is the ratio between the mass and the volume of a body. Usually its variation with the temperature is not relevant, however the variation with the pressure might be more important as the lubricant film thickness is highly influenced by the contact pressure.

2.6.3. Other properties

- **Specific Heat** $[kJ/kg\,^\circ K]$: Amount of heat necessary to transfer to a body of unitary mass to increase its temperature of one Kelvin degree.
- **Thermal Conductivity** $[W/m^\circ K]$: Heat flow transferred due to a unitary temperature gradient per unit of time in a normal direction to a surface of unitary area.
- **Thermal Diffusivity** $[m^2/s]$: Property that describes the temperature propagation within a substance, defined by the ratio between the thermal conductivity and the product between the density and the specific heat.

2.6.4. Glass transition temperature

When a lubricant is cooled at constant pressure, its viscosity increases continuously until it reaches values of about 10^{12} Pa.s. From a certain temperature, the lubricant exhibits a behaviour similar to that of an amorphous or glassy solid, this temperature being called "glass transition temperature".

This transformation also occurs at constant temperature, if the pressure at which the lubricant is submitted continually increases. The pressures and temperatures involved in the operation of a elastohydrodynamic contact are sufficient for such transformation to occur or at least to achieve extremely high viscosities. [2]

2.6.5. Environmental Specifications

As an example, the two following environmental certificates are applicable to oils: GreenMark whose symbol is represented in the figure on the left and Blauer Engel which is represented in the right figure. The GreenMark is Chinese (Taiwan) while the Blauer Engel is a German certificate. Both symbols however represent the green certification, ie, the non-toxic behaviour of the lubricant to the environment and nature. [10]

Figure 2.4.: Green certification symbols

2.7. Additives

The amount of additive used varies from a few hundredths up to 30%. The additives, improving the characteristics of lubricating oils, have largely contributed to the progress of the primitive combustion engines and all industrial mechinery. [2]

Although the additives have multiple functions, only the types that have a specific purpose are shown below:

- **Additives that improve the viscosity index**: are used to increase the viscosity of the base oil at high temperature and/or decrease it at lower temperatures. These additives are usually polymers;
- **Anti-wear (AW)**: Reinforce the anti-wear properties of the lubricants, by creating a protective film, resulting from their reaction with the contacting surfaces;
- **Extreme-pressure (EP)**: Avoid the adhesion between the metallic surfaces in relative slip at extreme pressure conditions, these additives combine chemically with the contacting surfaces, generating a protective film, which avoid the micro-welding of the roughness tips and consequently their fracture controlling surface damage;
- **Antioxidants**: Additives that interrupt the chemical reaction between the oxygen and the hydrocarbons, decreasing the lubricants oxidation and ageing. These additives increase the resistance to high temperatures allowing to increase the lubricant service life;
- **Dispersing additive - detergents**;
- **Corrosion inhibitors**;
- **Rust inhibitors**;
- **Foam inhibitors or anti-foaming additives**;
- **Additives to lower the freezing point**;
- **Additives for greases**;
- **pH modifiers**;

Unfortunately there is still no way to predict exactly the effect of mixing some chemicals on the base oils, since they are mutually affected. Therefore, some properties of the lubricant can only be obtained by testing or even by trial and error [11]

2.8. Windmill gear oils

Some of the most common windmill turbines failures are due to the poor lubrication of the gearbox gears and rolling bearings. Especially when the winds are light, the gearbox components are submitted to high loads and very low speeds. This severe conditions cause frequently the rupture of the lubricant film leading to the structure's overheating and sometimes the collapse. Therefore, there is a high need for lubricants which can overcome these severe conditions and ensure the mechanism's stability. The windmill gear oils have high viscosity grades and also have extreme pressure and anti-wear additives, in order to resist these severe operating conditions.

Three oils were used in this study:

- MINERAL - Mineral based oil;
- PAO - Polyalphaolephine based;
- ESTER - Ester based (biodegradable);

The three oils have the viscosity grade ISO VG 320. The most significant properties of all three lubricants are shown in Table 2.2, according to the informations given by the manufacturers. The quality level shown in the Table 2.3 was also obtained from the manufacturers catalogues.

Table 2.2.: Lubricants properties.

		Base oil ISO VG	MINERAL 320	PAO 320	ESTER 320
Parameter	Units	Method			
Physical Properties					
Density 15°C	g/cm^3	ASTM D4052	0.899	n/a	n/a
Viscosity 40°C	cSt	ASTM D445 DIN 51562 – 1	320	320	320
Viscosity 100°C	cSt	ASTM D445 DIN 51562 – 1	24.03	35.5	36
Viscosity Index	/	ASTM D2270 DIN ISO2909	95	158	160
Inflammability Point	°C	ASTM D92 DIN ISO2592	210	210	270
Pour Point	°C	ASTM D97 DIN ISO3016	−9	−42	−45
Corrosion Resistance Properties					
Copper corrosion 3h at 100°C	/	ASTM D130	1a	n/a	n/a
Rust, method A	/	ASTM D665	Pass	Pass	n/a
Rust, method B	/	ASTM D665	Pass	n/a	n/a
Wear Properties					
FAG FE-8 Roller wear	mg	DIN 51819-3	3	n/a	n/a
Micropitting Test	/	FVA 54/7	GF>10	n/a	GF>10
FZG A20/8,3/90°	/	DIN 51354	>12	>12	>12

Table 2.3.: Lubricants quality level.

Base oil ISO VG	MINERAL 320	PAO 320	ESTER 320
Quality level	Din 51517 Part 3 CLP Flender Industrial Gear ISO 12925-1 CKD	Din 51517 Part 3 CLP Flender Industrial Gear US Steel 224 AGMA 9005 – $E02EP$ Cincinnati Lamb: P-35 (ISO 460), P-59 (ISO 320) P-76 (ISO 100), P-77 (ISO 150) P-74 (ISO 220)	Din 51517 Part 3 CLP Biodegradability > 90% CEC L-33-A-93

During this work, the lubricants tested were also submitted to density and viscosity measurements to confirm the data provided by the manufacturers. The results were slightly different and are shown in the Table 2.4.

Table 2.4.: Physical properties of the lubricants.

		Base oil ISO VG	MINERAL 320	PAO 320	ESTER 320
Parameter	Units	Method			
Density 15°C	g/cm^3	/	0.902	0.892	0.957
Density 25°C	g/cm^3	/	0.896	0.886	0.950
Viscosity 40°C	cSt	ASTM D341	319.24	313.56	324.03
Viscosity 70°C	cSt	ASTM D341	65.77	84.97	88.23
Viscosity 100°C	cSt	ASTM D341	22.51	34.07	36.07
Viscosity Index	/	"based" on ASTM D341	85	153	159
Thermoviscosity 40°C	K^{-1}	ASTM D341	0.0639	0.0507	0.0499
Thermoviscosity 70°C	K^{-1}	ASTM D341	0.0428	0.0362	0.0358
Thermoviscosity 100°C	K^{-1}	ASTM D341	0.0301	0.0267	0.0266
Piezoviscosity 40°C	Pa^{-1}	ASTM D341	$2.21E-08$	$1.59E-08$	$1.45E-08$
Piezoviscosity 70°C	Pa^{-1}	ASTM D341	$1.77E-08$	$1.34E-08$	$1.22E-08$
Piezoviscozity 100°C	Pa^{-1}	ASTM D341	$1.53E-08$	$1.18E-08$	$1.08E-08$

3. Elastohydrodynamic Lubrication

3.1. Normal contact between elastic solids of revolution - Theory of Hertz

When two elastic solids of revolution are bring into contact with each other, initially they touch at single point or along a line. When pressed against each other by a normal load, they deform in the neighborhood of the initial point of contact, generating a small contact area, whose dimensions are significantly smaller that the dimensions of the contacting bodies.

In order to analyze this problem a contact theory or contact model is needed, for determining the contact area and its evolution with increasing loads as well as the intensity and distribution of normal contact pressures, transmitted through the contact surface. Finally, knowing the contact pressures, it is possible to evaluate the displacement, stress and strain fields applied to the contacting bodies, on the surface and sub-surface of the contacting solids. [1]

The macro and micro geometry of the surfaces in contact have a significant influence on the contact behaviour, being necessary to define their geometry with detail and precision. When bring into contact the two solids touch each other at a single point, O, designated initial point of contact. This point is also the origin of a rectangular coordinate system, in which the plane [XOY] is the common tangent plane to the contacting surfaces, while Z axis, is normal to the common tangent plane, in the direction of the lower solid, as shown in Figure 3.1.

For smooth surfaces and before applying the straight sections of the two bodies containing point O are continuous curves that is, the two bodies are solids of revolution. Thus, it is also possible to define principal planes of curvature for each of the solids $(x_1Oz_1, y_1Oz_1, x_2Oz_2, y_2Oz_2)$ and determine the corresponding principal radii of curvature, respectively, Rx_1, Ry_1 *and* Rx_2, Ry_2. The line of action of the normal load Fn passes through the centers of curvature of the two solids and the initial contact point, O, being normal to the common tangent plane [1].

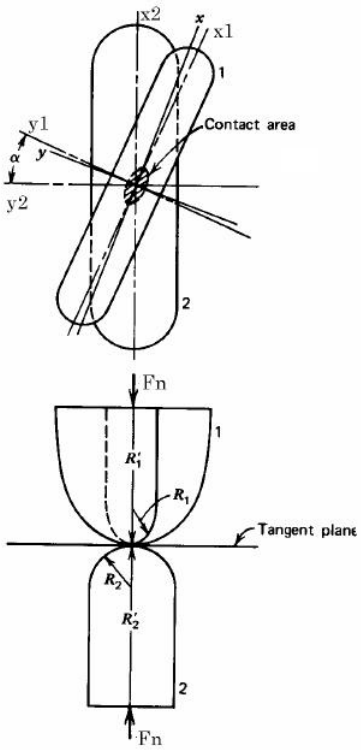


Figure 3.1.: Plans and radii principal of curvature [1].

3.1.1. Contact model

Essentially, the contact model relates the distance between the surfaces of solids in contact, measured along the normal to the common tangent plane, before and after the elastic deformation generated by the applied normal load [1].

Defining A and B ($A > B$) as,

$$A = \frac{1}{R_x} = \frac{1}{2}\left(\frac{1}{R_{x1}} + \frac{1}{R_{x2}}\right) \tag{3.1}$$

$$B = \frac{1}{R_y} = \frac{1}{2}\left(\frac{1}{R_{y1}} + \frac{1}{R_{y2}}\right) \tag{3.2}$$

The sets of points for which $\mathbf{z = Ax^2 + By^2 = constant}$, correspond to points within the same distance to the common tangent place, corresponding to an ellipse.

3.1.2. Shape of the contact surface

The points of both surfaces that come into contact as the normal load is applied, correspond to points within the same distance to the common tangent plane , that is, points for which $\mathbf{z = Ax^2 + By^2 = constant}$, and consequently the contact area has an elliptical shape, given by

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{3.3}$$

where a and b represent the minor and major axes of the contact ellipses.

3.1.3. Hertz theory

The solution to the problem of contact between two elastic solids of revolution is due to Hertz and dated 1882. To derive such a solution, Hertz established several assumptions or hypotheses, that should be recalled:

i) The materials of the contacting solids are homogeneous, isotropic and linear elastic according to Hooke's law;

ii) The contacting bodies are solids of revolution, their surfaces are continuous and their principal radii of curvature in the neighbourhood of the initial contact point are known;

iii) The applied load is purely normal, and the surfaces do not transmit tangential tractions (frictionless contact).

In order to evaluate the local displacements, Hertz considered the contacting solids as elastic half-spaces, submited to a normal load, applied on a small elliptical area. This simplification implies, two addicional hypotheses that must be satisfied:

iv) The dimensions of the contact area are very small when compared to the dimensions of each solid in contact;

v) The dimensions of the contact area must be very small compared to the radii of curvature.

Hypothesis iv) is required to ensure that the solid resembles to an elastic half-space and, therefore, the contact pressures are not influenced by the presence of solid borders along the contact area. The last hypothesis ensures that the surfaces of the solids outside of the contact area, are similar to the plane surface of the elastic half-space [1].

3.1.4. Hertz Solution

Equivalent Young's modulus for the two solids in contact (E *), is defined by

$$\frac{1}{E*} = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right) \tag{3.4}$$

The maximum Hertz pressure, p_0, and the mean pressure inside the contact, p_m, are equal to,

$$p_o = \frac{3}{2} \frac{F_n}{\pi a b} \tag{3.5}$$

$$p_m = \frac{F_n}{\pi a b} \tag{3.6}$$

where,

$$a = C_a \sqrt[3]{\frac{F_n}{(A+B)E^*}} \tag{3.7}$$

The values of C_a and k can be obtained from Table 3.2 and 3.3, depending on the value of A/B. Once determined the values a and k, the value of b results of the expression,

$$b = \frac{a}{k} \tag{3.8}$$

A/B	k	1/k	e	C_a	C_δ
1.0	1.000	1.000	0.000	0.909	2.356
1.1	1.000	1.000	0.000	0.909	2.356
1.2	0.886	1.129	0.464	0.856	2.215
1.3	0.840	1.190	0.543	0.834	2.155
1.4	0.799	1.252	0.601	0.815	2.100
1.5	0.763	1.311	0.646	0.797	2.049
1.6	0.731	1.368	0.682	0.782	2.003
1.7	0.702	1.425	0.712	0.767	1.959
1.8	0.676	1.479	0.737	0.754	1.919
1.9	0.652	1.534	0.758	0.742	1.882
2.0	0.631	1.585	0.776	0.731	1.846
2.1	0.611	1.637	0.792	0.721	1.813
2.2	0.592	1.689	0.806	0.711	1.782
2.3	0.575	1.739	0.818	0.702	1.753
2.4	0.559	1.789	0.829	0.693	1.725
2.5	0.544	1.838	0.839	0.685	1.699
2.6	0.530	1.887	0.848	0.678	1.674
2.7	0.517	1.934	0.856	0.671	1.650
2.8	0.505	1.980	0.863	0.664	1.627
2.9	0.493	2.028	0.870	0.658	1.605
3.0	0.483	2.070	0.876	0.652	1.584
3.1	0.472	2.119	0.882	0.646	1.564
3.2	0.463	2.160	0.886	0.640	1.545
3.3	0.453	2.208	0.892	0.635	1.527
3.4	0.445	2.247	0.896	0.630	1.509
3.5	0.436	2.294	0.900	0.625	1.492
3.6	0.428	2.336	0.904	0.620	1.475
3.7	0.421	2.375	0.907	0.616	1.460
3.8	0.413	2.421	0.911	0.612	1.444
3.9	0.407	2.457	0.913	0.607	1.430
4.0	0.400	2.500	0.917	0.603	1.415
4.1	0.394	2.538	0.919	0.600	1.401
4.2	0.387	2.584	0.922	0.596	1.388
4.3	0.382	2.618	0.924	0.592	1.375
4.4	0.376	2.660	0.927	0.589	1.363
4.5	0.370	2.703	0.929	0.585	1.350
4.6	0.365	2.740	0.931	0.582	1.338
4.7	0.360	2.778	0.933	0.579	1.327
4.8	0.355	2.817	0.935	0.576	1.316
4.9	0.351	2.849	0.936	0.573	1.305
5.0	0.346	2.890	0.938	0.570	1.290

A/B	k	1/k	e	C_a	C_δ
5.1	0.342	2.924	0.940	0.567	1.284
5.2	0.337	2.967	0.942	0.564	1.274
5.3	0.333	3.003	0.943	0.562	1.264
5.4	0.329	3.040	0.944	0.559	1.254
5.5	0.325	3.077	0.946	0.557	1.245
5.6	0.322	3.106	0.947	0.554	1.236
5.7	0.318	3.145	0.948	0.552	1.227
5.8	0.314	3.185	0.949	0.549	1.218
5.9	0.311	3.215	0.950	0.547	1.210
6.0	0.308	3.247	0.951	0.545	1.202
6.1	0.304	3.289	0.953	0.543	1.194
6.2	0.301	3.322	0.954	0.540	1.186
6.3	0.298	3.356	0.955	0.538	1.178
6.4	0.295	3.390	0.955	0.536	1.170
6.5	0.292	3.425	0.956	0.534	1.163
6.6	0.289	3.460	0.957	0.532	1.156
6.7	0.287	3.484	0.958	0.530	1.148
6.8	0.284	3.521	0.959	0.528	1.141
6.9	0.281	3.559	0.960	0.527	1.135
7.0	0.279	3.584	0.960	0.525	1.128
7.1	0.276	3.623	0.961	0.523	1.121
7.2	0.274	3.650	0.962	0.521	1.115
7.3	0.271	3.690	0.963	0.520	1.108
7.4	0.269	3.717	0.963	0.518	1.102
7.5	0.267	3.745	0.964	0.516	1.096
7.6	0.264	3.788	0.965	0.515	1.090
7.7	0.262	3.817	0.965	0.513	1.084
7.8	0.260	3.846	0.966	0.511	1.078
7.9	0.258	3.876	0.966	0.510	1.073
8.0	0.256	3.906	0.967	0.508	1.067
8.1	0.254	3.937	0.967	0.507	1.061
8.2	0.252	3.968	0.968	0.505	1.056
8.3	0.250	4.000	0.968	0.504	1.051
8.4	0.248	4.032	0.969	0.503	1.045
8.5	0.246	4.065	0.969	0.501	1.040
8.6	0.244	4.098	0.970	0.500	1.035
8.7	0.243	4.115	0.970	0.498	1.030
8.8	0.241	4.149	0.971	0.497	1.025
8.9	0.239	4.184	0.971	0.496	1.020
9.0	0.238	4.202	0.971	0.495	1.016
9.1	0.236	4.237	0.972	0.493	1.011
9.2	0.234	4.274	0.972	0.492	1.006
9.3	0.233	4.292	0.972	0.491	1.002
9.4	0.231	4.329	0.973	0.490	0.997
9.5	0.230	4.348	0.973	0.488	0.993
9.6	0.228	4.386	0.974	0.487	0.988
9.7	0.227	4.405	0.974	0.486	0.984
9.8	0.225	4.444	0.974	0.485	0.980
9.9	0.224	4.464	0.975	0.484	0.976
10.0	0.222	4.505	0.975	0.483	0.972

Figure 3.2.: Factors for the solution of Hertz.

A/B	k	1/k	e	C_a	C_δ
1.0	1.000	1.000	0.000	0.909	2.356
2.0	0.631	1.585	0.776	0.731	1.846
3.0	0.483	2.070	0.876	0.652	1.584
4.0	0.400	2.500	0.917	0.603	1.415
5.0	0.346	2.890	0.938	0.570	1.294
6.0	0.308	3.247	0.951	0.545	1.202
7.0	0.279	3.584	0.960	0.525	1.128
8.0	0.256	3.906	0.967	0.508	1.067
9.0	0.238	4.202	0.971	0.495	1.016
10.0	0.222	4.505	0.975	0.483	0.972
11.0	0.209	4.785	0.978	0.472	0.933
12.0	0.198	5.051	0.980	0.463	0.899
13.0	0.189	5.291	0.982	0.455	0.869
14.0	0.180	5.556	0.984	0.447	0.842
15.0	0.172	5.814	0.985	0.441	0.817
16.0	0.166	6.024	0.986	0.435	0.795
17.0	0.160	6.250	0.987	0.429	0.774
18.0	0.154	6.494	0.988	0.424	0.756
19.0	0.149	6.711	0.989	0.419	0.738
20.0	0.144	6.944	0.990	0.414	0.722
21.0	0.140	7.143	0.990	0.410	0.707
22.0	0.136	7.353	0.991	0.406	0.692
23.0	0.132	7.576	0.991	0.402	0.679
24.0	0.129	7.752	0.992	0.398	0.667
25.0	0.126	7.937	0.992	0.395	0.655
26.0	0.123	8.130	0.992	0.392	0.644
27.0	0.120	8.333	0.993	0.388	0.633
28.0	0.118	8.475	0.993	0.385	0.623
29.0	0.115	8.696	0.993	0.383	0.614
30.0	0.113	8.850	0.994	0.380	0.605
31.0	0.110	9.091	0.994	0.377	0.596
32.0	0.108	9.259	0.994	0.375	0.588
33.0	0.106	9.434	0.994	0.373	0.580
34.0	0.104	9.615	0.995	0.370	0.572
35.0	0.103	9.709	0.995	0.368	0.565
36.0	0.101	9.901	0.995	0.366	0.558
37.0	0.099	10.101	0.995	0.364	0.551
38.0	0.098	10.204	0.995	0.362	0.545
39.0	0.096	10.417	0.995	0.360	0.538
40.0	0.095	10.526	0.995	0.358	0.533
41.0	0.093	10.753	0.996	0.356	0.527
42.0	0.092	10.870	0.996	0.354	0.521
43.0	0.091	10.989	0.996	0.353	0.516
44.0	0.089	11.236	0.996	0.351	0.510
45.0	0.088	11.364	0.996	0.349	0.505
46.0	0.087	11.494	0.996	0.348	0.501
47.0	0.086	11.628	0.996	0.346	0.496
48.0	0.085	11.765	0.996	0.345	0.491
49.0	0.084	11.905	0.996	0.343	0.487
50.0	0.083	12.048	0.997	0.342	0.482

A/B	k	1/k	e	C_a	C_δ
51.0	0.082	12.195	0.997	0.341	0.478
52.0	0.081	12.346	0.997	0.339	0.474
53.0	0.080	12.500	0.997	0.338	0.470
54.0	0.079	12.658	0.997	0.337	0.466
55.0	0.078	12.821	0.997	0.336	0.462
56.0	0.077	12.987	0.997	0.334	0.459
57.0	0.077	12.987	0.997	0.333	0.455
58.0	0.076	13.158	0.997	0.332	0.452
59.0	0.075	13.333	0.997	0.331	0.448
60.0	0.074	13.514	0.997	0.330	0.445
61.0	0.074	13.514	0.997	0.329	0.442
62.0	0.073	13.699	0.997	0.327	0.438
63.0	0.072	13.889	0.997	0.326	0.435
64.0	0.072	13.889	0.997	0.325	0.432
65.0	0.071	14.085	0.997	0.324	0.429
66.0	0.070	14.286	0.998	0.323	0.426
67.0	0.070	14.286	0.998	0.322	0.423
68.0	0.069	14.493	0.998	0.321	0.421
69.0	0.068	14.706	0.998	0.320	0.418
70.0	0.068	14.706	0.998	0.320	0.415
71.0	0.067	14.925	0.998	0.319	0.413
72.0	0.067	14.925	0.998	0.318	0.410
73.0	0.066	15.152	0.998	0.317	0.408
74.0	0.066	15.152	0.998	0.316	0.405
75.0	0.065	15.385	0.998	0.315	0.403
76.0	0.065	15.385	0.998	0.314	0.400
77.0	0.064	15.625	0.998	0.313	0.398
78.0	0.064	15.625	0.998	0.313	0.396
79.0	0.063	15.873	0.998	0.312	0.394
80.0	0.063	15.873	0.998	0.311	0.391
81.0	0.062	16.129	0.998	0.310	0.389
82.0	0.062	16.129	0.998	0.310	0.387
83.0	0.061	16.393	0.998	0.309	0.385
84.0	0.061	16.393	0.998	0.308	0.383
85.0	0.060	16.667	0.998	0.307	0.381
86.0	0.060	16.667	0.998	0.307	0.379
87.0	0.060	16.667	0.998	0.306	0.377
88.0	0.059	16.949	0.998	0.305	0.375
89.0	0.059	16.949	0.998	0.305	0.373
90.0	0.058	17.241	0.998	0.304	0.371
91.0	0.058	17.241	0.998	0.303	0.369
92.0	0.058	17.241	0.998	0.303	0.368
93.0	0.057	17.544	0.998	0.302	0.366
94.0	0.057	17.544	0.998	0.301	0.364
95.0	0.057	17.544	0.998	0.301	0.362
96.0	0.056	17.857	0.998	0.300	0.361
97.0	0.056	17.857	0.998	0.299	0.359
98.0	0.056	17.857	0.998	0.299	0.357
99.0	0.055	18.182	0.998	0.298	0.356
100.0	0.055	18.182	0.998	0.298	0.354

Figure 3.3.: Factors for the solution of the Hertz (continued).

3.1.5. Linear contact

In case of the contact between two solid cylinders, initially in contact along their generatrices, the problem becomes two-dimensional as shown in Figure 3.4.

When submited to a normal load per unit length $W(W = F_n/l)$, the two cylinders give rise to a rectangular contact area in the form of a very narrow band ($width = 2a$ and $length = l$) equal to that of two cylinders in contact.

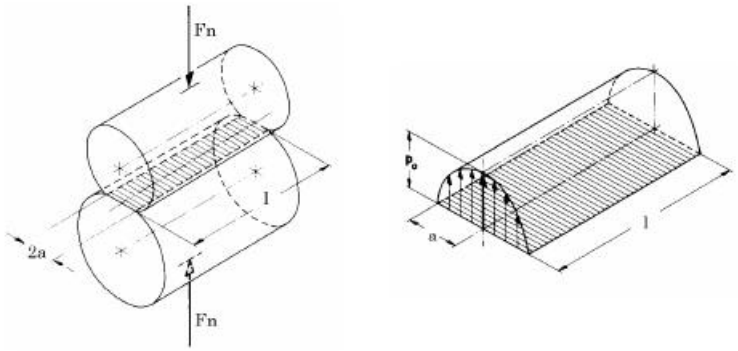


Figure 3.4.: Linear contact

Hertz examined this problem by treating it as the limit of an elliptical contact, where the size b of the ellipse has become very large compared with a ($b = l/2 >> a$). In this case the ellipticity $k(k = a/b)$ tends to 0.

The semi-width of Hertz is set by

$$a = \frac{p_0}{AE^*} = \frac{R_x p_0}{E^*} \tag{3.9}$$

Considering the results of a, given by expression 3.9, the maximum hertzian pressure becomes

$$p_0 = \sqrt{\frac{2}{\pi}\frac{F_n}{l}AE^*} = \sqrt{\frac{2}{\pi}\frac{F_n}{l}\frac{E^*}{R_x}} \tag{3.10}$$

and consequently,

$$a = \sqrt{\frac{2}{\pi}\frac{F_n}{l}\frac{1}{AE^*}} = \sqrt{\frac{2}{\pi}\frac{F_n}{l}\frac{R_x}{E^*}} \tag{3.11}$$

3.2. Elastohydrodynamic Lubrication

Elastohydrodynamic Lubrication (EHD) theory is the key feature to understand lubrication, friction and energy phenomena in heavily loaded contacts, such as lubricated Hertzian contacts. EHD lubrication allows the evaluation three crucial aspects in the performance of a lubricated Hertzian contact (or elastohydrodynamic):

- The thickness of the lubricant film generated between the contacting surfaces, accompanied by elastic deformation of the contacting solids;
- The friction between the contact surfaces due to visco-elastoplastic deformation of the oil film, taking into account the rheological behaviour of the lubricant;
- The energy balance of contact, taking into account the power dissipation in the lubricant film due to shear stresses installed and heat evacuation by the flow of lubricant and surfaces in contact.

Considering the isolated effect of each of these physical phenomena, the elasticity of surfaces and pressure effect on viscosity, usually neglected in the hydrodynamic lubrication, did not explain the behaviour of counter-formal contacts.

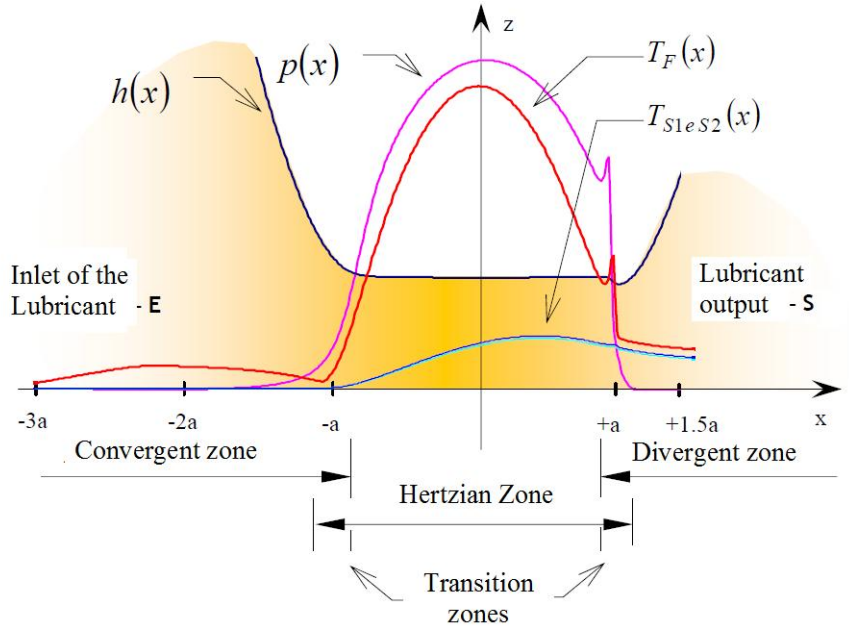


Figure 3.5.: Lubricated Hertzian contact [2].

Where,

T_{S1S2} - Evolution of surface temperatures along the x-direction;
T_F - Evolution of lubricant temperature along the x-direction;
p - Hertz pressure distribution.

In 1949, Grubin showed that the simultaneous consideration was fundamental in the analysis of counter-formal contacts, leading to the prediction of the film thickness separating the surfaces and the loads characteristics of these contacts, giving rise to a new area of study - elastohydrodynamic lubrication.

Petrusevich (1951), confirmed the results of Grubin and obtained solutions that satisfy both the equations of hydrodynamics and elasticity of surfaces, for a wide range of operating conditions, and identified two important characteristics of EHD contacts:(i) the near parallelism between the surfaces deformed with a small restriction on the thickness near the exit of the contact and (ii) a nearly Hertzian pressure distribution in full contact, with a second peak pressure also near the exit of the contact (see Figure 3.5) [2].

3.3. Lubricant film thickness

EHD lubrication is the most common type of lubrication in mechanical components such as rolling bearings, gears and cams.

In elastohydrodynamic contacts lubrication is accessed through the average film thickness that separates the roughness between two surfaces. Nowadays, the lubricant film thickness prediction follows the D. Dowson and G.R. Higginson theory, which implicates an isothermal contact between smooth surfaces and fully flooded lubrication [12].

- The centre film thickness in linear contacts (**thrust roller bearing**), h_o, and the minimum lubricant film thickness , h_m, are defined by the following equations (Dowson and Higginson) [2],

$$h_0 = 0.975 R_x U^{0,727} G^{0,727} W^{-0,091} \tag{3.12}$$

$$h_m = 1.325 R_x U^{0,70} G^{0,54} W^{-0,13} \tag{3.13}$$

or,

$$h_0 = 0.975 \frac{\left[\alpha \eta_0 \left(U_1 + U_2\right)\right]^{0.727} R_x^{0.364} \left(l E^*\right)^{0.091}}{F_n^{0.091}} \tag{3.14}$$

$$h_m = 1.186 \frac{\left[\eta_0 \left(U_1 + U_2\right)\right]^{0.70} \alpha^{0.54} R_x^{0.43} l^{0.13}}{F_n^{0.13} E^{*0.03}} \tag{3.15}$$

Where,

Rx - Equivalent curvature radius,

$$\frac{1}{R_x} = \frac{1}{2}\left(\frac{1}{R_{x1}} + \frac{1}{R_{x2}}\right) \tag{3.16}$$

E* - Equivalent young modulus,

$$\frac{1}{E^*} = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right) \tag{3.17}$$

U - Velocity parameter,

$$U = \frac{\eta_0 \left(U_1 + U_2\right)}{2R_x E^*} \tag{3.18}$$

η_0 - Lubricant dynamic viscosity at lubricant feeding temperature;

G - Material parameter,

$$G = 2\alpha E^* \tag{3.19}$$

ν - Lubricant kinematics viscosity at lubricant feeding temperature;

α - Lubricant piezoviscosity coefficient at lubricant feeding temperature,

$$\alpha = s\nu^t \times 10^{-9} \left[Pa^{-1}\right] \tag{3.20}$$

W - Load parameter,

$$W = \frac{F_n}{R_x l E^*} \tag{3.21}$$

Fn - Normal load,

l - Length of contact.

- The centre film thickness in point contact (**thrust ball bearing**), h_o, and the minimum lubricant film thickness h_m are defined by the following equations (Hamrock and Dowson) [2],

$$h_0 = 1.345\ R_x\ \ U^{0.670}\ \ G^{0.530}\ \ W^{-0.067}\underbrace{\left\{1 - 0.61Exp\left[-0.752\left(\frac{R_y}{R_x}\right)^{0.64}\right]\right\}}_{C_0} \tag{3.22}$$

$$h_m = 1.815\ R_x\ \ U^{0.680}\ \ G^{0.490}\ \ W^{-0.073}\underbrace{\left\{1 - Exp\left[-0.7\left(\frac{R_y}{R_x}\right)^{0.64}\right]\right\}}_{C_m} \tag{3.23}$$

or,

$$H_0 = 1.165\ \ C_0\ \ \frac{\left[\eta_0\left(U_1 + U_2\right)\right]^{0.67}\alpha^{0.53}R_x^{0.464}}{F_n^{0.067}E^{*0.073}} \tag{3.24}$$

$$H_m = 1.438\ \ C_m\ \ \frac{\left[\eta_0\left(U_1 + U_2\right)\right]^{0.68}\alpha^{0.49}R_x^{0.466}}{F_n^{0.073}E^{*0.117}} \tag{3.25}$$

Where,

The parameters U, G and Rx are determined similarly of the case of linear contact,

Ry-Equivalent curvature radius direction y,

$$\frac{1}{R_y} = \frac{1}{2}\left(\frac{1}{R_{y1}} + \frac{1}{R_{y2}}\right) \tag{3.26}$$

W- Load parameter,

$$W = \frac{2F_n}{E^*R_x^2} \tag{3.27}$$

h - Lubricant film thickness,

$$H = \frac{h}{R_x} \tag{3.28}$$

3.4. Correction of lubricant film thickness

The solutions presented for the lubricant film thickness (linear and point contacts) were obtained taking into account the following conditions,

- The contact is isothermic,
- Lubrication is abundant,
- The surfaces are smooth.

However, the lubricant film thickness must be corrected to take into account:

- The heating of the lubricant in contact inlet,

$$h_{0T} = \phi_T \; h_o \tag{3.29}$$

Were,

ϕ_T - Inlet shear heating parameter

3.4.1. Influence of heating in the EHD contact inlet

In the contact inlet, the lubricant film suffers a very high shear deformation, due to the pressure gradient and to the rolling and sliding speeds.

This shear deformation results in a sharp energy dissipation (inlet shear heating) which causes the increase of temperature lubricant (ΔT_f), the decrease of viscosity (η_0) and consequently the decrease in lubricant film thickness (h_0) [9].

This reduction in lubricant film thickness is defined by parameter (ϕ_T), such that,

$$h_{0T} = \phi_T \; h_o \tag{3.30}$$

3.4.2. Determination the temperature correction factor in convergent

The average lubricant temperature increase in contact inlet is defined by

$$\overline{\Delta T_f} = \frac{\eta_o (U_1 + U_2)^2}{20 K_f} \tag{3.31}$$

The inlet shear heating parameter is given by

$$\phi_T = \frac{h_{0T}}{h_0} \cong \left[1 - \frac{\beta\eta_o(U_1+U_2)^2}{20K_f}\right]^{0.727} \tag{3.32}$$

that is,

$$\phi_T = \left(1 - \frac{L}{20}\right)^{3/4} \tag{3.33}$$

with,

$$L = \frac{\beta\eta_o(U_1+U_2)^2}{K_f} \tag{3.34}$$

Correction factor of the lubricant film thickness at the contact center

Expression (3.32) does not take into consideration both the sliding speed between the solids in contact or the lubricant piezoviscosity. Taking into account this two factors the correction of the lubricant film thickness in the contact centre takes the following form,

$$\phi_T = \left\{1 + 0.1\left[\left(1 + 14,8V_e^{0.83}\right)L^{0.64}\right]\right\}^{-1} \tag{3.35}$$

where,

$$V_e = \frac{|U_1 - U_2|}{|U_1 + U_2|} \tag{3.36}$$

3.4.3. Correction due to roughness of the surfaces in contact

Very often surface roughness is classified according to their preferred orientation in longitudinal, isotropic and transverse. In practice, this classification seems to correspond to many current applications.

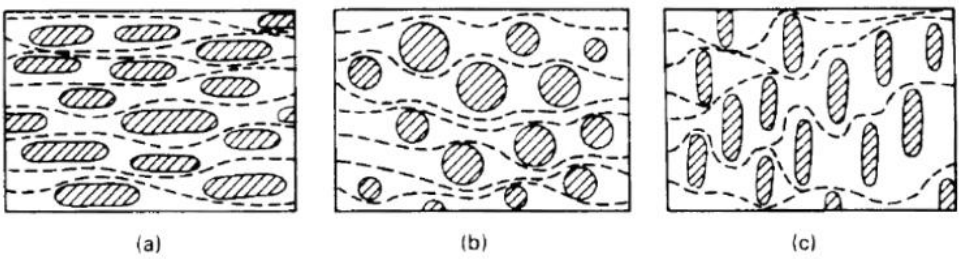


Figure 3.6.: Types of orientation of surface roughness (a-Longitudinal, b-Isotropic, c-Transverse).

Table 3.1.: Orientation of the roughness.

a) Longitudinal	b) Isotropic	c) Transverse
Bearing raceway Roller bearing Cams	Balls bearing	Gears

3.4.3.1. Specific thickness of the lubricant film

In general, the influence of surface roughness on lubricant film thickness is presented in function of the specific lubricant film thickness, that is,

h_o - Lubricant film thickness at contact centre,

$\sigma = (\sigma_1^2 + \sigma_2^2)^{1/2}$ - Equivalent roughness of the contacting surfaces,

$\Lambda = \frac{h_0}{\sigma}$ - Lubricants specific film thickness.

Table 3.2 presents typical values of the composite roughness for rolling bearings.

Table 3.2.: Composite roughness of rolling bearings.

Kind of bearing	$\sigma = R_q = (\sigma_1^2 + \sigma_2^2)^{1/2}\,[\mu m]$
Precision balls	0.05
Balls	0.18
Cylindrical rollers	0.36
Tapered rollers	0.23

3.5. Lubrication regimes

Three elastohydrodynamic lubrication regimes might be defined: full film, mixed film and boundary film. These three schemes exhibit the characteristics described in Table 3.3

Table 3.3.: EHD Lubrication regimes

$\Lambda = \frac{h_0}{\sigma}$	**Regimes**	**Observations**
$\Lambda \geq 10 \times \Lambda_1$	**Hidrodynamic**	Lubricant film very thick.
$\Lambda \geq \Lambda_1$	**Full film**	Contact surfaces completely separated by the lubricant film.
$\Lambda_0 < \Lambda < \Lambda_1$	**Mixed film**	Surfaces in contact partially separated by the lubricant film partially in direct metal-to-metal contact.
$\Lambda < \Lambda_0$	**Boundary film**	There isn't a lubricant film separating the surfaces in contact. Metal-to-metal contact is predominant.

Typical values of Λ_0 and Λ_1 depend on the application considered. Typical values considered for rolling bearings and gears are shown in Table 3.4

Table 3.4.: Typical values of Λ_0 and Λ_1 in EHD lubrication

EHD Lubrication Regimes		
$\Lambda = \frac{h_0}{\sigma}$	**Bearings** $\Lambda_0 = 1.0 \quad \Lambda_1 = 3.0$	**Gears** $\Lambda_0 = 0.7 \quad \Lambda_1 = 2.0$
Full film	$\Lambda \geq 3.0$	$\Lambda \geq 2.0$
Mixed film	$1.0 < \Lambda < 3.0$	$0.7 < \Lambda < 2.0$
Boundary film	$\Lambda \geq 1.0$	$\Lambda \geq 0.7$

3.6. Relationship between lubrication regime and damage surface

The experimental results clearly show that a relationship exists between the specific of the lubricant film thickness and the probability of a surface failure (scuffing, contact fatigue, excessive wear, ...) in elastohydrodynamic contact.

The concept of specific film thickness is of crucial importance in the design of mechanical components operating under EHD conditions. [2]

4. Rolling Bearings Tested

In this work two different types of bearings were tested, thrust roller and ball bearings, respectively SKF 81107 TN (TRB) and SKF 51107 (TBB). Each type of bearing was tested using three different types of windmill gear oils a Mineral, one PAO and one Ester, all with a viscosity grade 320.

4.1. Thrust roller bearing - TRB

In Table 4.1 and in Figure 4.1 and 4.2 the most important characteristics of the thrust roller bearing are reported as well as its dimensions.

Table 4.1.: Characteristics of the thrust roller bearing 81107 TN.

Basic load ratings ratings		**Fatigue load limit**	**Minimum load factor**	**Speed ratings**		**Mass**	**Designations**
Dynamic	Static			Reference speed	limiting speed		Complete bearing
C	C_0	Pu	A				
kN		kN	-	r/min	r/min	kg	
29	93	9,15	0,00069	2800	5600	0,073	81107 TN

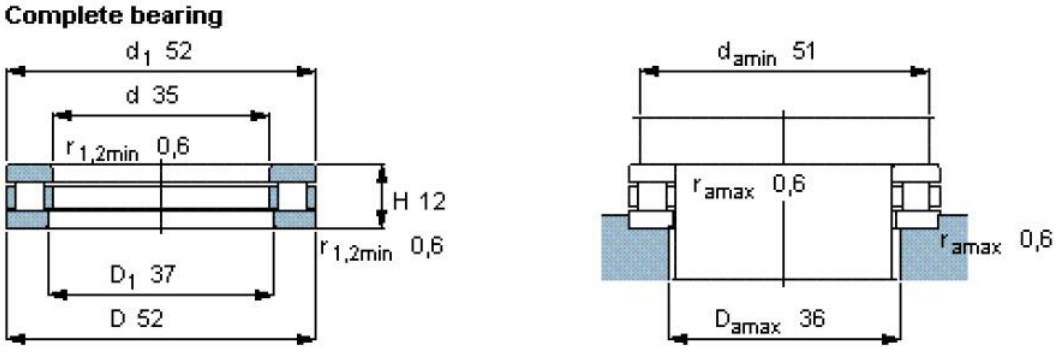


Figure 4.1.: Dimensions of the thrust roller bearing SKF 81107 TN.

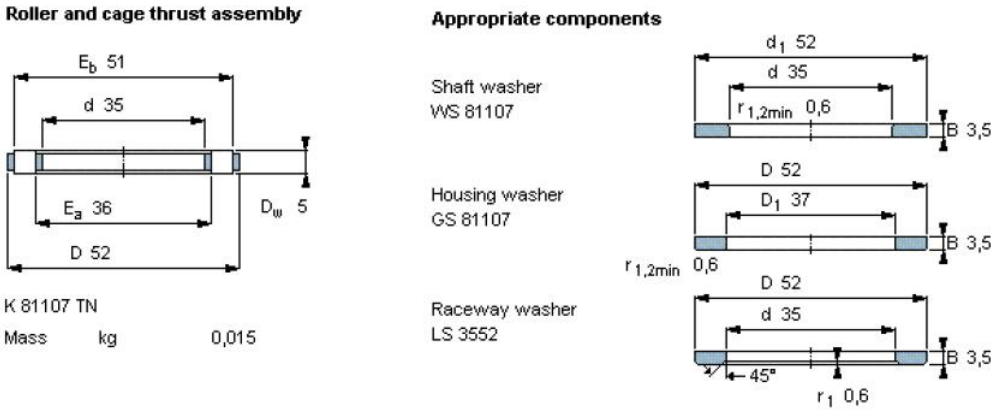


Figure 4.2.: Dimensions of the components of the thrust roller bearing SKF 81107 TN.

4.2. Thrust ball bearing - TBB

In Table 4.2 and in Figure4.3, the most important characteristics of the thrust ball bearing as well as its dimensions, are shown. [3]

Table 4.2.: Characteristics of the thrust ball bearing 51107.

Basic load ratings ratings		**Fatigue load limit**	**Minimum load factor**	**Speed ratings**		**Mass**	**Designations**
Dynamic	Static			Reference speed	limiting speed		Complete bearing
C	C_0	Pu	A				
kN		kN	-	r/min	r/min	kg	
19,9	51	1,86	0,013	5600	7500	0,080	51107

Dimensions:

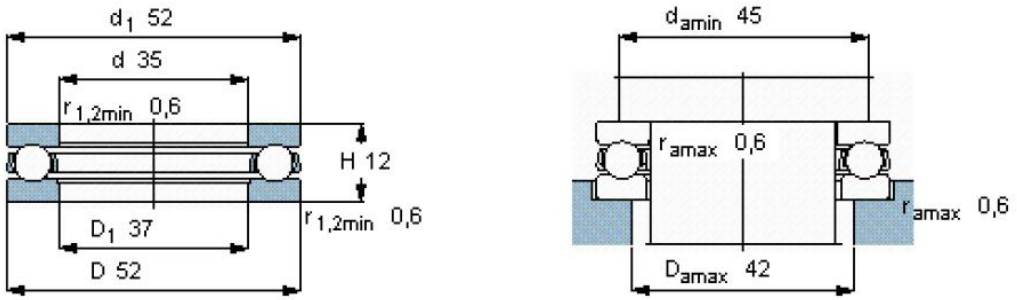


Figure 4.3.: Dimensions of the thrust ball bearing SKF 51107.

4.3. Rating life of bearings

In modern high quality rolling bearings, the basic rating life can deviate significantly from the useful life in a particular application. The lifetime for a specific application depends on a variety of influencing factors, including lubrication, contamination, misalignment, appropriate installation and environmental conditions.

Therefore, the ISO 281:1990 / Amd 2:2000 standard contains a modified life equation to complement the basic rating life. This fatigue life calculation uses a modification factor to take into account the conditions of lubrication and contamination of the bearing and the fatigue limit of the material.

The ISO 281:1990 / Amd 2:2000 standard also determines that the bearing manufacturers recommend an appropriate method to calculate the modification factor of life to be applied on a rolling bearing, based in the operating conditions. The modification factor SKF Life a_{SKF} applies the concept of a fatigue load limit Pu analogous to that used in calculating other machine elements. The values of the fatigue load limit are provided in the product tables. In addition, the modification factor SKF Life a_{SKF} considers the lubrication conditions (viscosity relationship k) and a factor η_c for contamination level that reflects the operating conditions of the application.

The equation for the nominal life SKF according with ISO 281:1990/Amd 2:2000 [3] standard is given by

$$L_{rm} = a_1 a_{SKF} L_{10} = a_1 a_{SKF} \left(C/P\right)^p \tag{4.1}$$

At constant speed (n), life can be expressed in hours of operation, using the equation,

$$L_{rmh} = a_1 a_{SKF} 10^6 / \left(60n\right) L_{10} \tag{4.2}$$

where,

L_{rm} = SKF rating life (with $100 - r$ % reliability), in millions of revolutions,

L_{rmh} = SKF rating life (with $100 - r$ % reliability), in operating hours,

L_{10} = Basic rating life (with 90 % reliability), in millions of revolutions,

a_1 = Life adjustment factor for reliability,

a_{SKF} = SKF life modification factor,

C = Basic dynamic load rating [kN],

P = Equivalent dynamic bearing load [kN],

n = rotational speed [rpm],

p = exponent of the life equation, 3 for ball bearings, 10/3 for roller bearings

The life ajustment factor a_1 is defined in Table 4.3

Table 4.3.: Life adjustment factor a_1

Reliability	**Failure probability** n	**SKF rating life** Lrm	**Life adjustment factor** a1
%	%	-	-
90	10	L10m	1
95	5	L5m	0.62
96	4	L4m	0.53
97	3	L3m	0.44
98	2	L2m	0.33
99	1	L1m	0.21

The viscosity ratio K is defined by $K = \nu/\nu_1$,

where,

ν = operating viscosity of the lubricant $[mm^2/s]$

ν_1 = rated viscosity depending on the bearing mean diameter and rotational speed $[mm^2/s]$, shown in Figure 4.4

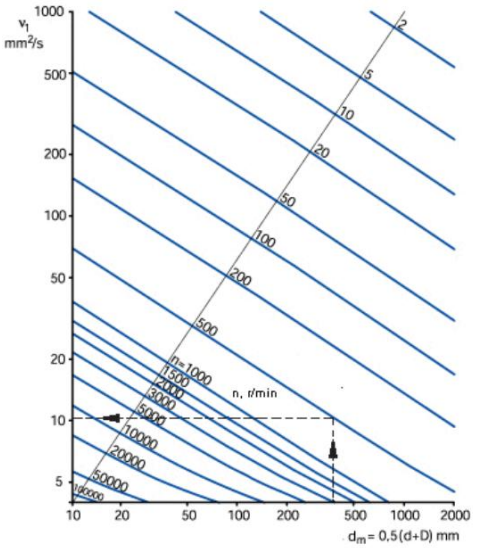


Figure 4.4.: Viscosity ratio, K.

Parameter a_{skf} is defined in Figures 4.5 and 4.6 where η_c is the contamination factor.

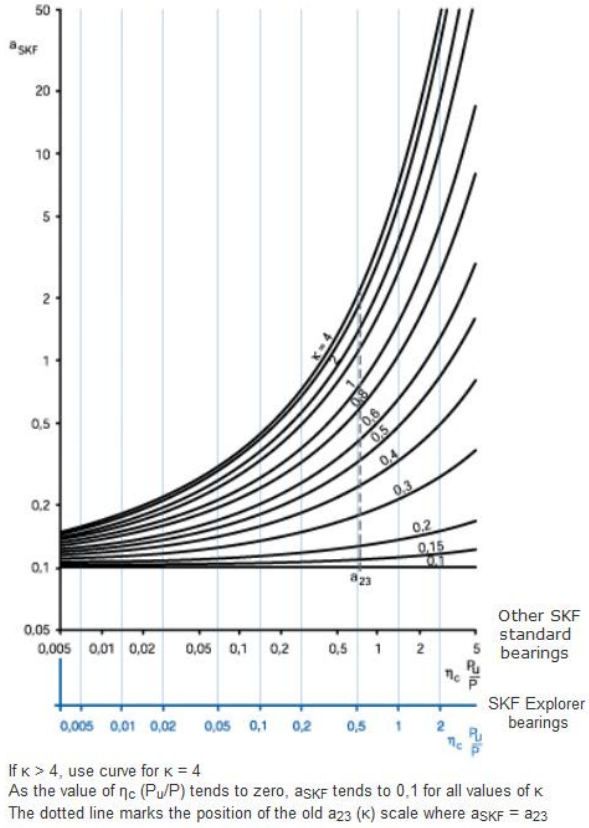


Figure 4.5.: Determination of a_{skf} for thrust roller bearings.

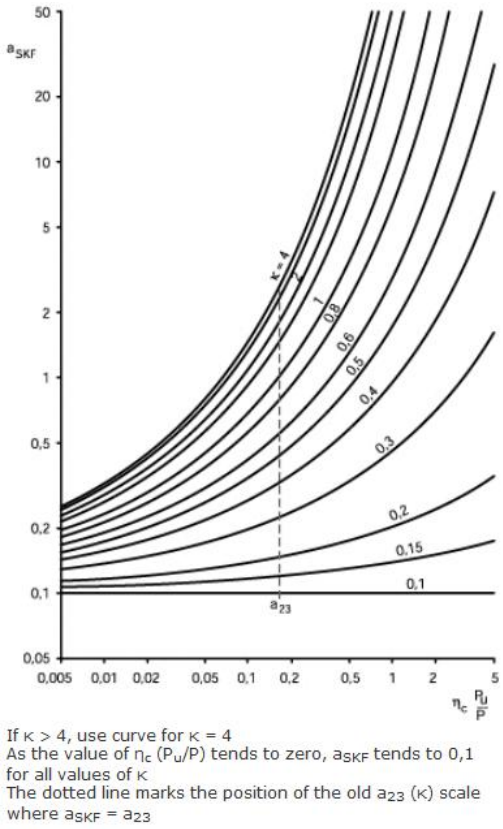


Figure 4.6.: Determination of a_{skf} for thrust ball bearings.

4.3.1. Number of revolutions

Since the tests performed lasted $50h$ and the rotation speed was 500 and 1000rpm (TRB) or 500 and 1200rpm (TBB), the number of revolutions for each case is,

In the case of n = 500 rpm

$$500rpm \times 50h \times 60min = 1,5 \; millions \; of \; revolutions$$

In the case of n = 1000 rpm

$$1000rpm \times 50h \times 60min = 3 \; millions \; of \; revolutions$$

In the case of n = 1200 rpm

$$1200rpm \times 50h \times 60min = 3,6 \; millions \; of \; revolutions$$

4.3.2. Bearing life - incomplete bearing

As mentioned above, the wear tests using thrust roller and ball bearing (SKF ref. 81107 TN and 51107, respectively) and three different oils, lasted 50h. The axial load applied in all tests was 7000N (the maximum axial load possible in the Four-Ball Machine is 8000N). At the end of the these tests no significant damage either on raceways or in the rolling elements was observed. In order to have more severe operating conditions, several rollers/balls were removed from each bearing in order to increase the contact pressure between rolling elements and raceways (keeping F_n = 7000N and 50h).

In the case of the TRB, 10 of the initial 20 rollers were removed, increasing twice the load applied on each roller ($F_{R0} = 350N$ to $F_R = 700N$).

In the case of TBB, 14 of the initial 21 balls were removed, and the load was carried out only by 7 balls. In this way the contact pressure increased as well as the severity of the tests ($F_{B0} = 333,3(3)$ to $F_B = 1000N$).

In the calculation of the bearing life (SKF model) it is not possible to modify the number of rolling elements of each bearing. To obtain an estimation of the bearing life for the bearings with 10 rollers and 7 balls, an axial load was applied to the standard bearing that generates a load on each rolling element of $F_R = 700N$ and $F_B = 1000N$ for the modified roller and ball bearings, respectively, corresponding to the same load per rolling element used on the modified bearings. In the bearing life calculations the viscosity of lubricating oils at the operating temperature of each test, were taken into account.

As a basis for rolling bearing life calculations, a uniform definition of "fatigue life" or rating life, that is the anticipated running period of bearing groups, must be found. This raises the question of the failure probability on which this term should be based [13]. In Europe, the assumption was made as long ago as the 1920s, that 90% of the bearings reach or exceed the rating life. This survival probability corresponds to a failure probability of 10%. In the United States, however, a frequent former assumption was a failure probability of 50%, when 50% of the bearings exceed the rating life [13].

The rating life of bearings was obtained from the SKF site (www. skf.com), in calculations/bearing life. The estimate rating life of bearing, available on the website of SKF, is calculated with a 10% probability of failure.

4.3.3. Life of TRB 81107 TN

In Figures 4.7 and 4.8 the life rating of TRB 81107 TN, with 20 and 10 rollers, is given, when lubricated with MINERAL OIL ISO VG 320. Similar calculations were performed considering the other two lubricants.

In table 4.4 such bearing lives are compared for the three lubricants tested.

	Bearing	81107 TN			
Select η_c	d [mm]	35			
0.95	D [mm]	52			
	C [kN]	29			
	P_u [kN]	9.15			
	P [kN]	7			
	n [r/min]	500			
	v [mm²/s]	105			
			L_{10}	110	L_{10h} 3810
κ	3.19				
v_1	32.9				
a_{SKF}	4.79		L_{10m}	550	L_{10mh} 18200
Old a_{23} method for comparison					
a_{23}	2.15		L_{10a}	250	L_{10ah} 8190

Figure 4.7.: Life rating of *SKF* TRB 81107 *TN* with 20 rollers, lubricated with MIN-320 at 500rpm. [3]

	Bearing	81107 TN			
Select η_c	d [mm]	35			
0.95	D [mm]	52			
	C [kN]	29			
	P_u [kN]	9.15			
	P [kN]	14			
	n [r/min]	1000			
	v [mm²/s]	29			
			L_{10}	11	L_{10h} 190
κ	1.61				
v_1	18				
a_{SKF}	1.03		L_{10m}	12	L_{10mh} 200
Old a_{23} method for comparison					
a_{23}	1.37		L_{10a}	16	L_{10ah} 260

Figure 4.8.: Life rating of *SKF* TRB 81107 *TN* with 10 rollers, lubricated with MIN-320 at 1000rpm. [3]

Table 4.4.: L_{10m}, bearing life rating of TRB *SKF* 81107 *TN*

Fn=7000N							
		500 rpm			**1000 rpm**		
	Number of rollers	Operating temp. °C	Millions of revol.	Hours of operation	Operating temp. °C	Millions of revol.	Hours of operation
MIN	**20**	60.0	550	18200	89.0	320	5360
	10	63.0	17	560	92.0	12	200
PAO	**20**	56.4	640	21200	78.2	600	9950
	10	58.4	20	670	79.8	19	310
EST	**20**	60.1	640	21200	74.2	640	10600
	10	74.2	18	610	80.7	19	320

The Table 4.4 shows that at 500 rpm and 1000 rpm, and whatever the oil considered, the life of the 81107 TN TRB decreases very significantly when the load increase from $F_{R0} = 350N$ per roller (20 rollers) to $F_B = 700N$ per roller (10 rollers).

Table 4.4 also shows that a reduction in bearing life may occur when the operating speed increases from 500 to 1000 rpm, and the operating temperature also increases. Such reduction is very significant for the MINERAL oil and very small for the PAO and ESTER oils.

For the same speed and number of rollers, PAO and ESTER oils generate a very significant bearing life increase in relation to the MINERAL oil, about 20% at 500 rpm and 100% at 1000 rpm.

It is important to notice that, the test with 20 rollers at 1000 rpm were performed in the framework of a different project (Ref. FCT - PTDC/EME-PME/100808/2008). The temperature increasing between the tests with 20 and 10 rollers at 1000 rpm were used for estimate the operating temperatures for the case of the 10 rollers at 500 rpm.

4.3.4. Life of TBB 51107

In Figures 4.9 and 4.10 the life rating of TBB 51107, with 21 and 7 balls, is given, when lubricated with MINERAL OIL ISO VG 320. Similar calculations were performed considering the other two lubricants.

In Table 4.5 such bearing lives are compared for the three lubricants tested.

		Rolamento	51107		
Selecionar η_c		d [mm]	35		
0.95		D [mm]	52		
		C [kN]	19.9		
		P_u [kN]	1.86		
		P [kN]	7		
		n [r/min]	500		
		v [mm²/s]	199.1		
			L_{10}	23	L_{10h} 770
κ	6.06				
v_1	32.9				
a_{SKF}	4.98		L_{10m}	110	L_{10mh} 3810
Método a_{23} antigo para comparação					
a_{23}	2.5		L_{10a}	57	L_{10ah} 1910

Figure 4.9.: Life rating of *SKF* TBB 51107 with 21 balls, lubricated with MIN-320 at 500rpm

		Bearing	51107		
Select η_c		d [mm]	35		
0.95		D [mm]	52		
		C [kN]	19.9		
		P_u [kN]	1.86		
		P [kN]	21		
		n [r/min]	1200		
		v [mm²/s]	47.3		
			L_{10}	1	L_{10h} 12
κ	2.88				
v_1	16.4				
a_{SKF}	1.12		L_{10m}	1	L_{10mh} 13
Old a_{23} method for comparison					
a_{23}	2.01		L_{10a}	2	L_{10ah} 24

Figure 4.10.: Life rating of *SKF* TBB 51107 with 7 balls, lubricated with MIN-320 at 1200rpm

Table 4.5.: L_{10m}, bearing life rating of SKF 51107

	Fn=7000N						
		500 rpm			**1200 rpm**		
	Number of balls	Operating temp. °C	Millions of revol.	Hours of operation	Operating temp. °C	Millions of revol.	Hours of operation
MIN	**21**	47.5	110	3810	70.8	110	1570
	7	55.8	1	35	78.3	1	13
PAO	**21**	46.2	110	3810	67.8	110	1590
	7	49.2	1	35	70.1	1	15
EST	**21**	46.5	110	3810	64.4	110	1590
	7	56.5	1	35	74.6	1	15

The Table 4.5 shows that at 500 rpm and 1200 rpm, and whatever the oil considered, the life of the 51107 thrust ball bearing decreases very significantly when the load increase from $F_{B0} = 333,3(3)N$ per roller (21 balls) to $F_B = 1000N$ per ball (7 balls).

In Table 4.5 also shows that a reduction in bearing life may occur when the operating speed increases from 500 to 1200 rpm, and the operating temperature also increases. Such reduction is very significant for all oils.

For the same speed and number of balls, MINERAL, PAO and ESTER oils generate a similar bearing life.

The estimate of the bearing life with a 10% probability of failure, for the case of tests with 7 balls, suggests a number of operating hours very low, whatever the speed or the oil considered.

It is important to refer that, the operating temperatures were estimated for the tests with 21 balls at 1200 rpm based on the result obtained in the framework of different project (Ref. FCT - PTDC/EME-PME/100808/2008), where the tests were carried out with 21 balls at 1000 rpm. Although the operating temperatures for the case of the 7 balls at 500 rpm were predicted based on the temperature increasing between the tests with 21 and 7 balls at 1200 rpm.

5. Bearing Tests

5.1. Four-Ball Machine

There are two major friction sources inside a rolling bearing: the friction occurring in the contact between the rolling elements and raceways and the friction due to the lubricant flow between the bearing elements (rings, rolling elements and cage).

In order to measure the friction torque inside a rolling bearing and compare the performance of different lubricants, it was necessary to adapt a mechanical bearing housing, integrating a torque cell and several thermocouples that can be mounted on a Four-Ball machine (see Annex A.1), and test each combination of bearing type and lubricant.

The measured values of the bearing friction torque and of the bearing operating temperature, were used to evaluate the power loss and the heat evacuated, depending on the lubricant used and on the operating conditions.

5.1.1. Modified Four - Ball Machine

The rolling bearing tests were performed using a modified Four-Ball machine, where the four-ball arrangement was replaced by a rolling bearing assembly, as shown in Figure 5.1, for the case of a thrust ball bearing. This new assembly was developed to test different types of rolling bearings lubricated with oil or grease [14].

Rolling bearing assembly

The mounting phases for each test are the following (see Figure 5.1).

I – The lower race (3) is fitted on the spacer (2) with J6/p5 tolerance. This set (3+2) is fitted on the bearing house (1) with H6/j5 tolerance. The tight fit used among these parts of the group (A) ensures that there is no relative motion between them.

II – The upper race (5) is mounted on the shaft adapter (6) with P5/j6 tolerance, also to prevent relative motion between them, composing the group (B).

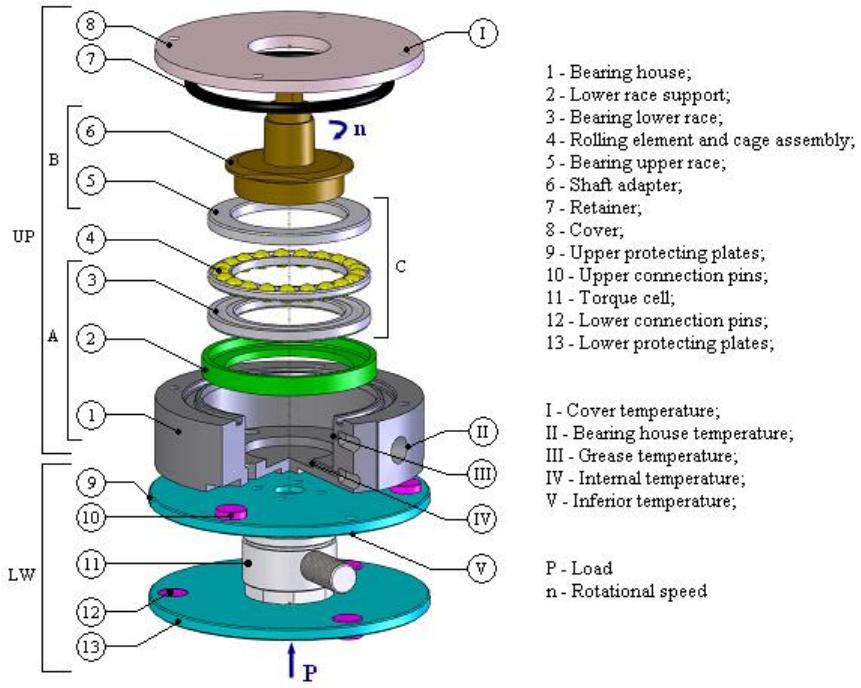


Figure 5.1.: Schematic view of the thrust rolling bearing assembly

III – To prevent contamination by external particles resulted from the mounting operations (groups A and B), and also to remove the oil film protection of the bearing package, the groups A and B and the rolling elements and cage (4) are washed with solvent in an ultrasonic bath.

IV – Rolling bearing lubrication:

IVa – **Oil bath lubrication:** The oil level should reach the centre of the lowest rolling element when the bearing is stationary. For the thrust ball bearing 51107, the oil volume required is approximately 14 ml. During this operation the rolling elements and cage (4) are already positioned on the lower race (3) and the thermocouples (III, IV) should be assembled on the bearing house (1), preventing oil leakage through the thermocouple holes.

IVb – **Grease lubrication:** The grease should be applied by an amount that will replenish the bearing without causing excessive churning and heat generation. As a general rule, when starting up only the bearing should be completely filled, while the free space in the housing should be partly filled with grease. A pre defined volume of $2cm^3$ was determined by the geometry of the bearing house (3), since the grease in excess (for values above $2cm^3$) between the rolling bearing (C) and bearing house (1) can contribute to increase the friction torque and heat generation. This grease volume fills completely the rolling bearing.

V – To complete the assembly of the upper set (UP), the retainer (7), the cover (8) and the thermocouples I and II are mounted. The lower set (LW) was previously assembled (and does not need to be reassembled for each test), and is composed by six connection pins (10 and 12) clamped to the torque cell protecting plates (9 and 13) and a torque cell (11). The lower plate (9) is mounted on the lower nonrotating shaft of the Four-Ball machine, which applies the load to the bearing. The three lower pins (12) assure that there is no relative rotation. The three upper pins (10) are used to connect the UP to the lower set (UP $\rightarrow$ LW) preventing any relative rotation. The thermocouple V is permanently mounted on the protecting plate (9).

VI – The final phase is to install UP and LW parts into the Four-Ball machine. First, UP is connected to the rotating shaft, and then the LW is mounted below. The conjunction will be locked by the lower shaft of the Four-Ball machine, which is moved up to apply the load.

The bearing assembly permits to test four types of rolling bearings, including thrust ball bearings, tapered roller bearings, angular contact ball bearings and cylindrical roller thrust bearings. The geometrical limitations imposed by the Four-Ball machine and by the bearing housing, allow a maximum bearing outer diameter of 56.0 mm and a maximum width of 14.3 mm. Table 5.1 shows the different types of rolling bearings that might be tested and the corresponding dimensions and references. Depending on the bearing type, items (2) and (6), shown in Figure 5.1, must be replaced.

Table 5.1.: Types of rolling bearings that can be tested in the modified Four-Ball Machine

Dimensions			**Dynamic load**	**Limit speed**	**Reference**
d(mm)	D(mm)	H(mm)	C(kN)	rpm	
Thrust ball bearings					
17	30	9	11.14	12000	51103
35	52	12	19.90	7500	51107
Cylindrical roller thrust bearings					
17	28	9	11.20	8500	81102 TN
35	52	12	29.00	5600	81107 TN
Angular contact ball bearings					
17	40	12	11.00	22000	7203
20	47	14	13.30	18000	7204
Tapper roller bearing					
15	42	14.25	22.40	18000	30302 J2
17	40	13.25	19.00	18000	30203 J2

Operation

In operation, the load (F_n) is applied on the lower plate (12) and the rotational speed (n) is transmitted to the shaft adapter (6), which is connected to the drive shaft of the machine (see Figure 5.1).

The rotating motion is conducted through the upper race (5) to the rolling elements and cage assembly (4). The motion generates the bearing internal friction torque, which is transmitted through the lower race (3) to the bearing house (1), to the upper plate (9) and to the torque cell (11), which are all clamped together.

During the test, the rolling bearing assembly is submitted to continuous forced air convection by two fans, having 38 mm in diameter and running at 2000 rpm, evacuating the heat generated during bearing operation.

Torque cell

A piezoelectric torque cell KISTLER® 9339A, whose characteristics are shown in Table 5.2, was selected to measure the bearing internal friction torque.

When a mechanical excitation is applied to the torque cell, the piezoelectric crystals change the electrical current. The current variation is very small and must be augmented and conditioned using an amplifier KISTLER®. The output signal is displayed and registered by the virtual instrument running in a computer.

The main restriction of the piezoelectric sensors is the undesirable changes of the output signal, called drift. This phenomenon happens as the result of two variable parameters: the temperature gradient and the measurement time. To avoid the drift effects in the measurements, a specified testing and measuring procedure has been developed.

Table 5.2.: Technical characteristics of the torque cell.

Reaction Torque sensor - KISTLER®(Type 9339A)		
Measuring range	Nm	-10 t0 +10
Overload	Nm	-12/+12
Sensitivity	pC/Nm	≈-460
Tensile/compression force, max.	kN	-5/+12
Side force, max.	kN	1,5
Bending moment	Nm	15
Operating temperatures	°C	-40 to +120

Thermocouples

Seven type **K** thermocouples with a measurement range between -40 °C and 200 °C and a sensibility of 41 μV°C $^{-1}$ are used to monitor the bearing operating temperatures. All thermocouples are positioned in strategic locations in order to measure the lubricant and bearing housing temperatures, so that the lubricant viscosity and the heat evacuated through the bearing housing can be calculated with reasonable precision. Two of these thermocouples (VI and VII) are used to record the temperatures of the air flow surrounding the bearing house and the room temperature, respectively.

Software

The developed virtual instrument was based on a LabView® platform to operate, to monitor and to control the test system. This software works in a Pentium 4 with 2.8 GHz and 1 GB of RAM.

5.2. Procedure for friction torque measurement

The test procedure is constrained by several factors, in particular, the operating limits of the Four-Ball machine and the torque cell characteristics. The operating conditions imposed by the Four-Ball machine allow tests with axial load and rotational speed up to 7000 N and 5500 rpm, respectively.

The *drift* effect from the torque cell, mentioned above, requires short periods of time (120 s) under stabilized temperatures ($\pm$ 2°C) to make the torque measurements. After a visual inspection of the assembly in the Four-Ball machine, the test is ready to start and the following procedure was used.

I- With the machine in off position, the desired load is applied (in the example 7000 N) and the rotational speed set to the required value (1200 rpm, for example); the fans are turned on to submit the rolling bearing assembly to a continuous forced air convection.

II- Turn on the machine and run the software to start the data acquisition. The operating temperatures rise continuously until stabilization is reached.

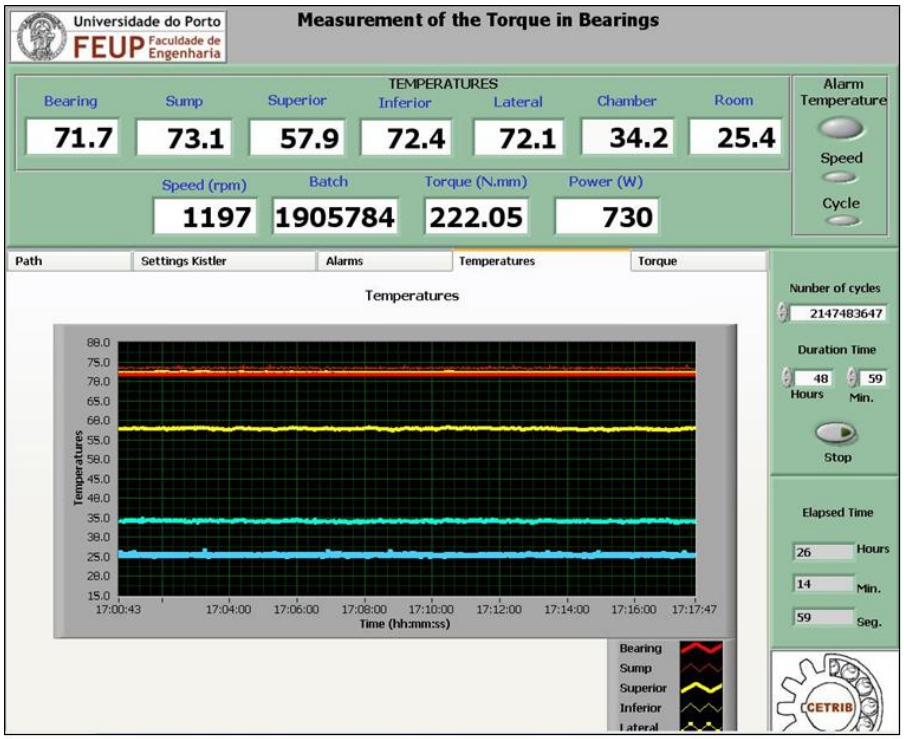


Figure 5.2.: Interface - The temperature history.

III- When the temperatures are stabilized, the machine is turned off and immediately restarted again, together with the torque measurement.

IV- After the torque measurement (120 s), maintain the rotational speed on and wait until the temperatures stabilizes.

V- Stages III and IV are repeated three times to get three measurements of the friction torque in the same conditions.

Figure 5.3.: Interface - Measurement of the Torque in Bearings

To measure the friction torque for other rotational speeds, the procedures described above should be repeated for each desired rotational speed. One extra procedure is taken when the friction torque is to be known at different rotational speeds: the tests should be always conducted from the lowest to the highest rotational speeds.

The friction torque value (for each rotational speed and load) is the average value of the three measurements taken during the 30th to 90th seconds from the period of 120s. This is because in the first 30s, there is a transition from the starting torque to the operating friction torque, and in the last 30s, sometimes, a slight *drift* effect is noticed.

When using piezoelectric torque cells, the torque should be measured during short periods of time at a stabilized temperature, as in the procedure implemented. In this way, the differences between the measured values, for the same operating conditions, are very small.

At the end of each test, lubricant samples can be obtained and analysed through ferrographic techniques to quantify and evaluate the wear occurred in the rolling bearing.

5.3. Volume of oil used

Oil bath is the simplest lubrication method when using oils. In this type of lubrication the oil level should be slightly below the center the rolling element which occupies the lowest position of the bearing, when it is stopped [7]. For the bearings 81107 TN and 51107, 14ml of lubricating oil were used.

5.4. Testing procedure and post-testing analysis

The tests performed during this work were followed by several post-testing analysis for the characterization and evaluation of the wear on the racetracks and rolling elements of each bearing. The following steps were adopted:

I – Weight the test bearing before starting the test.

II – Assembly the bearing in the bearing house (as shown in Figure 5.1, page 42).

III – Washing the assembly in ultrasound bath (using as solvent Petroleum Ether) to ensure that all contaminant particles are removed.

IV – Assembly of the thermocouples in the bearing house and the addition of 14ml of lubricating oil.

V – Assembly of the whole set in Four-Ball machine and start the wear test.

VI – After two hours of test (run-in), shut-down the machine and collect an oil sample for further analysis. Oil samples are always collectde under the same conditions in all tests, that is, the lubricating oil is placed in a suitable vial (properly washed) with the "help" of a solvent (Petroleum Ether) ensuring that most of the particles are collected.

VIII – Restart the test for more 48 hours without interruption (with the same rolling bearing and with 14ml of fresh lubricant oil).

IX – Wait temperature stabilization and measure the friction torque.

X – At the end of the 48h, stop the test collect all the oil for future analysis by Direct Reading Ferrography and Analytical Ferrography. The bearing is disassemble, washed and weighted to evaluate the mass loss. The raceways and rolling elements are observed by optical microscopy (with different magnifications). Finally, a topography of the racetracks is performed.

5.4.1. Mass loss measurement

The mass loss measurement (Figure 5.4) was made before and after each rolling bearing wear test, with an accuracy of $0.001g$. In order to discard any weighting measurement deviation, a reference bearing was used as comparison for each measurement made.

Figure 5.4.: Weighing scale with 0.001g accuracy.

5.4.2. Direct Reading Ferrography

The Direct Reading Ferrography measures, quantitatively, the ferrous particles concentration contained in a lubricant sample.

A 1ml lubricant sample is passed through a capillary tube submitted to a strong magnetic field and two light beams. The wear particles are deposited along the capillary tube. The largest particles are deposited in the beginning of the capillary tube and the smaller ones near the end of the capillary tube. Two light beams pass though the capillary tube, at defined positions (5mm and 45mm). The intensity of the light the crosses the tube in the two positions represents the amount of large particles D_L and small particles D_S, respectively. Knowing D_L and D_S it is possible to calculate the wear particle concentration index (CPUC) and the wear severity index (ISUC), that is,

$$CPUC = \frac{D_L + D_s}{d} \tag{5.1}$$

$$ISUC = \frac{D_L^2 - D_s^2}{d^2} \tag{5.2}$$

where "d" represents the dilution factor of the sample in cases of excessive contamination. A picture of the equipment is presented in Figure 5.5.

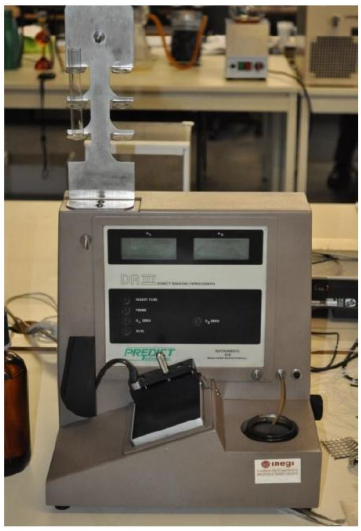


Figure 5.5.: Picture of the Direct Reading Ferrography equipment.

5.4.3. Analytic Ferrography

Analytic Ferrography is used to obtain more detailed information of the lubricant contaminant particles. The particles are deposited and fixed to a glass substrate using the same principle as the Direct Reading Ferrometer.

The larger particles deposit in the entrance of the ferrogram and progressively decrease in size along the glass substrate. A photography of the equipment is shown in Figure 5.6.

Figure 5.6.: Picture of the Analytic Ferrogafer.

The ferrogram is analysed using a bi-chromatic microscope (Figure 5.7) with transmitted light and reflected light, where several particle characteristics are observed, such as: dimension, morphology, color, brightness, surface type, etc.

Figure 5.7.: Bi-chromatic microscope.

5.4.4. Topography Measurement

Surface roughness is a parameter of extreme importance as mentioned before; therefore an accurate measurement of different roughness parameters is critical to a complete analysis of the rolling bearing (rolling elements and raceways).

The equipment used in this analysis was a Hommelwerke roughness tester (Figure 5.8) with a TK100 pick-up for the thrust roller bearings and TK300 pick-up for the thrust ball bearing.

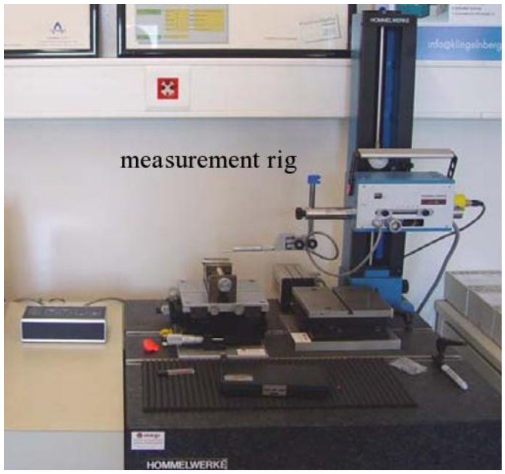


Figure 5.8.: Hommelwerke roughness tester.

5.5. Rolling bearing wear

The wear of a component is defined as the removal of surface material in the form of loose particles during service [15].

The result of wear is a continuing loss of the geometric accuracy of the rolling contact surfaces and gradual deterioration of bearing function, for example, increased deflection, increased friction and temperature, increased vibration, and so forth. [15].

Mild wear is frequently called simply wear. Distinction is often made between two types of mild wear as follows:

- Adhesive or two-body wear occurring at the interface of the contacting surfaces.
- Abrasive or three-body wear occurring due to extraneous hard particles acting at the interface of the contacting surfaces.

The worn surface to the naked eye appears "featureless, matte, and nondirectional" and characteristic finishing marks of the original manufactured surface are worn away. However, mild wear by itself , is not a mode of bearing failure, nor does it lead significantly to rapid bearing failure.

Severe wear or galling is defined as the transfer of component surface material in visible patches from a location on one surface to a location on the contacting surface, and possibly back on to the original surface. This transfer of material takes place because of high-friction shear forces due to sliding over the asperities of the surfaces. In rolling bearings, this severe wear phenomenon is also called smearing. It is a welding phenomenon entailing adhesive bonding between material portions of the contacting surfaces. Smearing indicates increased bearing friction and can lead to less-than-expected bearing endurance.

5.5.1. Micropitting

The micropitting result of a process of contact fatigue and only happens in zones where there are conditions for rolling with significant slip. Its appearance is due to the initiation of fatigue cracks in the surface. These cracks propagate to the interior of material, with a small inclination, in the direction of the tangential force.

5.5.2. Spalling

The spalling results from the initiation of fatigue cracks, deep in the contact sub-surface. These cracks are due and begin in microstructural defects of the material (inclusions, ...). Like micropitting, spalling, in a contact fatigue mechanism, where

the cracks propagate from the interior of the material to the surface (in opposition to what happens in micropitting).

6. Friction Torque Model of Rolling Bearings

Friction between bodies in contact in relative motion, with rolling and sliding is responsible for the power loss in mechanical components such as rolling bearings. Friction is the resistance encountered when two or more solid surfaces tend to slide between them [16].

The internal friction in a rolling bearing is a very important factor, influencing heat generation and, consequently, the operating temperature. It also affects the bearing performance, its speed limit and even its damage mechanisms. [4]

Thus, the evaluation of the internal friction torque in rolling bearings generated by different lubricants, has grown systematically, over the last decades.

6.1. Friction torque in rolling bearings

The models for determining the friction torque in rolling bearings have significantly improved in the last decade. Recently SKF has developed and proposed a new model for calculating the friction torque in bearings lubricated with oil or grease, which is available on the company website [3]. One of interesting characteristics of this model is that it takes into account the four physical sources of friction in bearings, including the friction generated by rolling, by sliding, by the seals (if existent) and the drag of the lubricant, thereby helping to better understand what happens with the bearing during operation. It also describes in detail the model used to calculate the friction torque. [4]

6.1.1. Total friction torque - Mt

The model developed by SKF to evaluate the friction torque in rolling bearings has the following restrictions,

- Grease lubrication or normal methods of oil lubrication;

- For pairs of bearings, calculate the internal friction torque for each bearing and then add the two. In this case, the radial load is divided equally;
- Loads above the recommended minimum load;
- Loads constant in magnitude and direction;
- Normal operating conditions.

The total internal friction torque is given by:

$$M_{total} = \phi_{ish} \cdot \phi_{rs} \cdot M_{rr} + M_{sl} + M_{drag} + M_{seal} \tag{6.1}$$

6.1.2. Rolling friction torque - Mrr

The losses generated by rolling friction are always present in a rolling contact, either the bearing is lubricated or not.

There are several sources that contribute to the rolling friction: one is the energy required to introduce the lubricant in contact and to reject the excess, the elastohydrodynamic lubrication process, another is the energy dissipated in the process of elastic deformation that occurs in the contact.

On the other hand, the fact that obtaining pure rolling is only a mathematical idealization, since, in truth, all rolling contact contains micro-slips caused by the deformation of surfaces, which in this model are designated as sliding friction.

To account for the rolling friction torque, designated as M_{rr}, load distribution on each rolling element must be established. This depends on the load to which the bearing is submitted (axial F_a and radial F_r forces), on the bearing geometry (type, size and number of rolling elements). The contributions all rolling elements, are added together.

This influence is accounted in the model SKF by variable G_{rr}. The data concerning the geometry of the bearing is expressed by the variables R_1, and the influence of lubricant used is accounted for by two other parameters, i.e., the viscosity at operating temperature and the operating speed, that is,

$$M_{rr} = G_{rr}.\left(\nu.n\right)^{0,6} \tag{6.2}$$

For thrust roller bearings (TRB 81107 TN), G_{rr}, is defined by

$$G_{rr} = R_1 \cdot d_m^{2,38} \cdot F_a^{0,31} \tag{6.3}$$

For thrust ball bearing (TBB 51107), Grr, is defined by

$$G_{rr} = R_1 \cdot d_m^{1,83} \cdot F_a^{0,54} \tag{6.4}$$

where the values of $R1$ and dm for the bearings tested are given in Table 6.1.

Table 6.1.: Geometric constans for rolling friction torque.

Parameters	TRB - 81107 TN	TBB - 51107
R_1	2.25E-06	1.03E-06
d_m (mm)	43.5	43.5

The rolling friction torque is also affected by two other factors: inlet shear heating (ϕ_{ish} factor of energy dissipation by shear deformation in contact inlet) and kinematic replenishment / starvation (ϕ_{rs} feeding factor of the contact).

6.1.2.1. Energy dissipation in contact inlet-Inlet shear heating

In the generation of the lubricant film only a small portion of the lubricant available in the contact inlet is dragged into the high pressure zone. The lubricant that doesn't enter into the contact generates a reverse flow between the ball and raceway, as shown in Figure 6.1, causing energy dissipation and a corresponding heat flow, the increase of temperature and consequently a decrease of the lubricant viscosity.

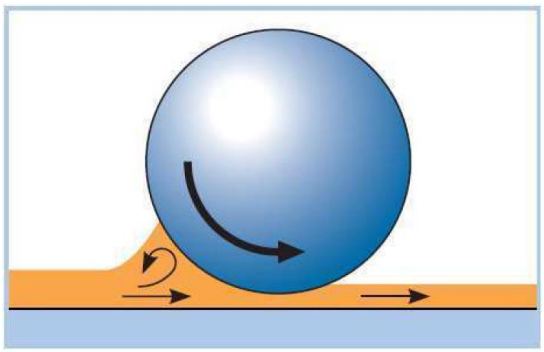


Figure 6.1.: Backflow of lubricant in the contact inlet. [4]

Equation 6.5 that describes the variation of the inlet shear heating factor, ϕ_{ish}, with the rotational speed, the average diameter and the operating viscosity of the rolling bearing.

$$\phi_{ish} = \frac{1}{1 + 1,84 \times 10^{-9} \left(n \cdot d_m\right)^{1,28} \cdot \nu^{0,64}} \tag{6.5}$$

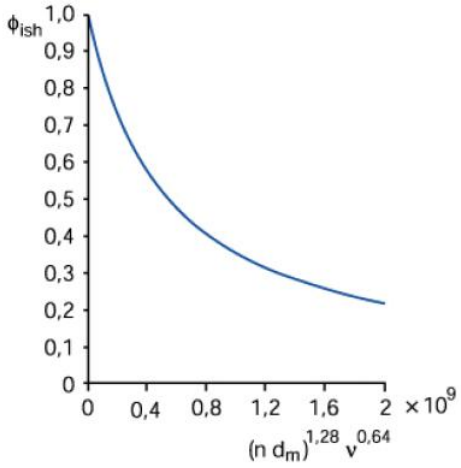


Figure 6.2.: Inlet shear heating factor. [4]

6.1.2.2. Feeding the contact - Kinematic replenishment/starvation

At high speeds or with high operating viscosities the lubricant doesn't have time to flow back into the center of the contact track after a rolling element has passed. This lack of lubrication, designated as contact starvation, generate a reduction of the volume of lubricant available in the contact, decreasing the film thickness and consequently the rolling resistance.

This effect is accounted for in the SKF model, by the replenishment factor ϕ_{rs}:

$$\phi_{rs} = \frac{1}{e^{K_{rs} \cdot \nu \cdot \eta (d+D) \cdot \sqrt{\frac{K_z}{2(D-d)}}}} \tag{6.6}$$

where Krs is a constant related to the type of lubricant and lubrication system, named by replenishment/starvation parameter and K_z is a constant related to the geometry of the bearing.

Table 6.2.: K_{rs} and geometric constant K_z for TRB and TBB. [4]

Parameters	TRB - 81107 TN	TBB - 51107
K_{rs}	3.0E-08	3.0E-08
K_z	4.4	3.8

6.1.3. Sliding friction torque - Msl

The sliding friction torque M_{sl} is defined by equation 6.7:

$$M_{sl} = G_{sl} \cdot \mu_{sl} \tag{6.7}$$

where the G_{SL} represents the influence of load and bearing geometry ($S1$) on the sliding friction torque.

For thrust ball bearings G_{SL} is given by,

$$G_{sl} = S_1 \cdot d_m^{0,05} \cdot F_a^{4/3} \tag{6.8}$$

For thrust roller bearing G_{SL} is given by,

$$G_{sl} = S_1 \cdot d_m^{0,62} \cdot F_a \tag{6.9}$$

In Table 6.3 the value of S_1 for thrust ball and roller bearings is provided.

Table 6.3.: Geometric constant S_1. [4]

Parameters	TRB - 81107 TN	TBB - 51107
S_1	1.54E-01	1.60E-02

Sliding friction is always present in a rolling/sliding contact. The sliding coefficient of friction, μ_{sl}, has two components dependent on the lubrication regime, full film lubrication (μ_{EHD}) and boundary film lubrication (μ_{bl}), and is given by equation 6.10:

$$\mu_{sl} = \phi_{bl} \cdot \mu_{bl} + (1 - \phi_{bl}) \cdot \mu_{EHD} \tag{6.10}$$

The sliding friction coefficient can be considered as the friction coefficient in mixed film lubrication, and depend on the load share function ϕ_{bl} which establishes the tangential load (F_{Tehd}) supported by the lubricant film (in full film lubrication) and the tangential load (F_{Tbl}) supported by the metal-to-metal contact (in boundary film lubrication), so that the total tangential load is given by $F_T = F_{Tehd} + F_{Tbl}$. In Table 6.4 relevant values for the friction coefficient in boundary lubrication are given for gear oils.

Factor ϕ_{bl} is strongly influenced by the additives contained in the lubricant, which increase the reaction of lubricant additives with metal surfaces, generating protective boundary films.

Table 6.4.: Friction coefficient in boundary lubrication μ_{bl}. [6]

	Min 320	PAO 320	Ester 320
μ_{bl}	0.09	0.10	0.11

The curve that depicts the typical behaviour of the friction torque as a function of rotational speed and viscosity, for conditions of mixed or boundary film ($\Delta < 2$) is shown in Figure 6.3.

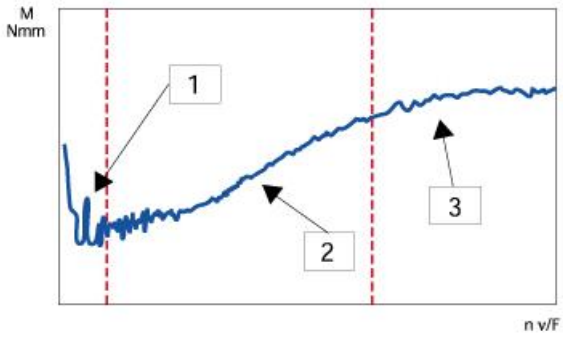


Figure 6.3.: Friction torque behaviour as a function of rotational speed and viscosity. [4]

where,

Zone 1 - Mixed film lubrication,
Zone 2 - EHD full film lubrication,
Zone 3 - EHD thermal starvation.

In zone 1 mixed film lubrication or boundary film lubrication prevails, but with increasing speed or viscosity, the friction torque decreases, a lubricating film is generated and the bearing operates in full film lubrication (zone 2). However, for very high speeds or viscosities of the friction torque increases significantly, until thermal effects and lack of lubrication in the contact center (starvation) start to reduce the friction torque again.

Factor ϕ_{bl}, given by equation 6.11, is the weighing factor between the influence of the roughness and shear rate of the lubricant, inside the contact.

$$\phi_{bl} = \frac{1}{e^{2{,}6\times10^{-8}(n\cdot\nu)^{1{,}4}dm}} \tag{6.11}$$

The evolution of ϕ_{bl} with the kinematics of the system, the rheological parameters and the geometry of the bearing is represented by equation 6.11 and its typical behaviour is shown in Figure 6.4.

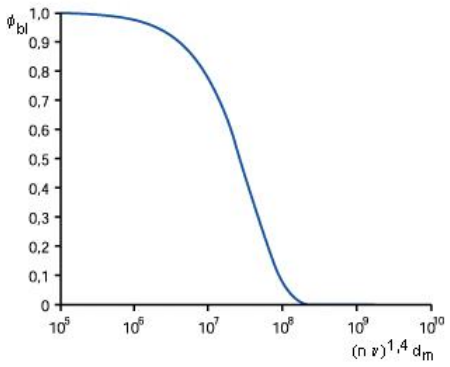


Figure 6.4.: ϕ_{bl} typical behaviour. [4]

6.1.4. Friction torque of seals - Mseal

The friction torque generated between the seal lip and the moving counterface (very often steel), may represent a large percentage of the total friction torque in rolling bearing.

The calculation methods for determining the friction torque generated by the seals will not be covered in detail, since the tests were carried out with unsealed bearings.

6.1.5. Friction torque of drag losses

The friction drag torque is only considered in oil bath lubrication, where the oil level H (see Figure 6.5) is used to determine the such drag torque.

The model for determining the torque generated by lubricant dragging presents some restrictions for very large bearings, high speeds and high oil levels, restrictions that do not apply to the tests performed.

This component of the friction torque may become very important, for completely submerged rolling bearings, where the size and geometry of the oil reservoir, thus the amount of oil used, can have significant impact on the total friction torque.

However, in this study only small bearings were used ($D_{max} = 56mm$) and the oil volume inside the bearing housing was also very small (14ml). Thus, the drag is less than 2% of the total friction torque recorded.

The drag friction torque is defined in equation 6.12:

$$M_{drag} = V_M \cdot K \cdot d_m^5 \cdot n^2 \tag{6.12}$$

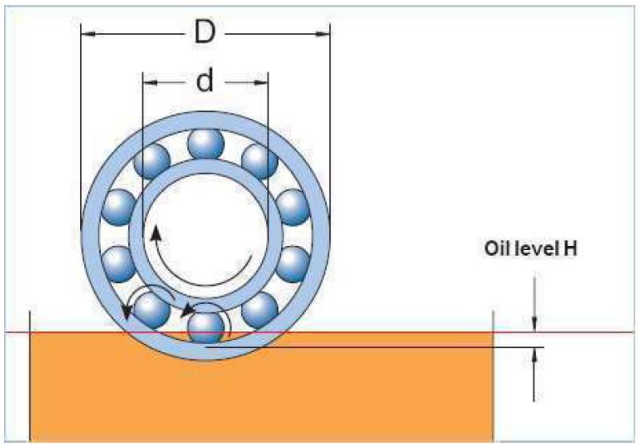


Figure 6.5.: Oil level H.

For thrust ball bearings the parameter K is given by

$$K_{ball} = \left[i_{rw} \cdot K_z \cdot \frac{(D+d)}{(D-d)} \right] \cdot 1 \times 10^{-12} \tag{6.13}$$

where, i_{rw} is the number of ball rows, and for thrust roller bearings the K parameter is defined by

$$K_{roll} = \frac{K_L \cdot K_Z \, (d+D)}{D-d} \times 10^{-12} \tag{6.14}$$

Table 6.5 gives the values of K_L and K_z for thrust ball and roller bearings.

Table 6.5.: Geometry constants K_L and K_z. [7]

Parameters	**TRB - 81107 TN**	**TBB - 51107**
K_L	0.43	-
K_Z	4.4	3.8

The drag friction torque is dependent on parameter M_V with is the ratio between the level of oil and the bearing size and K is a constant that relates the type and the geometry of the bearing.

6.1.6. Determination of sliding friction coefficient

Since the thrust roller and ball bearings (TRB 81107 TN and TBB 51107) had no seals and the drag losses produced by lubricating oils used and the operating conditions considered, were negligeable, only the rolling and sliding torques were considered. So, expression 6.1 can be rewritten as,

$$M_{total} = \phi_{ish} \cdot \phi_{rs} \cdot M_{rr} + M_{sl} \tag{6.15}$$

Through correlation with the experimental friction torque measurements ($M_{total} = M_{exp}$) it is possible determinate the sliding friction torque (M_{sl}),

$$M_{sl} = M_{exp} - \phi_{ish} \cdot \phi_{rs} \cdot M_{rr} \tag{6.16}$$

where

$$M_{rr'} = \phi_{ish} \cdot \phi_{rs} \cdot M_{rr} \tag{6.17}$$

and thus the sliding coefficient of friction (μ_{sl}) can be obtained, that is

$$\mu_{sl} = \frac{M_{exp} - \phi_{ish} \cdot \phi_{rs} \cdot M_{rr}}{G_{sl}} \tag{6.18}$$

7. Experimental Results

7.1. Testing conditions

Thrust ball and roller bearings were tested using three different lubricants typically used in windmill planetary gearboxes. Such tests are presented in Table 7.1.

Table 7.1.: Testing conditions.

Type	Reference	nº of rolling elements	speed	Lubricants
Thrust roller bearing	TRB	20	500	MIN320
	81107 TN	10	1000	PAO320
Thrust ball bearing	TBB	21	500	
	51107	7	1200	EST320

7.2. Theoretical lubricant film thickness

The EXCEL spreadsheet developed was also used to determine the lubricant film thickness inside the contact, taking into account the operating temperature (obtained by the thermocouples mounted on the bearing-housing), the geometry and kinematics of the bearings tested.

Through ASTM D341 it is possible to estimate the viscosity of lubricant at the operating temperature, and using a linear contact solution of Dowson and Higginson (TRB - SKF 81107 TN) and a point contact solution Hamrock e Dowson (TBB - SKF 51107) it is possible to estimate the lubricant film thickness in the contact.

Table 7.2 shows the operating temperatures of each one of the tests performed as well as the corresponding specific lubricant film thickness.

Table 7.2.: Maximum Hertzian pressure, operating temperature and specific lubricant film thickness.

	N° rolling elements	**n (rpm)**	Q_i **(N)**	p_0 **(Gpa)**		**MIN 320**	**PAO 320**	**ESTER 320**
TRB	20	500	333.3(3)	1.31	T_0	60.0 °C	56.4 °C	60.1°C
					Λ_{0c}	1.54	1.609	1.443
	10	1000	1000	1.85	T_0	92.0 °C	79.8 °C	80.7°C
					Λ_{0c}	0.948	1.374	1.364
TBB	21	500	350	2.48	T_0	47.5°C	46.2°C	46.5°C
					Λ_{0c}	1.467	1.521	1.364
	7	1200	700	3.58	T_0	78.3°C	70.1°C	74.6°C
					Λ_{0c}	0.910	1.192	1.091

Figures 7.1 to 7.4 show the thermally corrected lubricant film thickness (h_{0c}) in the contact between roller and raceway (TRB) and between ball and raceway (TBB) in all testing conditions and with all oils tested.

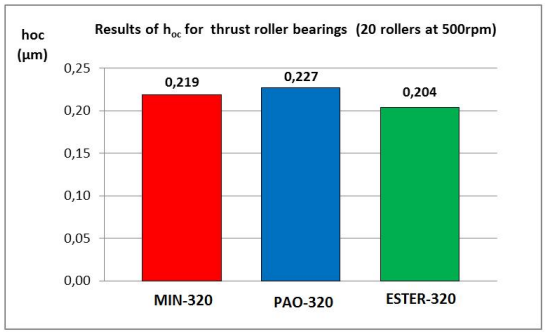


Figure 7.1.: Lubricant film thickness in TRB - 20 rollres

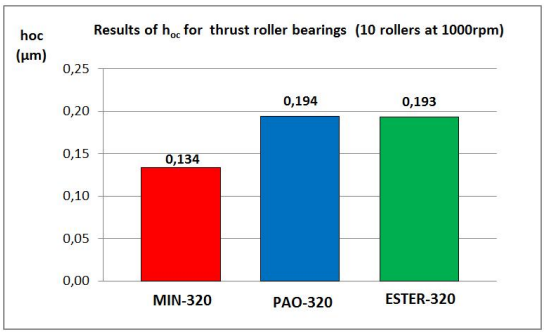


Figure 7.2.: Lubricant film thickness in TRB - 10 rollers

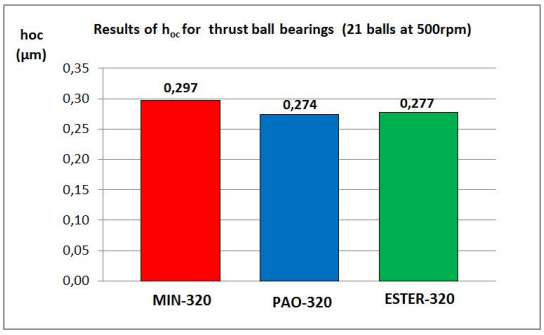


Figure 7.3.: Lubricant film thickness in TBB - 21 balls

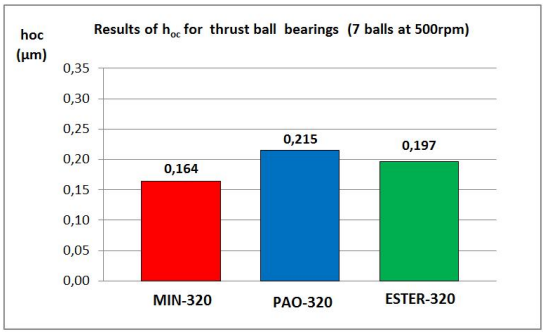


Figure 7.4.: Lubricant film thickness in TBB - 7 balls

7.3. Maximum Hertz pressure

An EXCEL spreadsheet was developed to analyse all aspects of point and line contacts and determine: i) contact pressure, contact ellipse dimensions and penetration, ii) sub-surface stress and location of maximum shear stress and maximum orthogonal shear stress, iii) lubricant film thickness and lubrication regime, and finally iv) contact coefficient of friction, among several other parameters.

As mentioned before, the applied load is normal to the common tangent plane, so there isn't any tangential load applied. The pressures inside the contact area, are unknown, but necessarily normal to the contact surface, compressive and greater than zero.

Table 7.3 shows the radius of curvature of the contacting surfaces inside the thrust roller and ball bearings, where x is the direction of the rolling speed.

In the wear tests performed with the thrust ball bearings (TBB) and thrust roller bearings (TRB) (SKF 51107 and SKF 81107 TN), the maximum axial load that can be applied in the Four-Ball machine is 8000N. All the tests were performed with an axial load of 7000N, in order to avoid any type of damage to the Four-Ball machine.

In the wear tests performed with "full" bearings (F_n = 7000N and $2h + 48h$), either roller or ball bearings, the bearings components, raceways and rollers/balls showed no significant wear.

To increase the severity of the tests, rollers and balls were removed from the corresponding bearings. In the 81107 TN TRB 10 of the 20 rollers were removed. In the 51107 TBB 14 of the 21 balls were removed and the tests were performed with 7 balls.

The removal of rollers and balls affect the contact pressure between the rolling bearing components, as shown in Tabe 7.2.

Table 7.3.: Radius of curvature (where x is the direction of rolling)

	Thrust roller bearing		**Thrust ball bearing**	
	Raceways	Rollers	Raceways	Balls
Rx (m)	∞	2.50E-03	∞	3.00E-03
Ry (m)	∞	∞	-3.38E-03	3.00E-03

7.4. Friction torque obtained from the torque cell

The rolling bearings were tested according to the procedure presented in section 5.2, and measurements of the bearing friction torque and of the operating temperature were made using the torque cell and the thermocouples. Table 7.4 and Figures 7.5 and 7.6 show the friction torque measurements obtained for thrust roller and ball bearings.

Table 7.4.: Rolling bearing measurements - Friction torque and operating temperature with F_n=7000N.

Type	n° of rolling elements	speed	MIN-320		PAO-320		EST-320	
			N.mm	°C	N.mm	°C	N.mm	°C
Thrust roller bearing	20	500	424,4	60.0	452.0	56.4	448.0	60.1
	10	1000	385.5	92.0	332.3	79.8	337.5	80.7
Thrust ball bearing	21	500	283.5	47.5	272.8	46.2	293.4	46.5
	7	1200	220.2	78.3	240.5	70.1	233.3	74.6

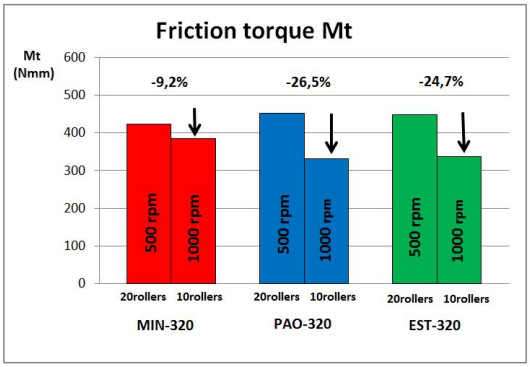


Figure 7.5.: Mt for thrust roller bearings (TRB 81107 TN).

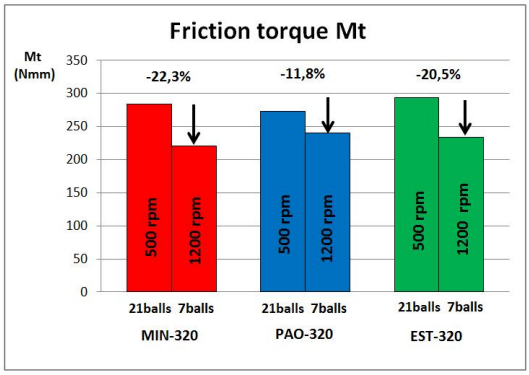


Figure 7.6.: Mt for thrust ball bearings (TBB 51107).

Table 7.4 and Figures 7.5 and 7.6 show a significant operating temperature increase and friction torque decrease when the number of rolling elements were reduced and the speed increased. This trend was observed for thrust ball and roller bearings whatever the lubricant tested, and can be easily explained by the increasing severity of the test when the operating conditions are modified. The reduction of the number of rolling elements increases the load supported by each one (for a constant operating axial load of 7000N). Simultaneously, the higher operating speed generates a higher operating temperature, leading to lower operating viscosity and lower specific lubricant film thickness.

The sliding friction coefficient μ_{sl}, calculated through equation 6.18, is presented in Table 7.5 for the TRB and TBB.

Table 7.5.: Sliding friction coefficient μ_{sl} with Fn=7000N.

Type	**nº of rolling elements**	**speed**	**MIN-320**		**PAO-320**		**EST-320**	
			μ_{sl}	**°C**	μ_{sl}	**°C**	μ_{sl}	**°C**
Thrust roller bearing	20	500	0.0220	60.0	0.0213	56.4	0.0220	60.1
	10	1000	-	92.0	-	79.8	-	80.7
Thrust ball bearing	21	500	0.0663	47.5	0.0591	46.2	0.0666	46.5
	7	1200	-	78.3	-	70.1	-	74.6

The μ_{sl} values are not given for the tests carried out with the "modified bearings" (see Table 7.5) since the friction torque model is not prepared for geometrically modified bearings. The model has several constraints related to a external/internal geometry which can not be modified, namely G_{rr} and G_{sl}.

7.4.1. Rolling, sliding and total friction torque in standard bearings

7.4.1.1. Thrust roller bearings (TRB 81107 TN) - 20 rollers

Figure 7.7 shows the operating temperature, the specific film thickness, the kinematic viscosity, the rolling, sliding and total friction torques, and the sliding coefficient of friction for the thrust roller bearings.

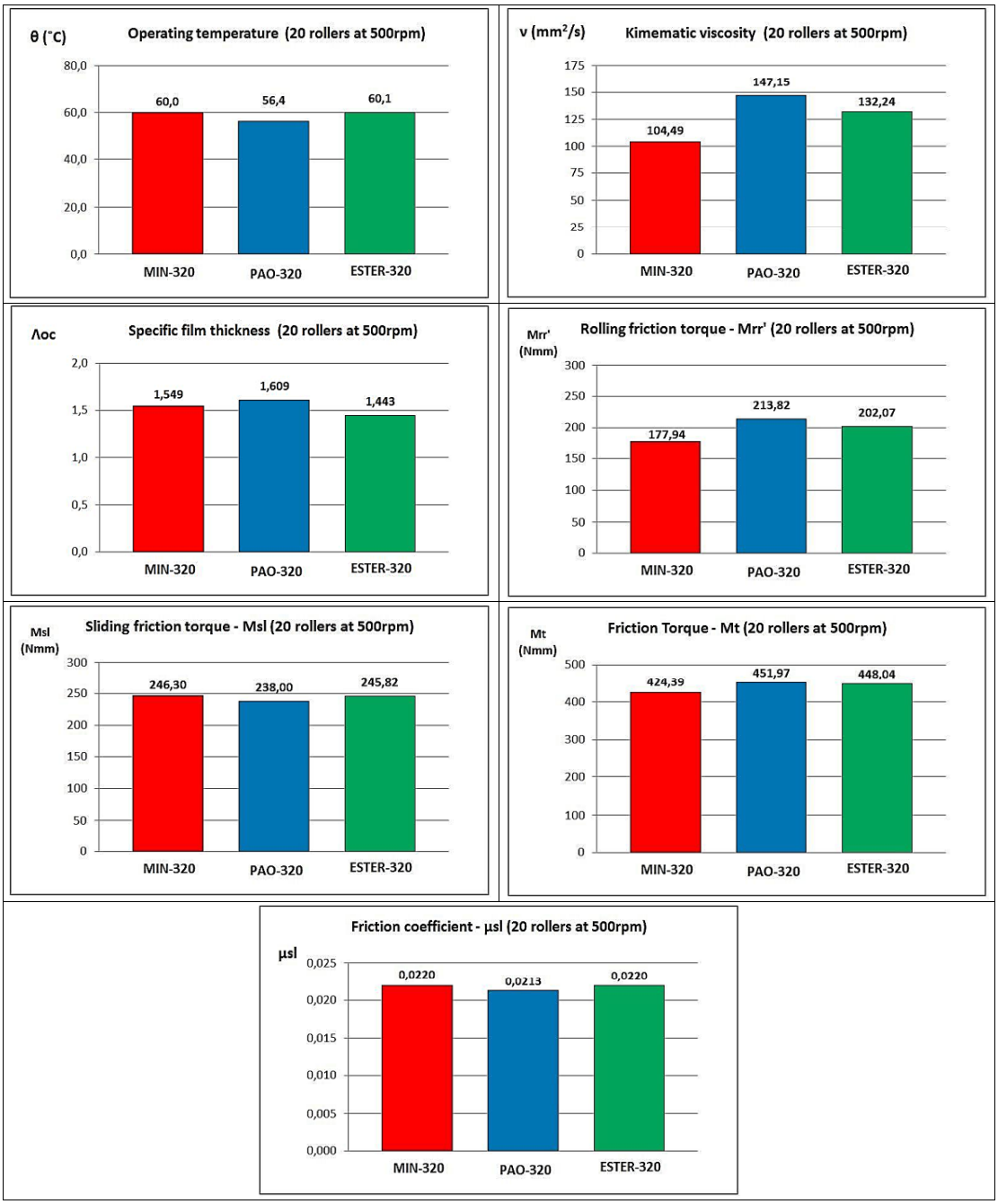


Figure 7.7.: Operating temperature, specific film thickness, kinematic viscosity, $M_{rr'}$, M_{sl}, Mt and μ_{sl} for TRB 81107 TN.

7.4.1.2. Thrust ball bearings (TBB 51107) - 21 balls

In Figure 7.8 shows the operating temperature, the specific film thickness, the kinematic viscosity, the rolling, sliding and total friction torques, and the sliding coefficient of friction for the thrust ball bearings.

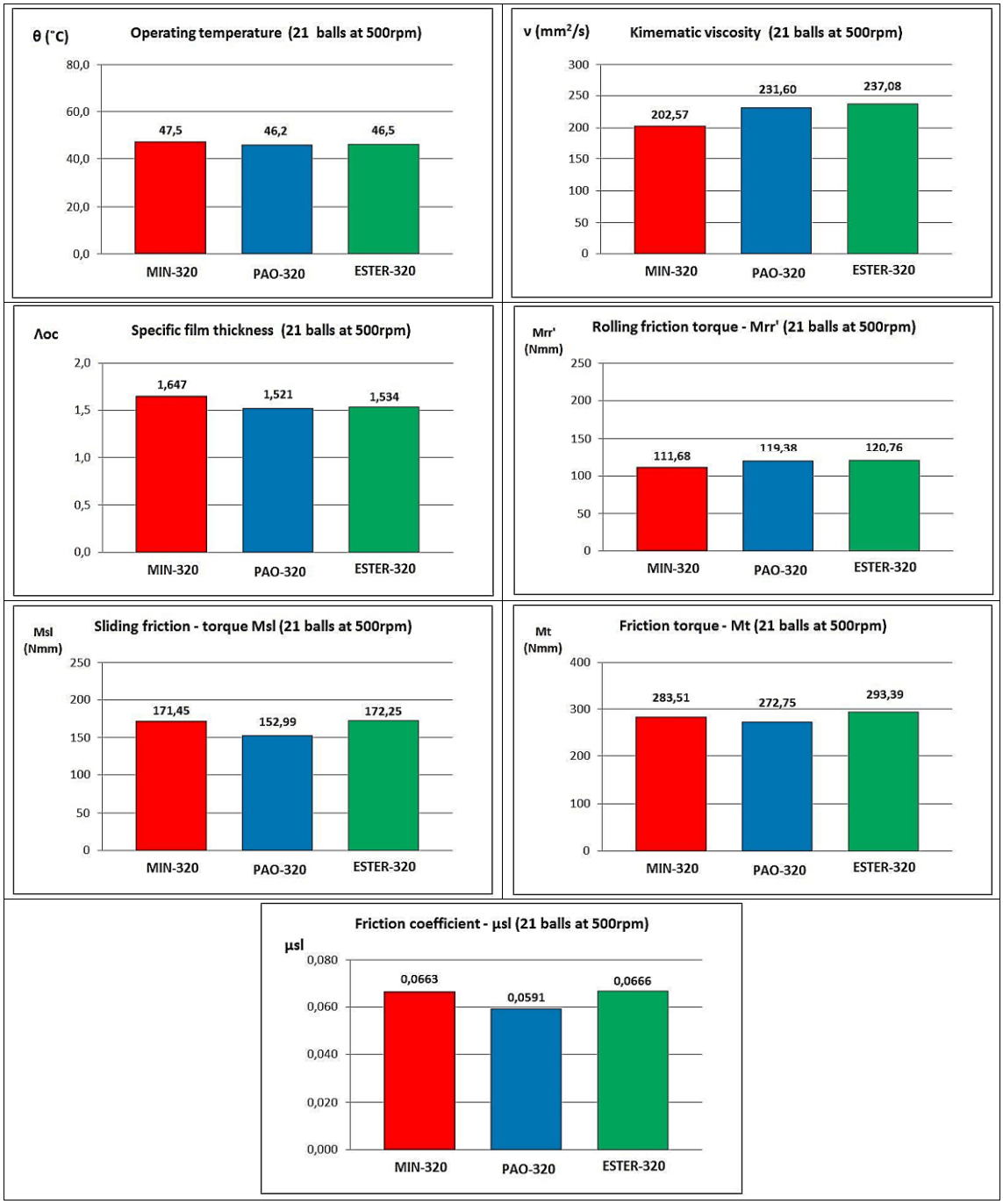


Figure 7.8.: Operating temperature, specific film thickness, kinematic viscosity, $M_{rr'}$, M_{sl}, Mt and μ_{sl} for TBB 51107.

7.4.1.3. Comparison between thrust ball bearing (21 balls) and thrust roller bearings (20 rollers)

Although there are significant differences on the operating viscosity, all the tests were carried out in the same lubrication regime ($1 < \Lambda < 3$, mixed film lubrication regime).

A direct relation between the rolling torque and the operating viscosity is seen in Figures 7.7 and 7.8, as expected. The highest the viscosity the highest the lubricant shear stress, and consequently, the highest is the resistance imposed to the rolling elements by the lubricant, i.e., the rolling torque is higher for higher oil viscosities. This behaviour (M_{rr}) is represented by equation 6.2.

The sliding torque values are quite similar for all tested oils, which was expected since the specific film thickness are also very similar. In mixed film lubrication the metal-to-metal contact of the asperities occurs due to the rolling-sliding between the raceway and rolling elements. The higher is Λ, the lower will be the coefficient of friction between the contacting asperities and consequently the sliding torque.

In the case of the thrust roller and ball bearings tested, with 20 rollers and 21 balls, at 500 rpm, the values of the operating specific film thickness are very similar: between 1.44 and 1.61 for TRB and between 1.52 and 1.65 for TBB. Consequently, the values of the sliding torque and of the sliding coefficient of friction are also very similar: 0.021-0.22 for TRB and 0.059-0.66 for TBB.

The small differences observed are related to the different base oils and additive packages of each gear oil formulation tested. The MINERAL and ESTER oils showed similar slidding coefficients of friction, while the PAO oil presented a slightly lower μ_{sl} value.

The sliding torque, which depends mainly on Λ, lubricant nature and additives package, follows exactly the same trends for the TBB and for TRB. This was expected since the Λ values are quite similar, i.e., the oil nature and additive package behaved in a similar way at the imposed operating conditions.

The total friction torque is the sum of the rolling and sliding torque (Eq. 6.15) and therefore does not present any linear relation with the lubricant properties and operating conditions.

It is clear that the operating temperatures are higher for TRB than for TBB whatever the oil used.

The rolling friction torque in TBB is lower than in TRB. Whatever the rolling bearing type, the MINERAL oil always generated a lower M_{rr} (higher temperature, lower viscosity) than the other two oils.

The sliding friction torque M_{sl} is almost independent of the oil type, but M_{sl}

in TBB in lower than in TRB. The rolling Mrr and M_{sl} torques in TBB are lower than in TRB, consequently, the total friction torque in TBB are also lower than in TRB.

The coefficient friction, μ_{sl}, in TBB is higher than in TRB, although the M_{sl} in TBB is lower than in TRB; this fact is due the geometric factor G_{sl} (rollers and for balls).

7.4.2. Friction torque and operating temperature in modified bearings

7.4.2.1. Thrust roller bearing (TRB 81107 TN) - 10 rollers

Figure 7.9 shows the operating temperature, the kinematic viscosity, the specific film thickness and the rolling friction torque for the modified thrust roller bearings (10 rollers).

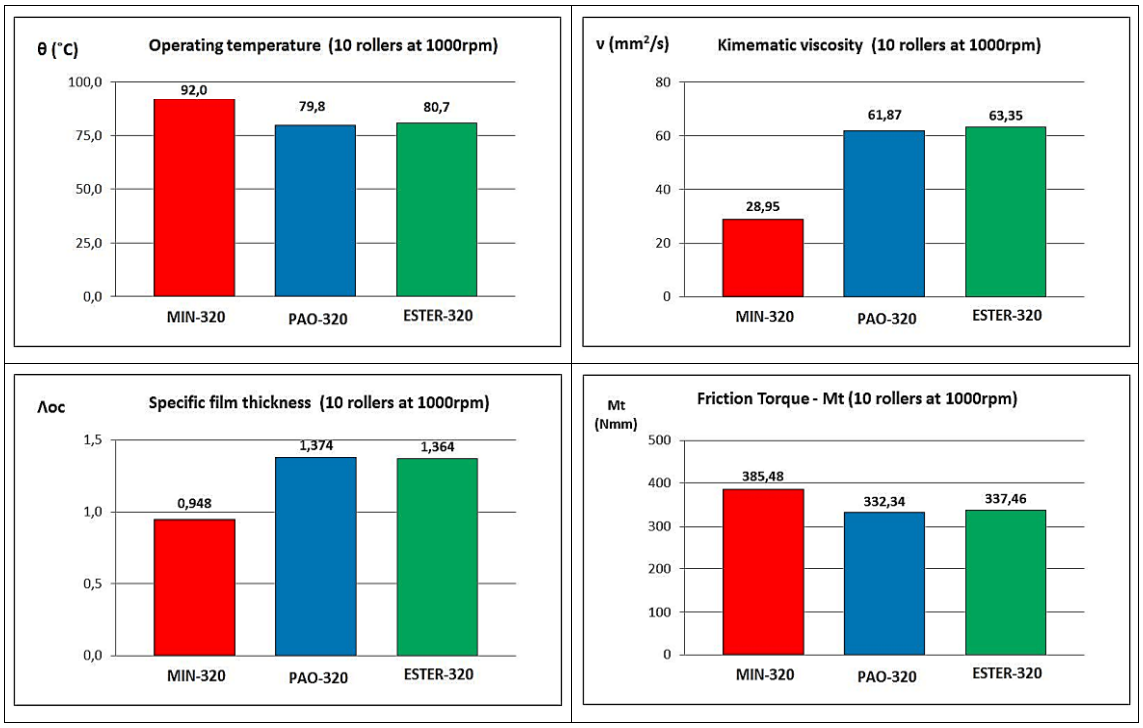


Figure 7.9.: Operating temperature, kinematic viscosity, specific film thickness and Mt for the modified TRB 81107 TN (10 rollers).

From the results presented in Figures 7.7 and 7.9 a general trend is observed. The higher operating speed (n=1000rpm) generates higher operating temperature, lower lubricant viscosities and, consequently, the specific film thickness decreases. It leads to significantly lower rolling torque, that mainly depends on viscosity and on

the number of rollers, and thus to lower total friction torque.

The total friction torque presented similar values for the PAO and ESTER oils, and higher values for the MINERAL oils, which can be directly related to the significant lower specific film thickness, ($\Lambda = 0,95$), since the bearings lubricated with MINERAL oil operated in boundary film lubrication ($\Lambda < 1$) while the bearings lubricated with ESTER and PAO oils operated in mixed film lubrication.

7.4.2.2. Thrust ball bearing (TBB 51107) - 7 balls

Figure 7.10 shows the operating temperature, the kinematic viscosity, the specific film thickness and the rolling friction torque for the modified thrust roller bearings (7 balls).

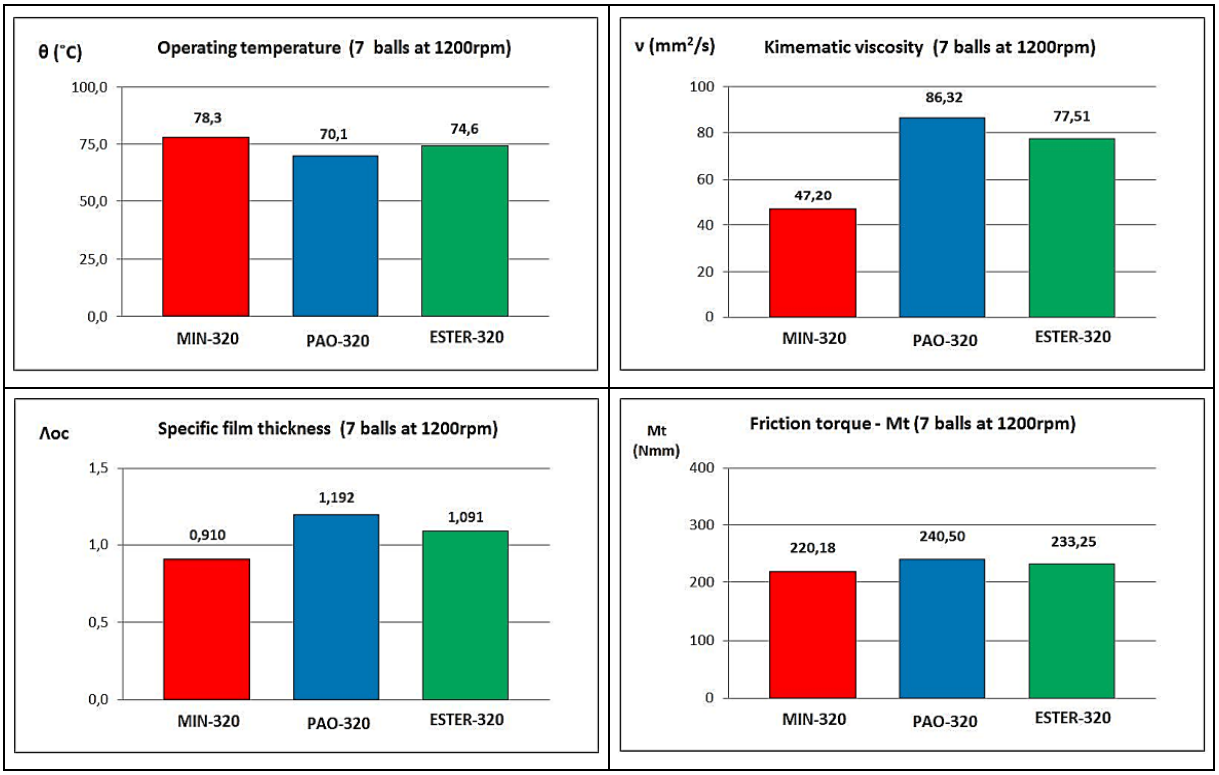


Figure 7.10.: Operating temperature, kinematic viscosity, specific film thickness and Mt for the modified thrust ball bearings 51107 (7 balls).

From the results presented in Figures 7.8 and 7.10, such as in the case of thrust roller bearings, a general trend is observed. The higher operating speed (n=1200 rpm) generates higher operating temperature, lower lubricant viscosities and, consequently, lower specific film thickness. It leads to significantly lower rolling torque , that mainly depends on viscosity and on the number of balls and thus to lower total friction torque.

The values of the specific film thickness are similar ($0,91 < \Lambda < 1,19$) and consequently the values of the total friction torque are also similar.

7.4.2.3. Comparison between thrust ball bearing (7 balls) and thrust roller bearings (10 rollers)

As well as in the case of the standard rolling bearing (21 balls and 20 rollers), the operating temperatures of the TRB are higher than those of the TBB, whatever the oil type used.

It is clear that the MINERAL oil generated a lower operating viscosity (whatever the rolling bearing type). The PAO and ESTER oils generates a similar operating viscosity, higher than operating viscosity of the MINERAL oil.

The total friction torque (measured) in TBB is lower in TRB whatever the oil type tested. However, the MINERAL oil generates a total friction torque (M_t)significantly higher than the PAO and ESTER oils for thrust roller bearings, whereas in the thrust ball bearings the MINERAL oil generates a lower M_t in relation to the PAO and ESTER oils.

7.5. Wear to the thrust ball bearings 51107

In the case of the wear tests performed with thrust ball bearings, using 21 and 7 balls, the bearing used for each type of oil was always the same, that is, for the same oil the bearing tested with 21 balls at 500 rpm is the same bearing tested with 7 balls at 1200 rpm. In other words, 14 balls were taken from the bearing with the aim of increasing the load on each ball (F_n=7000N, limit imposed by the Four-Ball machine). Figure 7.11 shows the test stages of the thrust ball bearings.

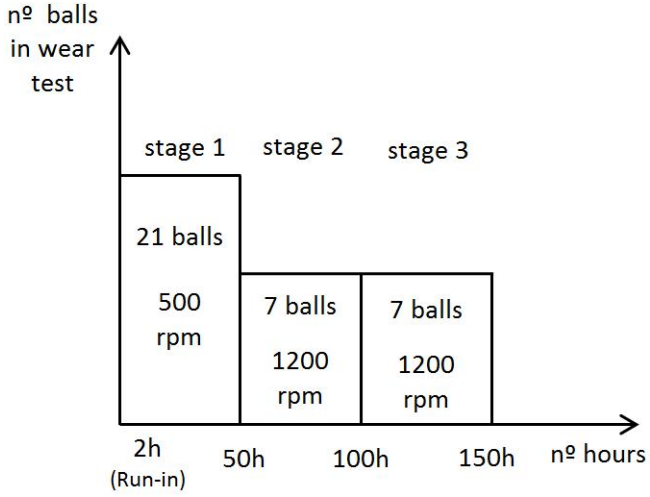


Figure 7.11.: Number of balls in the wear tests.

The parameter used for assessing the behaviour of the different lubricants was the bearing mass loss. The mass loss obtained in each bearing (associated with a type of oil) at the end of the three tests (first 50h with 21 balls at 500rpm and then two times 50h with 7 balls at 1200rpm) is presented in Table 7.6.

Table 7.6.: Total mass loss at the end of the three tests, operating temperature, specific film thickness during stage 2 and CPUC and ISUC indexes.

Thrust ball bearings		**MIN-320**	**PAO-320**	**EST-320**
Mass loss - stage 1+2+3 (mg)		7	3	10
Temperature - stage 2 (°C)		78.3	70.1	74.6
Specific film thickness - stage 2 (Λ)		0.910	1.192	1.091
CPUC	**stage 1**	99.6	50.9	135.1
	stage 2	93.9	82.2	1358.0
	stage 3	5500.0	369.0	8100.0
ISUC	**stage 1**	3.2E+03	1.1E+03	8.0E+03
	stage 2	4.5E+03	3.7E+03	1.2E+08
	stage 3	1.2E+07	8.3E+04	5.1E+07

As shown in Table 7.6, the evolution of the mass loss (ML) during the tests establishes that:

$$ML_{PAO} < ML_{MINERAL} < ML_{ESTER}$$

The results of the CPUC and ISUC indexes, presented in Table 7.6 and Figures 7.12 and 7.13, have the same tendency of the mass loss results, that is:

$$CPUC_{PAO} < CPUC_{MIN} < CPUC_{ESTER}$$

and

$$ISUC_{PAO} < ISUC_{MIN} < ISUC_{ESTER}$$

whatever the test stage considered 1^{st} with 21 balls and 2^{nd} and 3^{rd} with 7 balls.

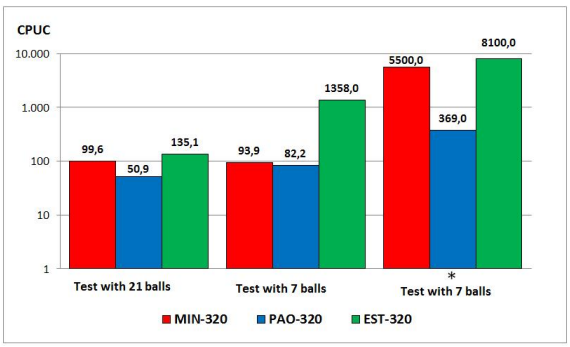


Figure 7.12.: CPUC - wear particle concentration index (SKF 51107).

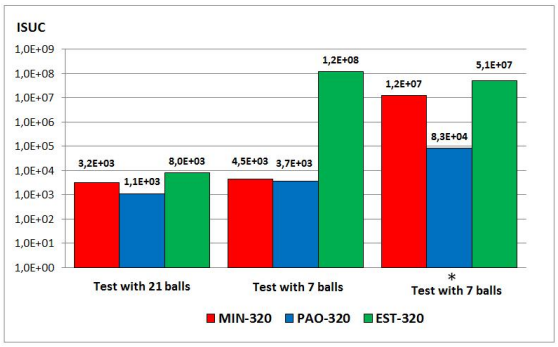


Figure 7.13.: ISUC - wear severity index (SKF 51107).

However, as can be seen in Figures 7.12 and 7.13, there is a large increase in the CPUC and ISUC indexes from the second to the third test. It should be noticed that in the case of the third test (*) the CPUC and ISUC indexes obtained for the PAO oil don't correspond to a complete test (50h), since, due to a spalling failure the test only lasted 5 hours.

The fhotographs of the ferrograms obtained by Analytical Ferrography and the CPUC and ISUC indexes obtained by Direct Reading Ferrography, during the first test stage (21 balls, 500rpm, 48h), are shown in Figure 7.14.

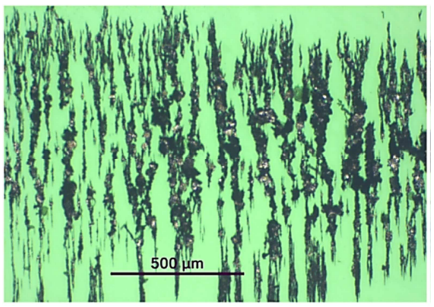
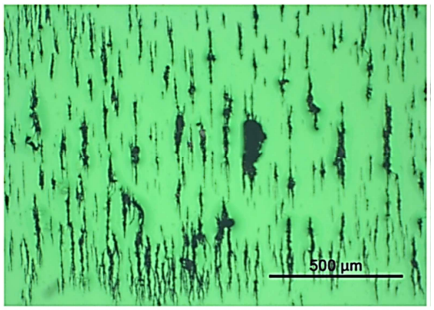
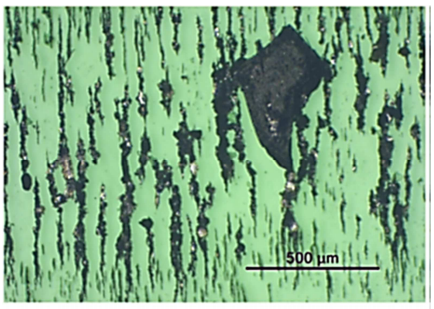
Analysis of Lubricants – Analytical Ferrography and Ferrometry		
	Thrust ball bearing (21 balls)	**Wear (48h)**
MIN - 320		d = 1 DL = 65,9 DS = 33,7 CPUC = 99,6 ISUC = 3,2E+03
PAO - 320		d = 1 DL = 36,1 DS = 14,8 CPUC = 50,9 ISUC = 1,1E+03
ESTER - 320		d = 1 DL = 97,2 Ds = 37,9 CPUC = 135,1 ISUC = 8,0E+03

Figure 7.14.: Analytical Ferrography and Direct Reading Ferrography.

The images of the ferrograms shown in Figure 7.14 concern in the zone of greatest concentration of wear particles (beginning of the ferrogram).

Comparing the images of the ferrograms with the values of the CPUC and ISUC indexes, it is clear that they agree with each other. Thus, PAO oil has a lower wear index and a lower severity index and the corresponding ferrogram presents significant less particles than those corresponding to the MINERAL and ESTER oils.

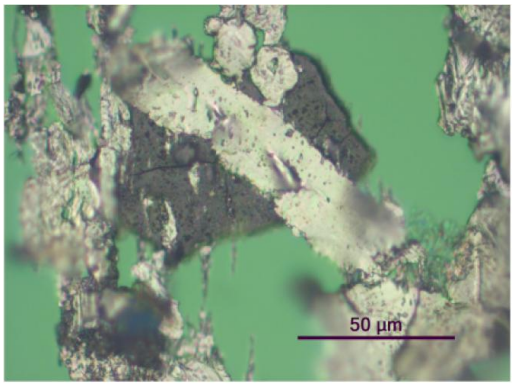


Figure 7.15.: MIN-Ferrogram 1

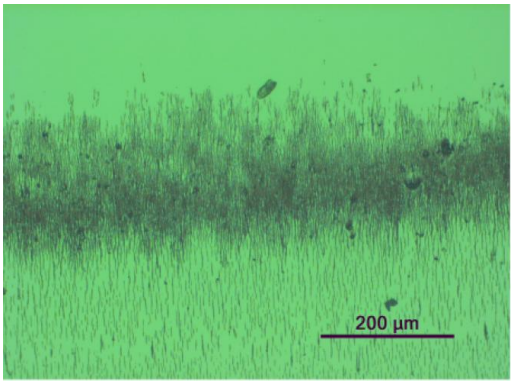


Figure 7.16.: MIN-Ferrogram 2

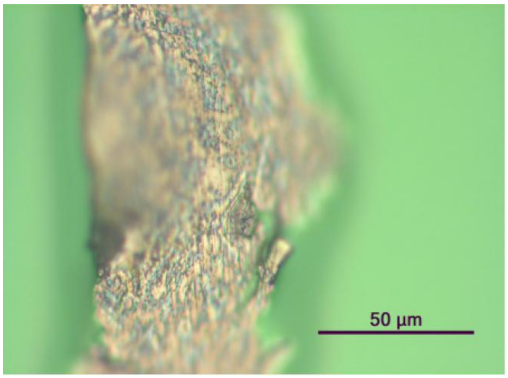


Figure 7.17.: PAO-Ferrogram 1

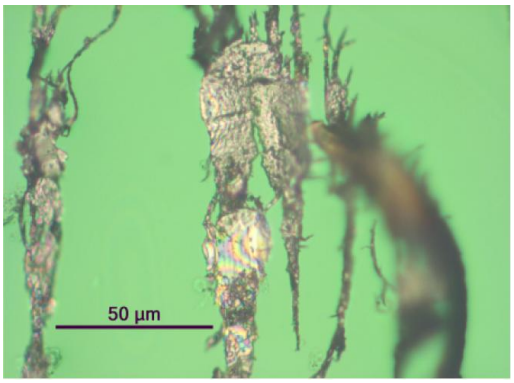


Figure 7.18.: PAO-Ferrogram 2

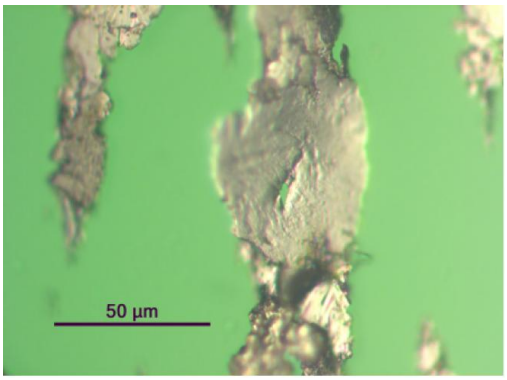


Figure 7.19.: ESTER-Ferrogram 1

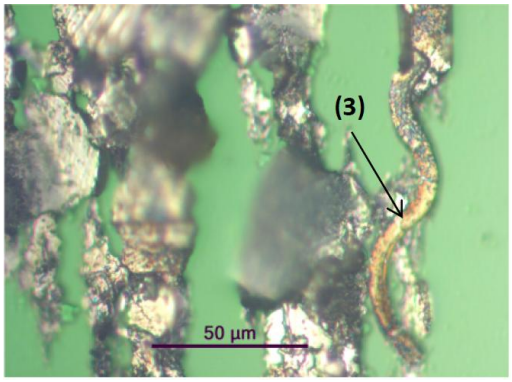


Figure 7.20.: ESTER-Ferrogram 2

In the ferrogram of the MINERAL oil, ferrous particles of small and large dimensions are observed. Using a higher magnification, the presence of many ferrous particles of large dimensions (some severely oxidized) are observed (see Figure 7.15). Figure 7.16 shows wear particles of very small dimensions, typical of corrosion wear (see Annex A.9), found near the exit of the ferrogram.

The PAO oil ferrogram also shows small and large ferrous particles. Magnifying its large ferrous particles, some severely oxidized are observed (see Figure 7.17). A significant presence of very fine and long particles, resulting from cutting wear are shown in Figure 7.18.

In the case of the ESTER oil, very large particles, typical of fatigue wear, are shown in Figure 7.19), and also cutting wear particles (see Figure 7.20).

For the other tests (7 balls, 1200 rpm, 50h+50h), the results obtained through Analytical Ferrography are also in conformity with Direct Reading Ferrography results. In Annex (A.10) the comparisons between the results from the two types of ferrography analysis as well as the individual analysis of each sample are presented.

It is important to notice that the fact of the higher wear observed (CPUC and ISUC) in the case of tests with ESTER oil in relation to the tests with the MINERAL and PAO oils can be related to the polarity of the ester oil. Once the forces of attraction (Van der waals) between the bearing surface and the additive molecules are governed by the polarity, in other words, a polar base oil will compete with additives (also polar) on the surface, making the action of additives less effective. The fact that the ESTER base oil is a polar oil may justify the greatest wear observed relatively to the PAO oil (although there are no significant differences in specific film thickness). What may also contribute to the worst performance of the ESTER oil, is the fact that it is biodegradable and so its additives are probably less toxic which can give rise to less effective additives.

Looking at the bearings raceways (micrographs of the raceways) at the end of the first two test stages (21 balls, 500 rpm plus 7 balls at 1200 rpm, see Figure 7.21), it is clear that the bearing raceways lubricated with ESTER oil are almost polished compared with the new surface, and in the case of the MINERAL oil some very small pits are observed. In the case of the bearing raceway lubricated with PAO a very mild wear is observed.

So, the analysis of the ferrography results (images of ferrograms, CPUC and ISUC indexes) and micrographs of the bearings raceways have the same tendency of the mass loss results.

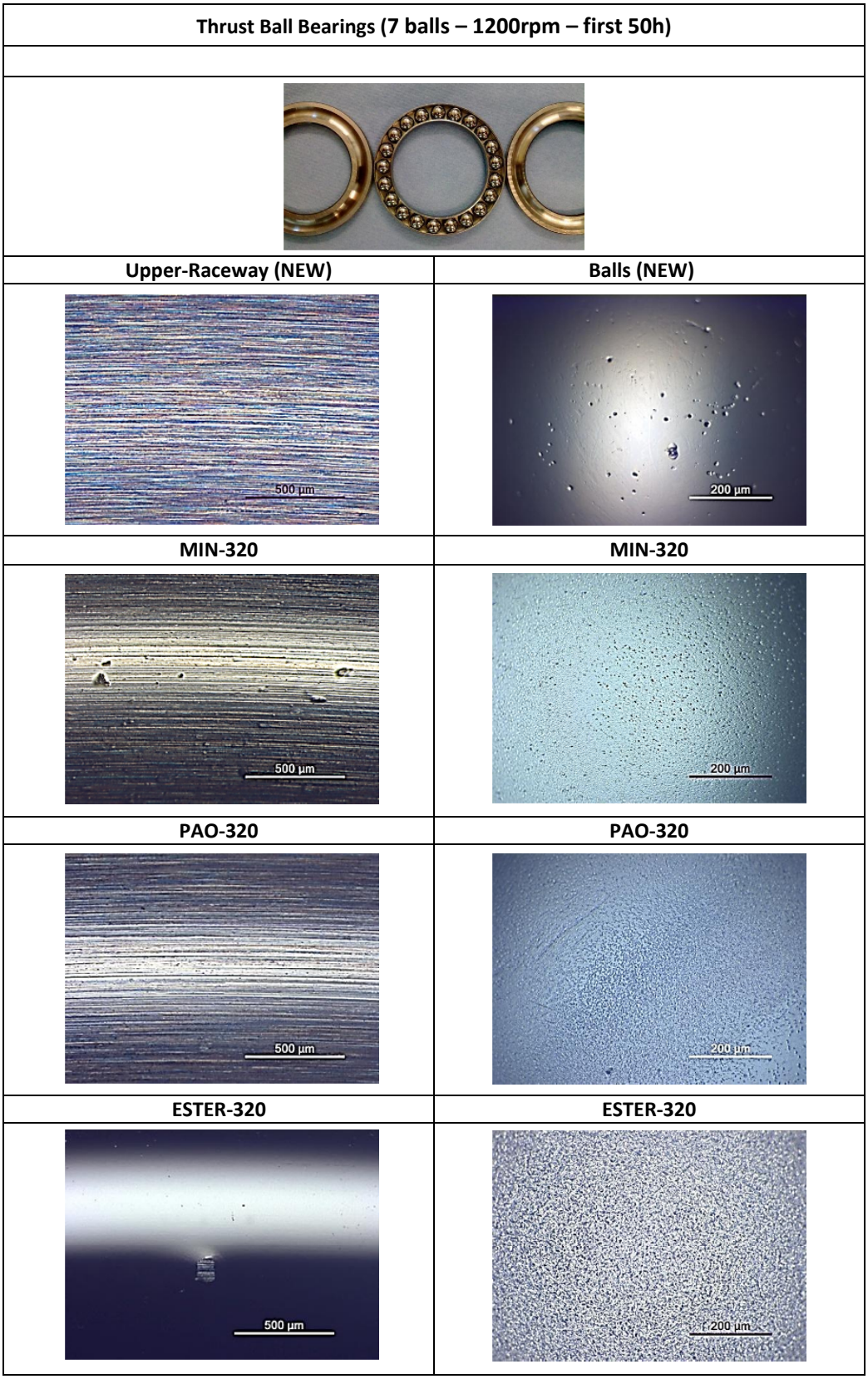


Figure 7.21.: Micrographs of the raceways and balls at the end of the test stage 2.

In the case of the TBB lubricated with ESTER oil, a small spall was observed in the raceway, meaning that a small particle has been released from the surface(see figure 7.22).

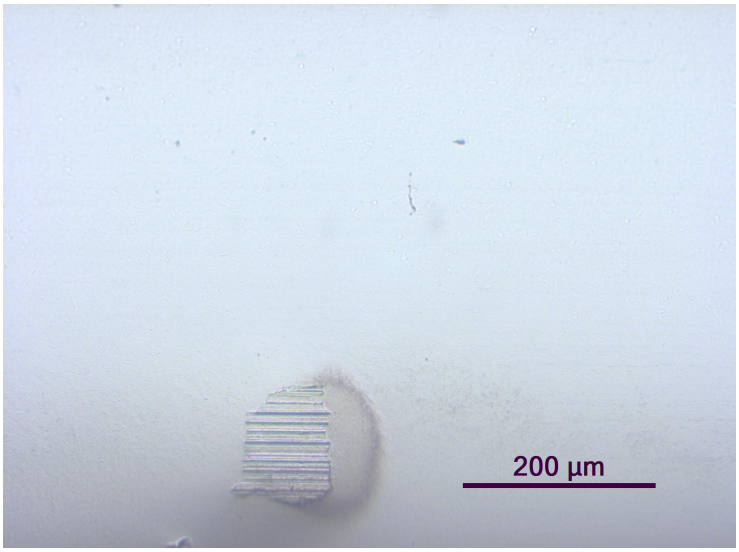


Figure 7.22.: Loose particle from the surface (typical of the phenomenon of spalling).

In the case of the bearing lubricated with PAO oil, many tiny micropitts can be observed on the ball wear track. This phenomenon may be related to the manufacturing process of the balls, since there may be local changes in the structure due to overheating in the forging process [17]. In the case of the raceways lubricated with MINERAL and ESTER oils very significant micropitting was observed in all the surfaces of the balls, specially in the case of the balls lubricated with the ESTER oil. This might explain that the CPUC and ISUC indexes are higher in the case of the ESTER oil.

It is important to notice that the last test stage with the PAO oil lasted only 5 hours due to the spalling generated by the surface fatigue failure. This phenomenon has origin in microstructural defects (for example: inclusions) and as can be seen in figure 7.23 were the raceway surface presents a large spall.

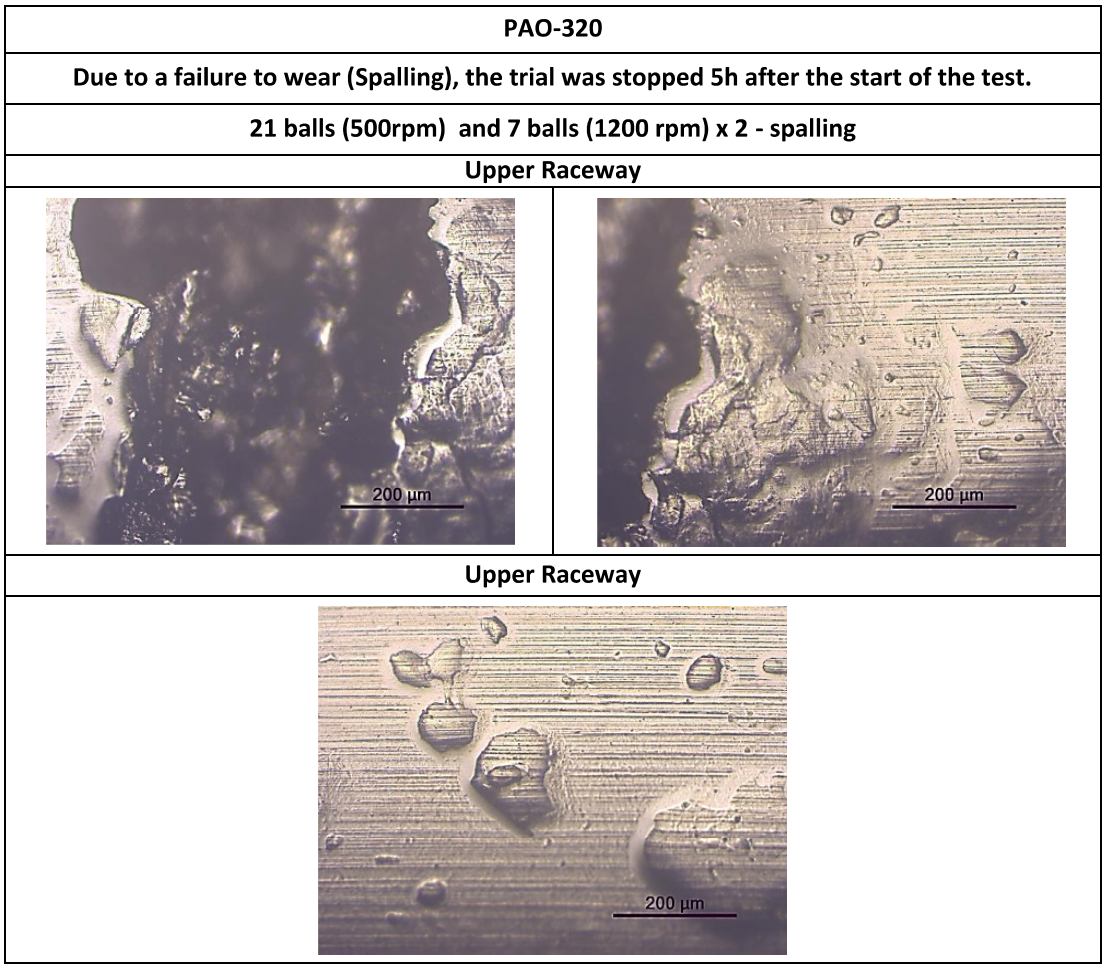


Figure 7.23.: Fatigue failure (Spalling).

Another way to evaluate surface wear is through the roughness parameters. As mentioned above, surface roughness 3D parameters were obtained from the topography measurements performed on the bearing raceways at the end of each test. Figure 7.24 shows the raceway surfaces, the roughness profiles in radial direction, as well as the evolution of the 3D roughness parameters of the surfaces Sp/Spo and Sv/Svo.

Where,

Sp - Surface maximum height,

and

Sv - Maximum depth of surface.

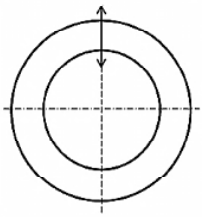
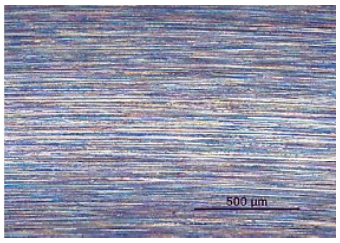
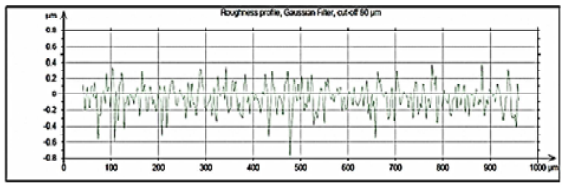
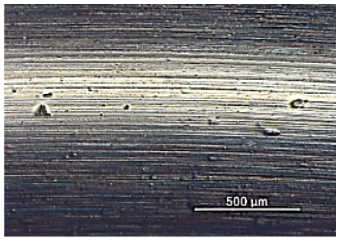
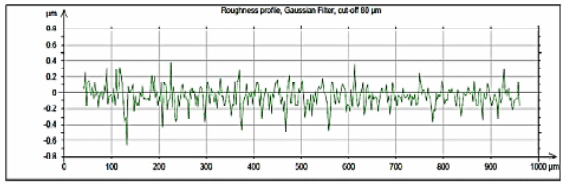
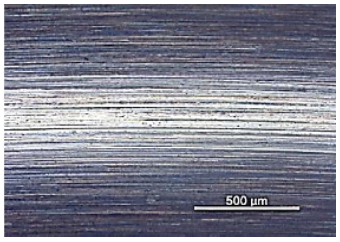
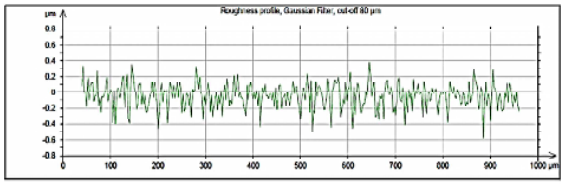
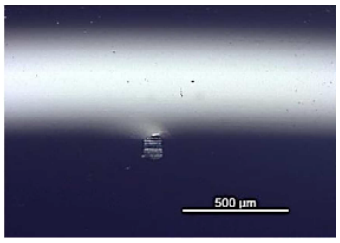
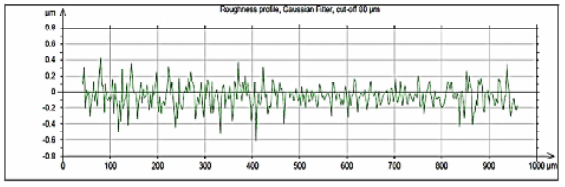
Upper Raceway (7 balls – 1200rpm – first 50h) – Contact Zone			
		Roughness profile direction 	**Specific film thickness** **Mass Loss** **Parameters for comparison**
NEW		 Sa=0,12 µm; Sq=0,16 µm; St=1,73 µm; Sp=0,79 µm; Sv=0,95 µm	/
MIN -320		 Sa=0,11 µm; Sq=0,14 µm; St=2,07 µm; Sp=0,80 µm; Sv=1,27 µm	λ = 0,910 1 mg $\frac{S_P}{S_{P0}} = 1,01$ $\frac{S_v}{S_{v0}} = 1,34$
PAO-320		 Sa=0,11 µm; Sq=0,14 µm; St=1,79 µm; Sp=0,84 µm; Sv=0,94 µm	λ = 1,192 0 mg $\frac{S_P}{S_{P0}} = 1,06$ $\frac{S_v}{S_{v0}} = 0,99$
ESTER-320		 Sa=0,11 µm; Sq=0,14 µm; St=1,85 µm; Sp=0,87 µm; Sv=0,98 µm	λ = 1,091 7 mg $\frac{S_P}{S_{P0}} = 1,10$ $\frac{S_v}{S_{v0}} = 1,03$

Figure 7.24.: Roughness profiles of the surfaces at the end of the second test.

In Annex (A.2, A.3 and A.4) all the topographies and the corresponding roughness parameters are presented. Table 7.7 shows the evolution of the roughness parameters during the tests.

Table 7.7.: Evolution of roughness parameters.

Test	Bearing (new)	MIN-320	PAO-320	EST-320
21 balls at 500 rpm (1)	St0 = 1.73	St1 = 2.21	St1 = 1.86	St1 = 2.43
	Sp0 = 0.79	Sp1/Sp0 = 1.05	Sp1/Sp0 = 1.03	Sp1/Sp0 = 1.20
	Sv0 = 0.95	Sv1/Sv0 = 1.46	Sv1/Sv0 = 1.09	Sv1/Sv0 = 1.16
		St1/St0 = 1.28	St1/St0= 1.08	St1/St0 = 1.40
7 balls at 1200 rpm (2)	/	St2 = 2.07	St2 = 1.79	St2 = 1.85
		Sp2/Sp1 = 0.96	Sp2/Sp1 = 1.04	Sp2/Sp1 = 0.92
		Sv2/Sv1 = 0.91	Sv2/Sv1 = 0.90	Sv2/Sv1 = 0.68
		St2/St1 = 0.94	St2/St1 = 0.96	St2/St1 = 0.76
7 balls at 1200 rpm (3)	/	St3 = 3.73	St3 = 3.37	St3 = 2.51
		Sp3/Sp2 = 1.06	Sp3/Sp2 = 1.30	Sp3/Sp2 = 1.40
		Sv3/Sv2 = 2.28	Sv3/Sv2 = 2.85	Sv3/Sv2 = 1.31
		St3/St2 = 1.80	St3/St2 = 1.88	St3/St2 = 1.36

Analysing the roughness values shown in Table 7.7, it turns out that at the end of the first test stage, regardless the type of oil used, there was a slight increase in the total roughness (St). However, there are differences in the increase of the total roughness between the different oils:

$$St1^{ESTER} > St1^{MINERAL} > St1^{PAO} > St0$$

which may indicate that the wear of the surfaces is more pronounced in same order, that is,

$$ML^{ESTER} > ML^{MINERAL} > ML^{PAO}$$

After the second test stage (the test conditions are different from the first test stage), the total roughness (St) decreases, for all oils. In the case of PAO and MINERAL oils the decrease in roughness from the first to the second test stages is very slight, indicating that there was no significant wear of the surface (as shown by the micrographs of the surfaces in Annex A.5). In relation to the ESTER oil, there is a significant reduction in surface roughness (due to the decrease of the valleys depth), indicating a possible polishing of the surface (see figure 7.21), which is consistent with the results of Direct Reading Ferrography.

At the end of the third test stage, also for all oils, the total roughness increased relative to the second test stage. This fact indicates an increased wear (severe wear) of the surfaces, that is, cavities appear on the surfaces, particles are released and indentations are generated, which causes an increase of the total roughness.

7.6. Wear to the thrust roller bearings 81107 TN

7.6.1. Rolling bearings with 20 rollers (500 rpm)

The thrust roller bearings were tested at 500 rpm, submitted to an axial load of 7000 N, with the three gear oils already mentioned. The tests were performed with a bearing containing all the (20) rollers.

Table 7.8 shows the mass loss of each bearing, depending on the gear oil used, as well as the operating temperature and CPUC and ISUC wear indexes.

Table 7.8.: Mass loss, operating temperature and CPUC and ISUC indexes of the TRB 81107 TN.

Thrust roller bearing	MIN-320	PAO-320	ESTER-320
Mass loss - 2h+48h (mg)	45	39	31
Temperature (°C)	60.0	56.4	60.1
Specific film thickness (-)	1.54	1.609	1.443
CPUC (-)	89.8	588.0	80.4
ISUC (-)	2.5E+03	1.3E+05	3.0E+03

For TRB the total mass loss includes the mass loss of the metallic parts (roller and raceway) as well as the mass loss of the polyamide cage, which is significantly higher.

So, it is important to notice that the mass loss measured at the end for each test does not correspond directly to the material loss of the raceways or the rollers (ferrous), since, as will be seen by Ferrography Analytical and Direct Reading Ferrography, the values of CPUC and ISUC indexes are not in agreement with the values obtained for the mass loss.

Through the weighing of the TRB is not possible to evaluate the mass loss of the bearings raceway, since the mass loss measured derives mainly from the bearing cage.

To analyse the wear on the raceways and on the rollers, it is necessary to analyse the oil samples collected at the end of each test by Direct Reading Ferrography and Analytical Ferrography. The values of the CPUC and ISUC indexes measured are reported in Table 7.8 and in Figures 7.25 and 7.26.

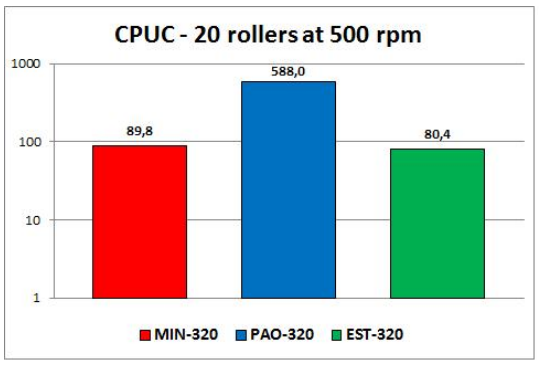


Figure 7.25.: CPUC - wear particle concentration index (TRB 81107 TN).

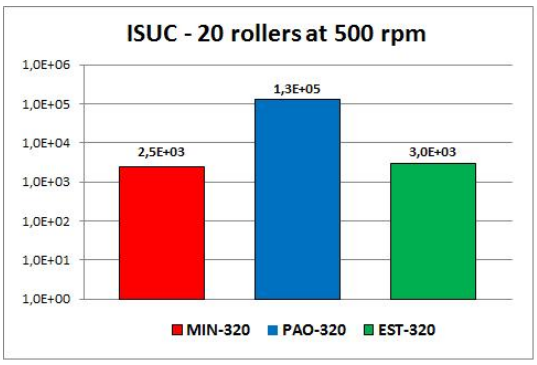


Figure 7.26.: ISUC - wear severity index (TBB 81107 TN).

In Figures 7.25 and 7.26 the CPUC and ISUC indexes are shown in logarithmic scale, since, there are large differences in the values associated with each type of oil. The TRB tested with the PAO oil has a wear particles concentration index (CPUC) higher than the indexes obtained for the MINERAL and ESTER oils.

This result is not very credible, since, the film thickness obtained for the three oils at their operating temperatures are very similar. One possible reason relates to the existence of a slight misalignment in the bearing assembly and/or the presence of wear particles trapped between the roller and the cage which prevents the roller to roll, thus accelerating the process of wear.

The values of CPUC and ISUC for the MINERAL and ESTER oils obtained with the TRB are very similar to the same values obtained with TBB (500 rpm, 21 balls).

The results of Analytical Ferrography at the end of the test (Figure 7.27), in the images corresponding to the ferrograms to MINERAL and ESTER oils, the concentration of particles is very similar, which is consistent with the results for Direct Reading Ferrography.

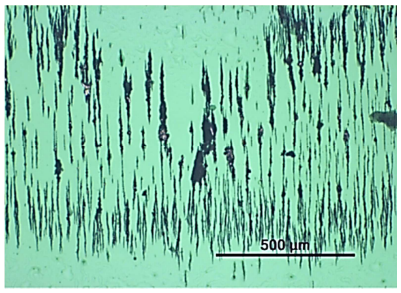
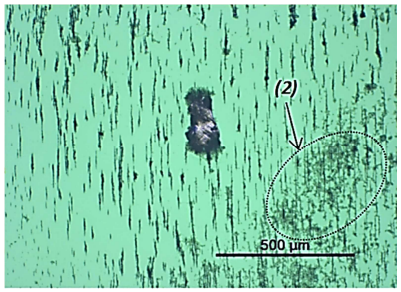
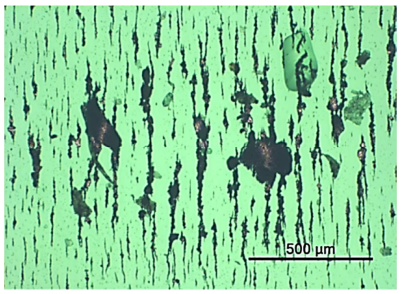
Analysis of Lubricants - Analytical Ferrography and Ferrometry		
	Thrust ball bearing (20 rollers)	Wear (48h)
MIN - 320		d = 1 DL = 58,7 DS = 31,1 CPUC = 89,8 ISUC = 2,5E+03
PAO - 320		d = 0,1 DL = 40,3 DS = 18,5 CPUC = 588,0 ISUC = 1,3E+05 (2)- Presence of friction polymer
ESTER - 320		d = 1 DL = 59,0 DS = 21,4 CPUC = 80,4 ISUC = 3,0E+03

Figure 7.27.: Analytical Ferrography and Direct Reading Ferrography results for thrust roller bearings.

In the case of PAO oil this evaluation is not directly since the sample was diluted 10 times. This dilution is necessary when the values of DL or DS of Direct Reading Ferrography exceed the value 100 (non-linear zone).

Heat treatment is performed using a hot plate and a surface thermometer. It consists in heat the plate until 330°C and put the ferrogram on the plate for 90 seconds. This heat treatment allows us to distinguish ferrous particles in three distinct classes:

- Low-alloy steel - Blue;
- Medium-alloy steel - Yellow / Bronze;
- High-alloy steel - No color change.

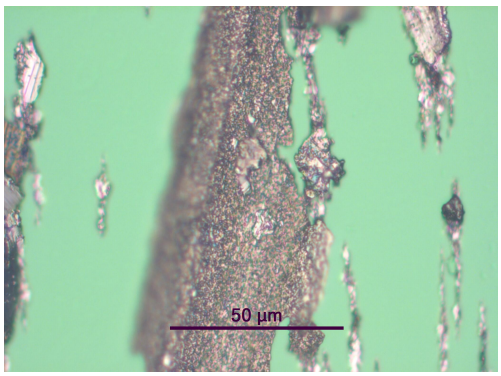


Figure 7.28.: MINERAL-Ferrogram 1

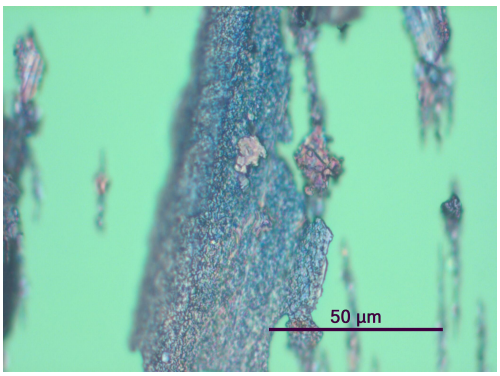


Figure 7.29.: MINERAL-Ferrogram 2

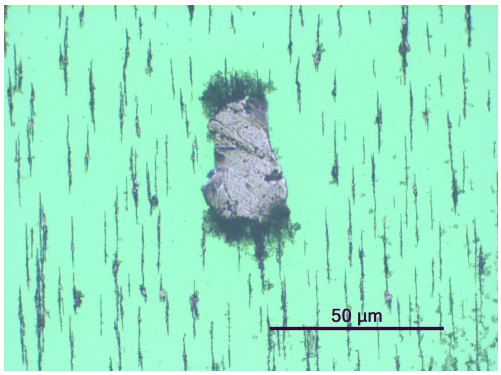


Figure 7.30.: PAO-Ferrogram 1

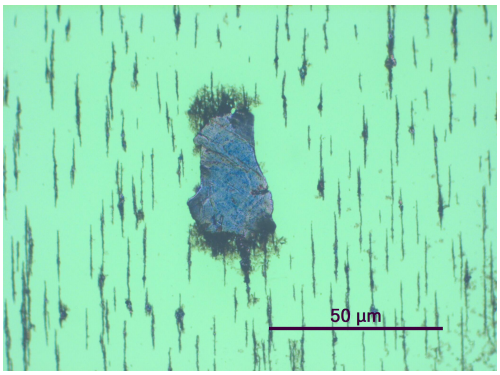


Figure 7.31.: PAO-Ferrogram 2

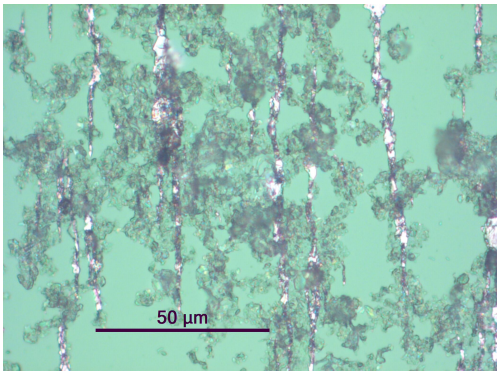


Figure 7.32.: PAO-Ferrogram 3

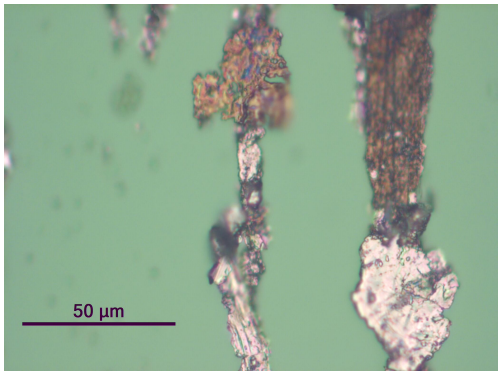


Figure 7.33.: ESTER-Ferrogram 1

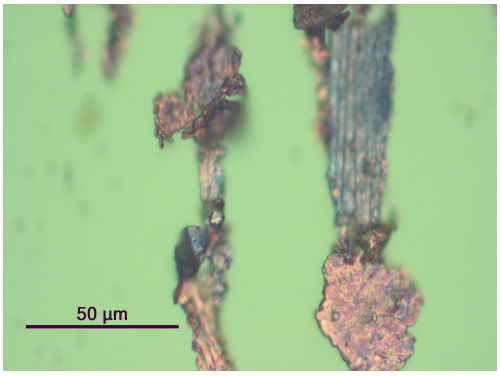


Figure 7.34.: ESTER-Ferrogram 2

In the ferrogram of the MINERAL oil there are small and large ferrous particles. However, along the ferrogram it is possible to see several large ferrous particles, some of them severely oxidized (see Figure 7.28). Figure 7.29 shows the same particle of Figure 7.28 after heat treatment. The color change from tint to blue indicates that it was a low-alloy steel particle.

In the ferrogram corresponding to the PAO oil shown in Figure 7.30 a wear ferrous particle of large dimensions and a few of medium and small size are observed. Friction polymers are also observed in the same figure. After heat treatment the large wear particle shown in Figure 7.30 changed its color from tint to blue, indicating it is made of low alloy steel.

In Figure 7.32 it is possible to observe small ferrous particles inside the polymer matrix (friction polymer).

In the ferrogram corresponding the ESTER oil, shown in Figure 7.33, several ferrous particles of large dimensions were also observed. Small particles contained in the polymer matrix are also observed. After heat treatment the particle color changed from tint to blue, indicating that we are in the presence of low alloy steel.

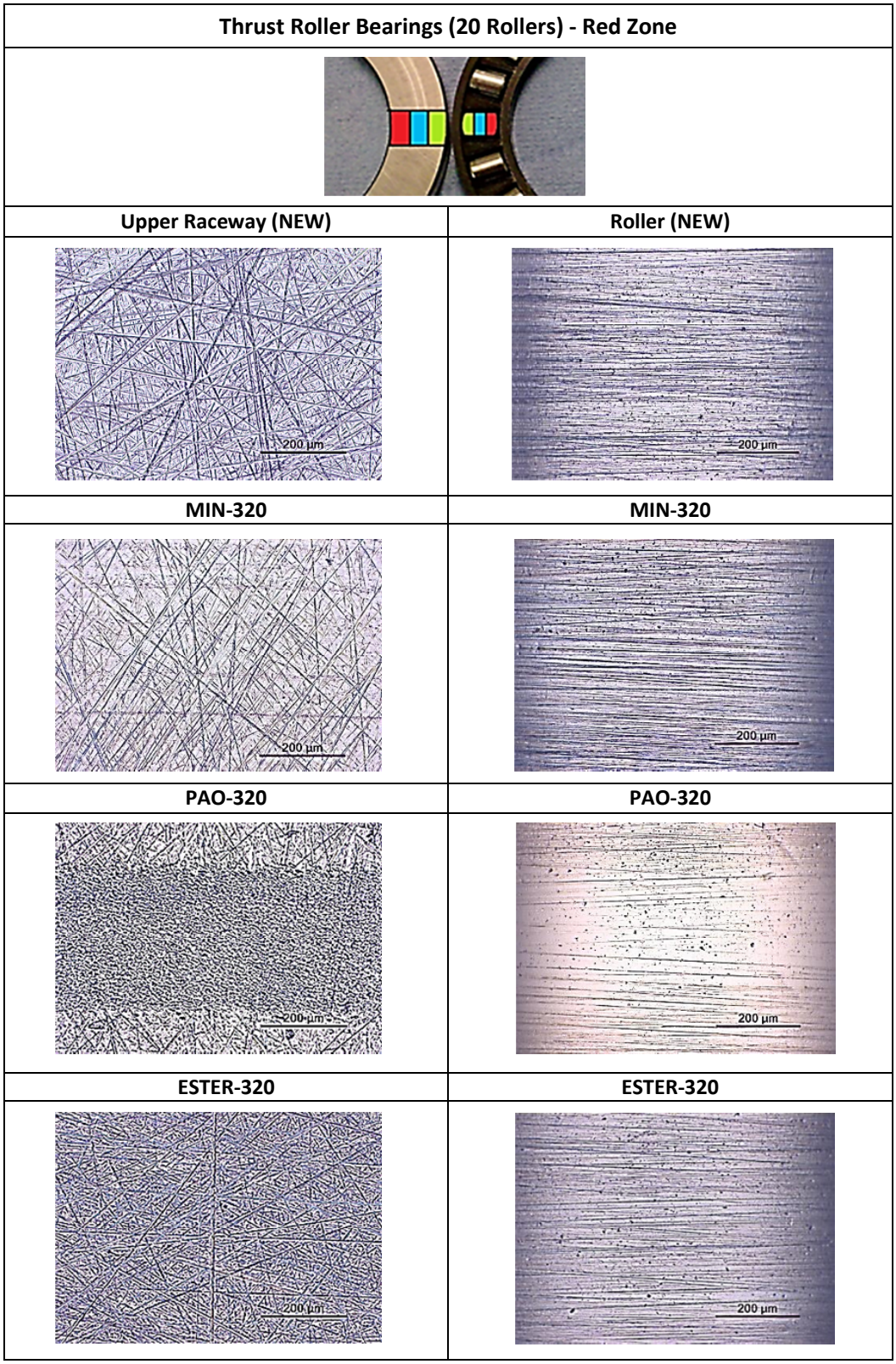


Figure 7.35.: Micrographs of the raceways and rollers at the end of the of the first test (20 rollers at 500 rpm).

Figure 7.35 shows images of the micrographs of the upper raceways for the different oils, made on the inner zone of the contact (red zone). The raceways of the bearing tested with PAO oil have a track of micropitting which is not observed in any of the other raceways tested with MINERAL or ESTER oils.

Figure 7.35 also presents images of the micrographs of the rollers for the different oils, made in the inner contact zone (red zone). In the case of the PAO oil, the surface of the roller is significantly more polished compared with the rollers tested with the other two oils.

The images of the micrographs for the different oils and for the different zones of the raceways and rollers are presented and analysed in Annex A.14. Note that in TRB there are three distinct wear zones, that is, there are two zones showing border effect (extremity of the rollers) and the central zone of contact (at the center of roller). The slide-to-roll ratio is higher at the contact border and so it is expected that surfaces wear is more pronounced in those zones.

Table 7.9 shows the evolution of the 3D roughness parameters for the different oils at end of test performed with complete thrust roller bearings (20 rollers) at 500 rpm.

Table 7.9.: Evolution of roughness parameters (bearing with 20 rollers).

Test	**Bearing (new)**	**MIN-320**	**PAO-320**	**EST-320**
20 rollers at 500 rpm (1)	St0 = 2.29	St1 = 2.08	St1 = 3.48	St1 = 2.77
	Sp0 = 1.39	Sp1/Sp0 = 0.73	Sp1/Sp0 = 0.82	Sp1/Sp0 = 0.88
	Sv0 = 0.90	Sv1/Sv0 = 1.19	Sv1/Sv0 = 2.59	Sv1/Sv0 = 1.71
		St1/St0 = 0.91	St1/St0= 1.52	St1/St0 = 1.21

Table 7.9 indicates that the raceway lubricated with PAO oil had a significant increase in the total surface roughness, which suggests higher surface wear (micropitting) when compared to the wear observed in the raceways lubricated with MINERAL and ESTER oils. This result is consistent with the values obtained by Direct Reading Ferrography (CPUC and ISUC). The values of the 3D roughness parameters measured on the raceway lubricated with the ESTER oil may not be representative of the surface, since the topography was performed in an area where there is a scratch on the surface (machining process) which increases significantly the value of Sv (see

topography, Annex A.11). All topographies performed on the raceways at the end of each test, are presented in Annex A.11.

7.6.2. Thrust roller bearing with 10 rollers (1000 rpm)

New thrust roller bearings were tested at 1000 rpm, submitted to 7000 N of axial load, but in this case, containing only 10 of the 20 rollers. These thrust roller bearings were tested in two consecutive stages of 50h each (without run-in), as shown in Figure 7.36.

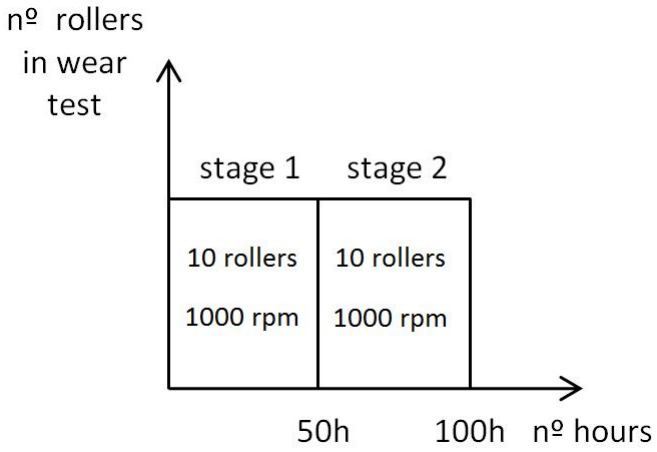


Figure 7.36.: Number of rollers in the wear tests.

The parameter used for assessing the behaviour of the different lubricants tested was the bearing mass loss. The mass loss measurements corresponding to each test stage are given in Table 7.10.

Table 7.10.: Mass loss, operating temperature, specific thickness and CPUC and ISUC index for the tests with the modified bearing (TRB 81107 TN).

Thrust ball bearings		**MIN-320**	**PAO-320**	**EST-320**
Mass loss (mg)	**stage 1**	30	31	36
	stage 2	1	2	0
Temperature - stage 1 (°C)		92.0	79.8	80.7
Specific fim thickness - stage 1 (Λ)		0.948	1.374	1.364
CPUC	**stage 1**	300.0	348.0	650.0
	stage 2	178.8	161.0	293.0
ISUC	**stage 1**	5.9E+04	6.6E+04	2.8E+05
	stage 2	1.4E+04	1.4E+04	5.5E+04

Table 7.10, indicates that a very high mass loss occurred during first test stage probably because of the bearing run-in. In the second test, regardless the type of

oil, the mass loss is a most null (same order of magnitude of the resolution of the balance, 0.001g).

The results of Direct Reading Ferrography (CPUC and ISUC) obtained for tests with 10 rollers at 1000 rpm are given in Table 7.10 as well as in Figures 7.37 and 7.38.

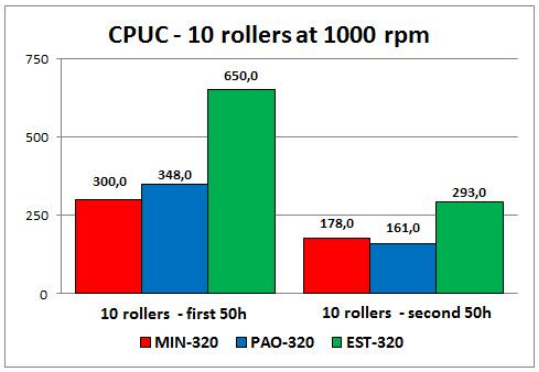


Figure 7.37.: CPUC - wear particle concentration index (10 rollers at 1000rpm).

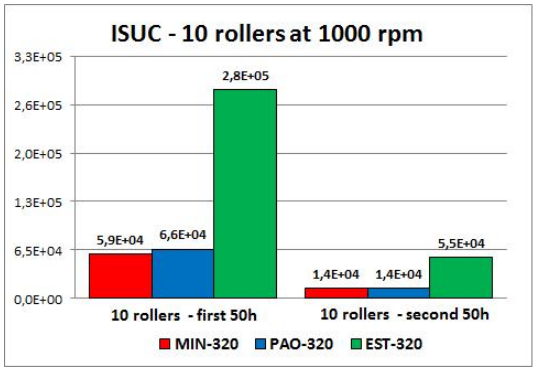


Figure 7.38.: ISUC - wear severity index (10 rollers at 1000rpm).

The oil samples corresponding to the thrust roller bearings lubricated with ESTER oil have CPUC and ISUC index significantly higher than those obtained with the MINERAL and PAO oils in both tests stages. Furthermore, there isn't a significant difference in CPUC and ISUC indexes between MINERAL and PAO oils.

Regardless the type of oil, there is a significant reduction of the CPUC and ISUC indexes from the first to the second test stage because the bearings were not run-in before the first test stage.

As in the case of the thrust ball bearings, the thrust roller bearings lubricated with ESTER oil had significantly higher CPUC and ISUC indexes, than the thrust roller bearings lubricated with MINERAL and PAO oils, which may be related to the higher polarity of the ESTER oil.

The results obtained by Direct Reading Ferrography (CPUC and ISUC) and Analytical Ferrography for the tests with thrust roller bearings with 10 rollers, at the end of the stage 2 are shown in Figure 7.39. The values of the CPUC and ISUC indexes are consistent with the images obtained through the Analytical Ferrografy.

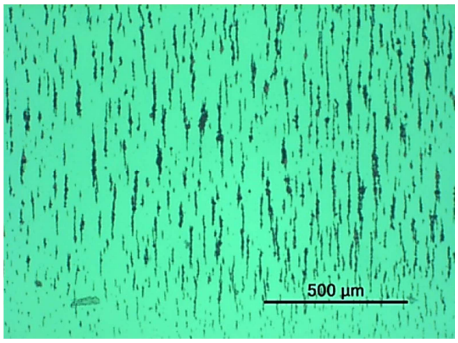
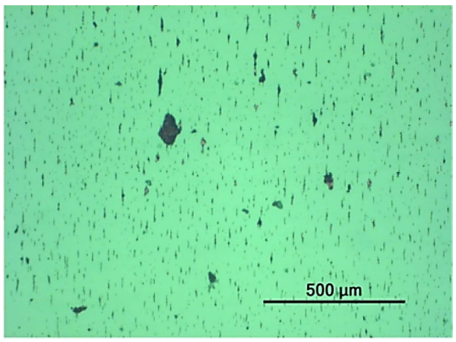
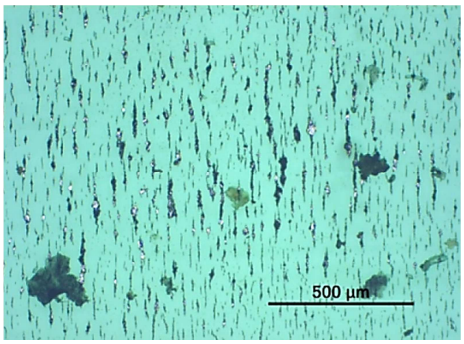
Analysis of Lubricants - Analytical Ferrography and Ferrometry		
	Thrust ball bearing 81107 TN	**Wear (10 rollers – second 50h)**
MIN - 320		d = 0,1 DL = 12,8 DS = 5,0 CPUC = 178,0 ISUC = 1,4E+04
PAO - 320		d = 0,1 DL = 12,5 DS = 3,6 CPUC = 161,0 ISUC = 1,4E+04
ESTER - 320		d = 0,1 DL = 24,1 Ds = 5,2 CPUC = 293,0 ISUC = 5,5E+04

Figure 7.39.: Analytical Ferrography and Direct Reading Ferrography.

Magnifications of the MINERAL, PAO and ESTER oils ferrograms are given in Figures 7.40 to 7.45.

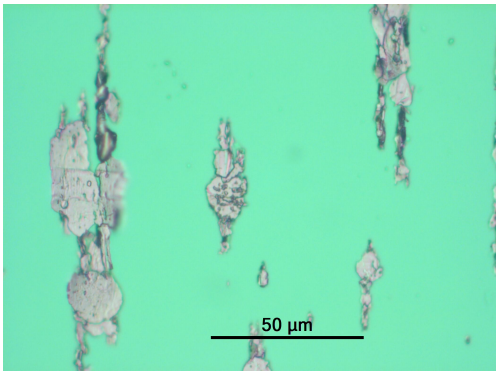


Figure 7.40.: MINERAL-Ferrogram 1

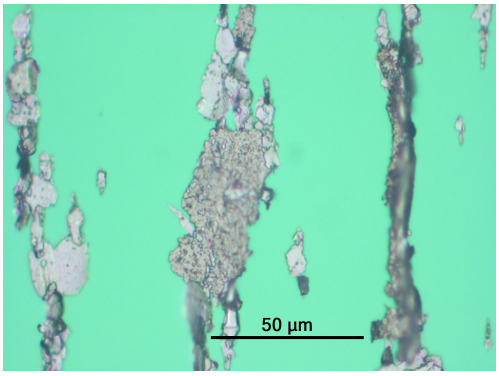


Figure 7.41.: MINERAL-Ferrogram 2

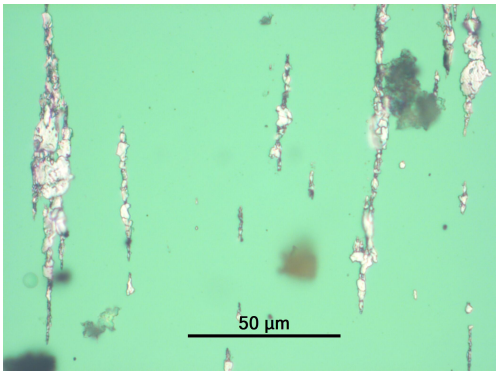


Figure 7.42.: PAO-Ferrogram 1

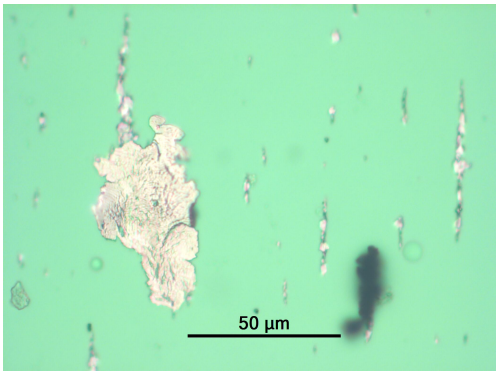


Figure 7.43.: PAO-Ferrogram 2

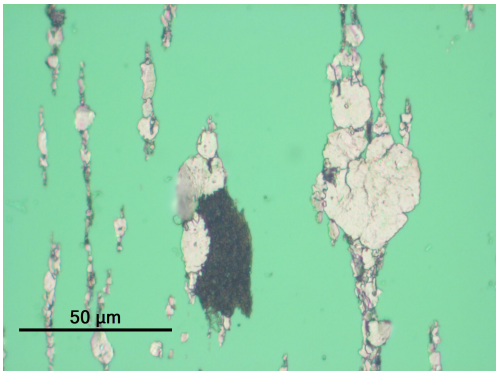


Figure 7.44.: ESTER-Ferrogram 1

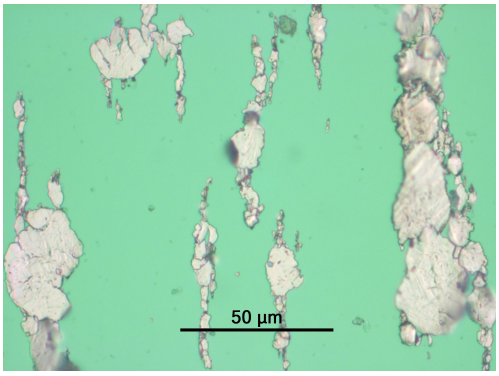


Figure 7.45.: ESTER-Ferrogram 2

Medium size ferrous particles are observed in Figure 7.40, while large oxidized ferrous particles typical of fatigue wear, are seen in Figure 7.41.

Figures 7.42 and 7.43 shown magnifications of the ferrogram corresponding to the PAO oil. In general small ferrous particles are observed, with a few large particles.

Figures 7.44 and 7.45 show magnifications of the ferrograms of the ESTER oil. In Figure 7.44 it is possible to see large ferrous particles, typical fatigue wear, and

even the presence of some thermal oxides. In Figure 7.45 it is possible to observe more large ferrous particles typical fatigue wear.

Figure 7.46 shows images of the micrographs of the lower raceways and rollers of the thrust roller bearings tested. These images correspond to the end of the second test stage.

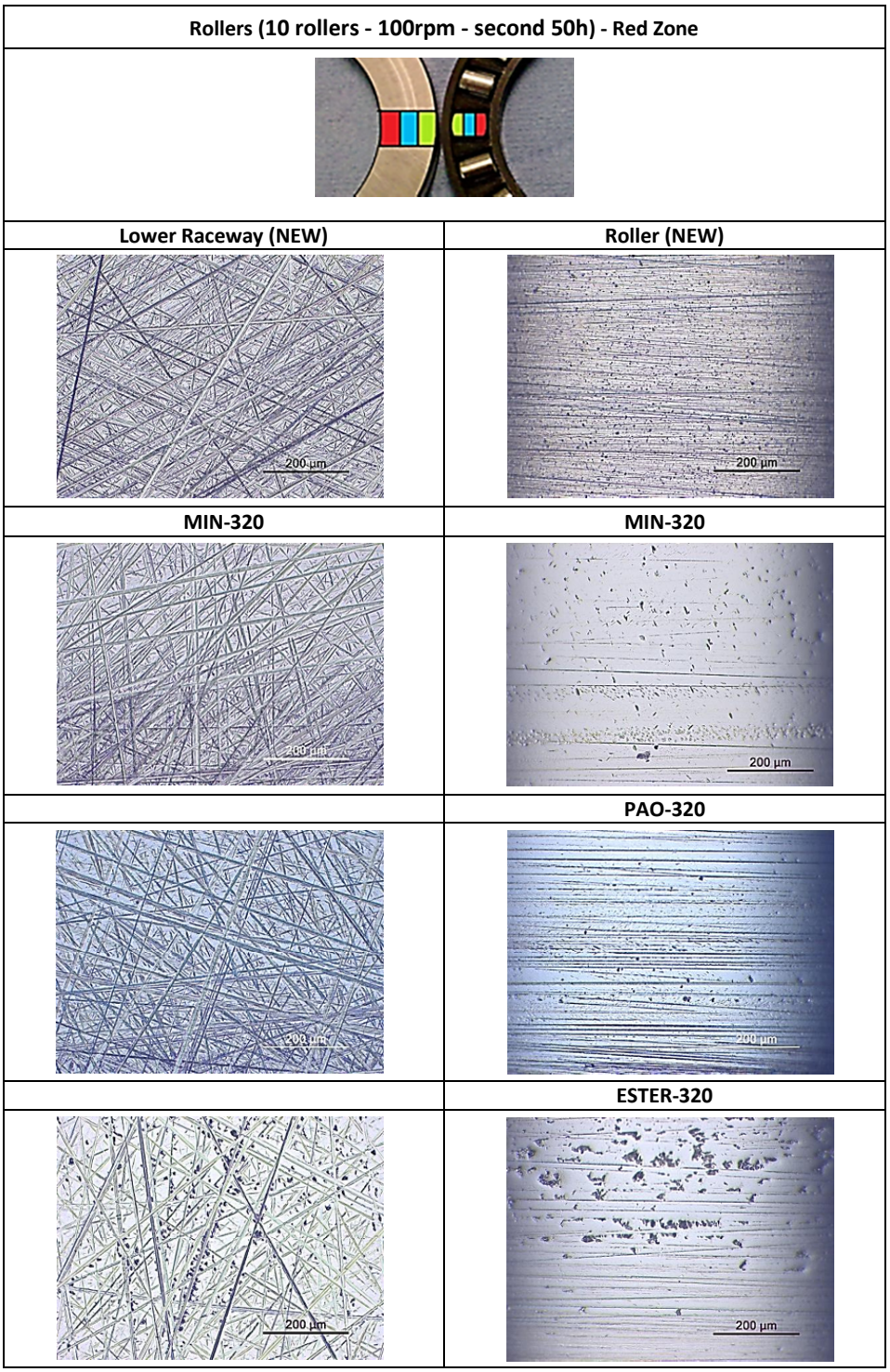


Figure 7.46.: Lower raceways and rollers comparison (10 rollers at 1000 rpm).

As can be seen in Figure 7.46, the micrograph corresponding to the raceway lubricated with the ESTER oil presents surface pits along the machining marks. The machining marks are still perfectly visible on the raceways of bearings lubricated with the MINERAL and ESTER oils.

The rollers lubricated with the ESTER oil show very severe wear on the border of the roller (red zone), when compared with the rollers lubricated with MINERAL and PAO oils. The rollers lubricated with MINERAL and PAO oils show several indentations and micropitts, more pronounced in the case of the roller lubricated with PAO oil.

Table 7.11 presents 3D roughness parameters for the raceways, at the end of the first and second test stages, performed with thrust roller bearings (10 rollers) at 1000 rpm.

Table 7.11.: Evolution of roughness parameters (TRB with 10 rollers).

Test	**Bearing (new)**	**MIN-320**	**PAO-320**	**EST-320**
10 rollers at 1000 rpm (1)	St0 = 2.95	St1 = 2.91	St1 = 2.73	St1 = 2.03
	Sp0 = 0.92	Sp1/Sp0 = 1.36	Sp1/Sp0 = 1.21	Sp1/Sp0 = 0.91
	Sv0 = 2.04	Sv1/Sv0 = 0.81	Sv1/Sv0 = 0.74	Sv1/Sv0 = 0.58
		St1/St0 = 0.99	St1/St0= 0.93	St1/St0 = 0.69
10 rollers at 1000 rpm (2)	/	St2 = 2.94	St2 = 2.43	St2 = 1.73
		Sp2/Sp1 = 0.95	Sp2/Sp1 = 0.95	Sp2/Sp1 = 0.79
		Sv2/Sv1 = 1.05	Sv2/Sv1 = 0.85	Sv2/Sv1 = 0.91
		St2/St1 = 1.01	St2/St1 = 0.89	St2/St1 = 0.85

Analysing the roughness parameters at the end of the first test stage, there is a decrease in total roughness with the order $\Delta St^{ESTER} > \Delta St^{PAO} > \Delta St^{MINERAL}$. This fact may indicate that there was a softening of the surface and consequently a decrease in roughness. This evolution of the roughness is in line with the results obtained by direct reading ferrography (CPUC and ISUC). At the end of the second test stage same trend was observed.

7.6.3. Comparison between thrust ball bearings and thrust roller bearings

As previously mentioned, the operating temperatures are higher on the tests performed with thrust roller bearings. The MINERAL oil generated a higher operating temperature in relation to the PAO and ESTER oils (it is noticed especially when it increases the severity of the test).

The total friction torque is lower for the thrust ball bearings in relation to the thrust roller bearings.

For the all tests performed (rollers and balls), except the test performed with PAO oil, 20 rollers at 500 rpm (high-wear), the ESTER oil generated a higher CPUC and ISUC indexes, following by MINERAL oil and finally PAO oil. This indicates a higher wear of the raceways and rolling elements for the rolling bearings lubricated with ESTER oil in relation to the MINERAL and PAO oils.

Analysing the images of the micrographs of the raceways and rolling elements surfaces, it is clear that the higher wear for the rolling bearings lubricated with ESTER oil in relation to the MINERAL and PAO oil. These trend is observed for the tests performed with thrust roller bearings (10 rollers) and with trust ball bearings (21 and 7 balls). This results agree with the results of the CPUC and ISUC indexes. Analysing the images of the ferrograms, it is observed that the particles concentration follows the same order, that is, $ESTER > MINERAL > PAO$.

8. Conclusions and Future Work

8.1. Conclusions

The results achieved for the different tests performed, in the case of Thrust Ball Bearings, showed that:

- In the first test stage (21 balls at 500 rpm), there aren't significant differences in operating temperatures, between the different gear oil formulations used.
- In the second and third test stages (7 balls at 1200 rpm), the operating temperatures are higher than those obtained in the case of the test with 21 balls at 500 rpm (for all oils). The following results were measured:

$$T^{MINERAL} > T^{ESTER} > T^{PAO}$$

- The modification in the operating conditions from 21 balls at 500 rpm to 7 balls at 1200 rpm, made the tests more severe and caused a decrease in film thickness for all oils (the speed and operating temperature increase does not compensate the decrease in oil viscosity). In the case of the MINERAL oil there is a shift in lubrication regime from mixed film to boundary film lubrication (PAO and ESTER maintained the mixed film lubrication regime).
- The same modification in the operating conditions generated an increase of 44,3% (2,48 to 3,58 GPa) of the maximum Hertzian pressure.
- The estimation of the fatigue life of thrust ball bearings indicated a very significant decrease when the operating conditions were modified, meaning an increase in the severity of the tests (increased wear). The fatigue life estimations of bearings indicated that $L_{10}^{MINERAL} < L_{10}^{PAO} < L_{10}^{ESTER}$, although L_{10}^{PAO} and L_{10}^{ESTER} were quite similar.
- There aren´t significant differences in the total friction torque between the different oils, either in the case of tests performed with 21 balls at 500 rpm either in the case of tests with 7 balls at 1200 rpm. However, a decrease in the

total friction torque was observed, regardless of the type of oil, when changing the test conditions from 21 balls at 500 rpm to 7 balls at 1200 rpm.

- The coefficient of sliding friction μ_{sl} are very similar for all oils, although, slightly higher in the case of MINERAL and ESTER oils and slightly lower in the case of PAO oil.

$$\mu_{sl}^{ESTER} \cong \mu_{sl}^{MIN} > \mu_{sl}^{PAO}$$

- The mass loss registered is higher in the case of ESTER oil followed by oil MINERAL and finally the oil PAO, that is,

$$ML^{ESTER} > ML^{MIN} > ML^{PAO}$$

- The results obtained through Direct Reading Ferrography (CPUC and ISUC) and Analytical Ferrography show exactly the same trends of the mass loss results.

In conclusion, the results obtained, indicate that the thrust ball bearing lubricated with the MINERAL oil showed higher operating temperatures, lower film thickness and the lower fatigue life than the bearings lubricated with PAO and ESTER oils. There aren't significant differences in the total friction torque measured experimentally for different oils. The bearings lubricated with ESTER oil had higher wear than the bearings lubricated with MINERAL and PAO oils. The higher wear observed in the case of MINERAL oil relatively to PAO oil was expected, since, it had a lower film thickness (boundary film in test with 7 balls at 1200 rpm), in other words, a higher metal-to-metal contact. The greatest wear presented by oil ESTER may be related with the polarity of the lubricant. Since the forces of attraction (Van der waals) between the bearing surface and the molecules of additives is governed by the polarity, in other words, a polar base oil compete with additives (also polar) on the surface, making the action of additives less effective. The fact that the base oil of ESTER be a polar oil, may justify the increased wear presented relatively to oil PAO (although there are no significant differences between specific film thickness). Another possible justification for the worst performance of the ESTER oil, is the fact that it is biodegradable, that is, its additives are probably less toxic and thus less effective.

In the case of tests carried out with the Thrust Roller Bearings, new bearings were used for the tests with 20 rollers at 500 rpm and for 10 rollers at 1000 rpm.

- In the tests performed with 20 rollers at 500 rpm, no significant differences in operating temperature was measured for the three oils.

- In the tests performed with 10 rollers at 1000 rpm, the operating temperatures are much higher than in the case 20 rollers of 500 rpm. The operating temperature is higher for the MINERAL oil followed by ESTER oil and PAO oil.

$$T^{MIN} > T^{ESTER} \cong T^{PAO}$$

- Since the temperatures are higher in tests with 10 rollers at 1000 rpm, it turns out the film thickness are lower (the increased speed of 500 rpm to 1000 rpm, does not compensate the decrease in viscosity), regardless of the type of oil. In the case of MINERAL oil, the lubrication regime is boundary film instead of mixed film lubrication regime of the tests (10 rollers at 1000 rpm) performed with PAO and ESTER oils.

- The maximum pressure of Hertz increased 41,2% (1,31 to 1,85 GPa), when the test conditions were modified from 20 rollers at 500 rpm to 10 rollers at 1000 rpm.

- The estimated fatigue life of the TRB is lower in the case of the MINERAL oil followed of the ESTER oil and the PAO oil, regardless of test conditions (20 rollers at 500 rpm or 10 rollers at 1000 rpm). The estimated fatigue life is lower in the case of tests performed with 10 rollers at 1000 rpm regardless of the type of oil, which indicate more severe testing conditions.

- There are no significant differences in the total friction torque for the different oils (under the same test conditions).

- The friction torque is lower in the case of tests performed with 10 rollers at 1000 rpm (regardless of the oil type).

- The coefficient of sliding friction μ_{sl} is equal for MINERAL and ESTER oils and slightly lower in the case of PAO oil (test with 20 rollers at 500 rpm).

- The mass loss, either in the case of test with 20 rollers at 500 rpm or in the case of test with 10 rollers at 1000 rpm, comes predominantly from the cage (Polyamide).

- The values obtained for the CPUC and ISUC indexes, in the case of the test with 20 rollers at 500 rpm, are similar for MINERAL and ESTER oils.

- In the case of the tests performed with 10 rollers at 1000 rpm, the CPUC and ISUC indexes are higher for the ESTER oil in relation to the PAO and MINERAL oils.

In the TRB tests performed with 20 rollers at 500 rpm, MINERAL and ESTER oils generated similar wear, although the bearing lubricated with MINERAL oil had lower specific film thickness. The CPUC and ISUC indexes and the ferrogram pictures also show the same trend as well as the observation by optical microscopy of the bearing raceways and rollers.

The wear of the TRB lubricated with PAO oil is much higher than that generated by the MINERAL and ESTER oils. What may have caused this result is related to a misalignment in the bearing assembly or a particle lodged between a roller and cage preventing its rotation, increasing the slip and as such the wear of raceways and rollers (higher concentration of particles).

In the case of tests performed with 10 rollers at 1000 rpm, although the MINERAL oil have a higher operating temperature, lower film thickness, lower fatigue life estimation and higher friction torque, the CPUC and ISUC wear indexes indicate a higher wear in the case of ESTER oil in relation to MINERAL and PAO oils (for these two oils, the CPUC and ISUC indices are very close).This is justified by the polarity of lubricating oils and the possibility of additives being less effective (biodegradability) in the case of the ESTER oil.

8.2. Future Work

In this field of research further work could be done, for example:

- In order to confirm the results obtained would be interesting to repeat some tests. For example, the test performed with the Thrust Roller Bearing lubricated with oil PAO and with 20 rollers at 500 rpm, would be interesting to repeat this test to confirm the values obtained for the indices CPUC and ISUC.
- To study the generation of *Tribofilm* under severe operating conditions, to check how the additives act on the surface (for the three oils tested MINERAL, PAO and ESTER). Through the use of a modified Machine Pin-Disk (roller instead of pin) and surface analyse technique.
- To analyze the influence of the lubricant in the different regimes of lubrication (boundary, mixed and full film), i.e., the three areas of STRIBECK CURVE. For example, making tests at different speeds with constant temperature of the bearing housing (oil bath and an electrical resistance) well as the applied load. It is then possible to analyze the three areas of the STRIBECK CURVE varying speed, viscosity or the load.

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A. Appendix

A.1. Four Ball Machine

Four - Ball Machine

The “Four Ball Machine" (Figure 1), was manufactured in the UK by Cameron-Plint and was cooperation developed by National Engineering Laboratory East Kilbride Scotland, machine as a 4 ball low and high speed. The serial number is TE82/7752.

Figure 1 – Four - Ball Machine

The 4 Ball Machine (Four-Ball Machine, "Cameron-Plint, ref TE82/7752) is mainly intended to characterize the anti-wear (AW) and extreme pressure (EP) oils and greases. This machine allows the testing of four balls with control of rotational speed and axial load up to 20,000 rpm and 8000 N, respectively.

The tests performed on this machine use 4 balls of 12.7mm diameter arranged in a pyramid shape of a triangular base. The spheres of the base may be fixed or free, allowing two different types of tests, in pure sliding and rolling pure, respectively. The movement is transmitted to the higher sphere, which is in contact with the three lower spheres, over which the load is applied.

With the standard layout shown in Figure 2, tests are carried out according to ASTM D2266, ASTM D2596, ASTM D2783, IP 239 and IP 300.

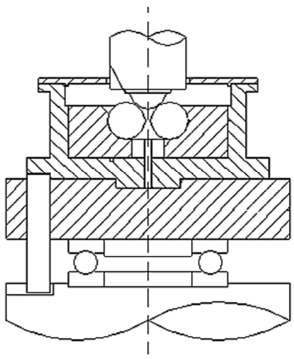


Figure 2 - Disposition of Standard Machine 4 Balls

A.2. Test data sheet for TBB 51107 with 21 balls (mass loss, photographs of the surfaces and topography)

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (50h)	**Brand Oil**	Repsol
Bearing :	Axial balls (21 balls)	**Base Oil**	Mineral
Bearing Ref.	SKF 51107	**Oil Ref.**	Super Tauro FND 320

Reference Bearing-initiation	
weighings	**Average**
77,048	77,048
77,049	
77,048	
Reference Bearing-end	
weighings	**Average**
77,048	77,048
77,048	
77,048	

Cage-initiation	
weighings	**Average**
24,015	24,016
24,016	
24,016	
Cage-end	
weighings	**Average**
24,015	24,015
24,015	
24,016	

Bearing-initiation	
weighings	**Average**
81,900	81,900
81,900	
81,900	
Bearing-end	
weighings	**Average**
81,900	81,900
81,900	
81,899	

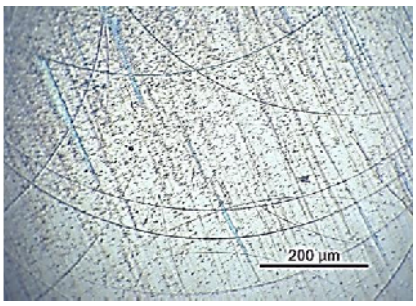
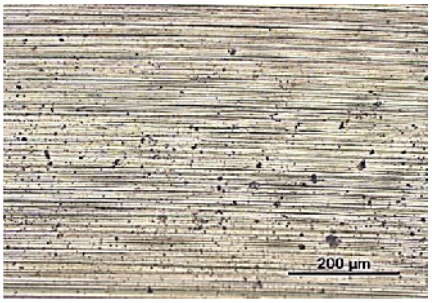
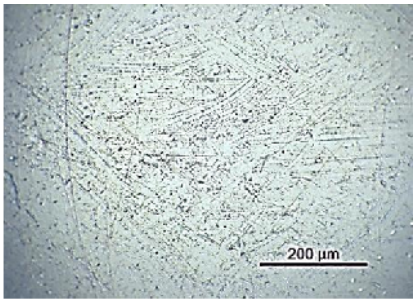
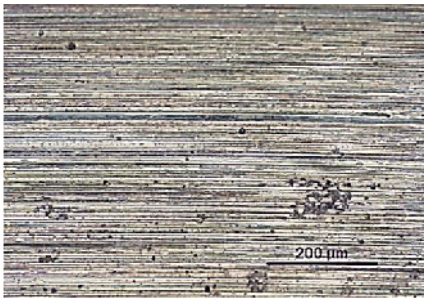
Date	
Initiation:	**23-03-2011**
End:	**25-03-2011**

Mass loss	
0,0	mg

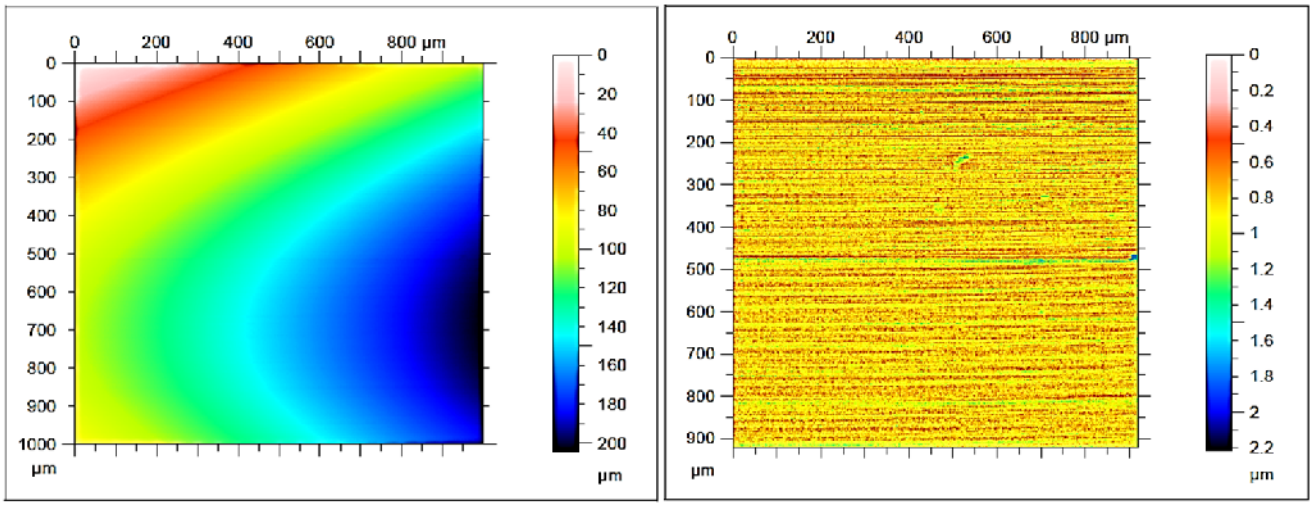
Identification of different contact zones

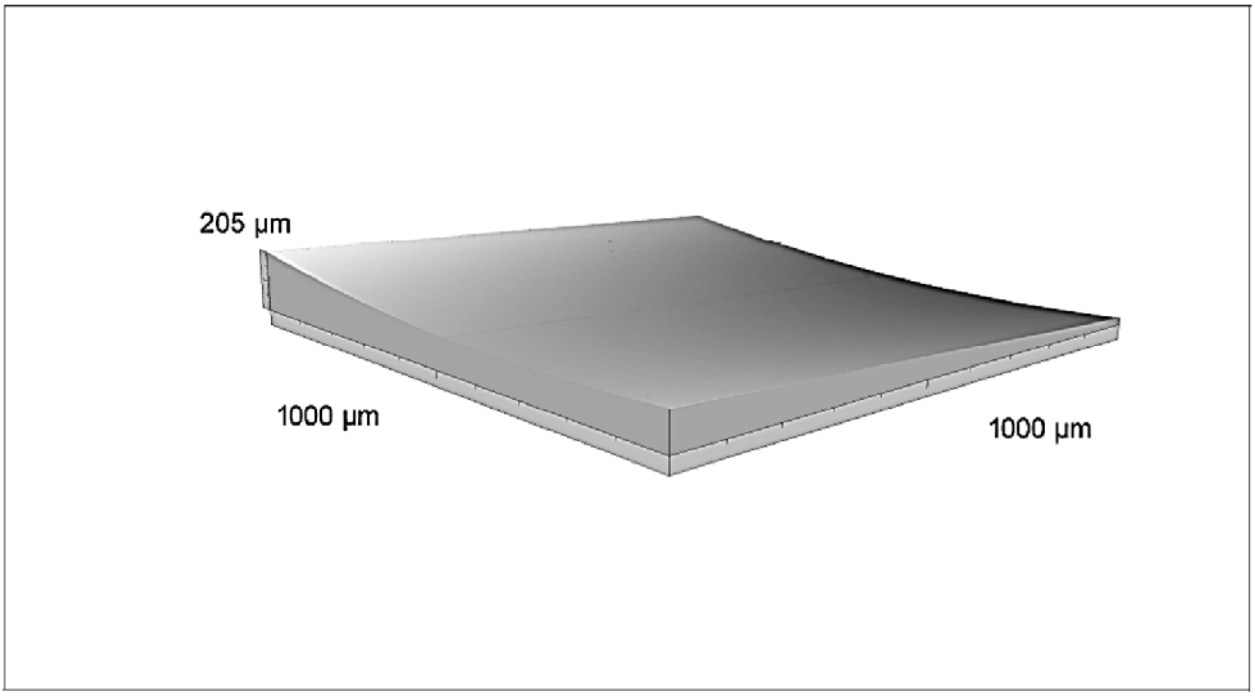
Scheme of the different contact zones analyzed

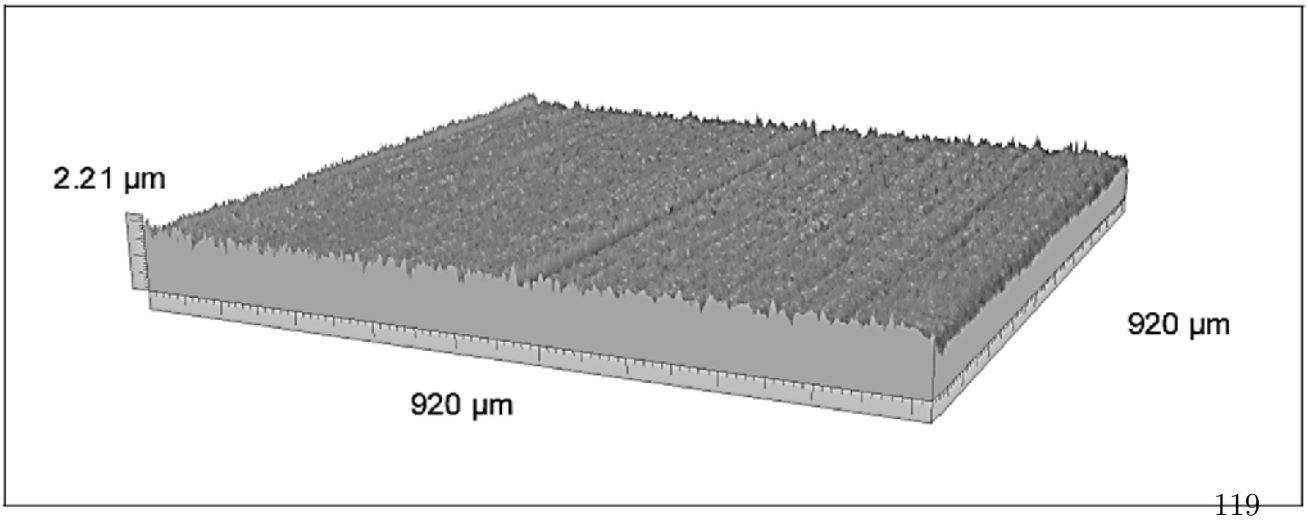
Brand Oil Repsol
Base Oil Mineral
Oil Ref. Super Tauro FND 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter, 80 µm





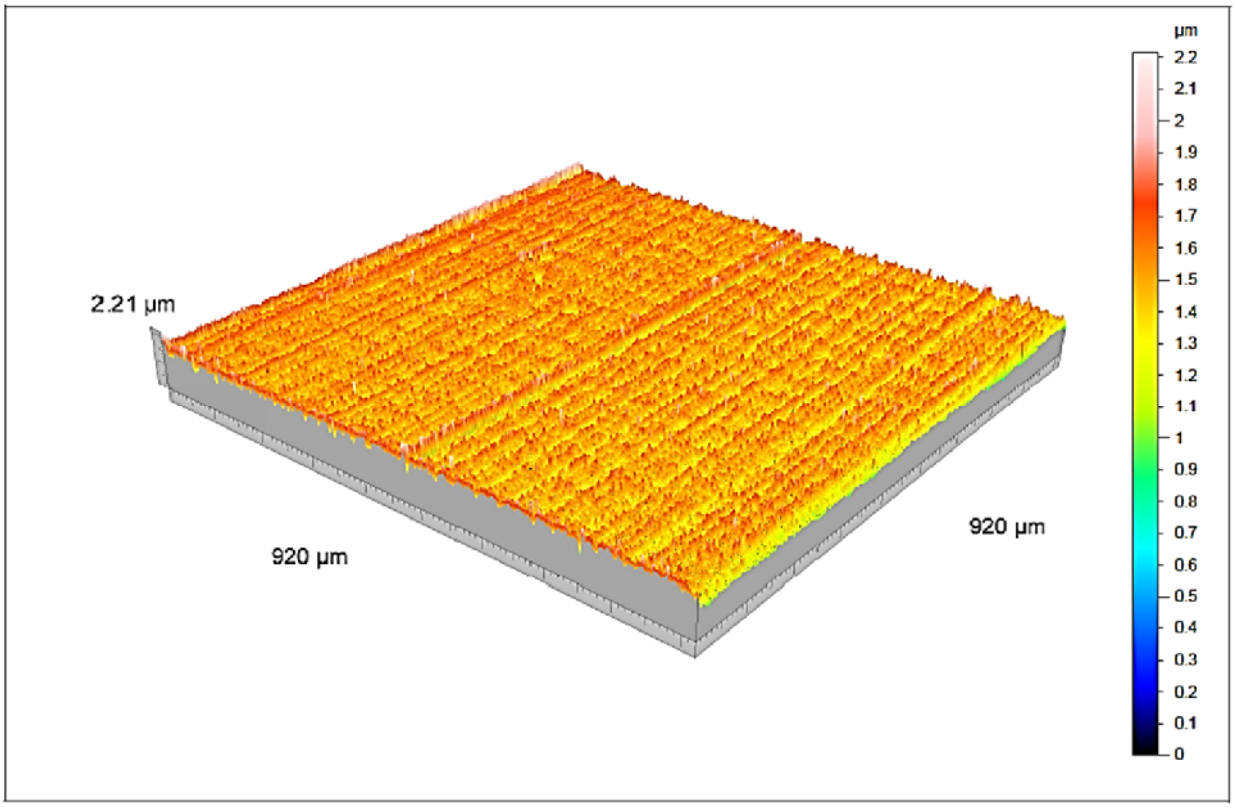


Parameters calculated on the surface D-AE-min-usado-320

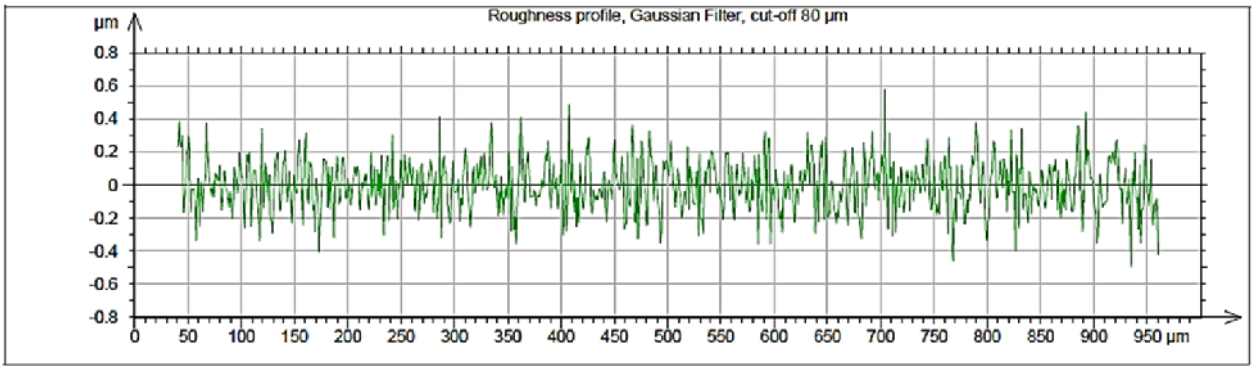
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.114 µm
Sq	=	0.149 µm
Sp	=	0.826 µm
Sv	=	1.39 µm
St	=	2.21 µm
Ssk	=	-0.345
Sku	=	4.29
Sz	=	2.21 µm



Profiles in the circumferential direction

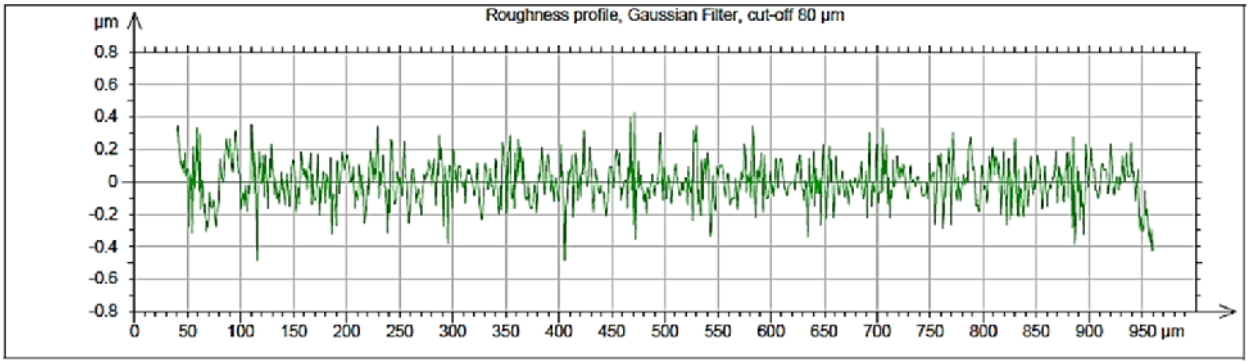


Parameters calculated on the profile D-AE-min-usado-320 > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0874 µm
Rq	= 0.127 µm
Rz	= 0.682 µm
Rt	= 1.1 µm
Rp	= 0.364 µm
Rv	= 0.318 µm
Rsk	= 0.17
Rku	= 4.19



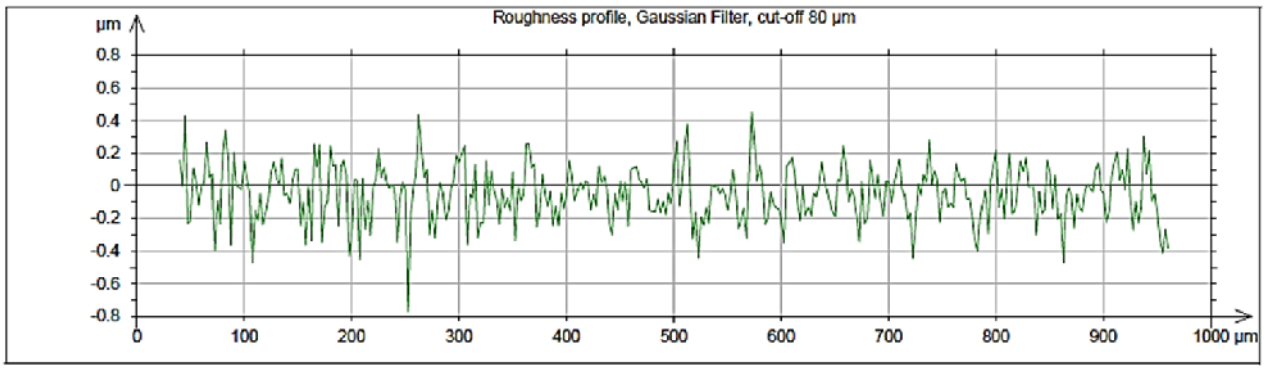
Parameters calculated on the profile D-AE-min-usado-320 > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0687 µm
Rq	= 0.108 µm
Rz	= 0.627 µm
Rt	= 0.9 µm
Rp	= 0.3 µm
Rv	= 0.327 µm
Rsk	= -0.0215
Rku	= 5.23

Profiles in the radial direction

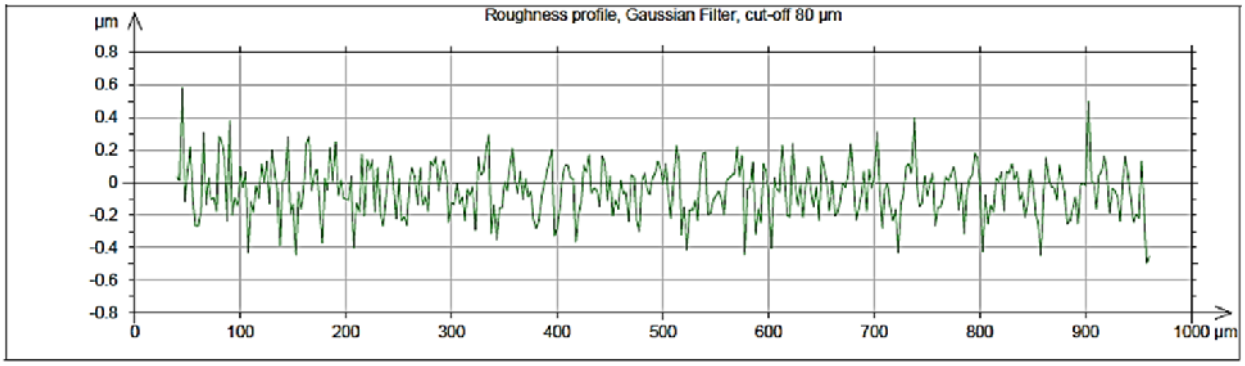


Parameters calculated on the profile D-AE-min-usado-320 > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0997 µm
   Rq     = 0.146 µm
   Rz     = 0.655 µm
   Rt     = 1.1 µm
   Rp     = 0.273 µm
   Rv     = 0.382 µm
   Rsk    = -1.13
   Rku    = 5.19
```



Parameters calculated on the profile D-AE-min-usado-320 > Extracted profile

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* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0931 µm
   Rq     = 0.138 µm
   Rz     = 0.609 µm
   Rt     = 0.9 µm
   Rp     = 0.264 µm
   Rv     = 0.345 µm
   Rsk    = -0.758
   Rku    = 4.29
```

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (50h)	**Brand Oil**	Repsol
Bearing :	Axial balls (21 balls)	**Base Oil**	PAO
Bearing Ref.	SKF 51107	**Oil Ref.**	Super Tauro Synthetic 320

Reference Bearing-initiation	
weighings	**Average**
77,048	77,048
77,048	
77,047	
Reference Bearing-close	
weighings	**Average**
77,049	77,049
77,048	
77,049	

Cage-initiation	
weighings	**Average**
24,042	24,042
24,042	
24,042	
Cage-end	
weighings	**Average**
24,042	24,042
24,042	
24,042	

Bearing-initiation	
weighings	**Average**
82,037	82,037
82,037	
82,036	
Bearing-end	
weighings	**Average**
82,036	82,036
82,036	
82,036	

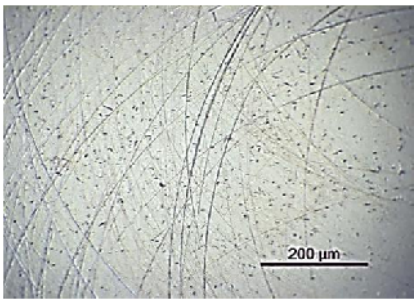
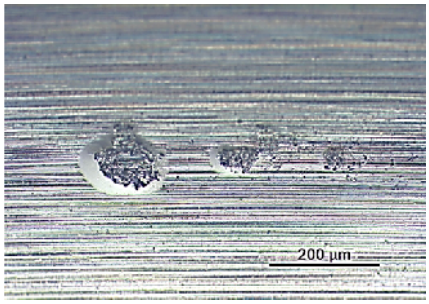
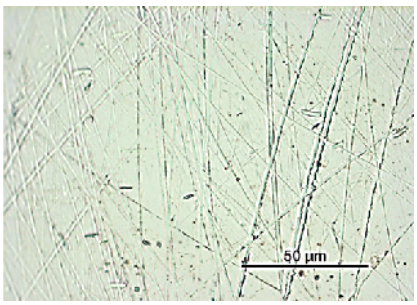
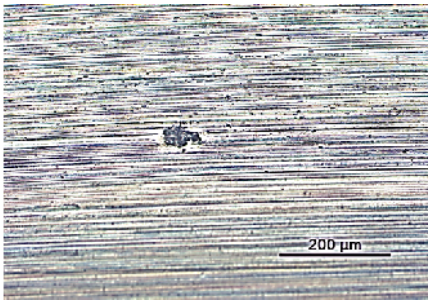
Date
Initiation: **21-03-2011**
End: **23-03-2011**

Mass loss	
2,0	mg

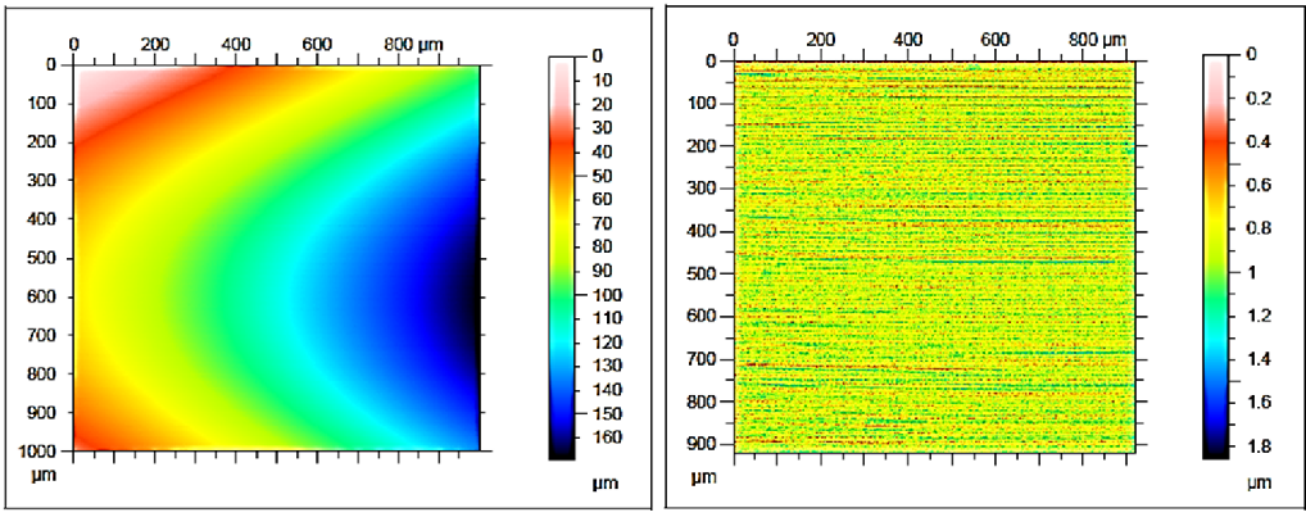
Identification of different contact zones

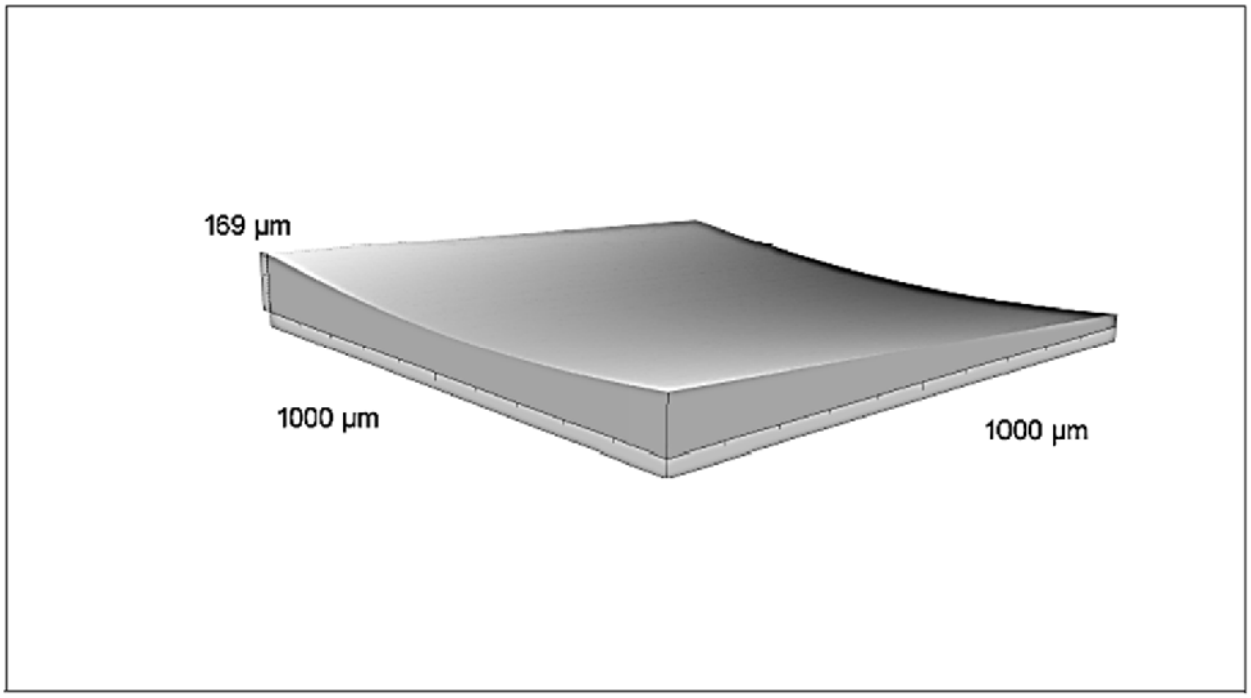
Scheme of the different contact zones analyzed

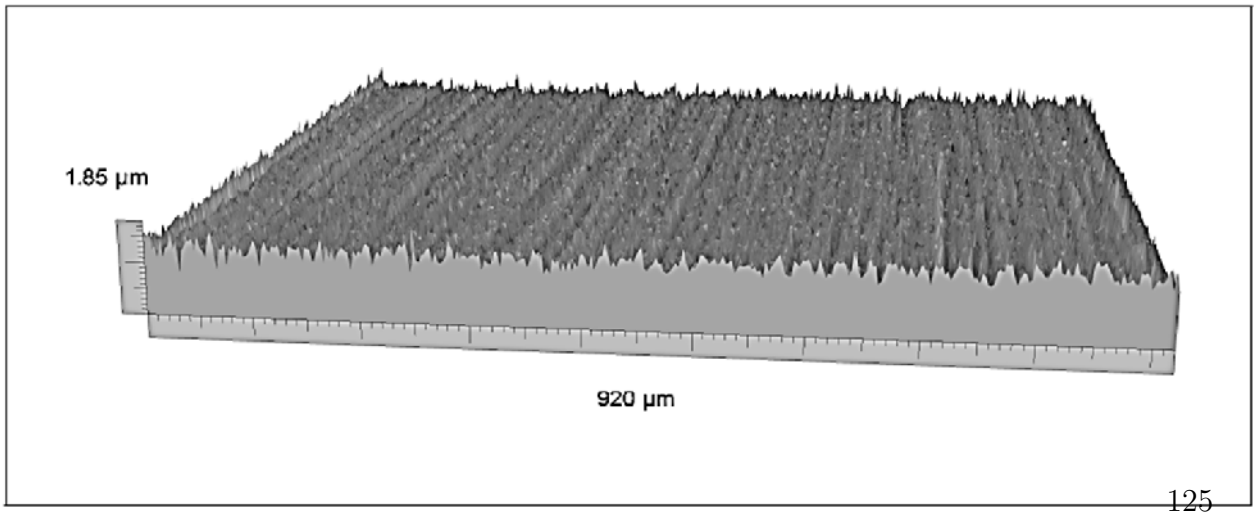
Brand Oil Repsol
Base Oil PAO
Oil Ref. Super Tauro Synthetic 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter, 80 µm





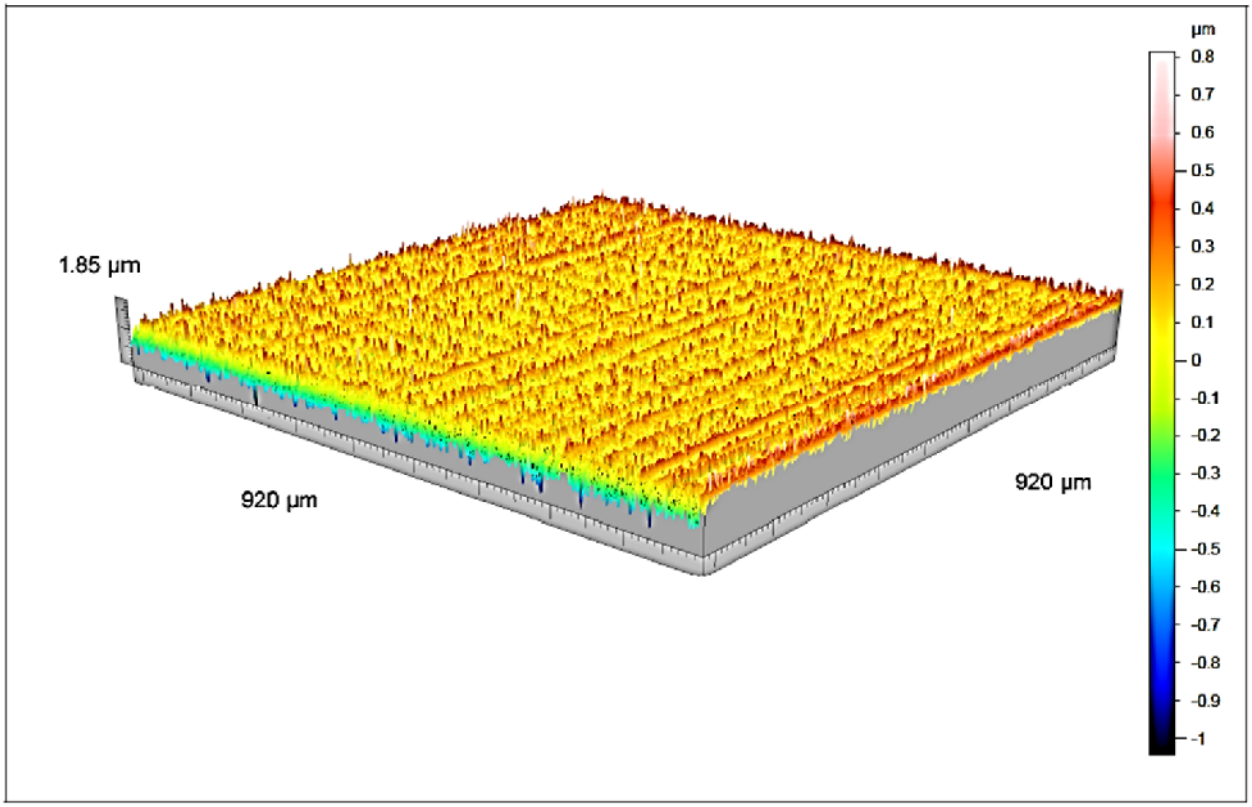


Parameters calculated on the surface D-AE-PAO-Usado21
Roughness, Gaussian Filter, 80 µm

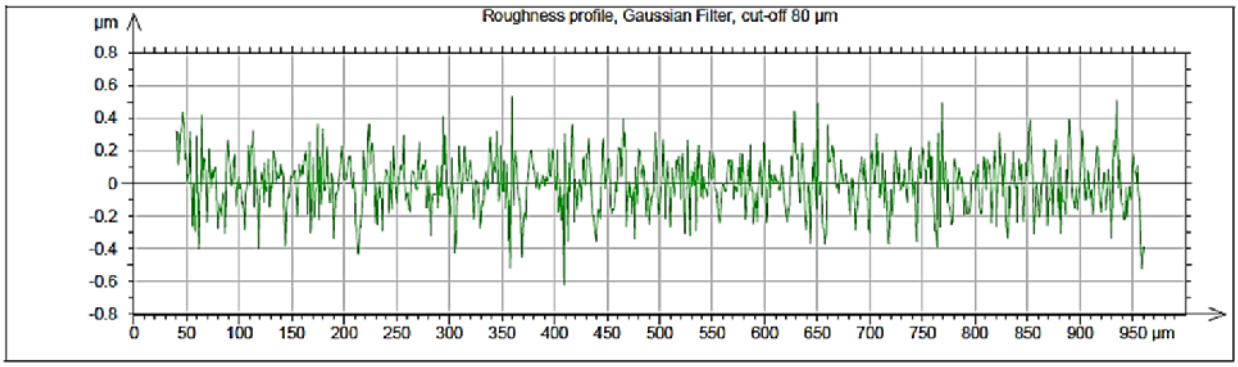
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.122 µm
Sq	=	0.159 µm
Sp	=	0.813 µm
Sv	=	1.04 µm
St	=	1.86 µm
Ssk	=	-0.869
Sku	=	3.86
Sz	=	1.86 µm



Profiles in the circumferential direction

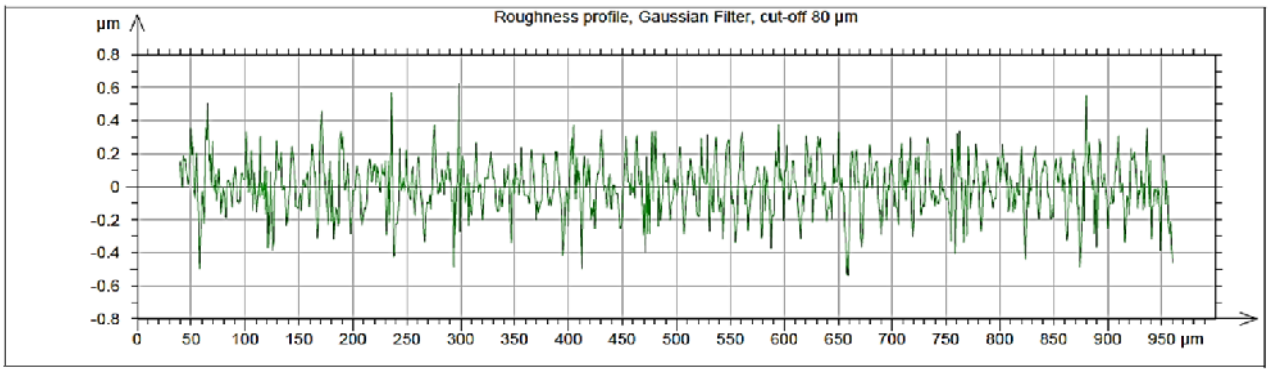


Parameters calculated on the profile D-AE-PAO-Usado21 > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0944 µm
   Rq     = 0.139 µm
   Rz     = 0.727 µm
   Rt     = 1.1 µm
   Rp     = 0.373 µm
   Rv     = 0.355 µm
   Rsk    = 0.0148
   Rku    = 4.32
```



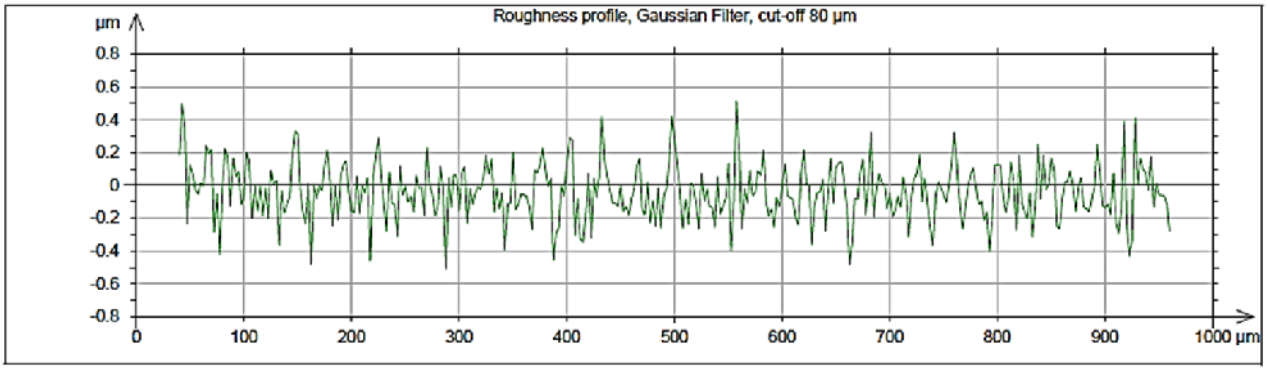
Parameters calculated on the profile D-AE-PAO-Usado21 > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0924 µm
   Rq     = 0.138 µm
   Rz     = 0.8 µm
   Rt     = 1 µm
   Rp     = 0.391 µm
   Rv     = 0.409 µm
   Rsk    = -0.171
   Rku    = 4.56
```

Profiles in the radial direction

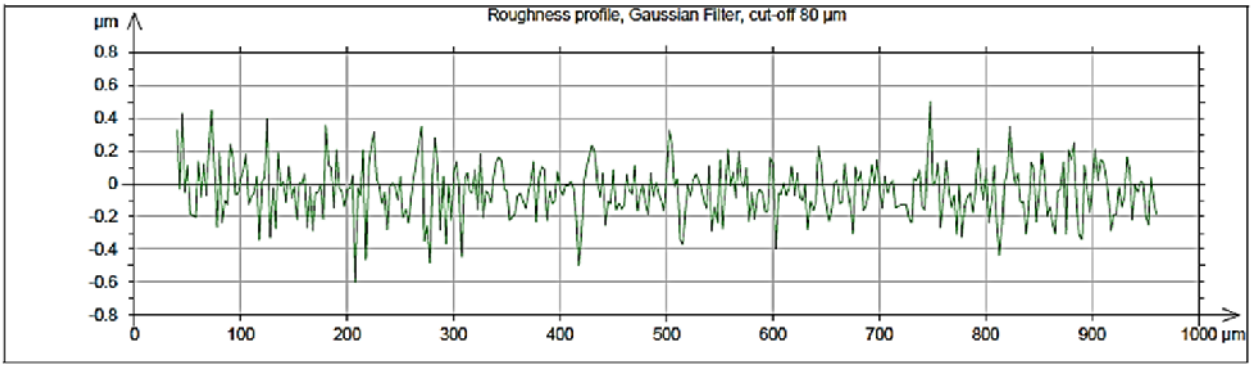


Parameters calculated on the profile D-AE-PAO-Usado21 > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.101 µm
Rq	= 0.147 µm
Rz	= 0.7 µm
Rt	= 0.9 µm
Rp	= 0.318 µm
Rv	= 0.382 µm
Rsk	= -0.644
Rku	= 3.99



Parameters calculated on the profile D-AE-PAO-Usado21 > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0972 µm
Rq	= 0.145 µm
Rz	= 0.664 µm
Rt	= 1.1 µm
Rp	= 0.291 µm
Rv	= 0.373 µm
Rsk	= -0.805
Rku	= 4.77

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (50h)	**Brand Oil**	Fuchs
Bearing :	Axial balls (21 balls)	**Base Oil**	Ester
Bearing Ref.	SKF 51107	**Oil Ref.**	Gearmaster ECO 320

Reference Bearing-initiation	
weighings	**Average**
77,048	77,048
77,049	
77,048	
Reference Bearing-close	
weighings	**Average**
77,048	77,048
77,049	
77,048	

Cage-initiation	
weighings	**Average**
24,000	24,002
24,003	
24,003	
Cage-end	
weighings	**Average**
24,000	24,001
24,001	
24,001	

Bearing-initiation	
weighings	**Average**
82,056	82,056
82,056	
82,056	
Bearing-end	
weighings	**Average**
82,056	82,056
82,056	
82,056	

Date

Initiation: **28-03-2011**

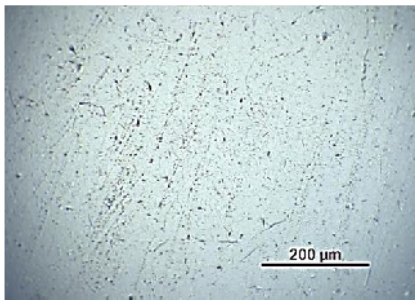
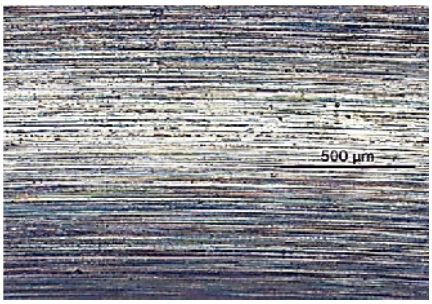
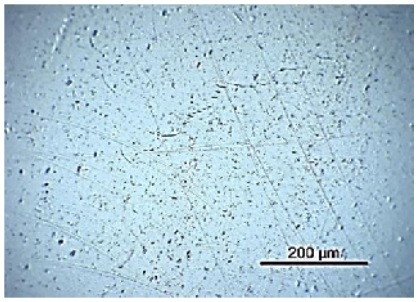
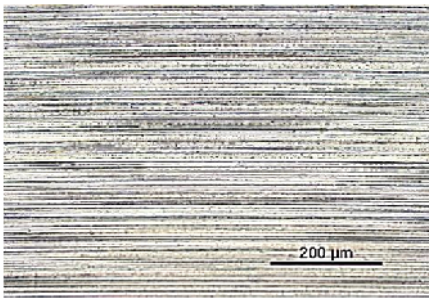
End: **30-03-2011**

Mass loss	
0,0	mg

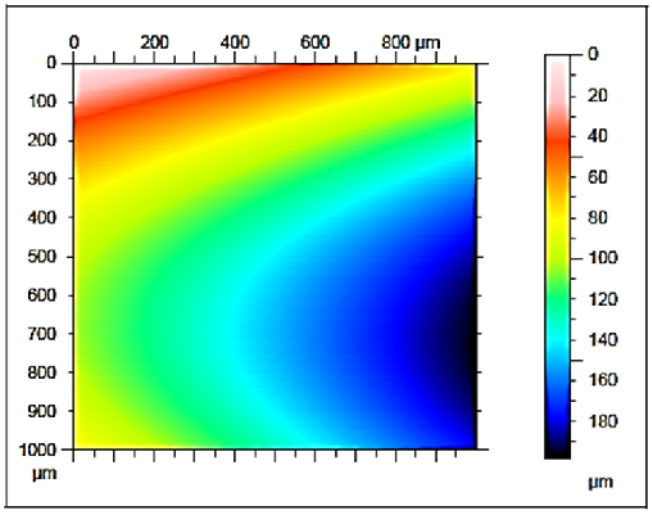
Identification of different contact zones

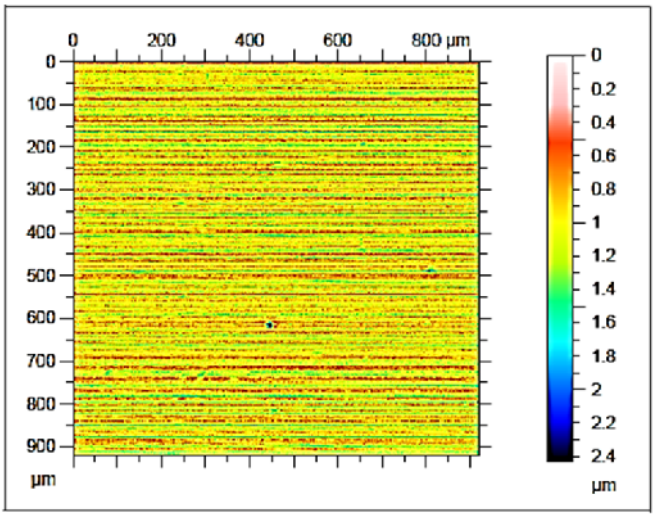
Scheme of the different contact zones analyzed

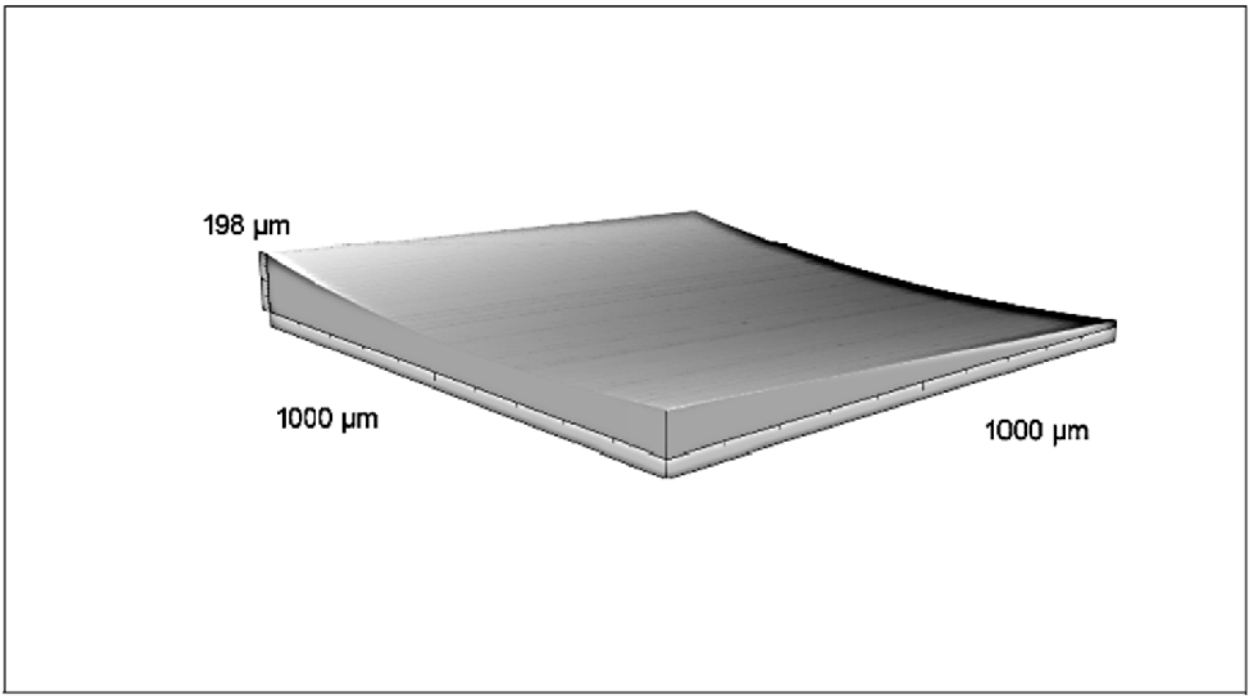
Brand Oil Fuchs
Base Oil Ester
Oil Ref. Gearmaster ECO 320

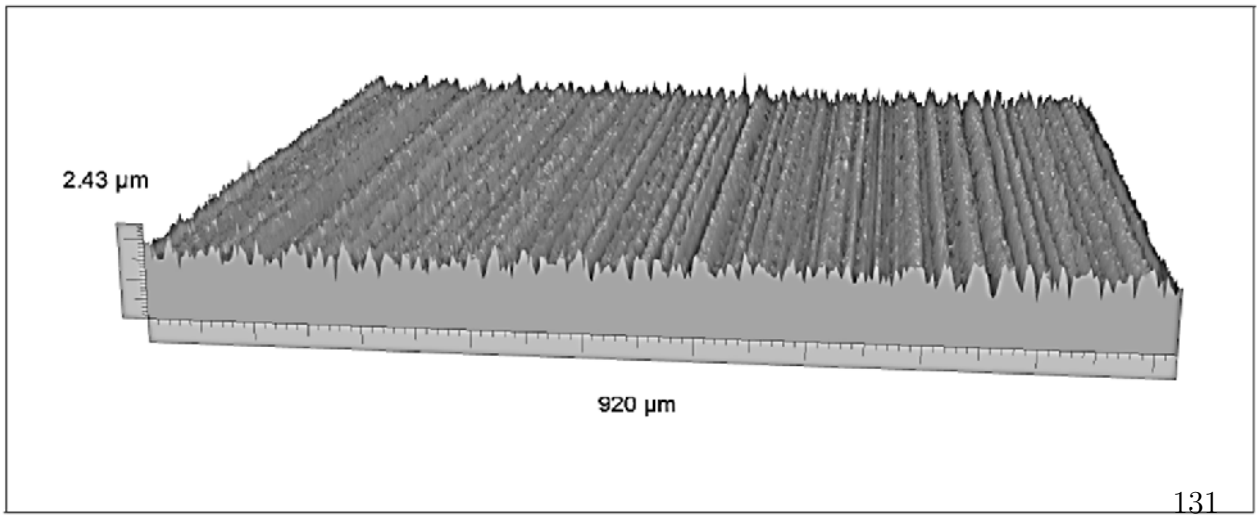
Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter,80 µm







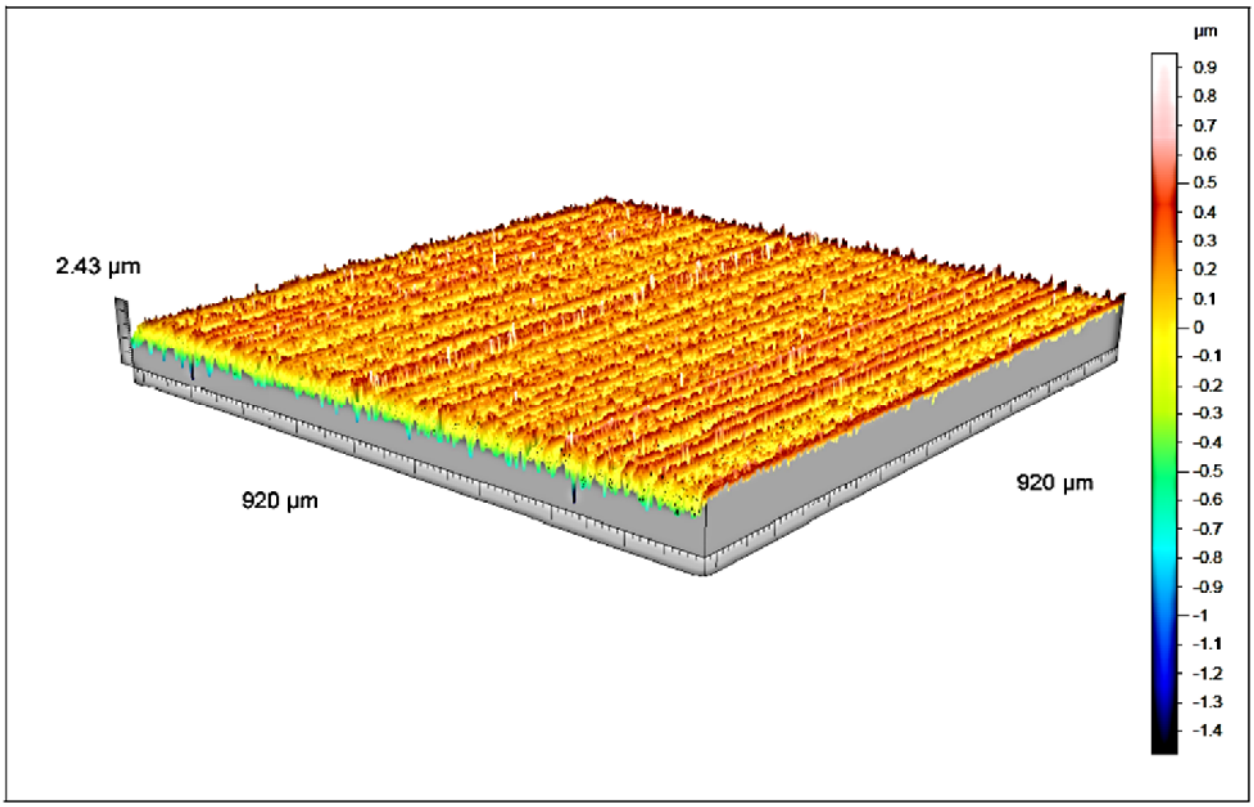


Parameters calculated on the surface D-AE-ESTER-21esf
Roughness, Gaussian Filter, 80 µm

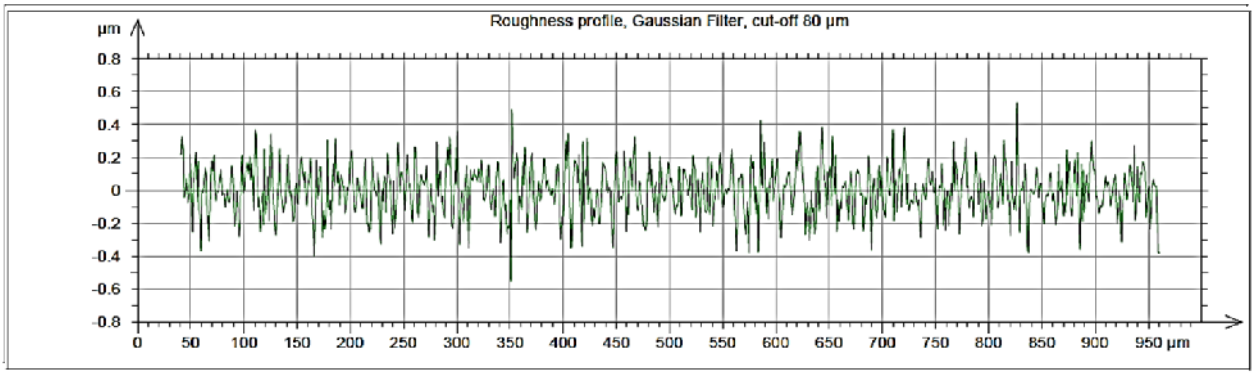
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.182 µm
Sq	=	0.229 µm
Sp	=	0.948 µm
Sv	=	1.48 µm
St	=	2.43 µm
Ssk	=	-0.919
Sku	=	3.16
Sz	=	2.43 µm



Profiles in the circumferential direction

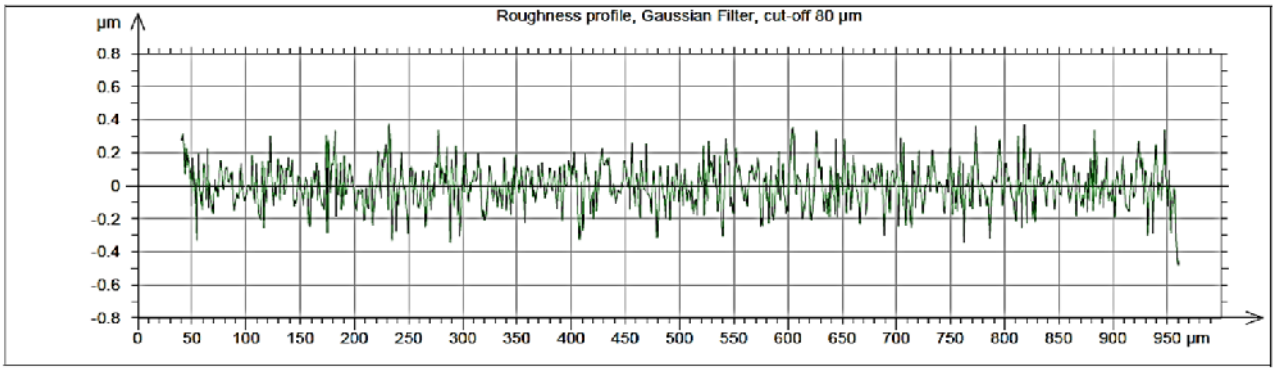


Parameters calculated on the profile D-AE-ESTER-21esf > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0853 µm
Rq	= 0.125 µm
Rz	= 0.682 µm
Rt	= 1 µm
Rp	= 0.345 µm
Rv	= 0.336 µm
Rsk	= 0.0114
Rku	= 4.14



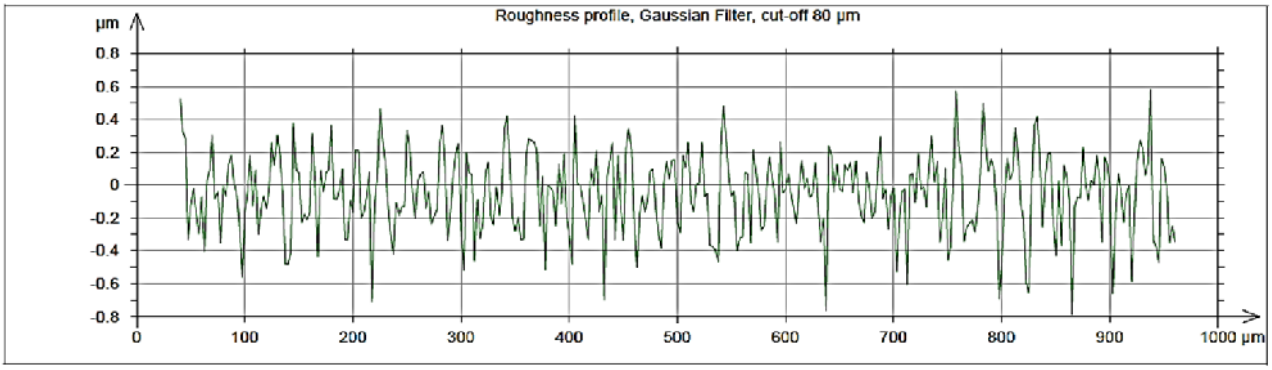
Parameters calculated on the profile D-AE-ESTER-21esf > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0654 µm
Rq	= 0.103 µm
Rz	= 0.545 µm
Rt	= 0.8 µm
Rp	= 0.282 µm
Rv	= 0.264 µm
Rsk	= 0.243
Rku	= 4.28

Profiles in the radial direction

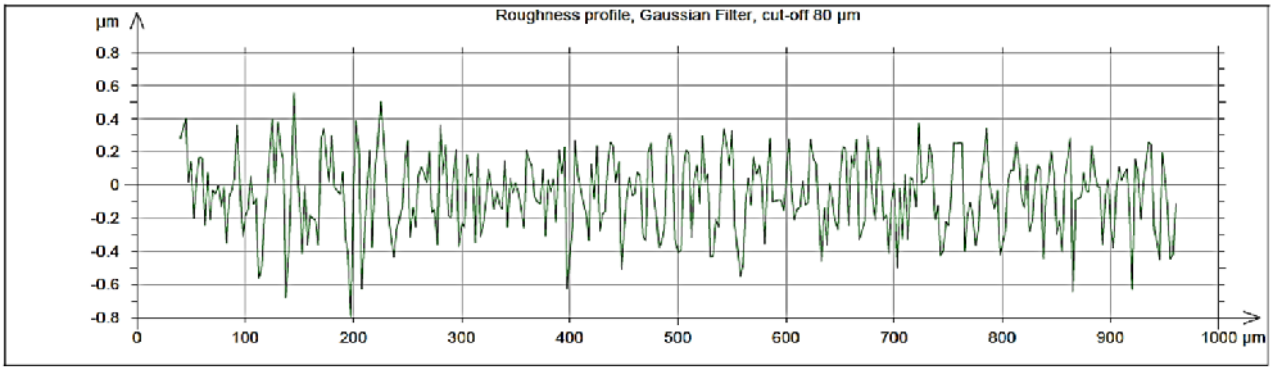


Parameters calculated on the profile D-AE-ESTER-21esf > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.152 µm
Rq	= 0.212 µm
Rz	= 0.964 µm
Rt	= 1.3 µm
Rp	= 0.418 µm
Rv	= 0.545 µm
Rsk	= -0.936
Rku	= 4.24



Parameters calculated on the profile D-AE-ESTER-21esf > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.156 µm
Rq	= 0.209 µm
Rz	= 0.836 µm
Rt	= 1.4 µm
Rp	= 0.318 µm
Rv	= 0.518 µm
Rsk	= -1.13
Rku	= 4.01

A.3. Test data sheet for TBB 51107 with 7 balls - first 50h (mass loss, photographs of the surfaces and topography)

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (21 balls 50h+7 balls 50h)	**Brand Oil**	Repsol
Bearing :	Thrust ball bearings (7 balls)	**Base Oil**	Mineral
Bearing Ref.	SKF 51107	**Oil Ref.**	Super Tauro FND 320

Reference Bearing-initiation	
weighings	**Average**
77,049	77,049
77,049	
77,049	
Reference Bearing-end	
weighings	**Average**
77,050	77,050
77,050	
77,049	

Cage-initiation	
weighings	**Average**
11,650	11,650
11,650	
11,650	
Cage-end	
weighings	**Average**
11,652	11,652
11,652	
11,652	

Bearing-initiation	
weighings	**Average**
69,535	69,535
69,536	
69,535	
Bearing-end	
weighings	**Average**
69,535	69,535
69,535	
69,535	

Date
Initiation: **11-04-2011**
End: **13-04-2011**

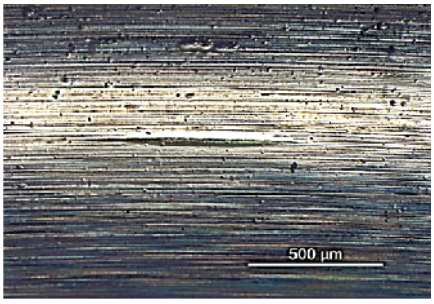
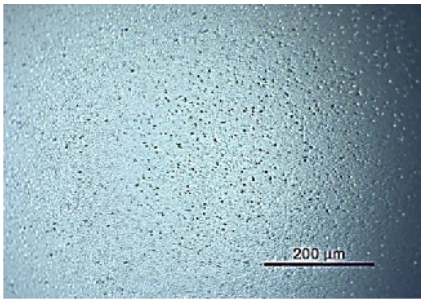
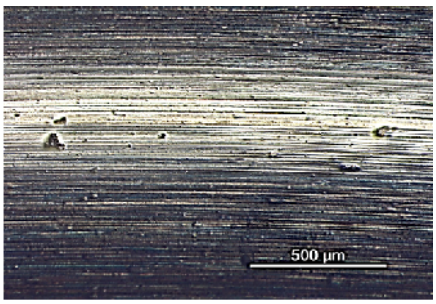
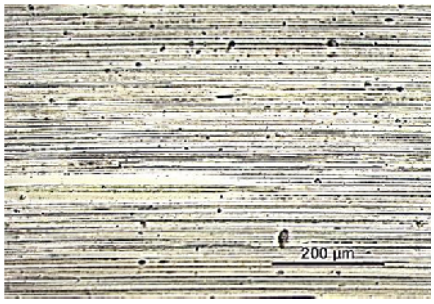
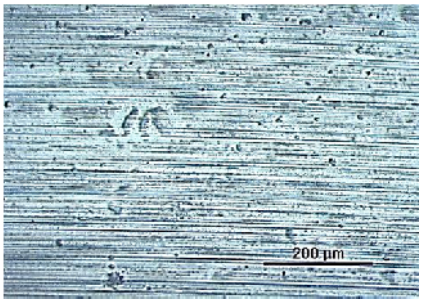
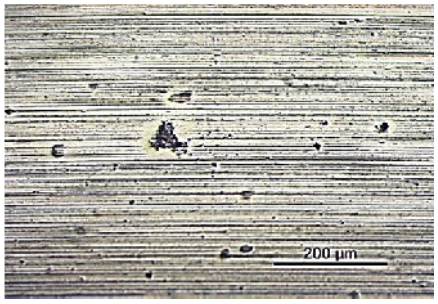
Mass loss	
1	mg

Note:
The first wear test was 50h at 500 rpm with 21 balls and the second was test were 50h at 1200 pm with 7 balls.

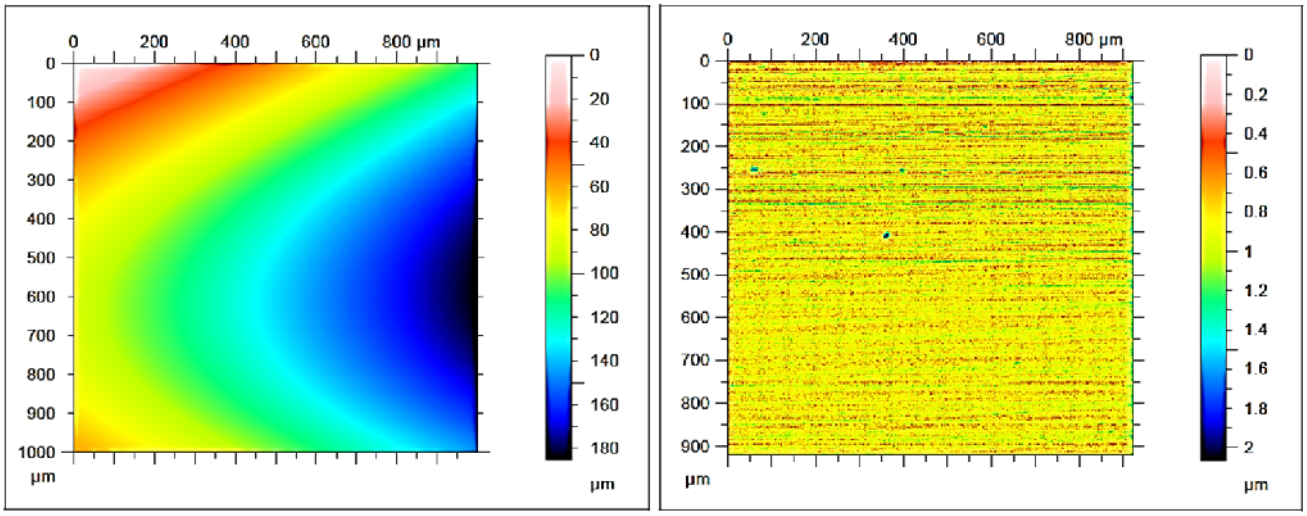
Identification of different contact zones

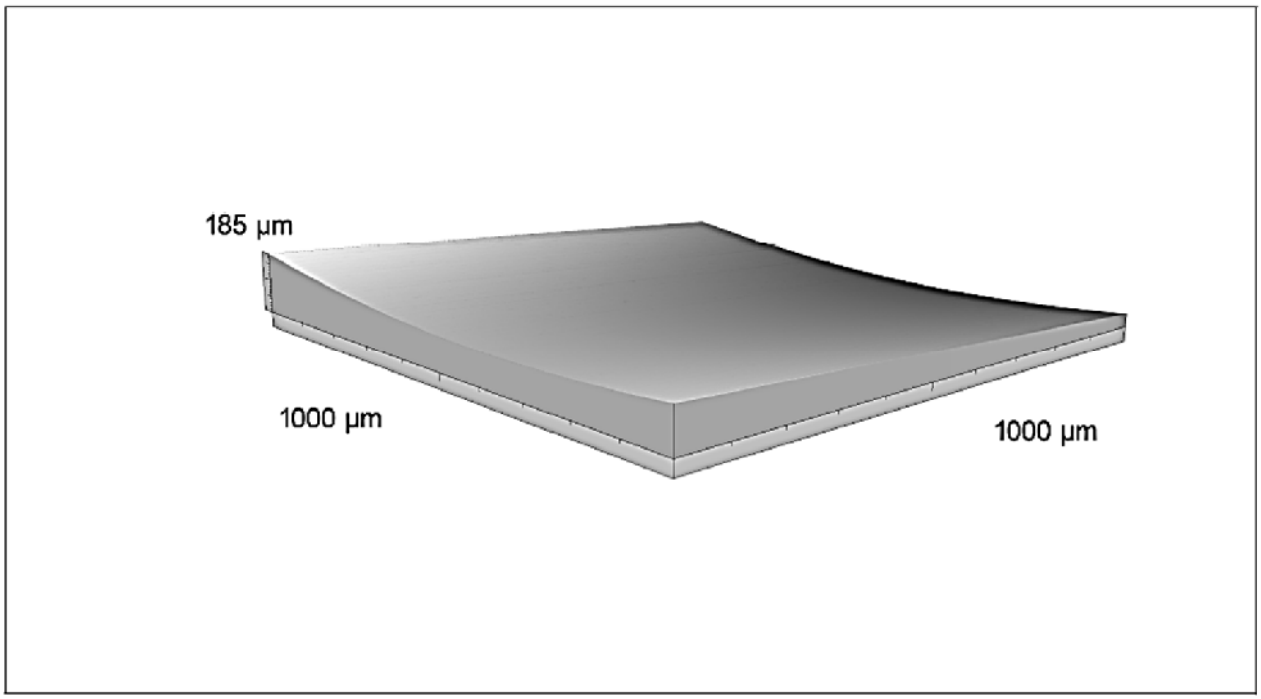
Scheme of the different contact zones analyzed

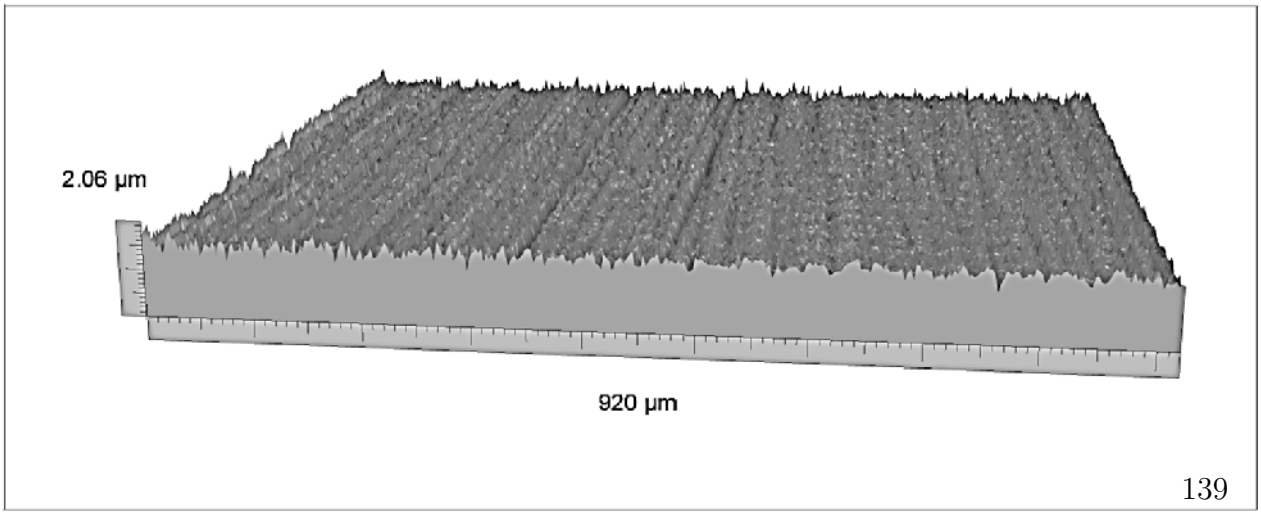
Brand Oil Repsol
Base Oil Mineral
Oil Ref. Super Tauro FND 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter, 80 µm





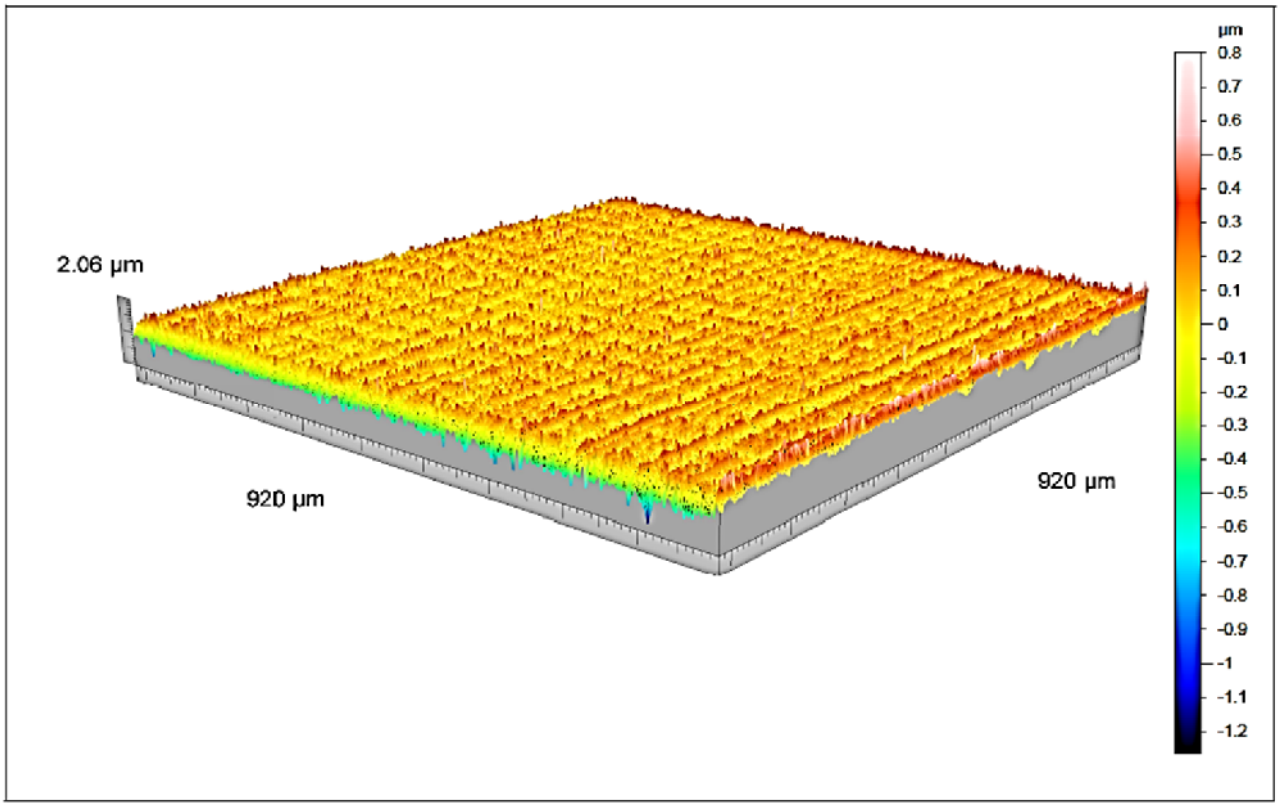


Parameters calculated on the surface AE_MIN320_7ESFERAS 50h+50h > Roughness, Gaussian Filter, 80 µm

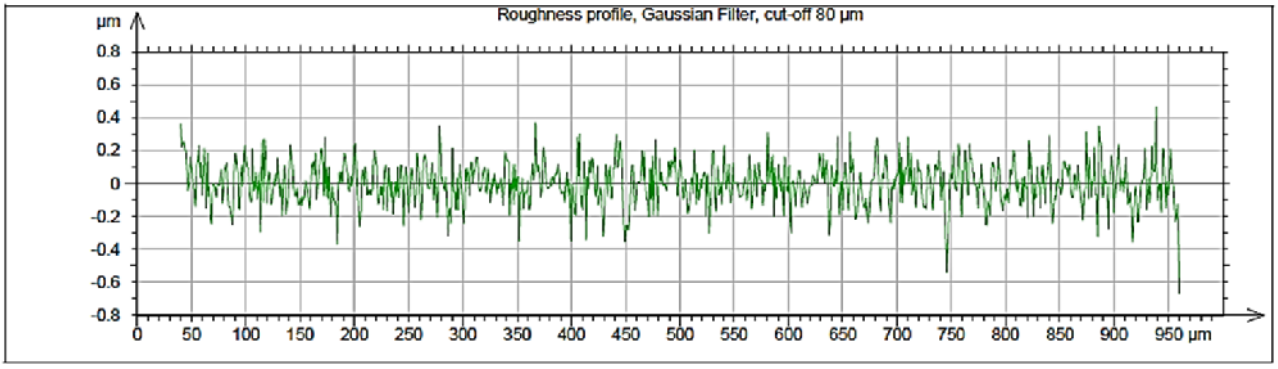
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.105 µm
Sq	=	0.138 µm
Sp	=	0.801 µm
Sv	=	1.27 µm
St	=	2.07 µm
Ssk	=	-1.12
Sku	=	4.57
Sz	=	2.07 µm



Profiles in the circumferential direction

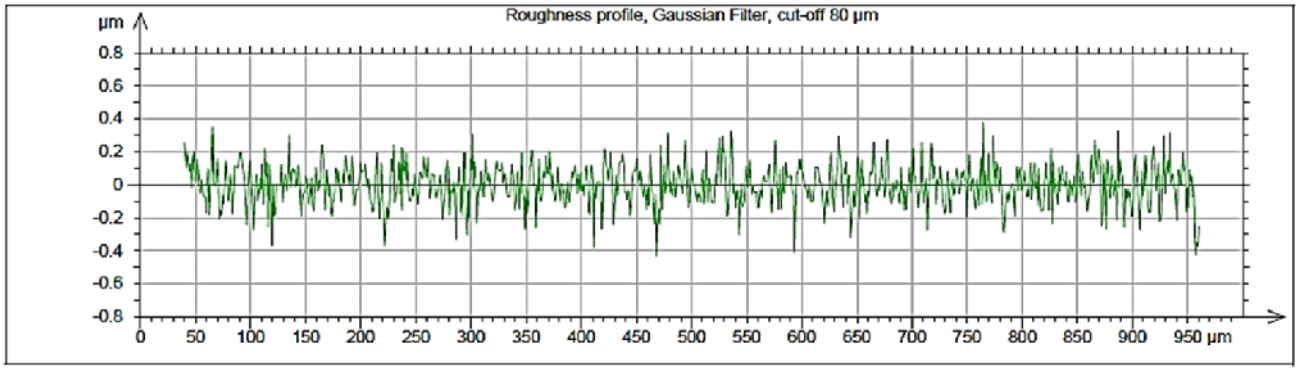


Parameters calculated on the profile AE_MIN320_7ESFERAS_50h+50h > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0664 µm
   Rq     = 0.104 µm
   Rz     = 0.591 µm
   Rt     = 1 µm
   Rp     = 0.282 µm
   Rv     = 0.309 µm
   Rsk    = -0.149
   Rku    = 4.65
```



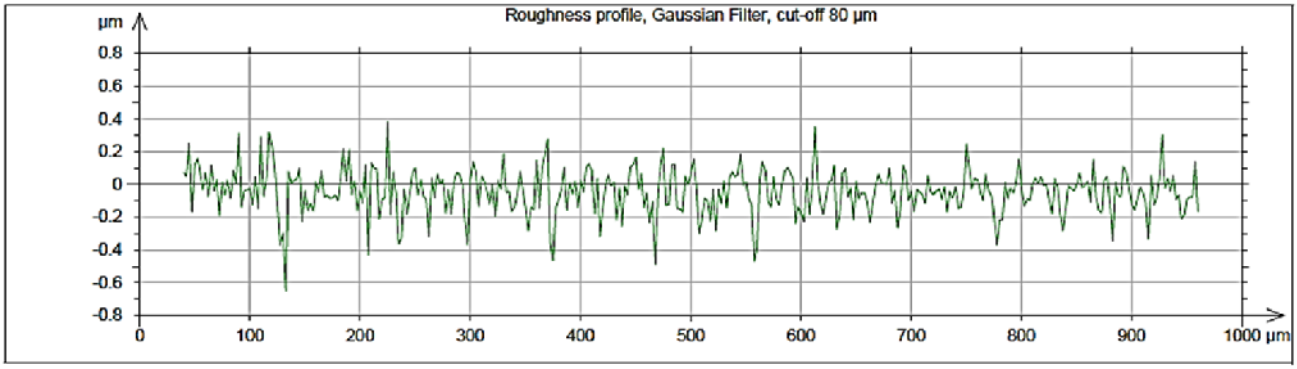
Parameters calculated on the profile AE_MIN320_7ESFERAS_50h+50h > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0636 µm
   Rq     = 0.0995 µm
   Rz     = 0.582 µm
   Rt     = 0.7 µm
   Rp     = 0.273 µm
   Rv     = 0.309 µm
   Rsk    = -0.00114
   Rku    = 4.74
```

Profiles in the radial direction

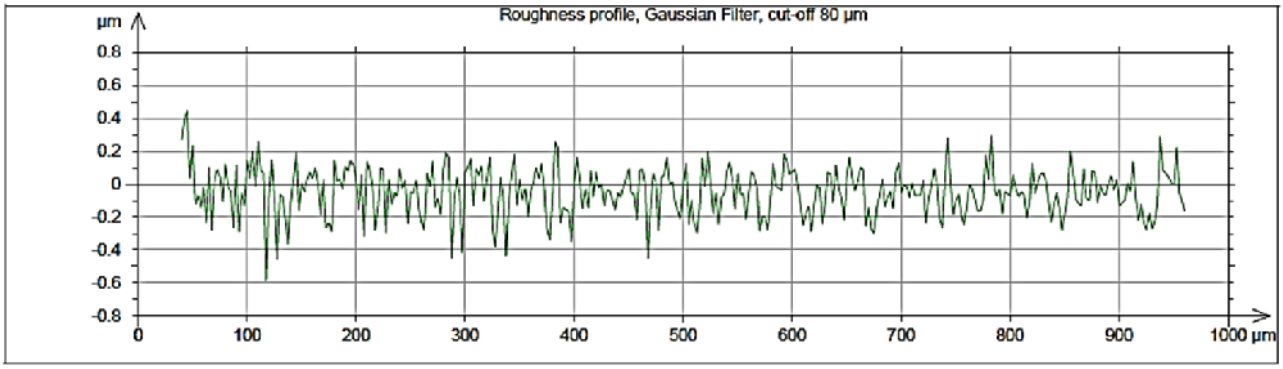


Parameters calculated on the profile AE_MIN320_7ESFERAS_50h+50h
> Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0725 µm
Rq	= 0.119 µm
Rz	= 0.564 µm
Rt	= 0.9 µm
Rp	= 0.218 µm
Rv	= 0.345 µm
Rsk	= -1.57
Rku	= 7.03



Parameters calculated on the profile AE_MIN320_7ESFERAS_50h+50h
> Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.081 µm
Rq	= 0.123 µm
Rz	= 0.5 µm
Rt	= 1 µm
Rp	= 0.191 µm
Rv	= 0.309 µm
Rsk	= -1.35
Rku	= 5.91

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (21 balls 50h+7 balls 50h)	**Brand Oil**	Repsol
Bearing :	Thrust ball bearings (7 balls)	**Base Oil**	PAO
Bearing Ref.	SKF 51107	**Oil Ref.**	Super Tauro Synthetic 320

Reference Bearing-initiation	
weighings	**Average**
77,051	77,051
77,050	
77,051	
Reference Bearing-close	
weighings	**Average**
77,049	77,049
77,049	
77,049	

Cage-initiation	
weighings	**Average**
11,691	11,690
11,689	
11,690	
Cage-end	
weighings	**Average**
11,689	11,689
11,690	
11,689	

Bearing-initiation	
weighings	**Average**
69,686	69,685
69,684	
69,685	
Bearing-end	
weighings	**Average**
69,683	69,683
69,684	
69,683	

Date

Initiation:	**13-04-2011**
End:	**15-04-2011**

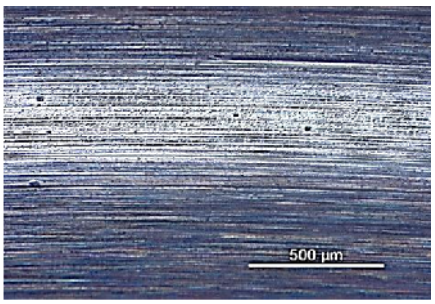
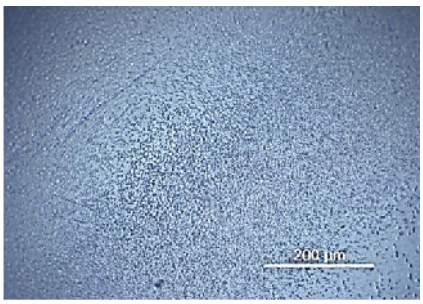
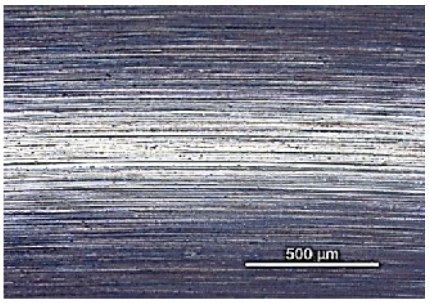
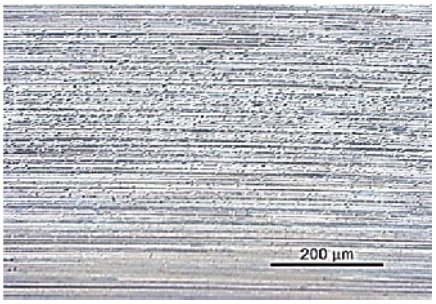
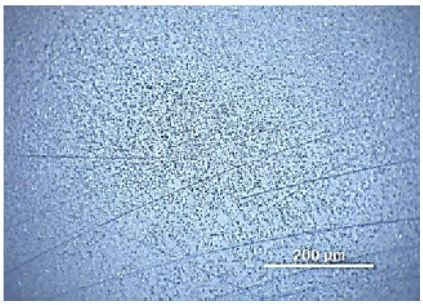
Mass loss	
0	mg

Note:
The first wear test was 50h at 500 rpm with 21 balls and the second wear test was 50h at 1200 pm with 7 balls.

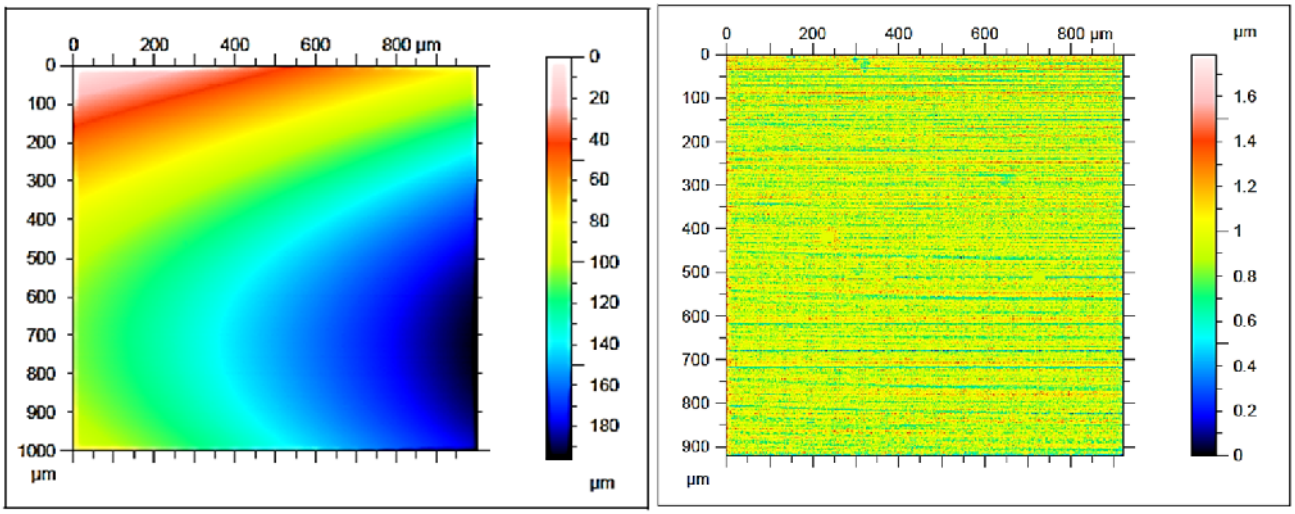
Identification of different contact zones

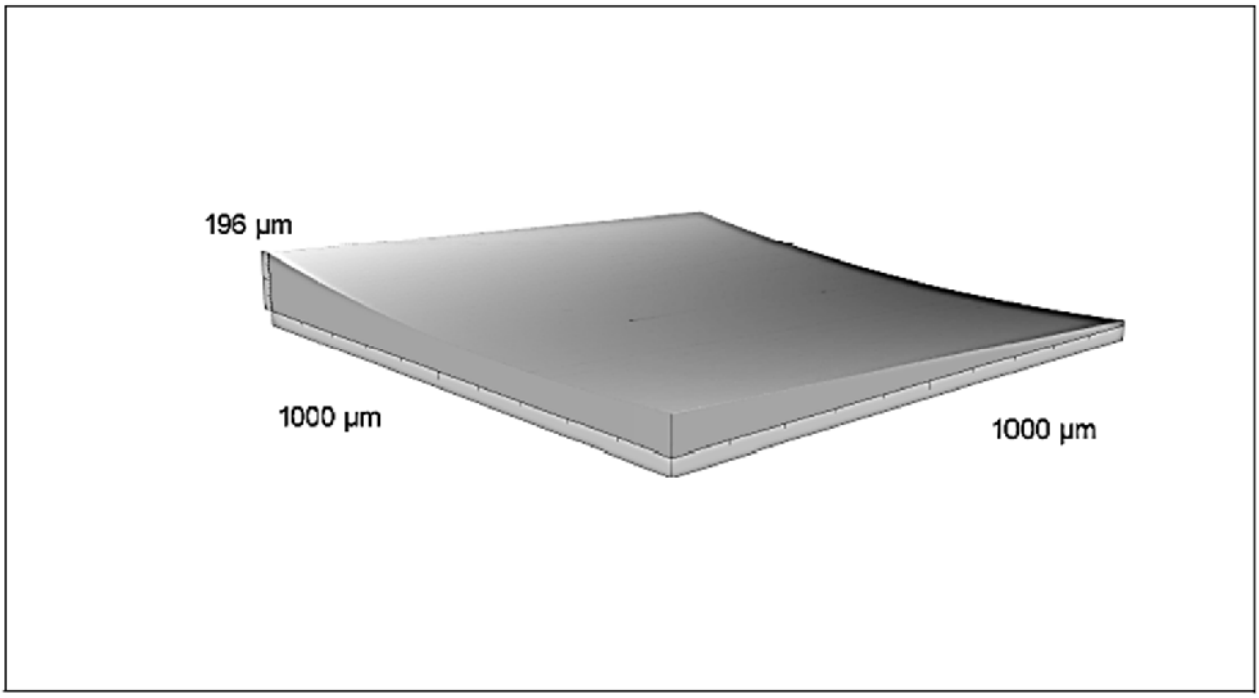
Scheme of the different contact zones analyzed

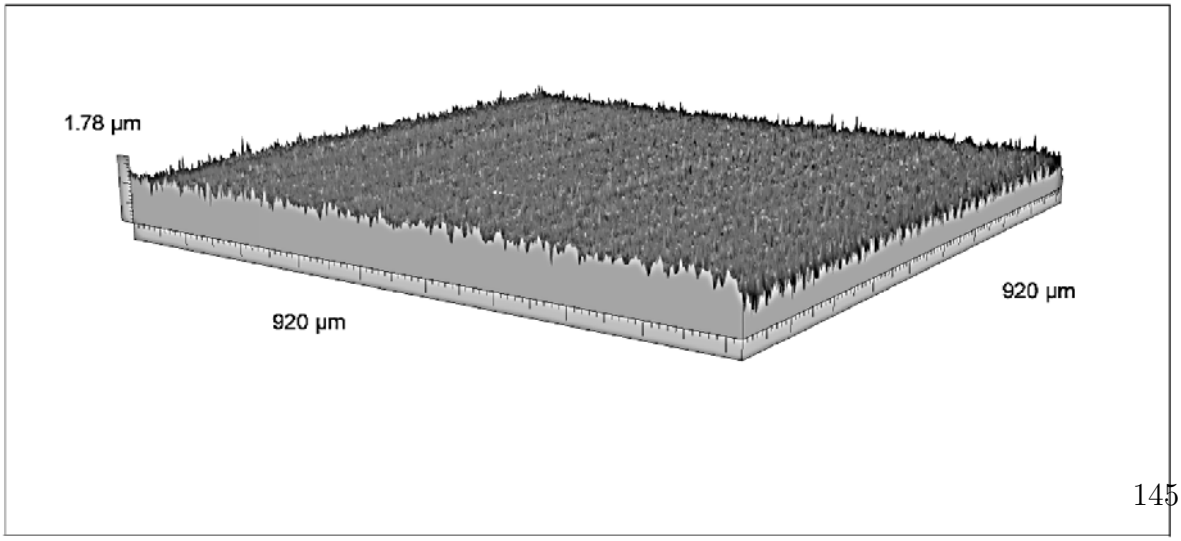
Brand Oil Repsol
Base Oil PAO
Oil Ref. Super Tauro Synthetic 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter, 80 µm





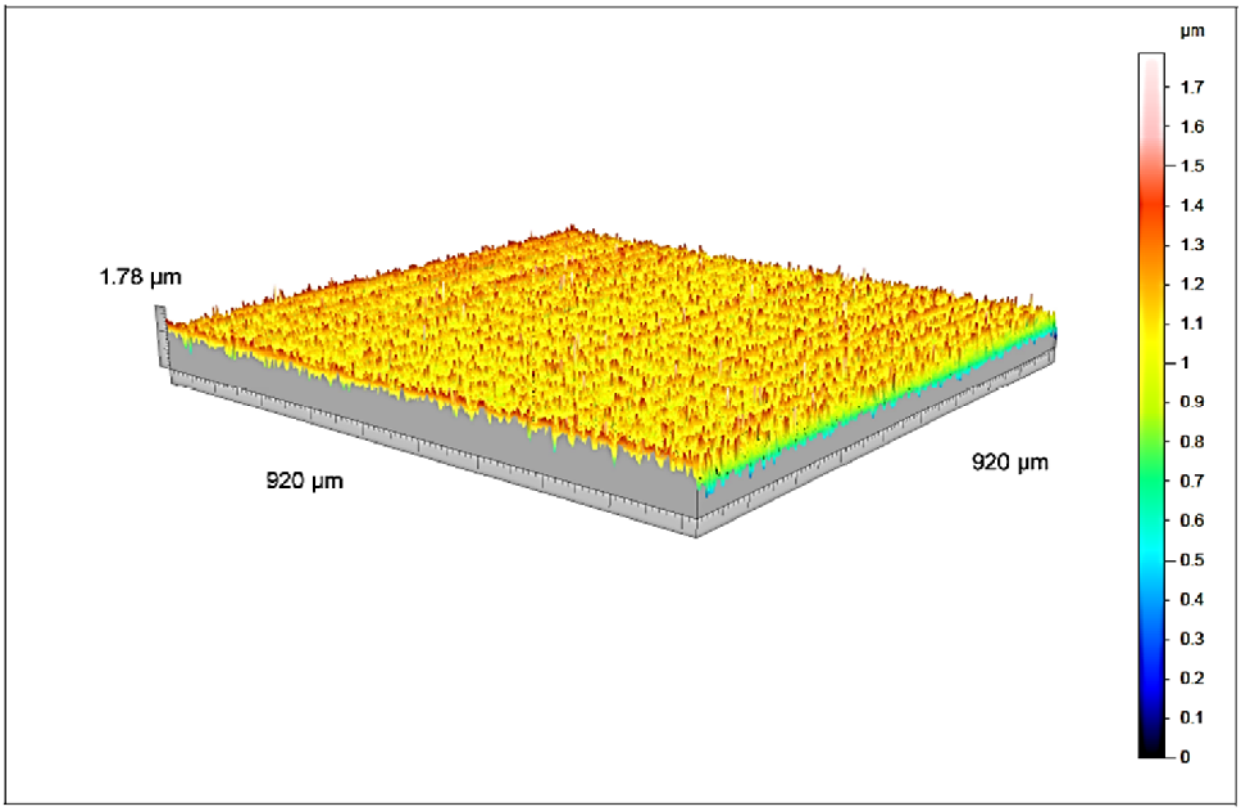


Parameters calculated on the surface PAO_AE_7ESF

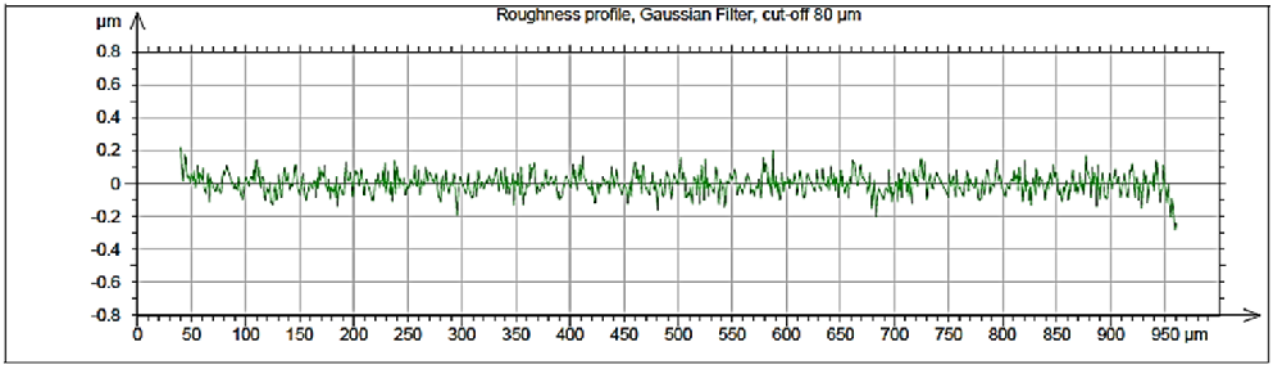
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.108 µm
Sq	=	0.14 µm
Sp	=	0.843 µm
Sv	=	0.943 µm
St	=	1.79 µm
Ssk	=	-0.337
Sku	=	3.91
Sz	=	1.79 µm



Profiles in the circumferential direction

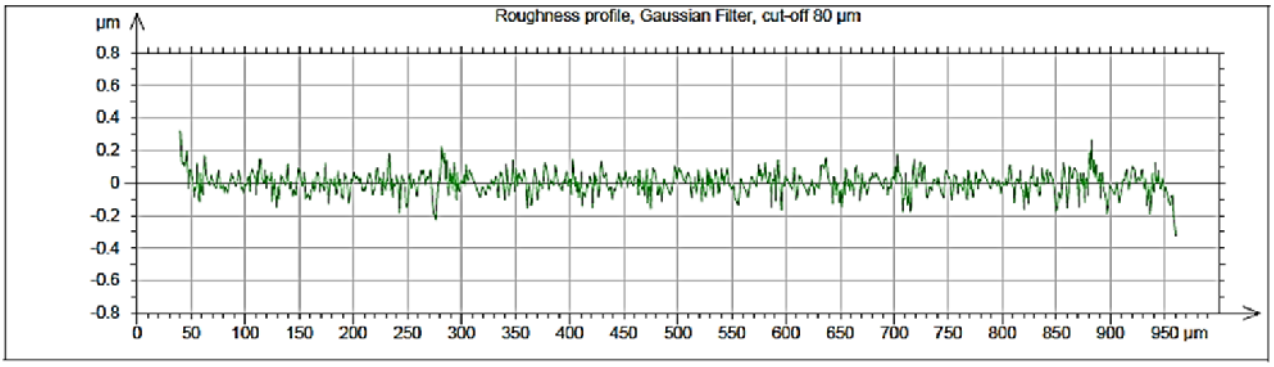


Parameters calculated on the profile PAO_AE_7ESF > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0159 µm
Rq	= 0.0405 µm
Rz	= 0.227 µm
Rt	= 0.4 µm
Rp	= 0.118 µm
Rv	= 0.109 µm
Rsk	= 0.371
Rku	= 7.66



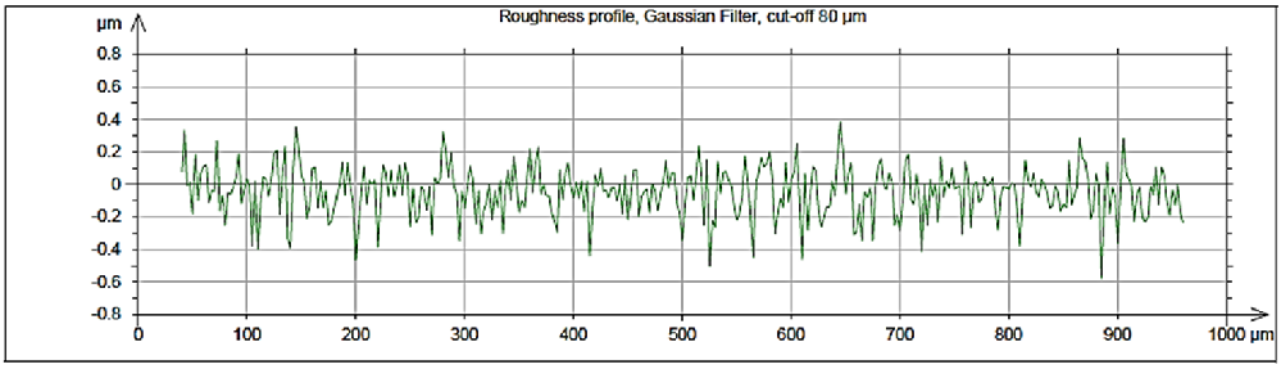
Parameters calculated on the profile PAO_AE_7ESF > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0172 µm
Rq	= 0.0433 µm
Rz	= 0.245 µm
Rt	= 0.6 µm
Rp	= 0.136 µm
Rv	= 0.109 µm
Rsk	= 0.511
Rku	= 10.9

Profiles in the radial direction

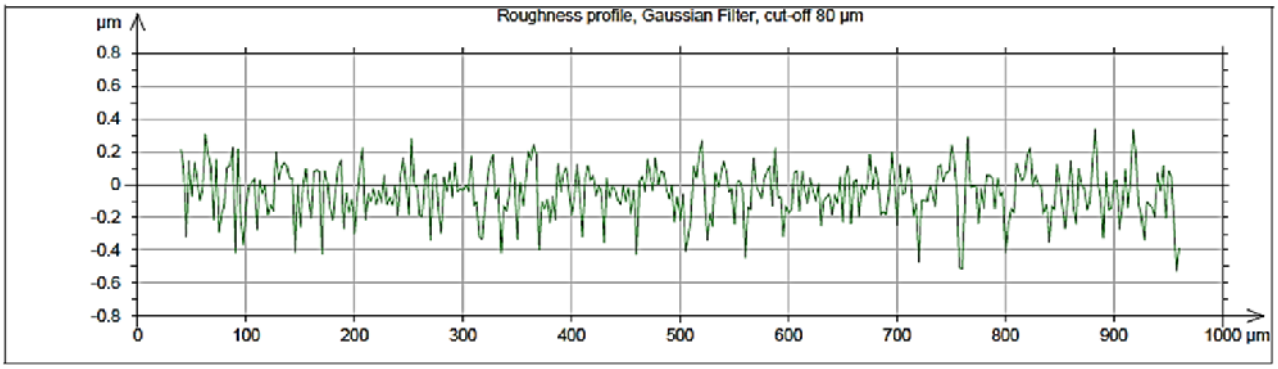


Parameters calculated on the profile PAO_AE_7ESF > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0865 µm
Rq	= 0.133 µm
Rz	= 0.6 µm
Rt	= 0.9 µm
Rp	= 0.227 µm
Rv	= 0.373 µm
Rsk	= -1.26
Rku	= 4.75



Parameters calculated on the profile PAO_AE_7ESF > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0906 µm
Rq	= 0.136 µm
Rz	= 0.573 µm
Rt	= 0.8 µm
Rp	= 0.218 µm
Rv	= 0.355 µm
Rsk	= -1.4
Rku	= 4.68

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (21 balls 50h+7 balls 50h)	**Brand Oil**	Fuchs
Bearing :	Thrust ball bearings (7 balls)	**Base Oil**	Ester
Bearing Ref.	SKF 51107	**Oil Ref.**	Gearmaster ECO 320

Reference Bearing-initiation	
weighings	**Average**
77,049	77,049
77,049	
77,049	
Reference Bearing-close	
weighings	**Average**
77,050	77,050
77,050	
77,049	

Cage-initiation	
weighings	**Average**
11,644	11,644
11,644	
11,644	
Cage-end	
weighings	**Average**
11,638	11,637
11,637	
11,637	

Bearing-initiation	
weighings	**Average**
69,700	69,700
69,699	
69,701	
Bearing-end	
weighings	**Average**
69,693	69,694
69,693	
69,695	

Date
Initiation: **28-03-2011**
End: **30-03-2011**

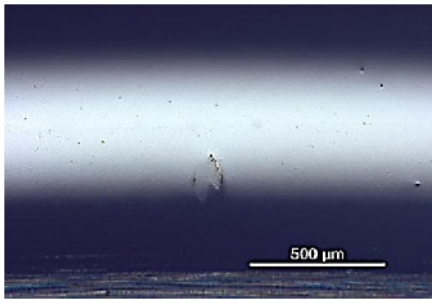
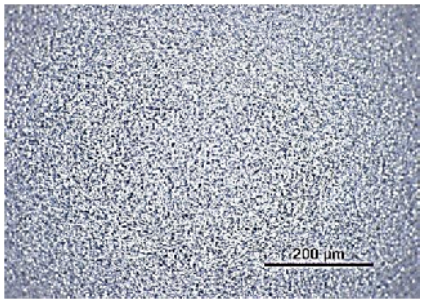
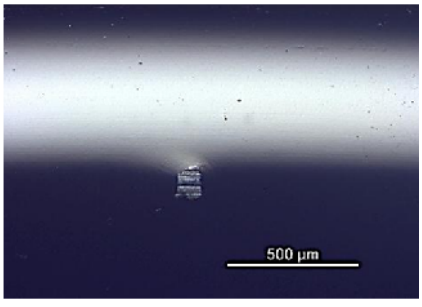
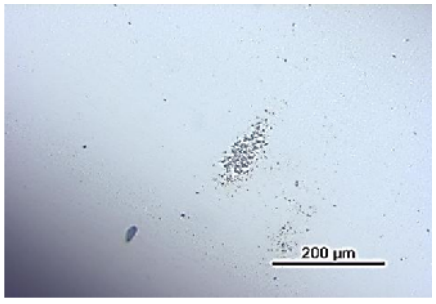
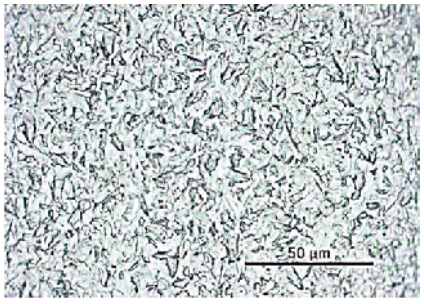
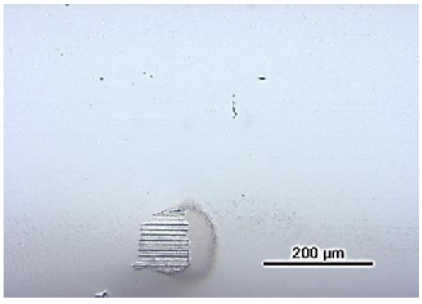
Mass loss	
7,0	mg

Note:
The first wear test was 50h at 500 rpm with 21 balls and the second wear test was 50h at 1200 pm with 7 balls.

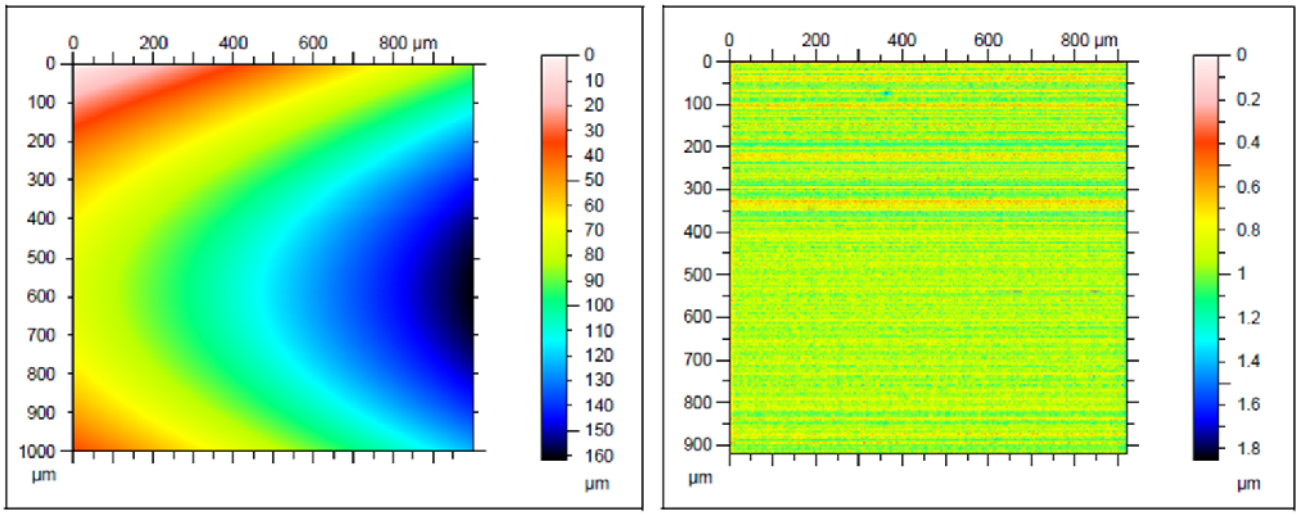
Identification of different contact zones

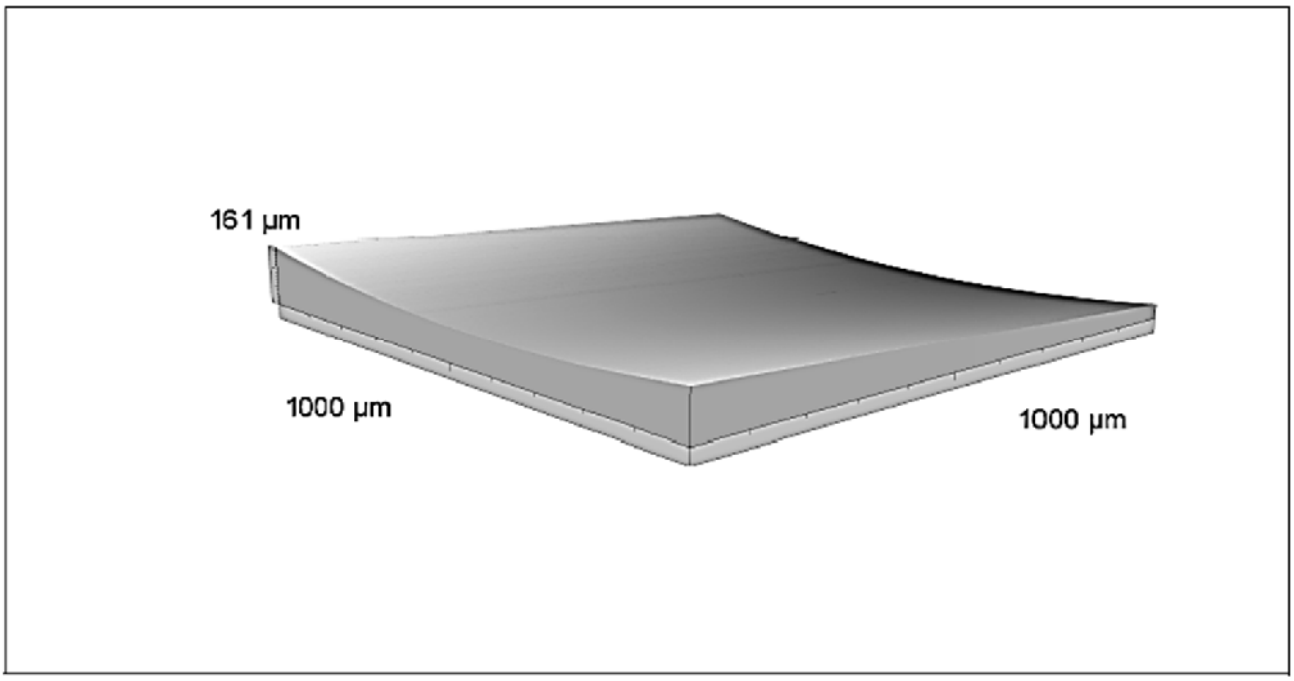
Scheme of the different contact zones analyzed

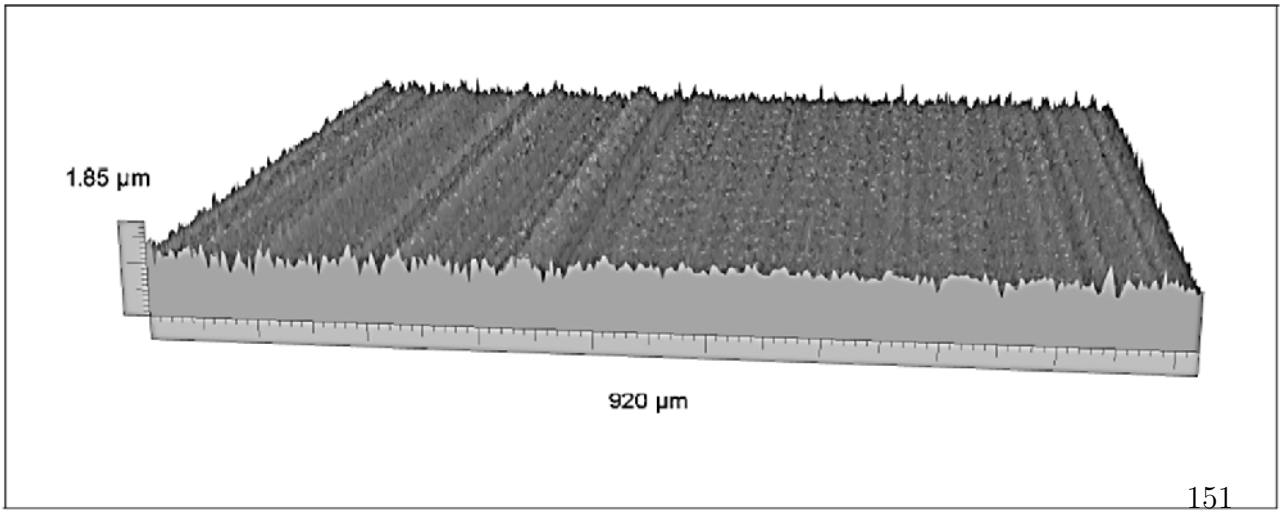
Brand Oil Fuchs
Base Oil Ester
Oil Ref. Gearmaster ECO 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter,80 µm





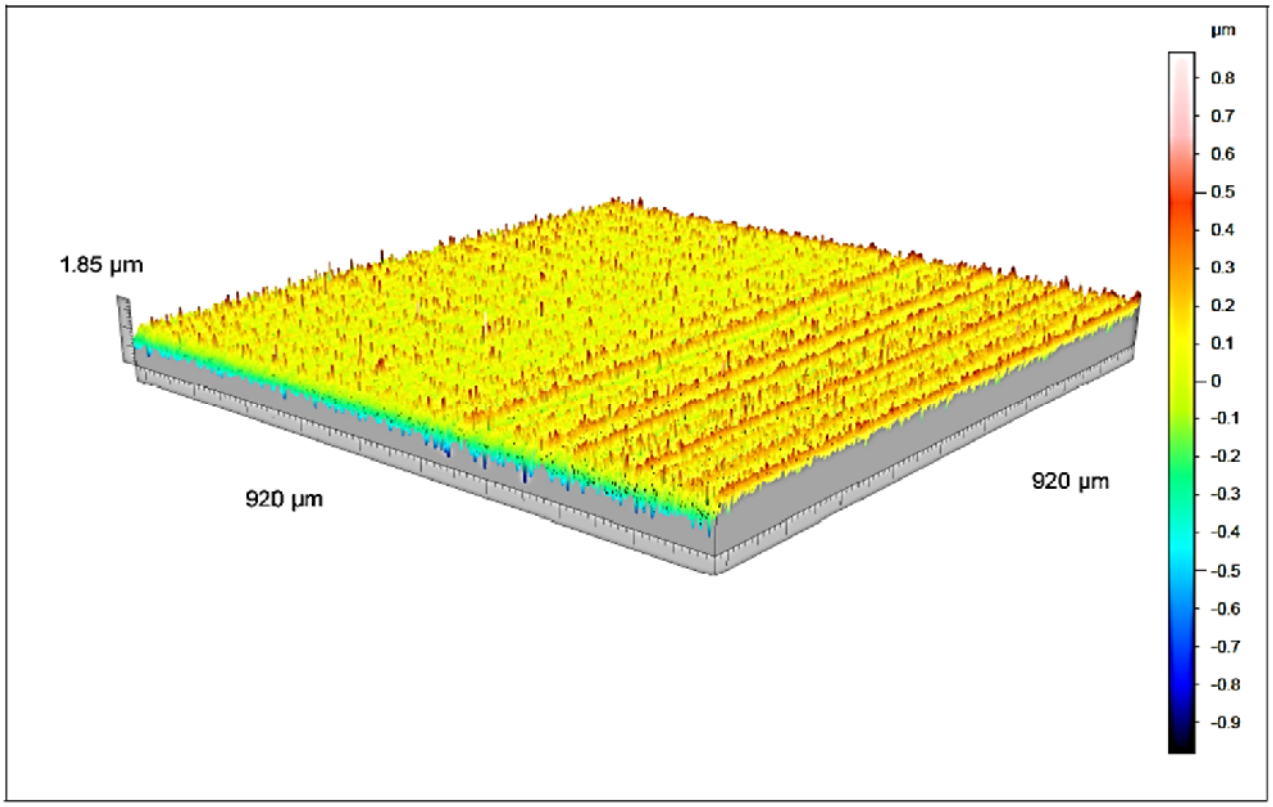


Parameters calculated on the surface ESTER_AE_7esferas 50h+50h > Roughness, Gaussian Filter, 80 µm

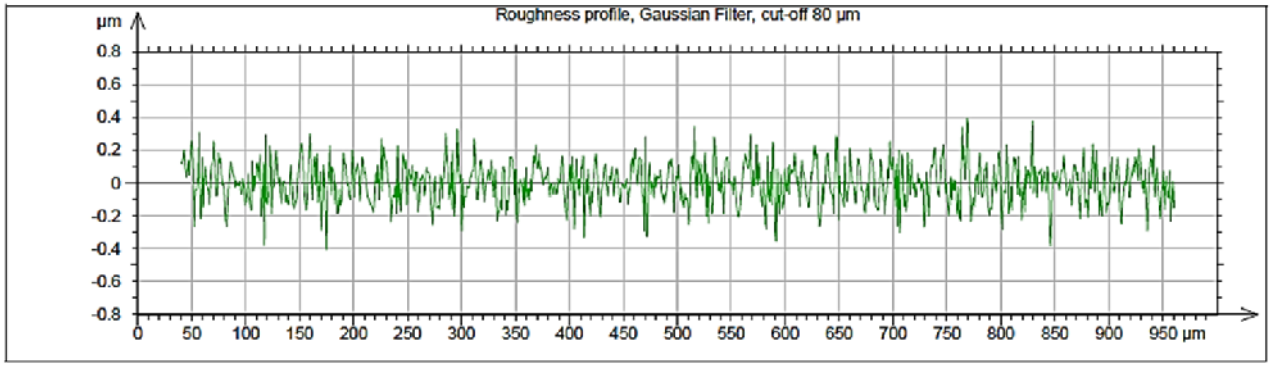
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.108 µm
Sq	=	0.141 µm
Sp	=	0.868 µm
Sv	=	0.982 µm
St	=	1.85 µm
Ssk	=	-1.04
Sku	=	4.04
Sz	=	1.85 µm



Profiles in the circumferential direction

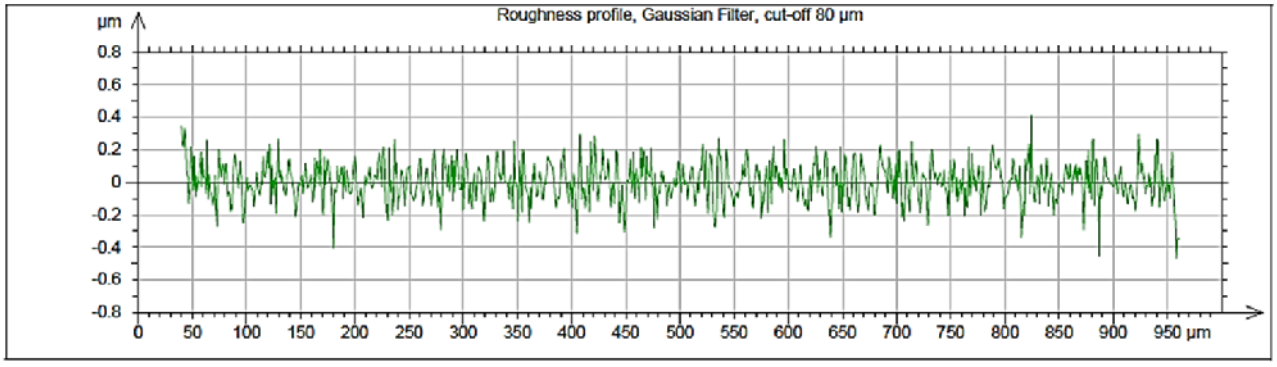


Parameters calculated on the profile ESTER_AE_7esferas50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0682 µm
Rq	= 0.103 µm
Rz	= 0.555 µm
Rt	= 0.8 µm
Rp	= 0.273 µm
Rv	= 0.282 µm
Rsk	= 0.00406
Rku	= 4.04



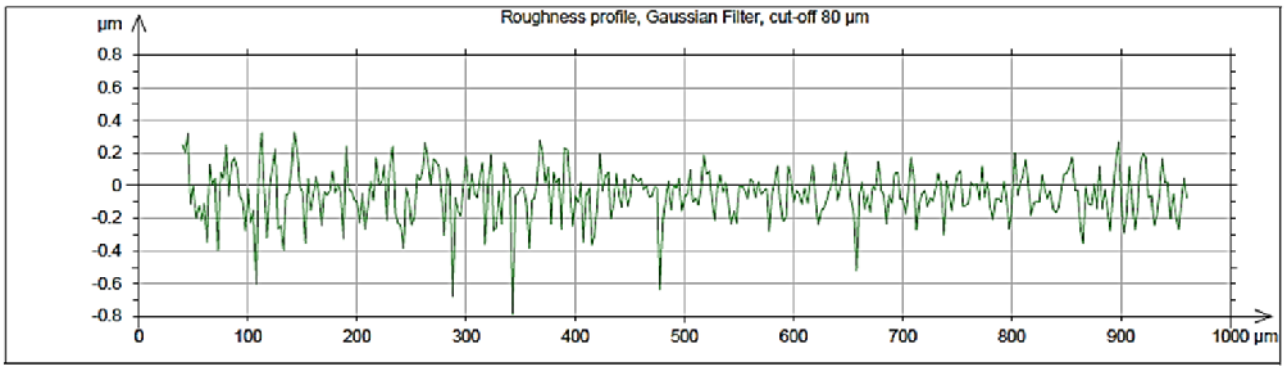
Parameters calculated on the profile ESTER_AE_7esferas50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0585 µm
Rq	= 0.095 µm
Rz	= 0.536 µm
Rt	= 0.8 µm
Rp	= 0.255 µm
Rv	= 0.282 µm
Rsk	= 0.038
Rku	= 4.82

Profiles in the radial direction

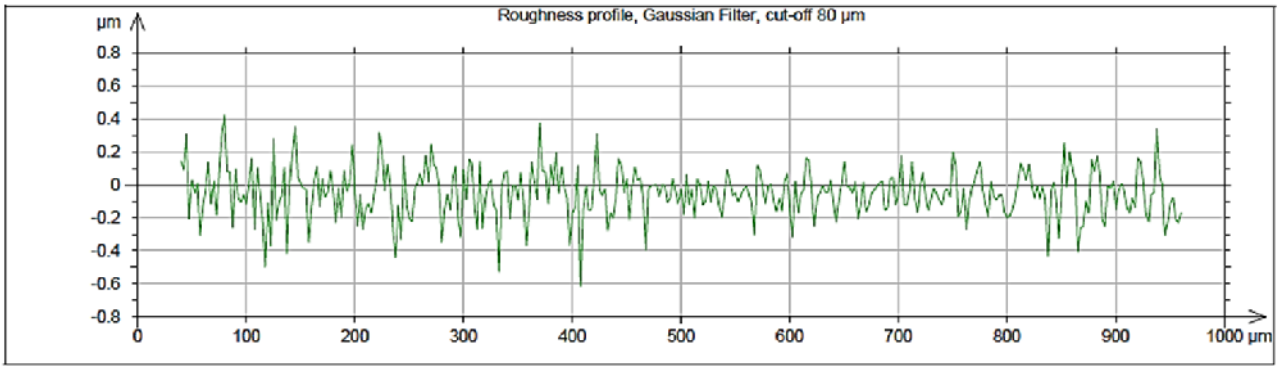


Parameters calculated on the profile ESTER_AE_7esferas50h+50h > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0843 µm
   Rq     = 0.134 µm
   Rz     = 0.627 µm
   Rt     = 1 µm
   Rp     = 0.209 µm
   Rv     = 0.418 µm
   Rsk    = -1.98
   Rku    = 8.42
```



Parameters calculated on the profile ESTER_AE_7esferas50h+50h > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0802 µm
   Rq     = 0.127 µm
   Rz     = 0.6 µm
   Rt     = 0.9 µm
   Rp     = 0.218 µm
   Rv     = 0.382 µm
   Rsk    = -1.36
   Rku    = 6.25
```

A.4. Test data sheet for TBB 51107 with 7 balls - second 50h (mass loss, photographs of the surfaces and topography)

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (21 balls 50h+7 balls 50h x2)	**Brand Oil**	Repsol
Bearing :	Thrust ball bearings (7 balls)	**Base Oil**	Mineral
Bearing Ref.	SKF 51107	**Oil Ref.**	Super Tauro FND 320

Reference Bearing-initiation	
weighings	**Average**
77,050	77,049
77,049	
77,049	
Reference Bearing-end	
weighings	**Average**
77,051	77,050
77,050	
77,05	

Cage-initiation	
weighings	**Average**
11,652	11,652
11,652	
11,652	
Cage-end	
weighings	**Average**
11,648	11,651
11,649	
11,6549	

Bearing-initiation	
weighings	**Average**
69,535	69,535
69,535	
69,535	
Bearing-end	
weighings	**Average**
69,531	69,530
69,530	
69,529	

Date

Initiation:	**01-05-2011**
End:	**03-05-2011**

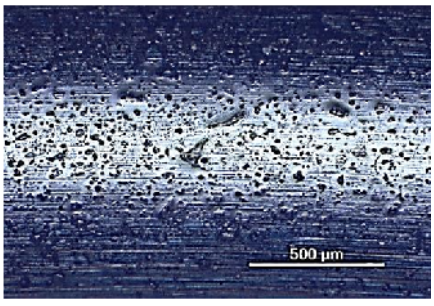
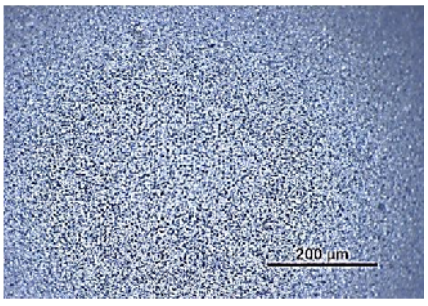
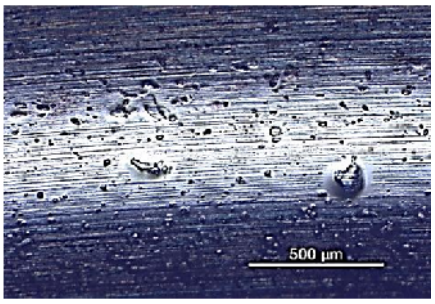
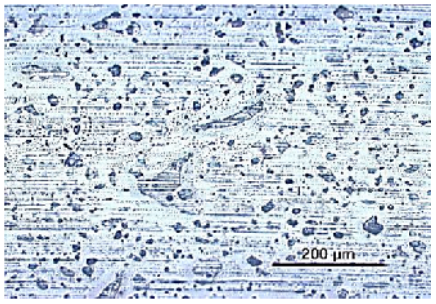
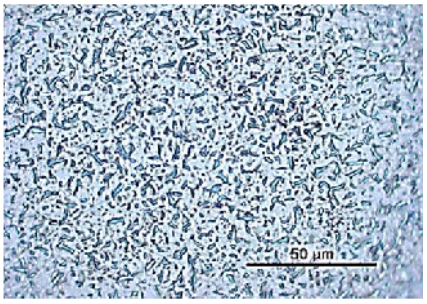
Mass loss	
6	mg

Note:
The first wear test was 50h at 500 rpm with 21 balls and the second/third were 50h at 1200 rpm with 7 balls.

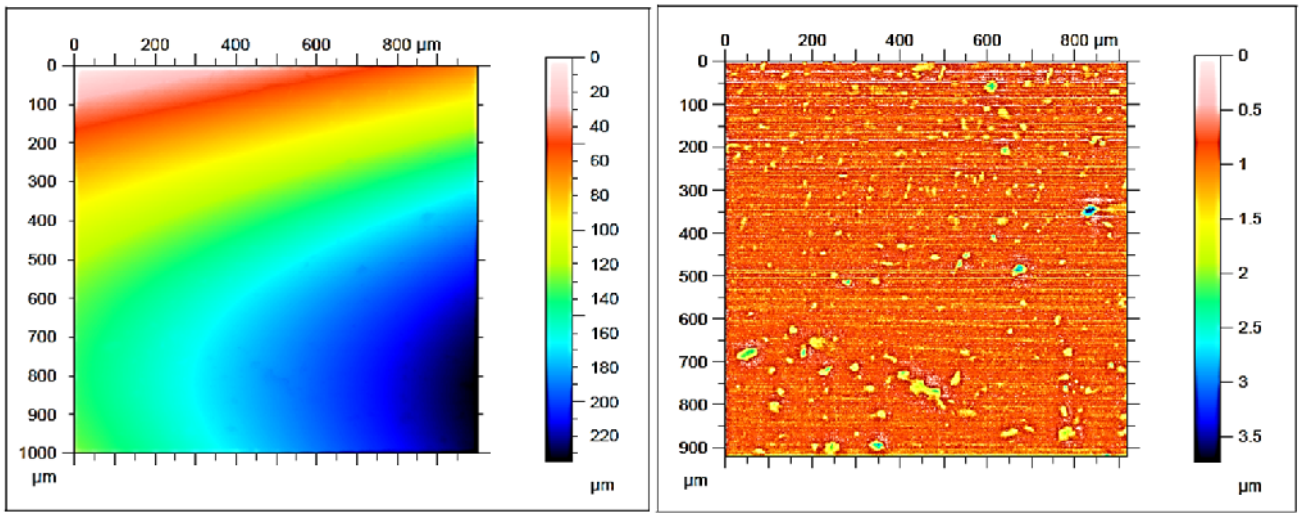
Identification of different contact zones

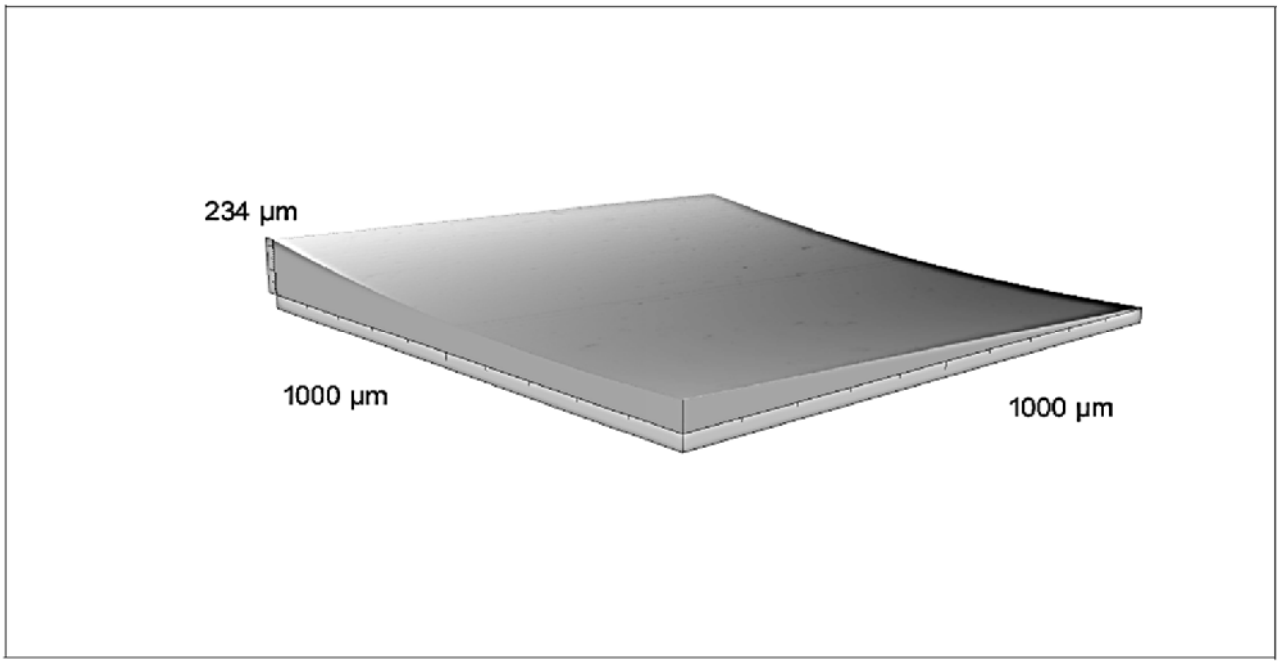
Scheme of the different contact zones analyzed

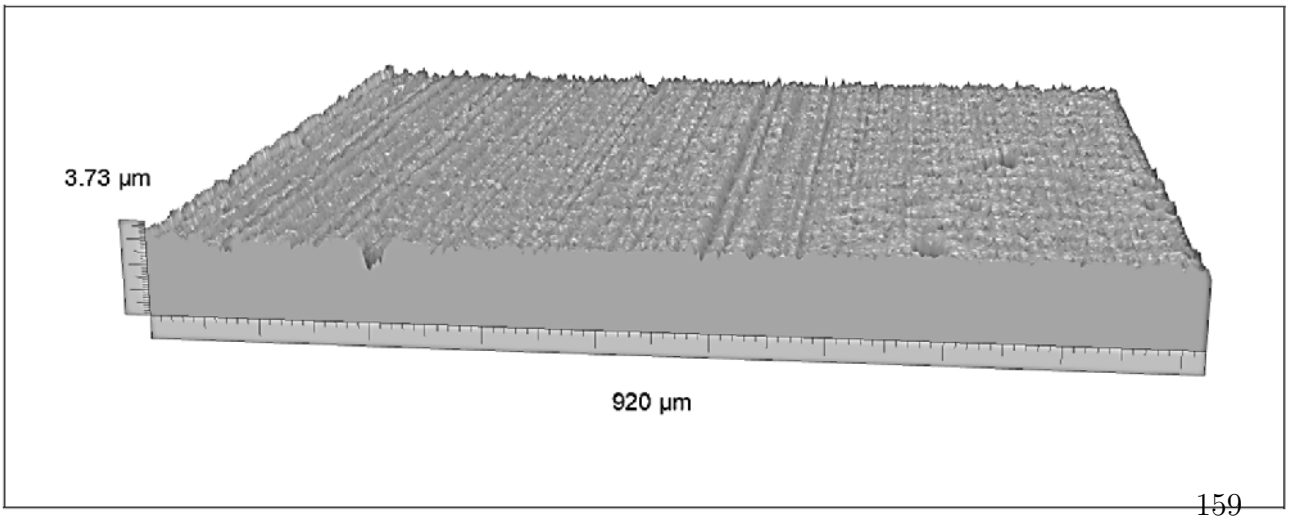
Brand Oil Repsol
Base Oil Mineral
Oil Ref. Super Tauro FND 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter, 80 µm





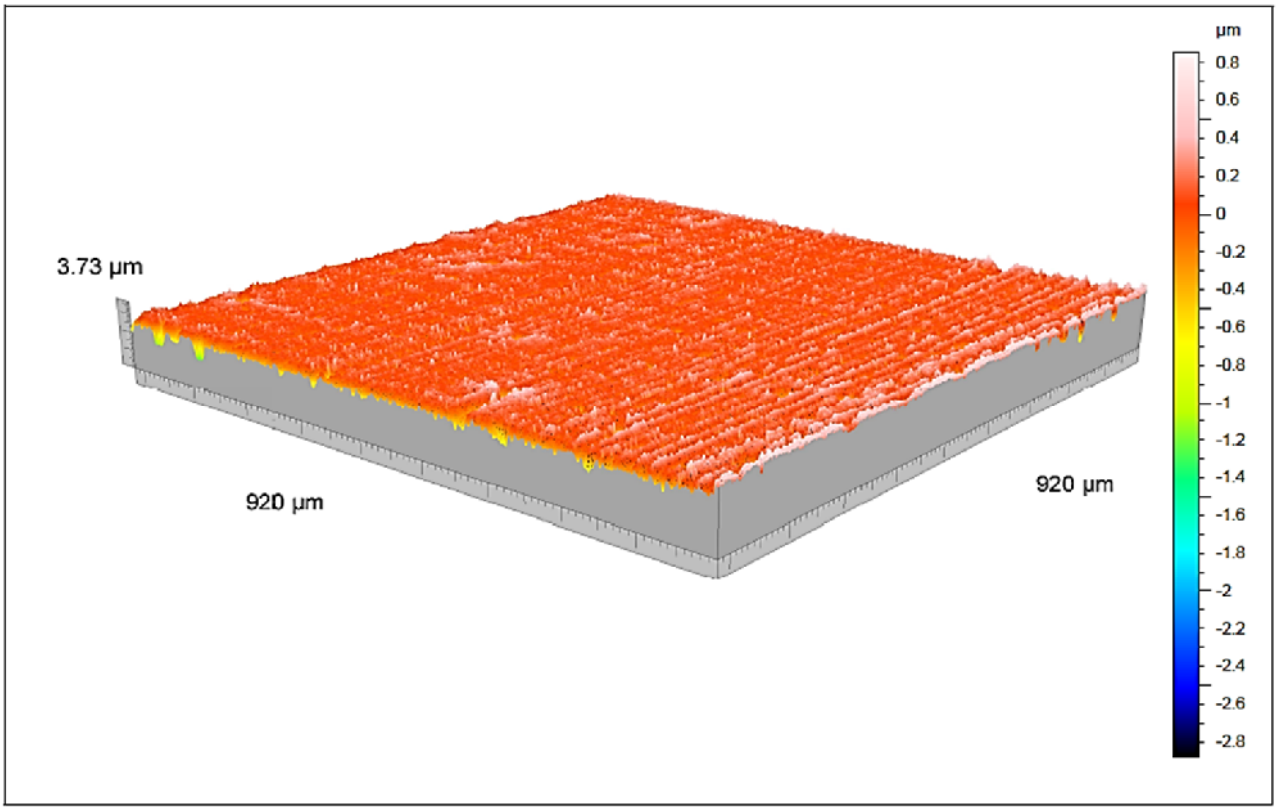


Parameters calculated on the surface AE_MINERAL320_7Balls 50h+50h+50h > Roughness, Gaussian Filter, 80 µm

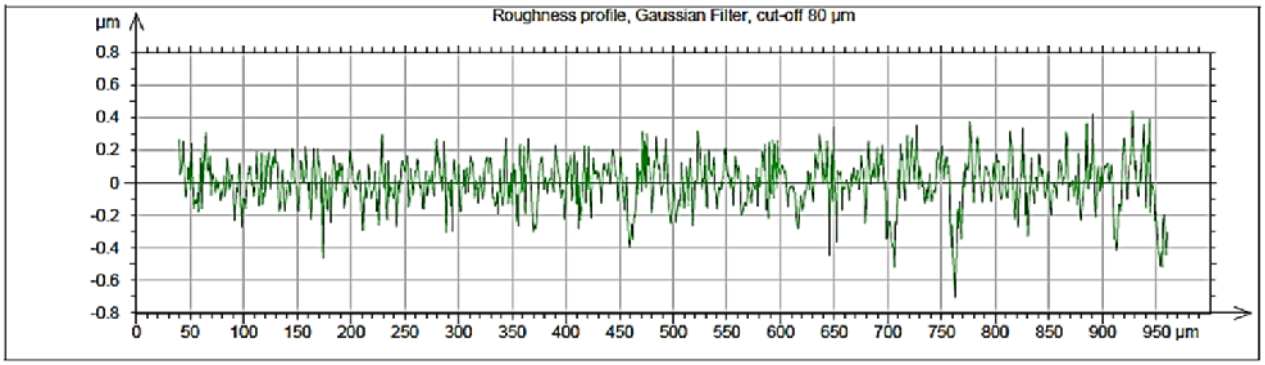
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.135 µm
Sq	=	0.203 µm
Sp	=	0.85 µm
Sv	=	2.88 µm
St	=	3.73 µm
Ssk	=	-2.41
Sku	=	15.1
Sz	=	3.73 µm



Profiles in the circumferential direction

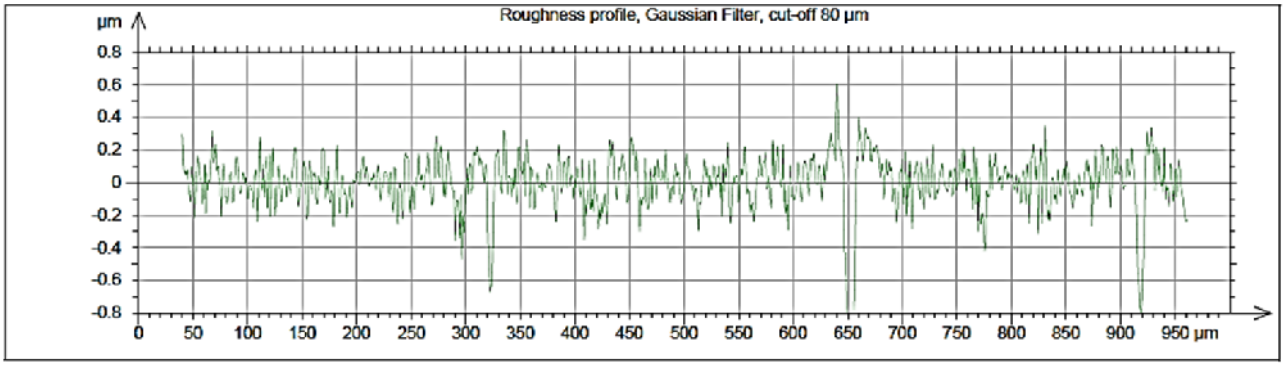


Parameters calculated on the profile AE_MINERAL320_7Balls_50h+ 50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0763 µm
Rq	= 0.117 µm
Rz	= 0.645 µm
Rt	= 1.1 µm
Rp	= 0.291 µm
Rv	= 0.355 µm
Rsk	= -0.678
Rku	= 6.46



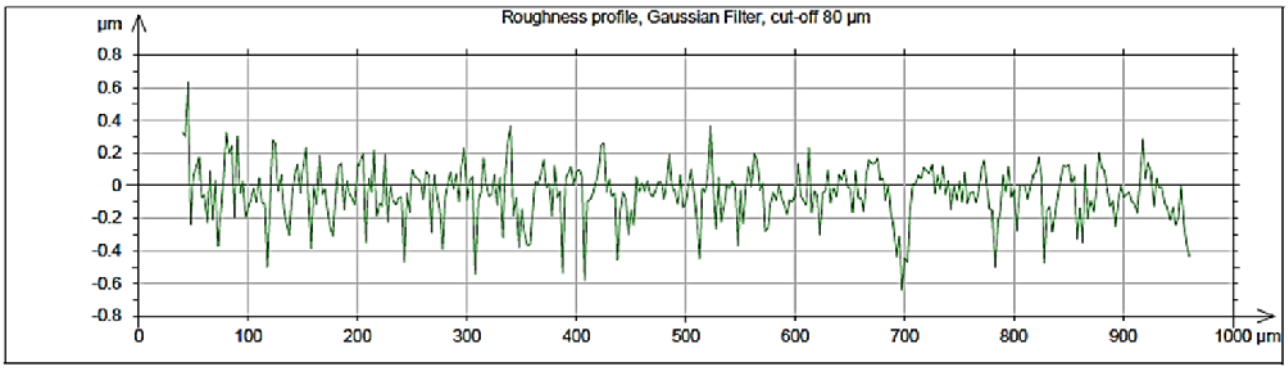
Parameters calculated on the profile AE_MINERAL320_7Balls_50h+ 50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0841 µm
Rq	= 0.139 µm
Rz	= 0.718 µm
Rt	= 2 µm
Rp	= 0.273 µm
Rv	= 0.445 µm
Rsk	= -5.52
Rku	= 47.3

Profiles in the radial direction

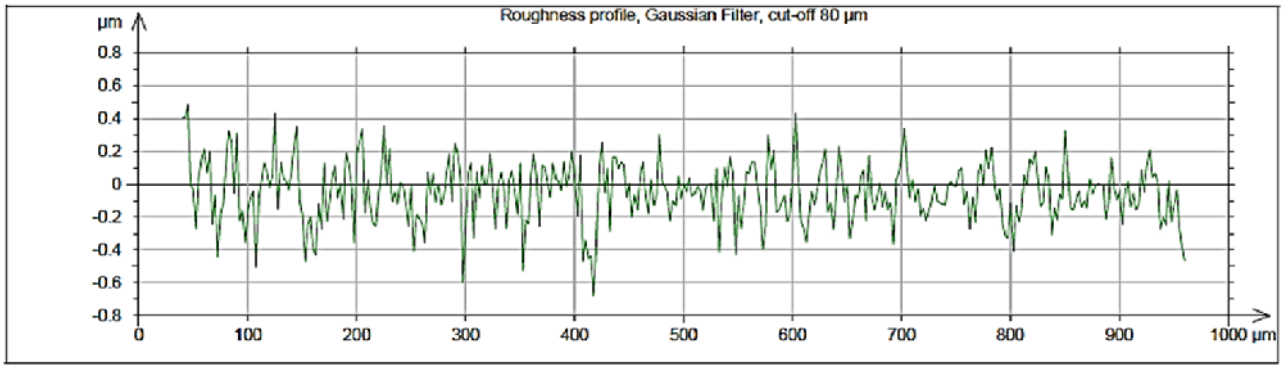


Parameters calculated on the profile AE_MINERAL320_7Balls_50h+50h+50h > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0937 µm
   Rq     = 0.146 µm
   Rz     = 0.664 µm
   Rt     = 1.2 µm
   Rp     = 0.236 µm
   Rv     = 0.427 µm
   Rsk    = -1.34
   Rku    = 6.35
```



Parameters calculated on the profile AE_MINERAL320_7Balls_50h+50h+50h > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.111 µm
   Rq     = 0.159 µm
   Rz     = 0.7 µm
   Rt     = 1 µm
   Rp     = 0.291 µm
   Rv     = 0.409 µm
   Rsk    = -1.01
   Rku    = 4.82
```

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (21 balls 50h+7 balls 50h x2)	**Brand Oil**	Repsol
Bearing :	Thrust ball bearings (7 balls)	**Base Oil**	PAO
Bearing Ref.	SKF 51107	**Oil Ref.**	Super Tauro Synthetic 320

Reference Bearing-initiation	
weighings	**Average**
77,049	77,049
77,049	
77,049	
Reference Bearing-close	
weighings	**Average**
77,050	77,050
77,050	
77,050	

Cage-initiation	
weighings	**Average**
11,691	11,690
11,690	
11,690	
Cage-end	
weighings	**Average**
11,691	11,691
11,691	
11,692	

Bearing-initiation	
weighings	**Average**
69,686	69,685
69,685	
69,685	
Bearing-end	
weighings	**Average**
69,685	69,685
69,685	
69,684	

Date
Initiation: **09-05-2011**
End: **11-05-2011**

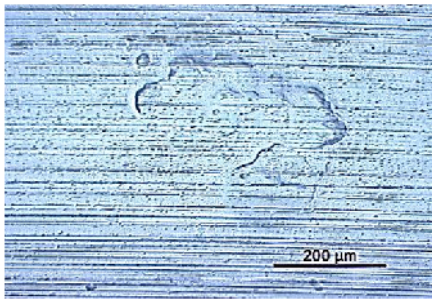
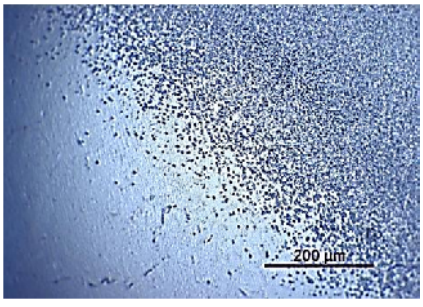
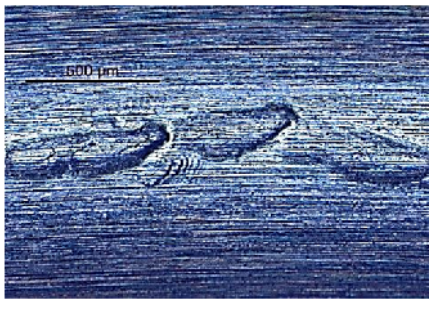
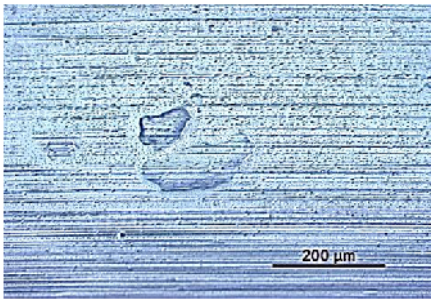
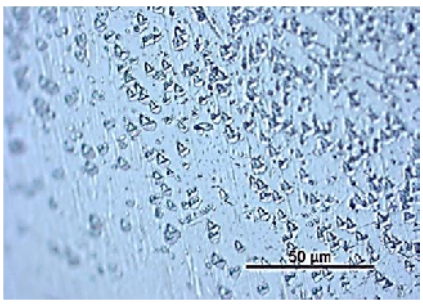
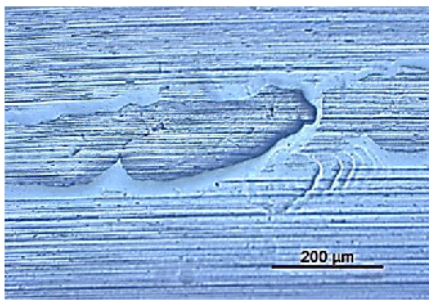
Mass loss	
1	mg

Note:
The first wear test was 50h at 500 rpm with 21 balls and the second/third were 50h at 1200 rpm with 7 balls.
Due to a wear failure, the test was stopped 5 h after the starting.

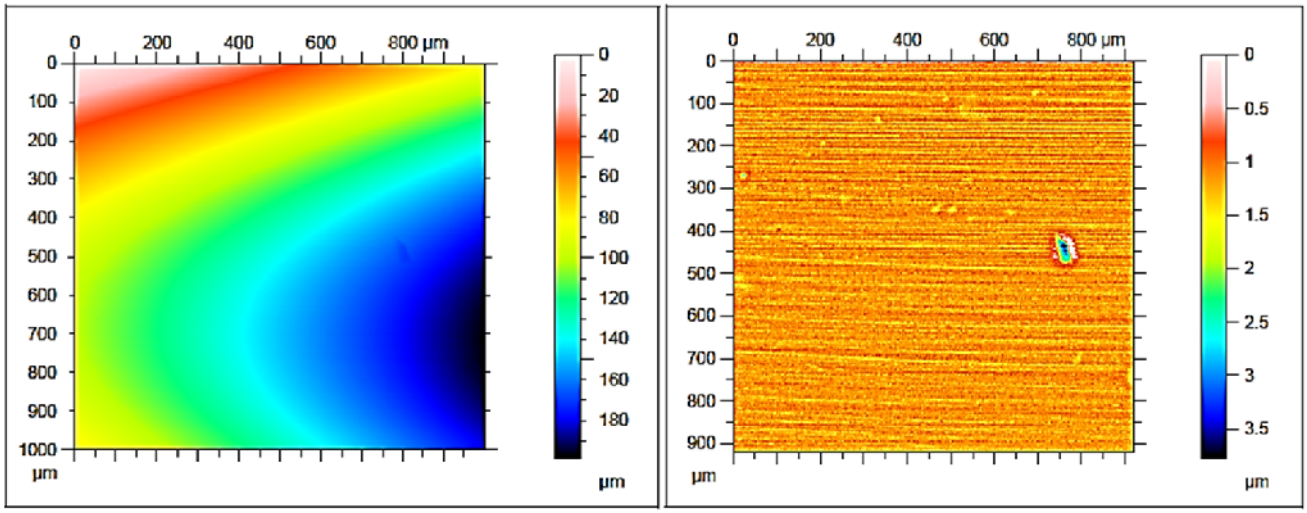
Identification of different contact zones

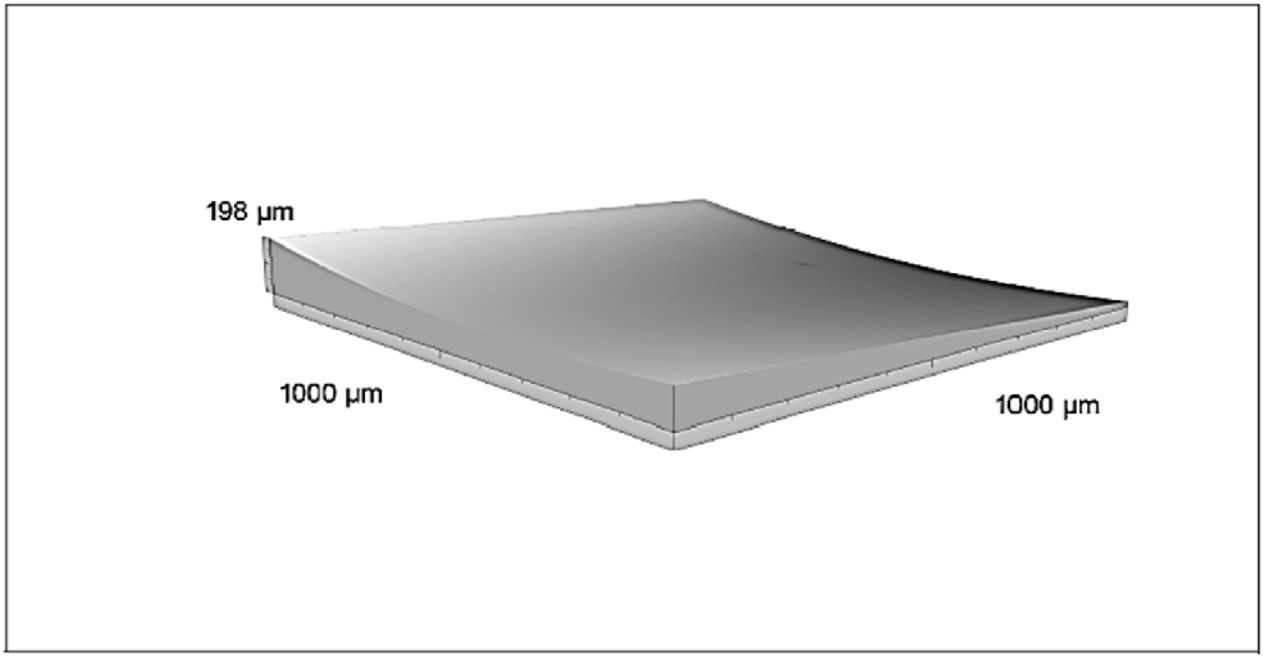
Scheme of the different contact zones analyzed

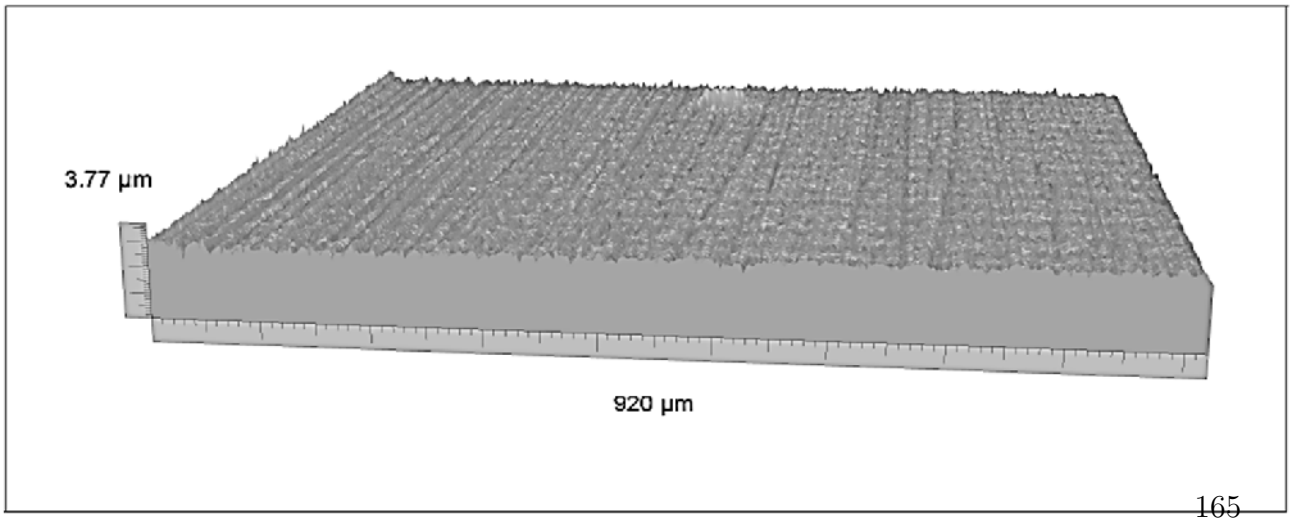
Brand Oil Repsol
Base Oil PAO
Oil Ref. Super Tauro Synthetic 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter, 80 µm





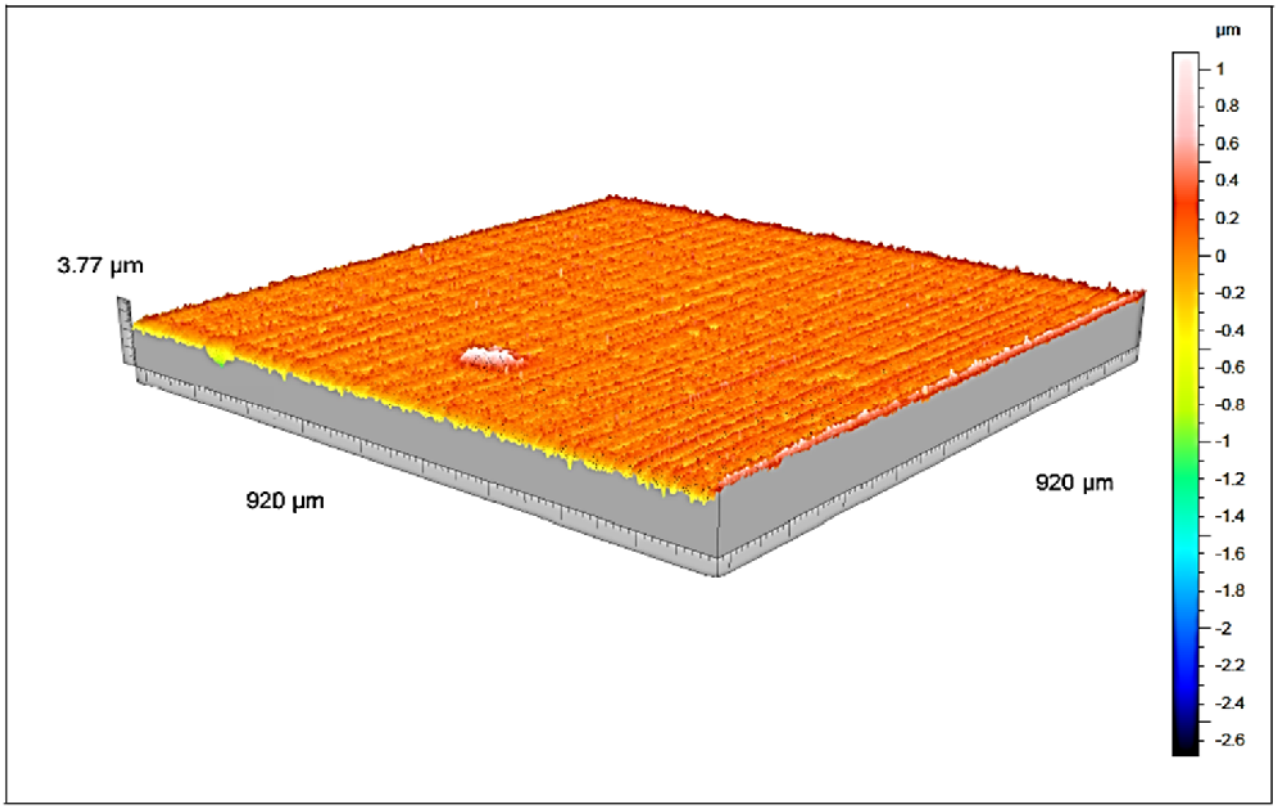


Parameters calculated on the surface AE_PAO320_7ESFERAS 50h+50h+50h > Roughness, Gaussian Filter, 80 µm

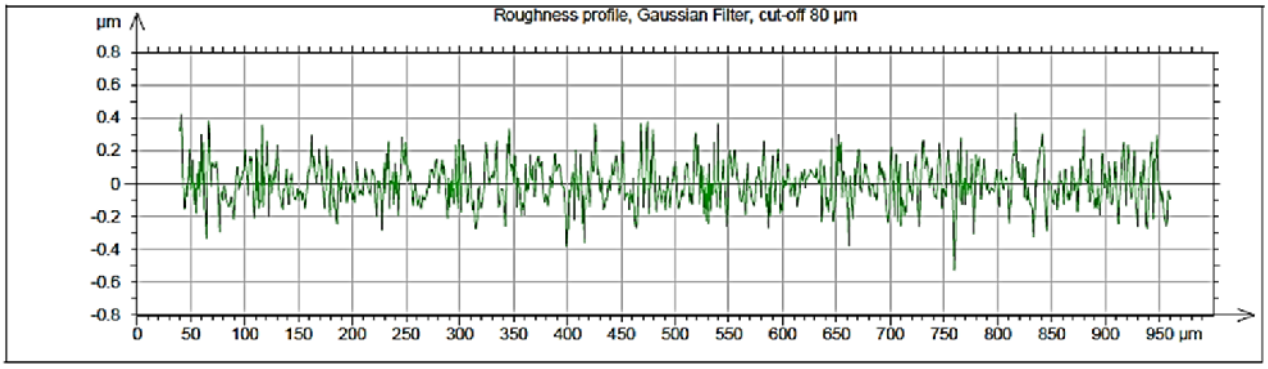
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.113 µm
Sq	=	0.157 µm
Sp	=	1.09 µm
Sv	=	2.68 µm
St	=	3.77 µm
Ssk	=	-1.82
Sku	=	17.7
Sz	=	3.77 µm



Profiles in the circumferential direction

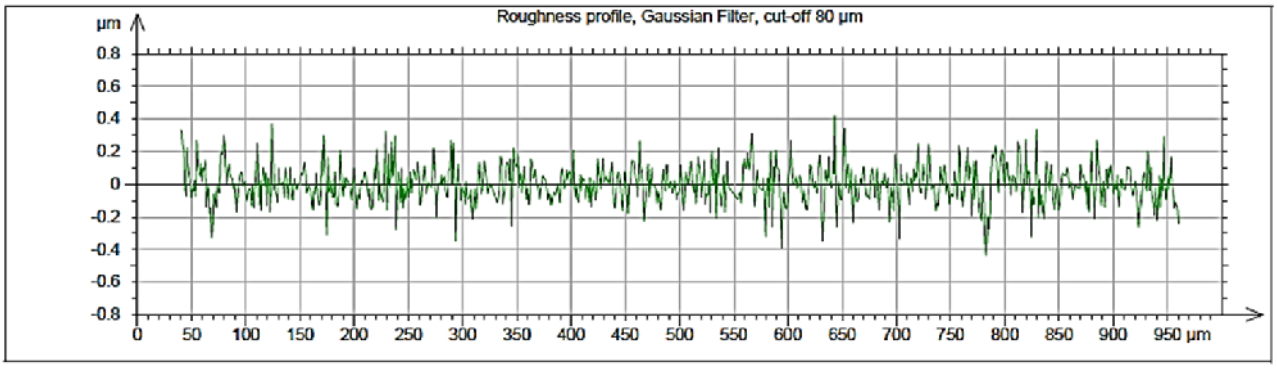


Parameters calculated on the profile AE_PAO320_7ESFERAS_50h+ 50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0701 µm
Rq	= 0.108 µm
Rz	= 0.609 µm
Rt	= 0.9 µm
Rp	= 0.318 µm
Rv	= 0.291 µm
Rsk	= 0.324
Rku	= 4.72



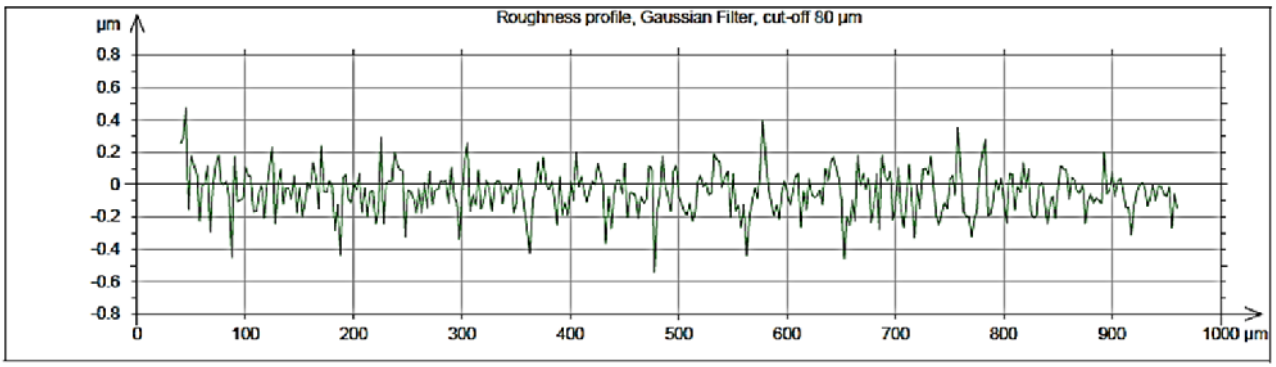
Parameters calculated on the profile AE_PAO320_7ESFERAS_50h+ 50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0523 µm
Rq	= 0.0893 µm
Rz	= 0.536 µm
Rt	= 0.8 µm
Rp	= 0.264 µm
Rv	= 0.273 µm
Rsk	= 0.23
Rku	= 6.48

Profiles in the radial direction

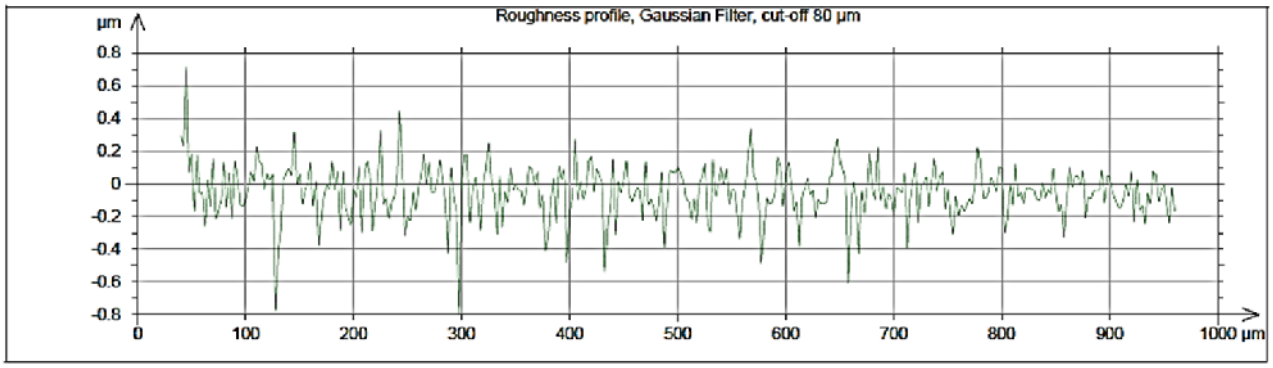


Parameters calculated on the profile AE_PAO320_7ESFERAS_50h+ 50h+50h > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

   Ra     = 0.0766 µm
   Rq     = 0.12 µm
   Rz     = 0.609 µm
   Rt     = 0.9 µm
   Rp     = 0.255 µm
   Rv     = 0.355 µm
   Rsk    = -1.06
   Rku    = 5.36
```



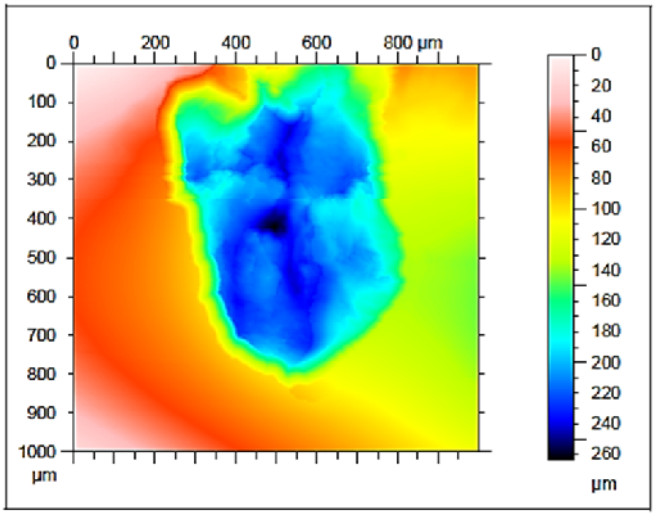
Parameters calculated on the profile AE_PAO320_7ESFERAS_50h+ 50h+50h > Extracted profile

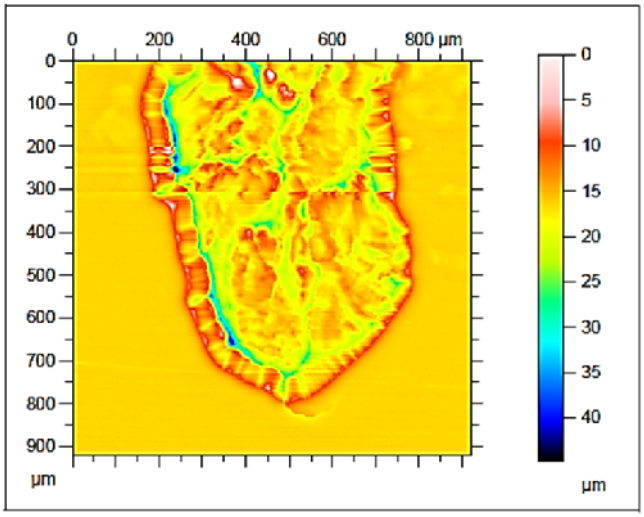
```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

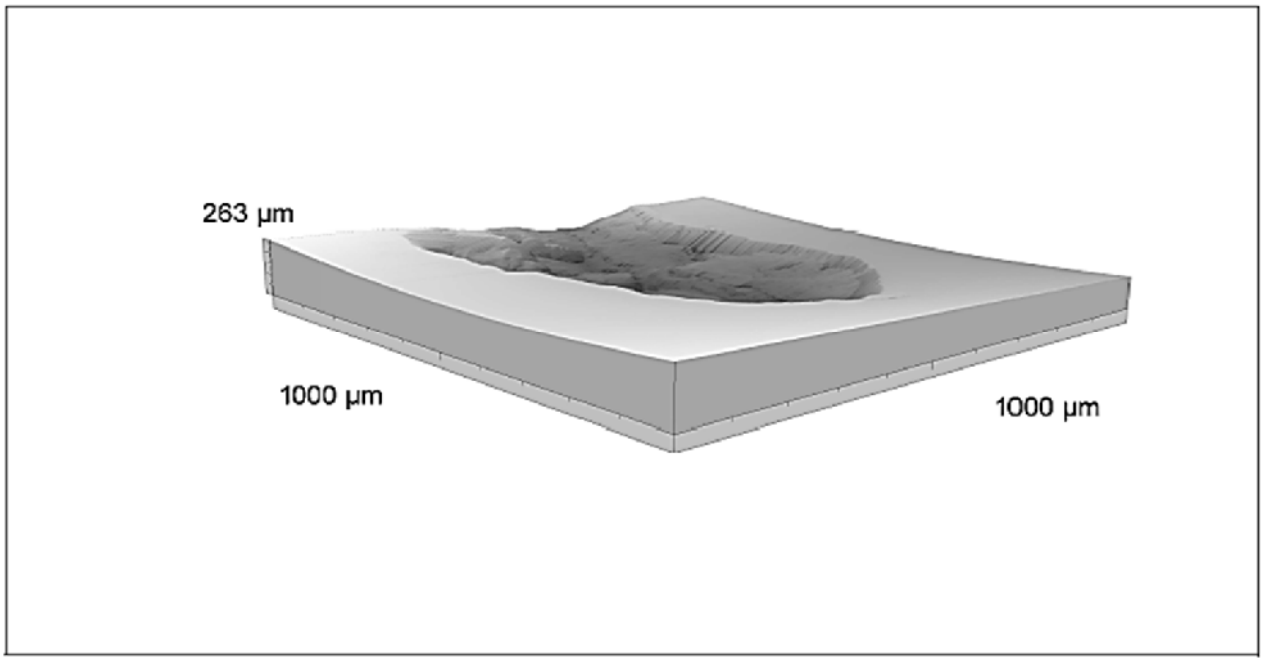
Roughness Parameters, Gaussian filter, 80 µm

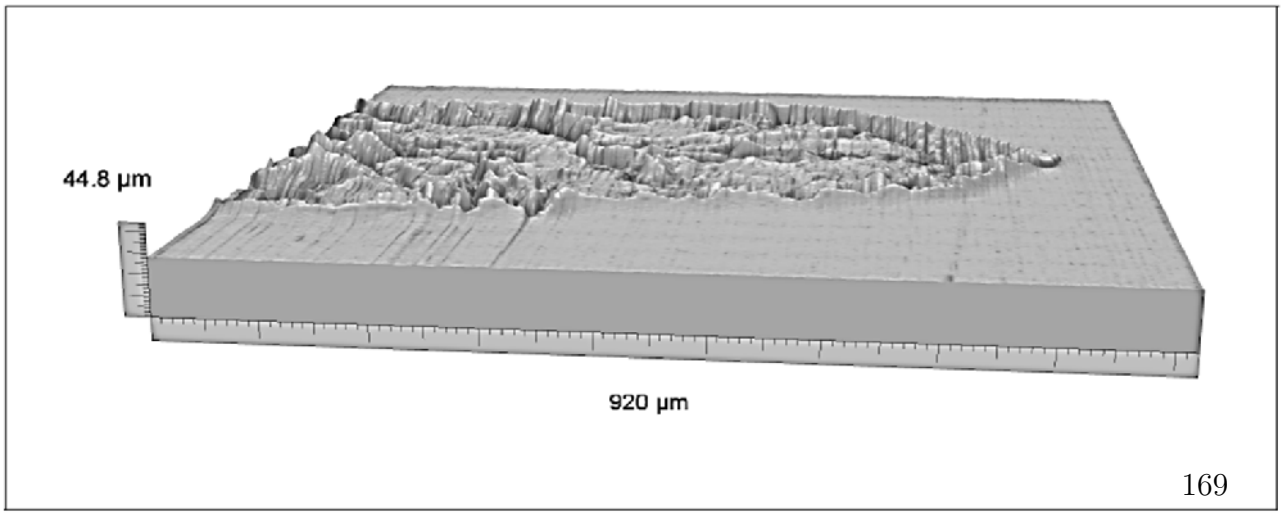
   Ra     = 0.0915 µm
   Rq     = 0.148 µm
   Rz     = 0.709 µm
   Rt     = 1.5 µm
   Rp     = 0.255 µm
   Rv     = 0.455 µm
   Rsk    = -1.65
   Rku    = 10.1
```

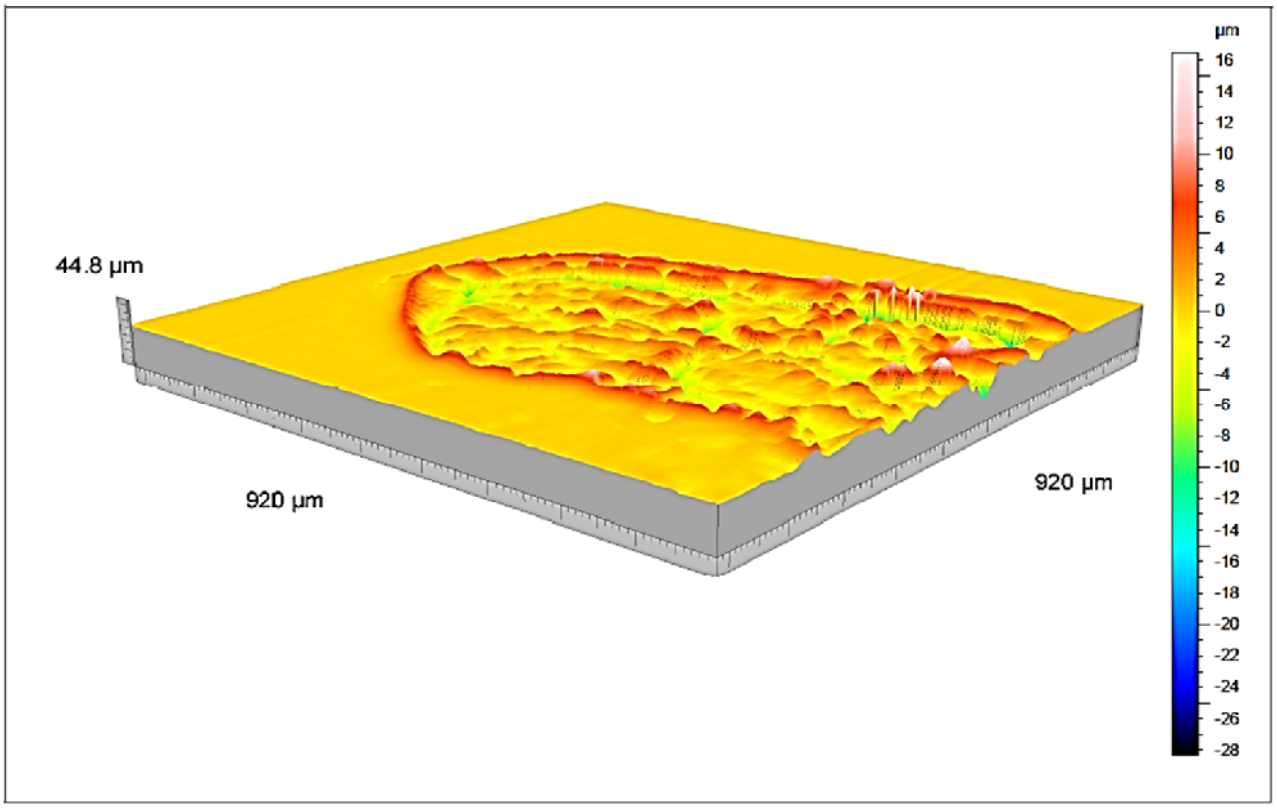
Due to a failure of wear (Spalling), the trial was stopped 5 h after the start of the test.










44.8 µm
920 µm
920 µm
µm
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (21 balls 50h+7 balls 50h x2)	**Brand Oil**	Fuchs
Bearing :	Thrust ball bearings (7 balls)	**Base Oil**	Ester
Bearing Ref.	SKF 51107	**Oil Ref.**	Gearmaster ECO 320

Reference Bearing-initiation	
weighings	**Average**
77,050	77,050
77,050	
77,049	
Reference Bearing-close	
weighings	**Average**
77,048	77,048
77,048	
77,049	

Cage-initiation	
weighings	**Average**
11,638	11,637
11,637	
11,637	
Cage-end	
weighings	**Average**
11,632	11,633
11,633	
11,634	

Bearing-initiation	
weighings	**Average**
69,693	69,694
69,693	
69,695	
Bearing-end	
weighings	**Average**
69,690	69,689
69,690	
69,688	

Date

Initiation:	**27-04-2011**
End:	**29-04-2011**

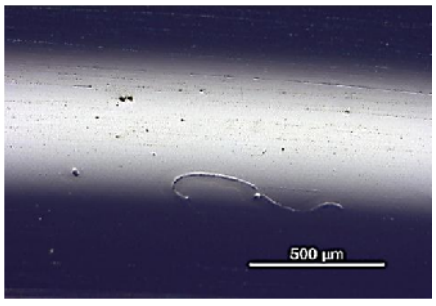
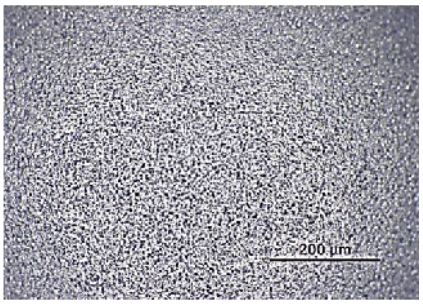
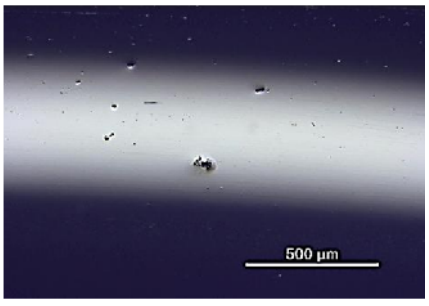
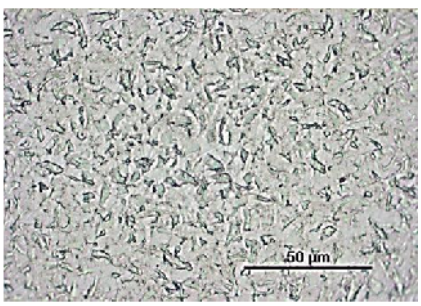
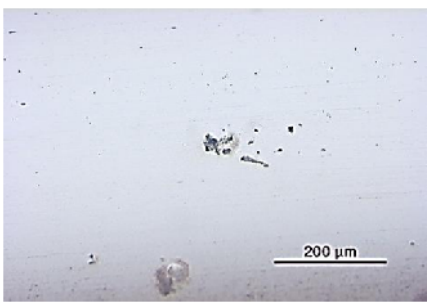
Mass loss	
3	mg

Note:
The first wear test was 50h at 500 rpm with 21 balls and the second/third were 50h at 1200 rpm with 7 balls.

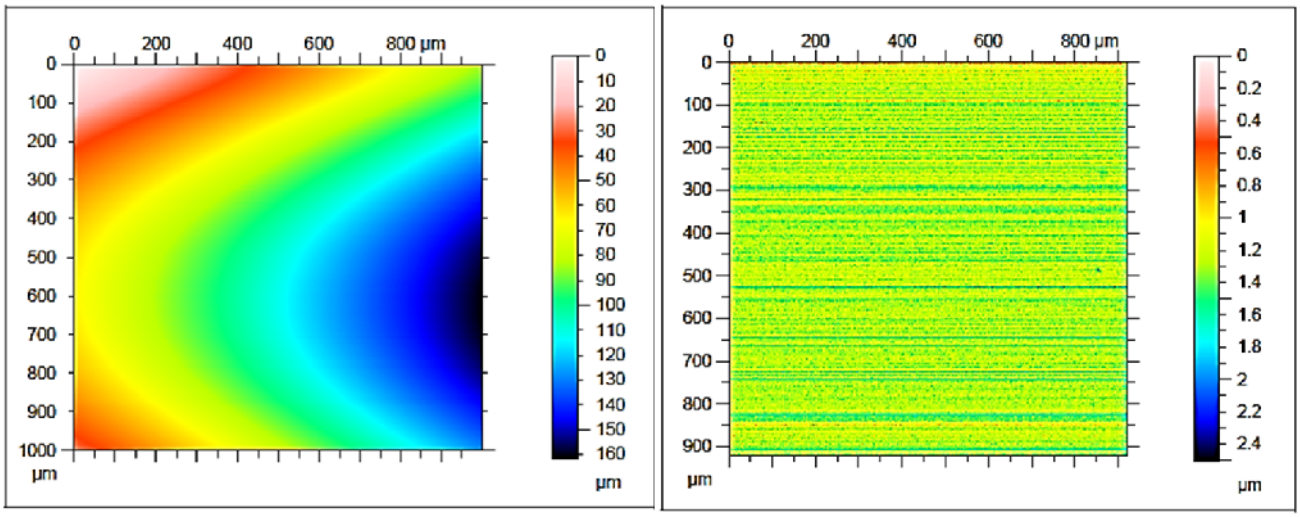
Identification of different contact zones

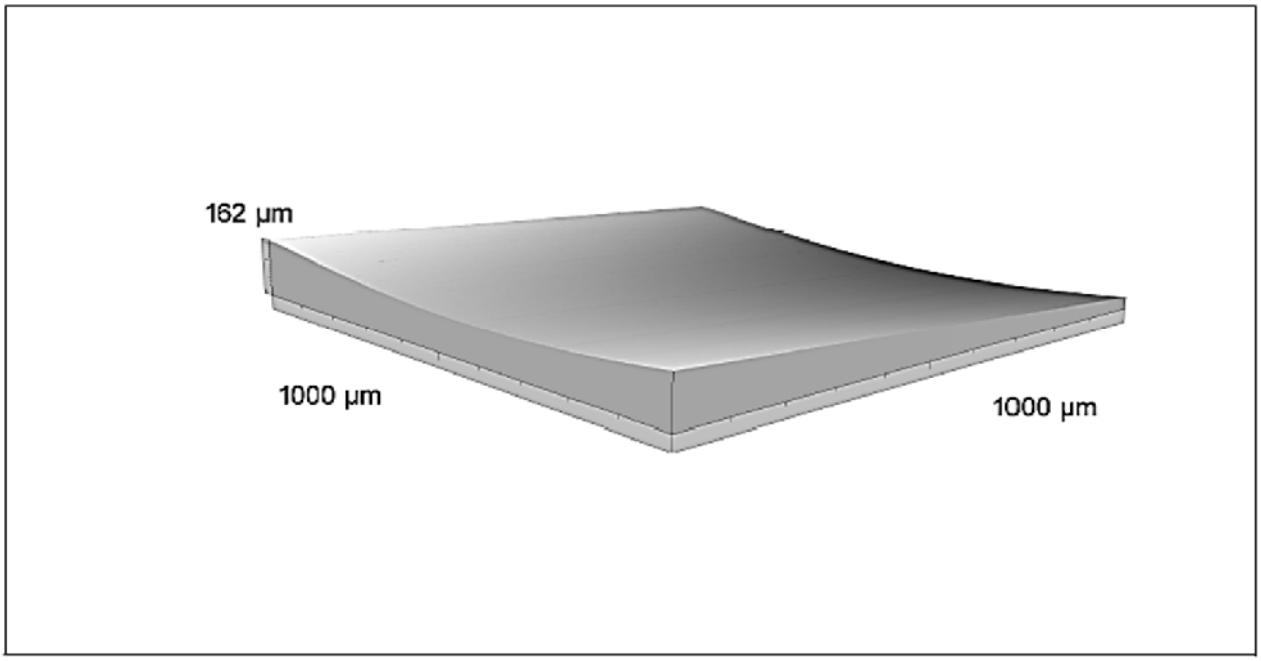
Scheme of the different contact zones analyzed

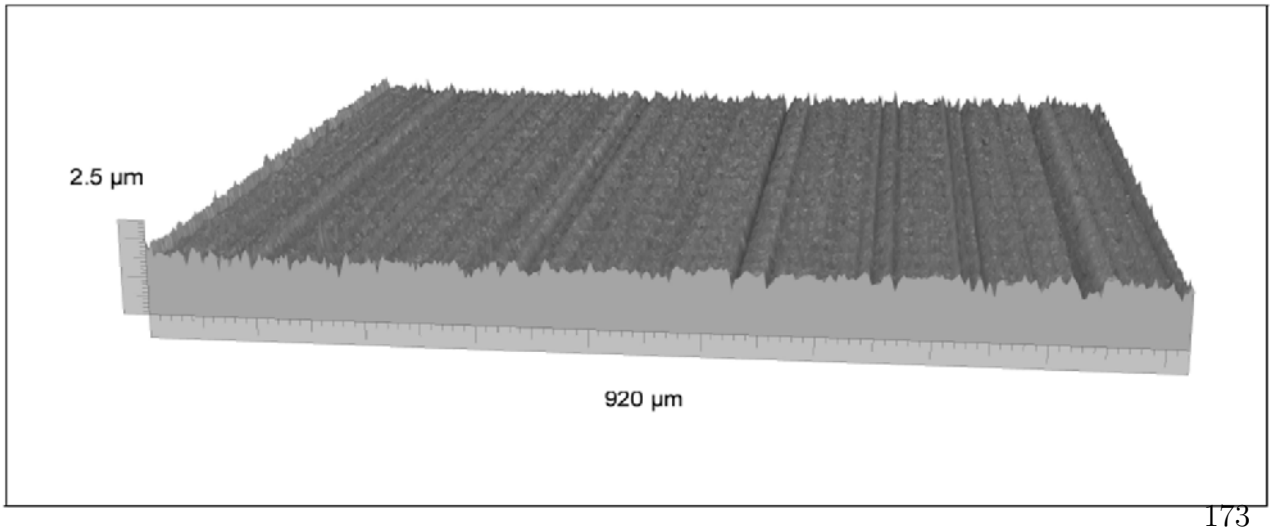
Brand Oil Fuchs
Base Oil Ester
Oil Ref. Gearmaster ECO 320

Lower raceway	Balls	Upper raceway
		
		

Topography, Gaussian Filter,80 µm





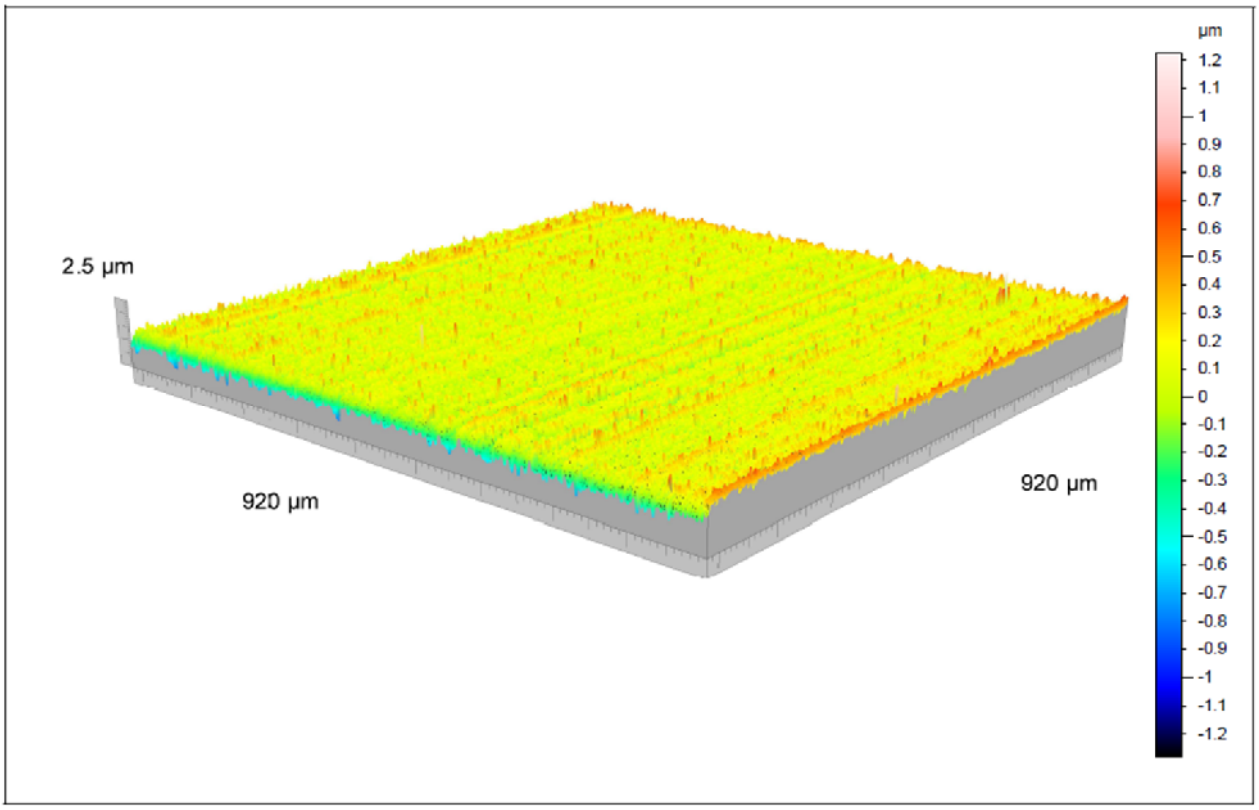


Parameters calculated on the surface AE_ESTER320_7ESFERAS 50h+50h+50h > Roughness, Gaussian Filter, 80 µm

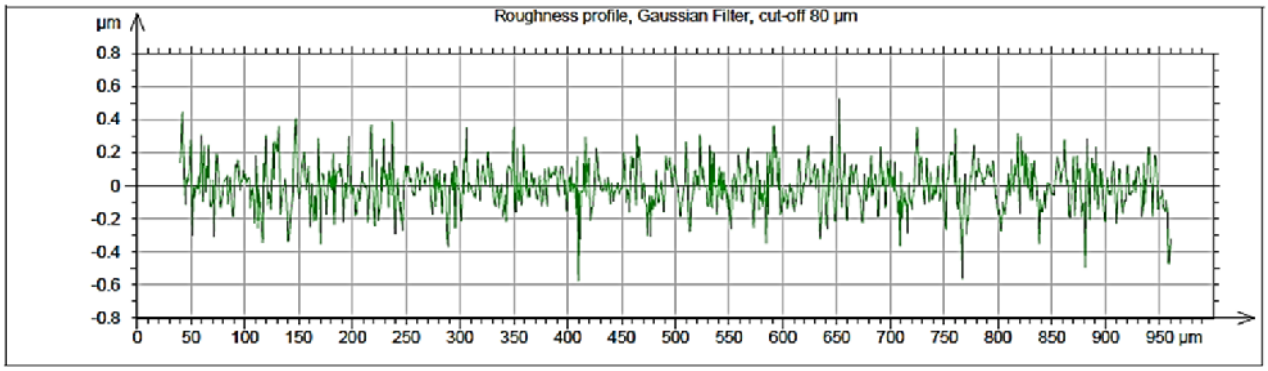
Sz, Sds and Ssc parameters are defined according to ISO standard.

Amplitude Parameters

Sa	=	0.117 µm
Sq	=	0.155 µm
Sp	=	1.22 µm
Sv	=	1.28 µm
St	=	2.51 µm
Ssk	=	-0.849
Sku	=	4.27
Sz	=	2.51 µm



Profiles in the circumferential direction

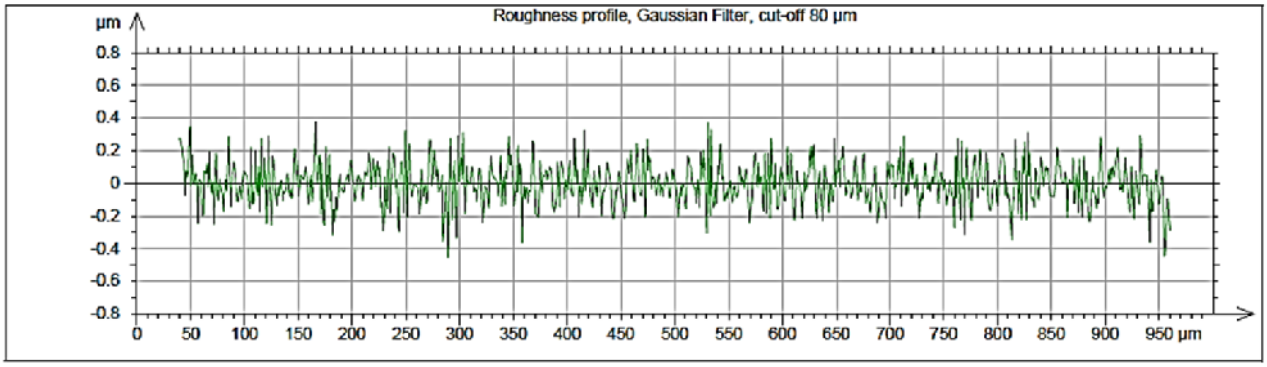


Parameters calculated on the profile AE_ESTER320_7ESFERAS_50h+ 50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0718 µm
Rq	= 0.114 µm
Rz	= 0.7 µm
Rt	= 1.1 µm
Rp	= 0.336 µm
Rv	= 0.364 µm
Rsk	= -0.0304
Rku	= 5.79



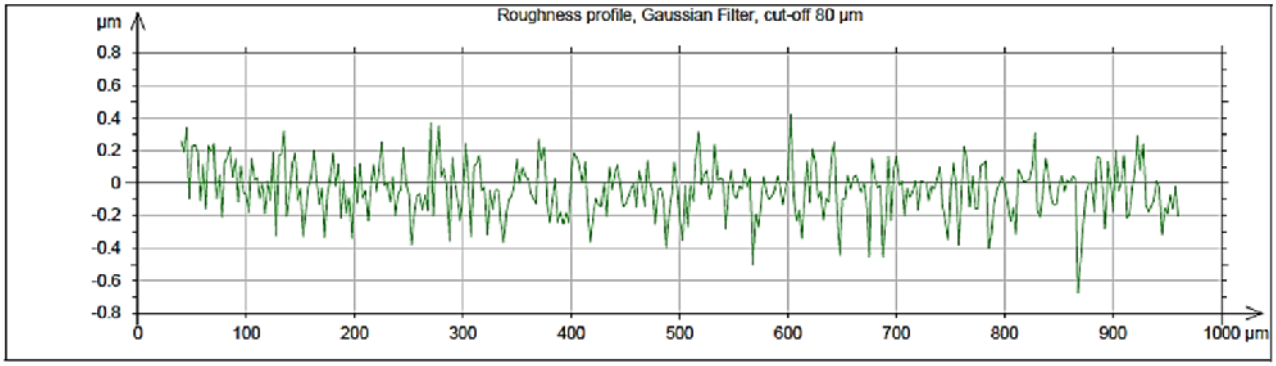
Parameters calculated on the profile AE_ESTER320_7ESFERAS_ 50h+50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0645 µm
Rq	= 0.102 µm
Rz	= 0.545 µm
Rt	= 0.8 µm
Rp	= 0.291 µm
Rv	= 0.255 µm
Rsk	= 0.173
Rku	= 4.37

Profiles in the radial direction

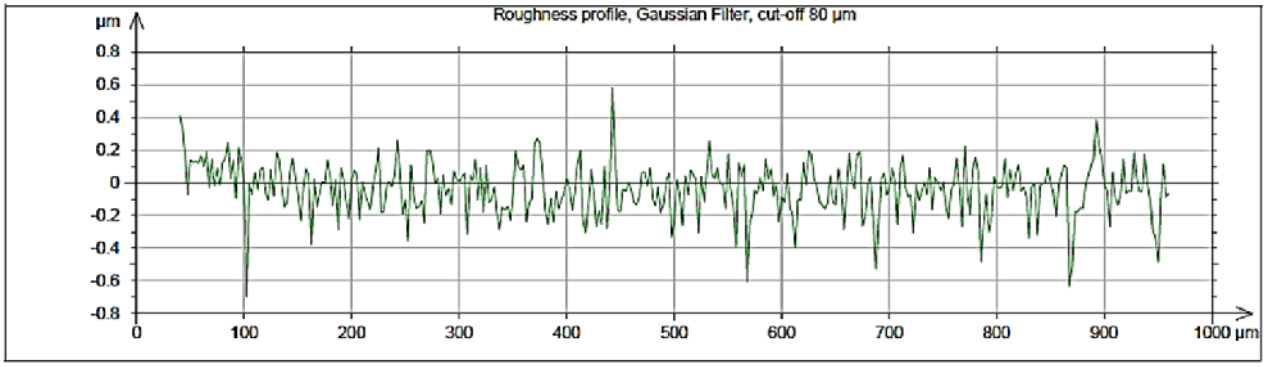


Parameters calculated on the profile AE_ESTER320_7ESFERAS_50h+50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.0939 µm
Rq	= 0.142 µm
Rz	= 0.636 µm
Rt	= 1 µm
Rp	= 0.264 µm
Rv	= 0.373 µm
Rsk	= -1.09
Rku	= 4.69



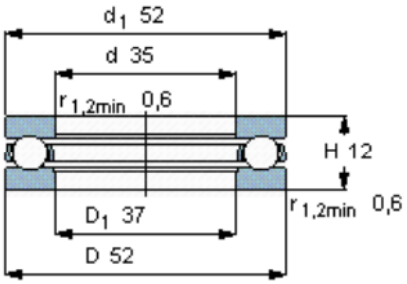
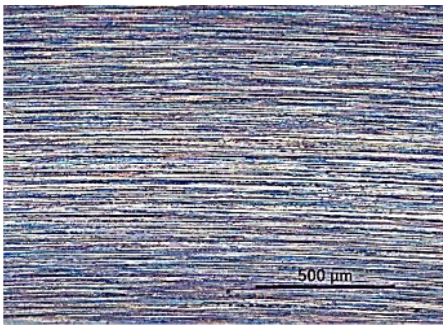
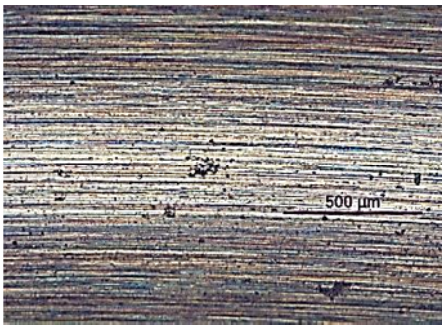
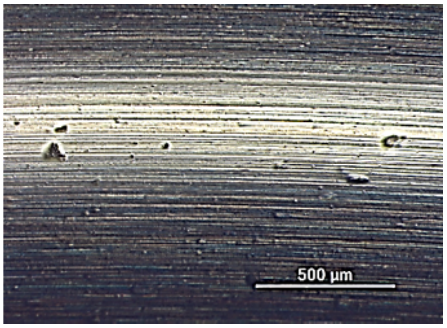
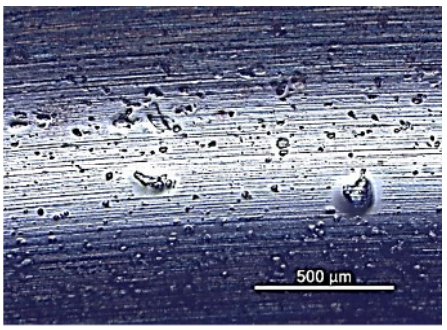
Parameters calculated on the profile AE_ESTER320_7ESFERAS_50h+50h+50h > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 80 µm

Ra	= 0.084 µm
Rq	= 0.134 µm
Rz	= 0.627 µm
Rt	= 1.2 µm
Rp	= 0.218 µm
Rv	= 0.409 µm
Rsk	= -1.38
Rku	= 7.83

A.5. Comparison between thrust ball bearings with 21 and 7 balls

MIN 320 - Upper Raceway - comparison				
				**Specific film thickness** **Mass Loss** **Parameters for comparison**
500 rpm with 21 balls-50h and 1200 rpm with 7 balls-50h				
NEW		Sa=0,12 µm; Sq=0,16 µm; St=1,73 µm; Sp=0,79 µm; Sv=0,95 µm	/	/
21 balls		Sa= 0,11 µm; Sq=0,15 µm; St=2,21 µm; Sp=0,83 µm; Sv=1,39 µm; T = 283,51 Nmm μ_{Kelley} = 0,0749 μ_{CFT} = 0,0018 μ_{SL} = 0,0663	θ_{oil} = 47,5 θ_{cham} = 24,4 $\Delta\theta_{oil-c}$ = 23,1 θ_{lab} = 19,1 $\Delta\theta_{oil-l}$ = 28,4	λ =1,647 0 mg $\frac{S_P}{S_{P0}}$ = 1,05 $\frac{S_v}{S_{v0}}$ = 1,46
7 balls		Sa=0,11 µm; Sq=0,14 µm; St=2,07 µm; Sp=0,80 µm; Sv=1,27 µm; T = 220,18 Nmm μ_{Kelley} = 0,073 μ_{CFT} = 0,0014	θ_{oil} = 78,3 θ_{cham} = 34,5 $\Delta\theta_{oil-c}$ = 43,8 θ_{lab} = 24,8 $\Delta\theta_{oil-l}$ = 53,5	λ = 0,910 1 mg $\frac{S_P}{S_{P0}}$ = 1,01 $\frac{S_v}{S_{v0}}$ = 1,34
7 balls		Sa=0,14 µm; Sq=0,20 µm; St=3,73 µm; Sp=0,85 µm; Sv=2,88 µm; T = 278,92 Nmm μ_{Kelley} = 0,072 μ_{CFT} = 0,0018	θ_{oil} = 74,1 θ_{cham} = 30,2 $\Delta\theta_{oil-c}$ = 43,9 θ_{lab} = 20,9 $\Delta\theta_{oil-l}$ = 53,2	λ = 1,031 6 mg $\frac{S_p}{S_{P0}}$ = 1,08 $\frac{S_V}{S_{v0}}$ = 3,04

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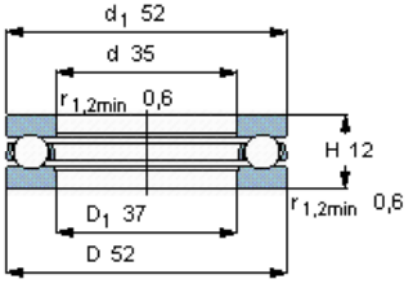
<tr><td colspan="2"> </td><td> 
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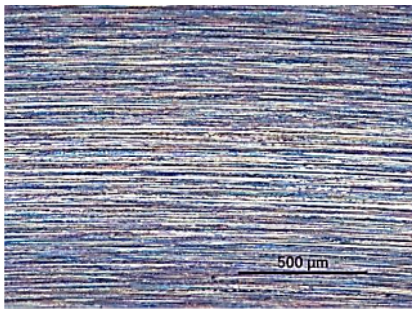
<tr><th colspan="3">500 rpm with 21 balls-50h and 1200 rpm with 7 balls-50h</th></tr>
<tr><td>NEW</td><td> 
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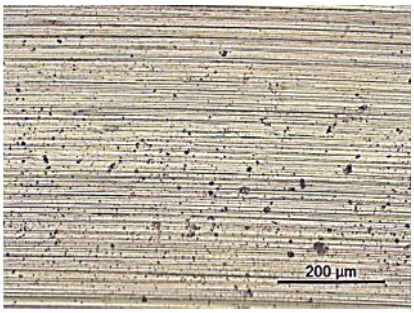
<tr><td>21 balls</td><td>
</td><td> 
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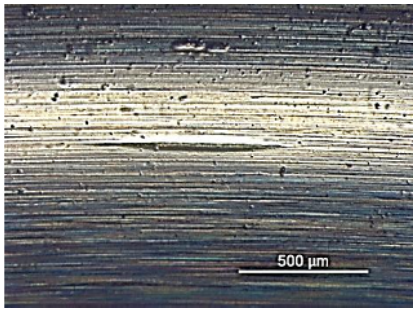
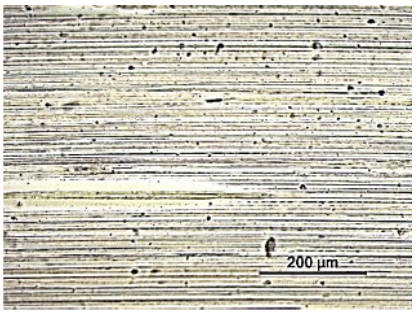
<tr><td>7 balls</td><td> 
</td><td> 
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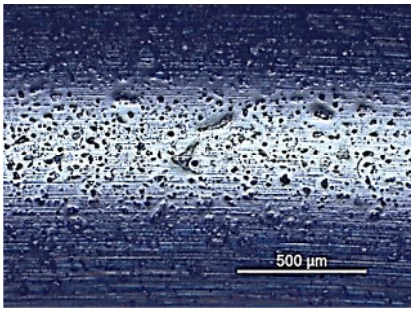
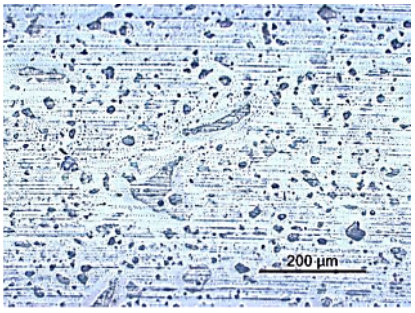
<tr><td>7 balls</td><td> 
</td><td> 
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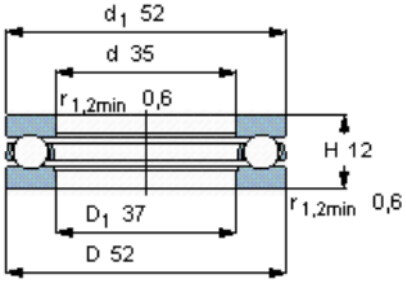
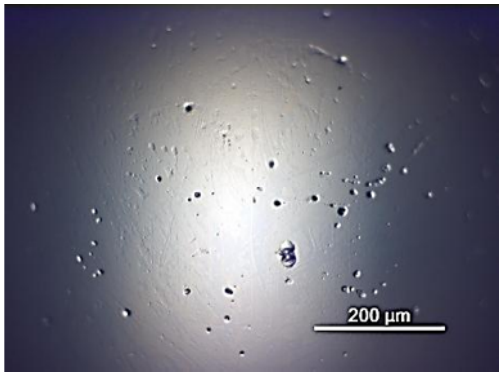
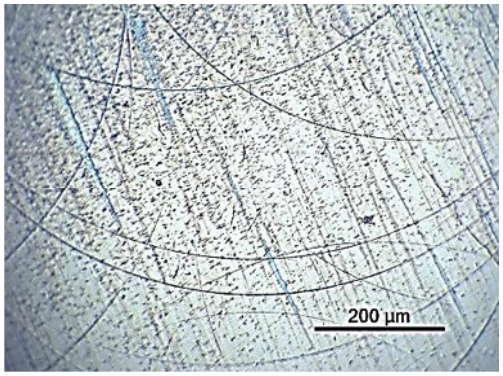
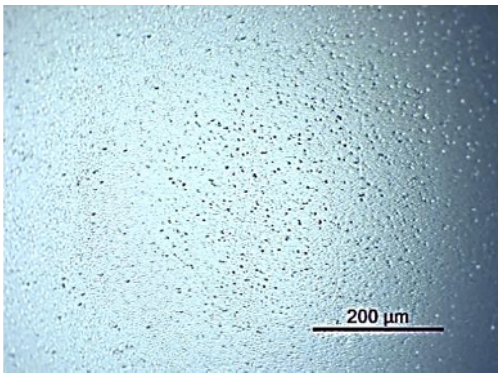
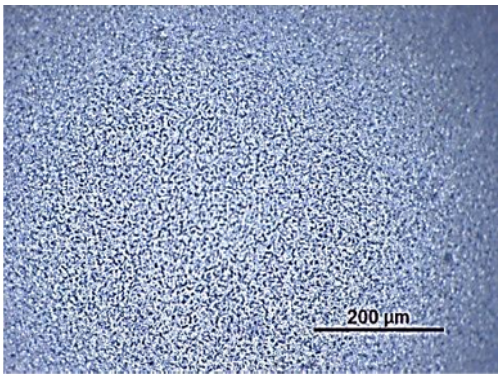
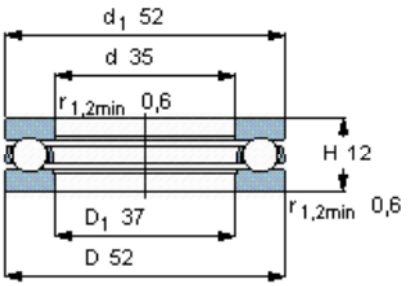
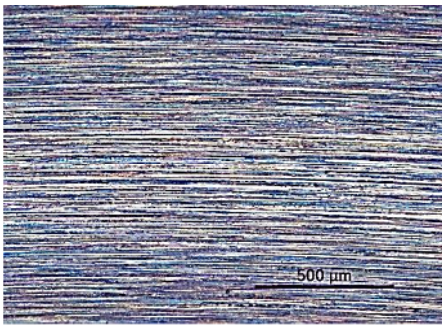
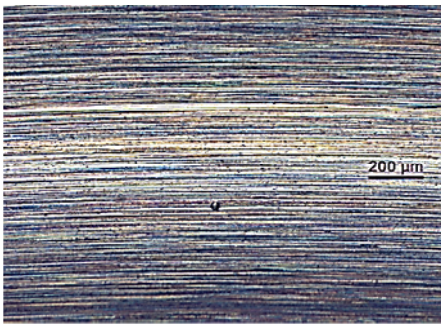
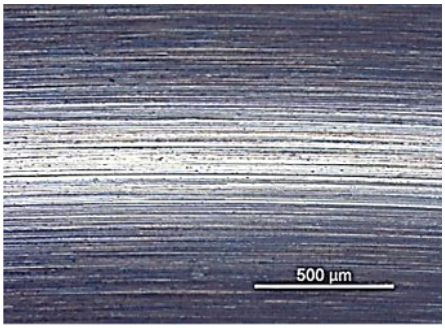
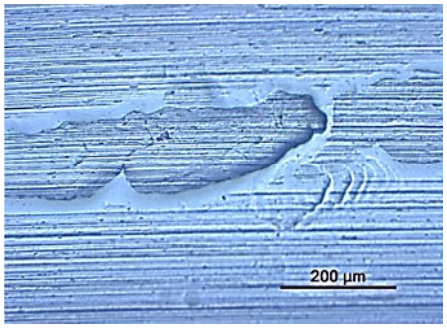
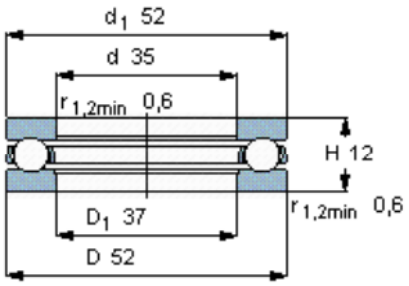
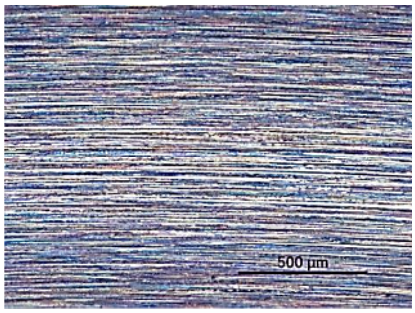
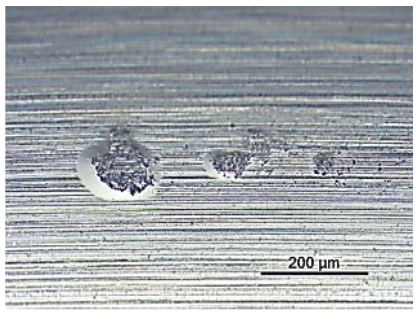
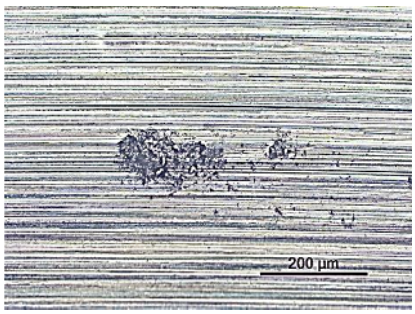
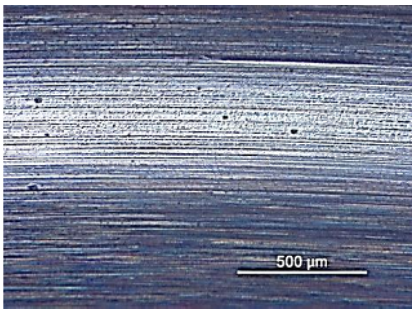
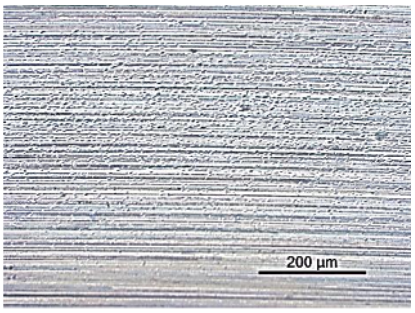
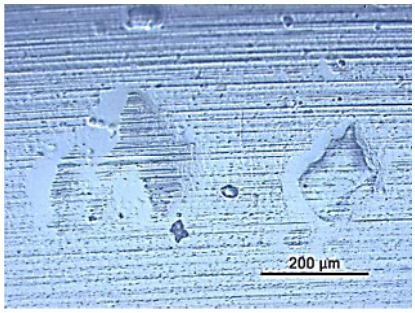
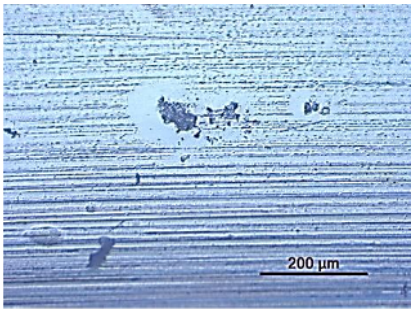
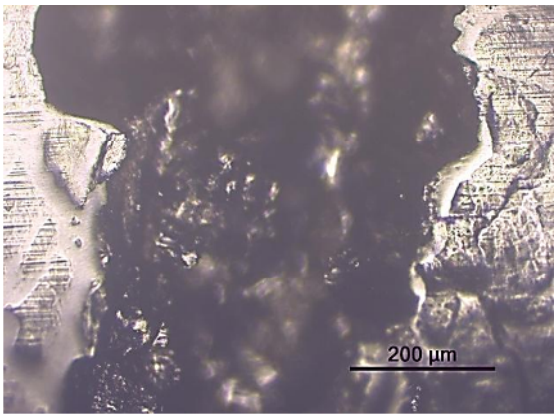
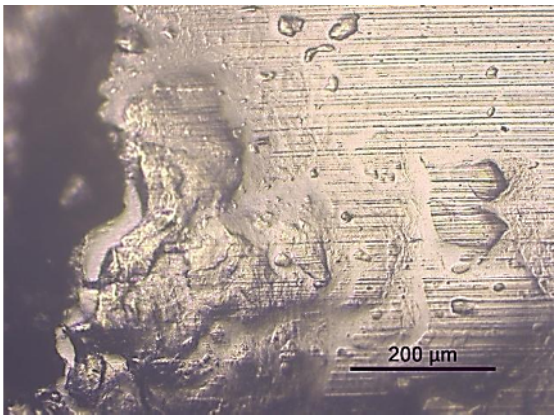
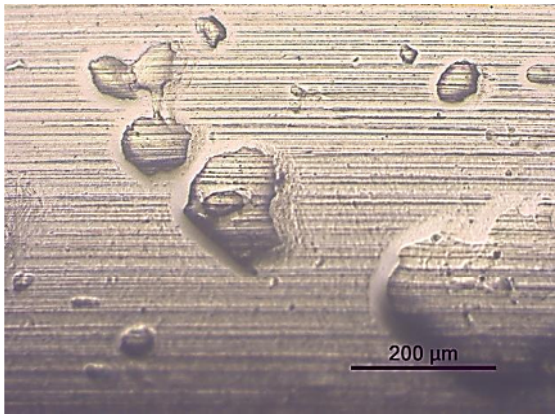
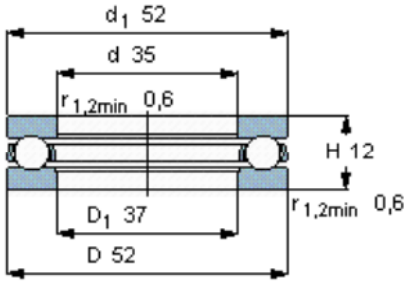
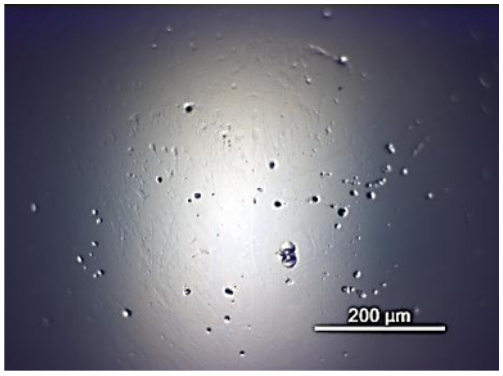
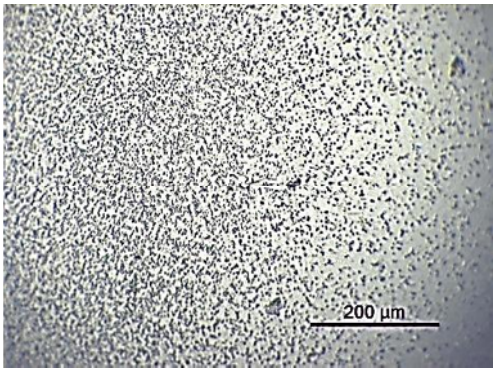
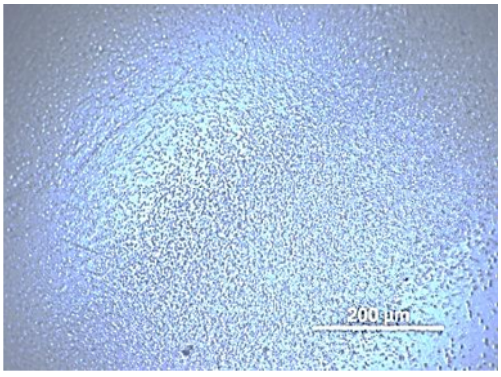
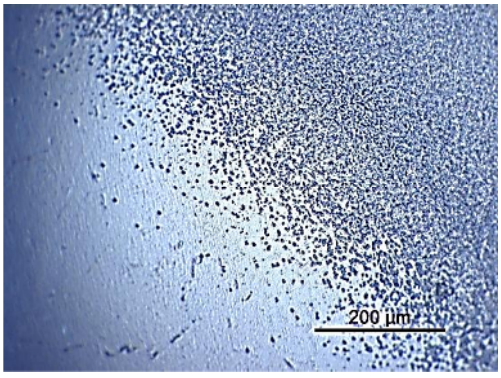
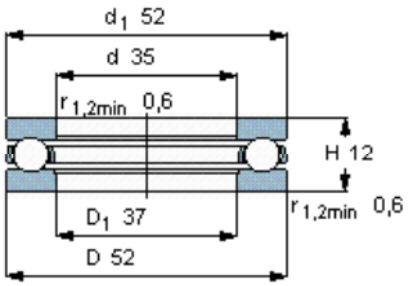
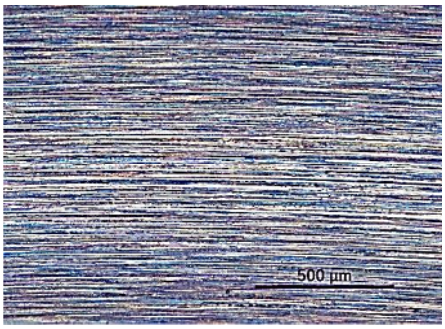
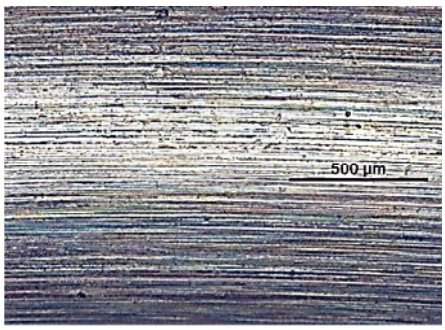
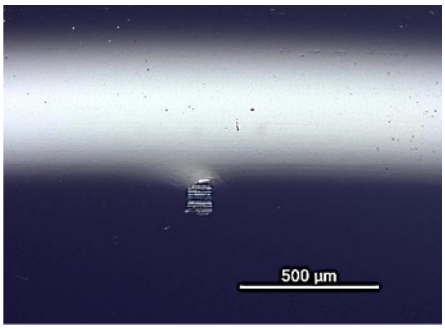
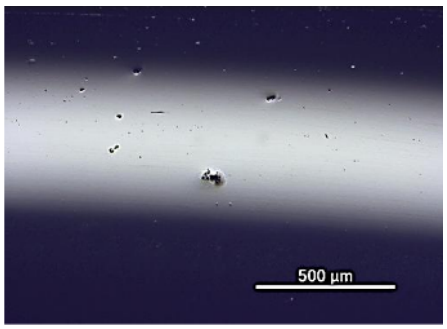
MIN-320	
Balls (21 balls-50h and 7 balls-50h) - comparison	
	
NEW	**21 balls (500 rpm)**
	
7 balls (1200 rpm)	**7 balls (1200 rpm)**
	

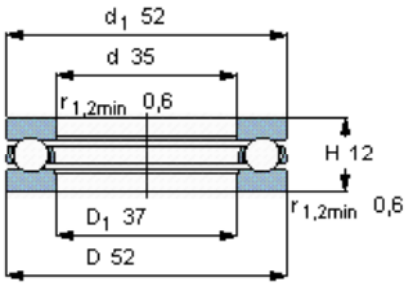
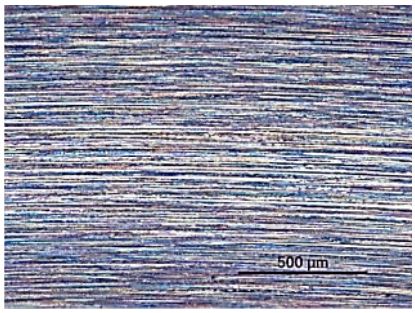
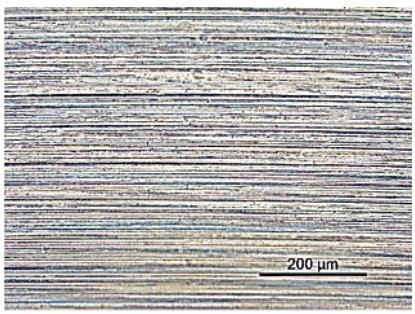
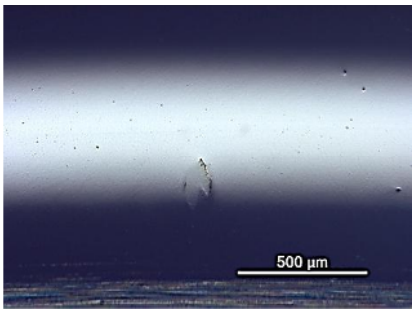
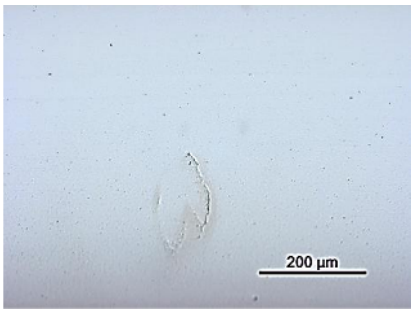
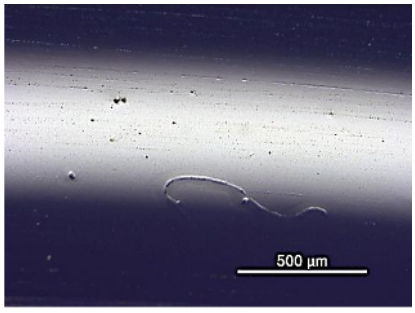
PAO 320 - Upper Raceway - comparison				
				**Specific film thickness** **Mass Loss** **Parameters for comparison**
500 rpm with 21 balls-50h and 1200 rpm with 7 balls-50h				
NEW		Sa=0,12 µm; Sq=0,16 µm; St=1,73 µm; Sp=0,79 µm; Sv=0,95 µm	/	/
21 balls		Sa=0,12 µm; Sq=0,16 µm; St=1,86 µm; Sp=0,81 µm; Sv=1,04 µm; T = 272,75 Nmm μ_{Kelley} = 0,0743 μ_{CFT} = 0,0018 μ_{SL} = 0,059	θ_{oil} = 46,2 θ_{cham} = 25,0 $\Delta\theta_{oil-c}$ = 21,2 θ_{lab} = 19,5 $\Delta\theta_{oil-l}$ = 26,7	λ = 1,521 2 mg $\frac{S_P}{S_{P0}}$ = 1,03 $\frac{S_v}{S_{v0}}$ = 1,09
7 balls		Sa=0,11 µm; Sq=0,14 µm; St=1,79 µm; Sp=0,84 µm; Sv=0,94 µm; T = 240,50 Nmm μ_{Kelley} = 0,0693 μ_{CFT} = 0,0016	θ_{oil} = 70,1 θ_{cham} = 33,1 $\Delta\theta_{oil-c}$ = 37,0 θ_{lab} = 23,5 $\Delta\theta_{oil-l}$ = 46,6	λ = 1,192 0 mg $\frac{S_P}{S_{P0}}$ = 2,45 $\frac{S_v}{S_{v0}}$ =1,29
7 balls		Sa= 0,11 µm; Sq=0,16 µm; St=3,77 µm; Sp=1,09 µm; Sv=2,68 µm; T = 240,50 Nmm μ_{Kelley} = 0,0695 μ_{CFT} = 0,0016	θ_{oil} = 71,3 θ_{cham} = 32,2 $\Delta\theta_{oil-c}$ = 39,1 θ_{lab} = 22,7 $\Delta\theta_{oil-l}$ = 48,6	λ = 1,155 1 mg $\frac{S_P}{S_{P0}}$ =1,38 $\frac{S_v}{S_{v0}}$ =2,82

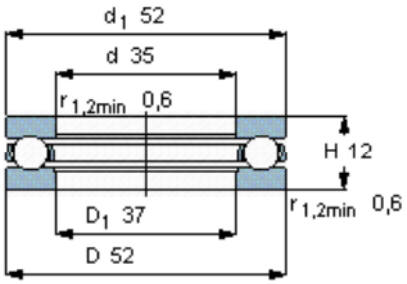
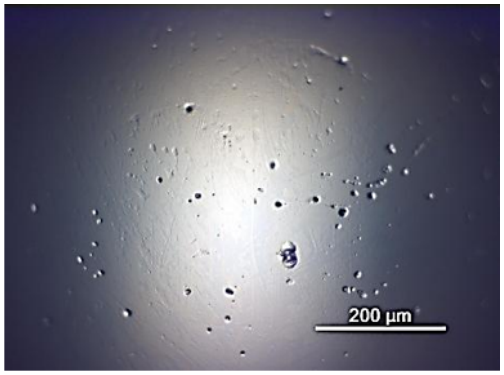
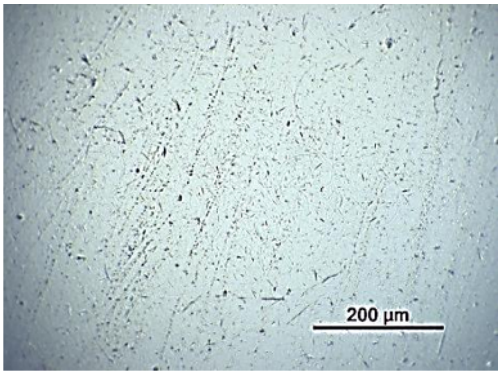
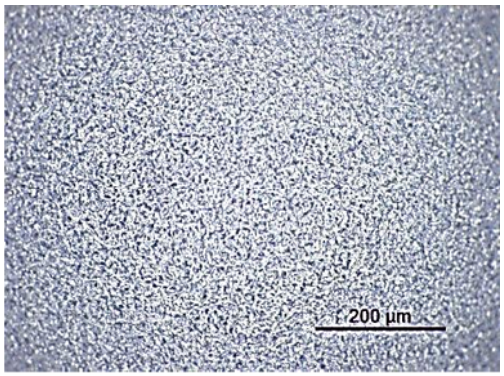
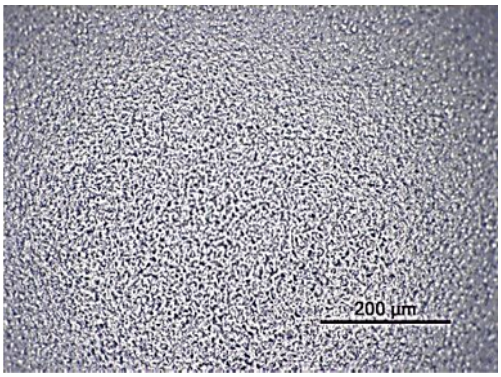
PAO 320 - Lower Raceway - comparison		
		
500 rpm with 21 balls-50h and 1200 rpm with 7 balls-50h		
NEW		/
21 balls		
7 balls		
7 balls		

PAO-320	
Due to a failure to wear (Spalling), the trial was stopped 5h after the start of the test.	
21 balls (500rpm) and 7 balls (1200 rpm) x 2 - spalling	
Upper Raceway	
	
Upper Raceway	
	

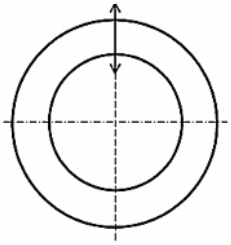
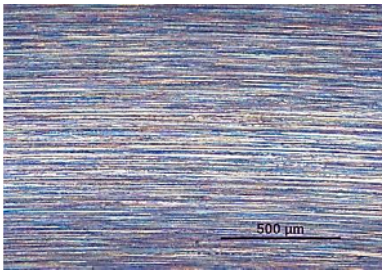
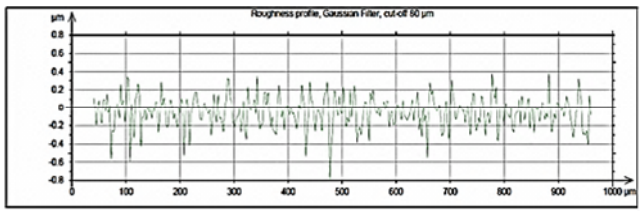
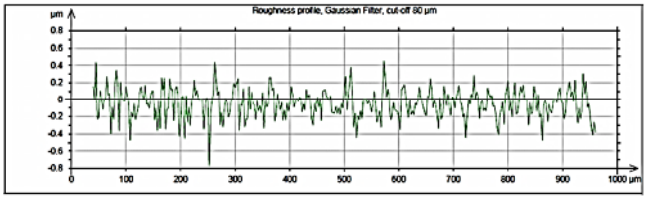
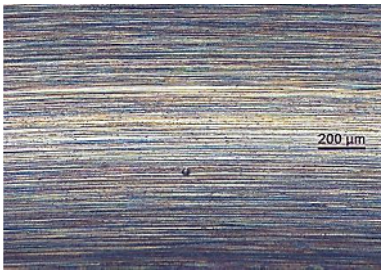
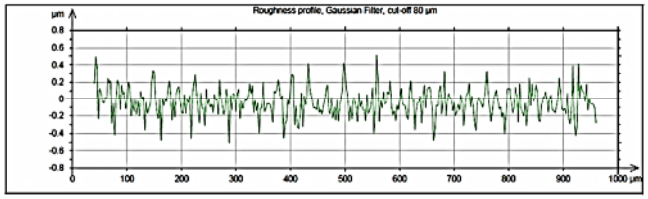
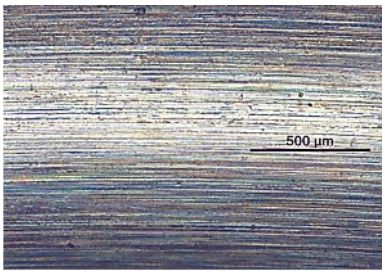
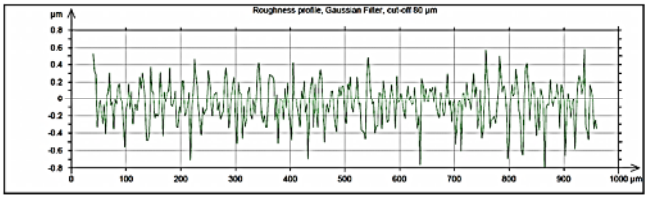
PAO-320	
Balls (21 balls-50h and 7 balls-50h) - comparison	
	
NEW	**21 balls (500 rpm)**
	
7 balls (1200 rpm)	**7 balls (1200 rpm)**
	

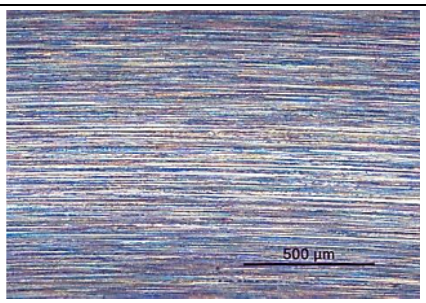
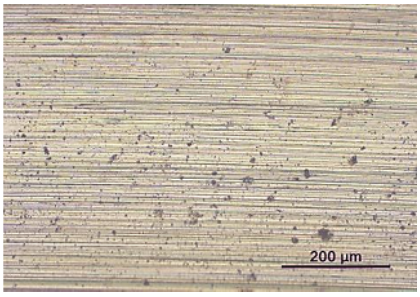
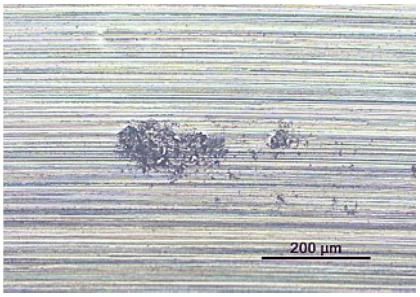
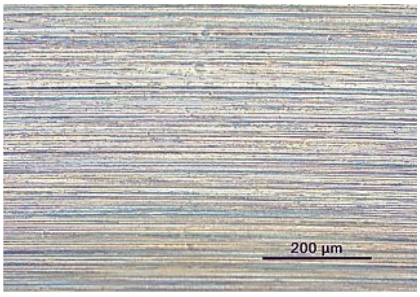
ESTER 320 - Upper Raceway - comparison				
				**Specific film thickness** **Mass Loss** **Parameters for comparison**
500 rpm with 21 balls-50h and 1200 rpm with 7 balls-50h				
NEW		Sa=0,12 µm; Sq=0,16 µm; St=1,73 µm; Sp=0,79 µm; Sv=0,95 µm	/	/
21 balls		Sa=0,18 µm; Sq=0,23 µm; St=2,43 µm; Sp=0,95 µm; Sv=1,48 µm; T = 293,39 Nmm μ_{Kelley} = 0,0738 μ_{CFT} = 0,0019 μ_{SL} = 0,0666	θ_{oil} = 46,5 θ_{cham} = 23,5 $\Delta\theta_{oil-c}$ = 23,0 θ_{lab} = 18,1 $\Delta\theta_{oil-l}$ = 28,4	λ = 1,534 0 mg $\frac{S_P}{S_{P0}}$ = 1,20 $\frac{S_v}{S_{v0}}$ = 1,56
7 balls		Sa=0,11 µm; Sq=0,14 µm; St=1,85 µm; Sp=0,87 µm; Sv=0,98 µm; T = 233,25 Nmm μ_{Kelley} = 0,0695 μ_{CFT} =0,0015	θ_{oil} = 74,6 θ_{cham} = 30,8 $\Delta\theta_{oil-c}$ = 43,8 θ_{lab} = 20,9 $\Delta\theta_{oil-l}$ = 53,7	λ = 1,091 7 mg $\frac{S_P}{S_{P0}}$ = 1,10 $\frac{S_v}{S_{v0}}$ = 1,03
7 balls		Sa=0,12 µm; Sq=0,16 µm; St=2,51 µm; Sp=1,22 µm; Sv=1,28 µm; T = 219,11 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0014	θ_{oil} = 71,1 θ_{cham} = 32,1 $\Delta\theta_{oil-c}$ = 39,0 θ_{lab} = 23,9 $\Delta\theta_{oil-l}$ = 47,2	λ = 1,191 3 mg $\frac{S_P}{S_{P0}}$ = 1,54 $\frac{S_v}{S_{v0}}$ = 1,35

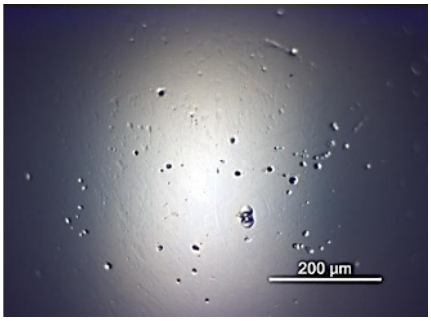
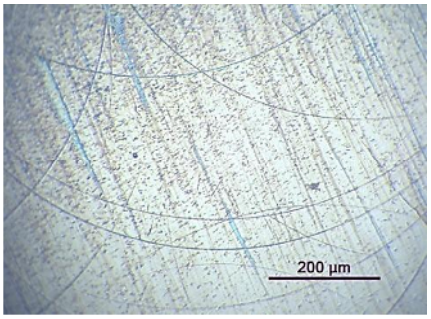
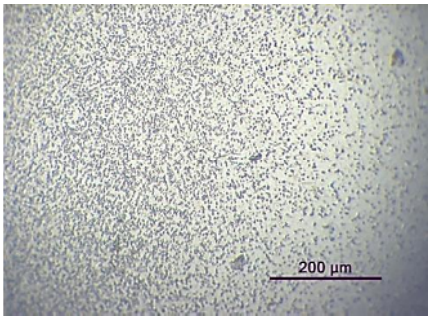
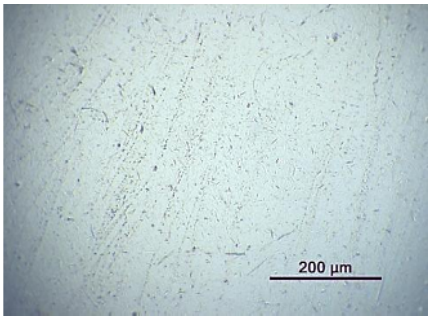
ESTER 320 - Lower Raceway - comparison		
		
500 rpm with 21 balls-50h and 1200 rpm with 7 balls-50h		
NEW		/
21 balls		
7 balls		
7 balls		

ESTER-320	
Balls (21 balls-50h and 7 balls-50h) - comparison	
	
NEW	**21 balls (500 rpm)**
	
7 balls (1200 rpm)	**7 balls (1200 rpm)**
	

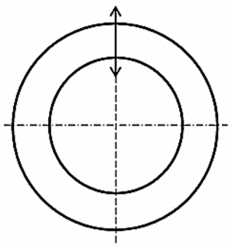
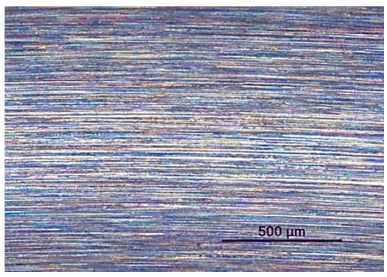
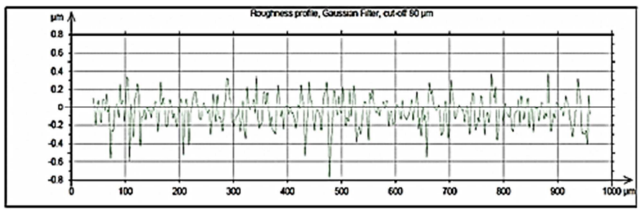
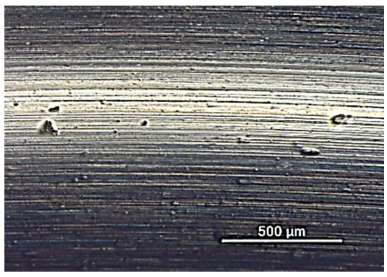
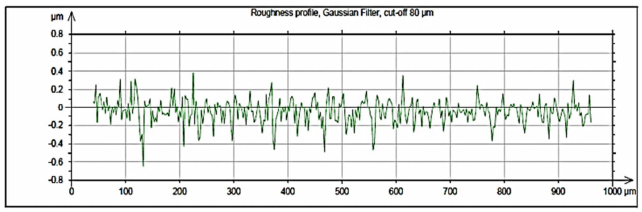
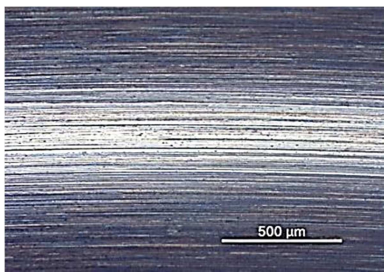
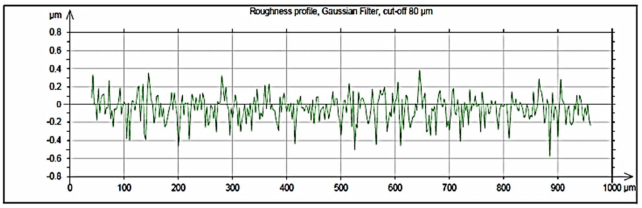
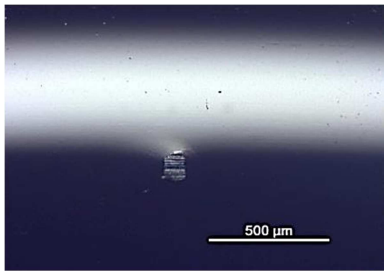
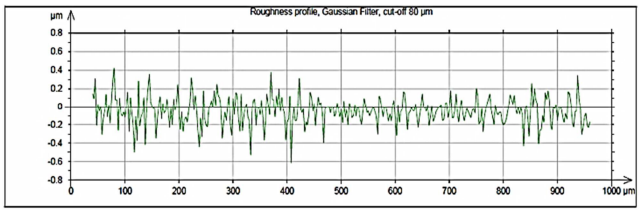
A.6. Comparison between the different oils for the test with TBB - 21 balls

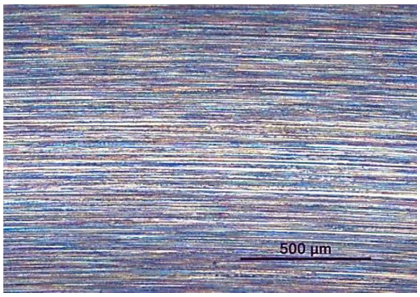
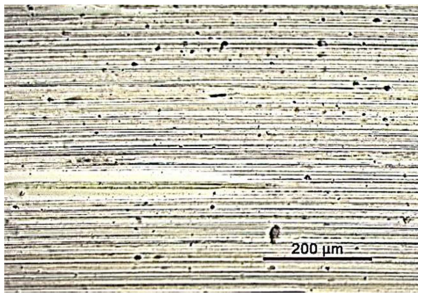
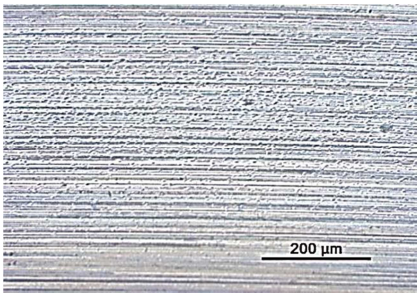
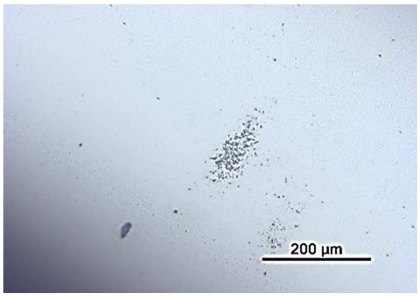
Upper Raceway (21 balls – 500rpm – 50h) – Contact Zone			
		Roughness profile direction 	**Specific film thickness** **Mass Loss** **Parameters for comparison**
NEW		 Sa=0,12 µm; Sq=0,16 µm; St=1,73 µm; Sp=0,79 µm; Sv=0,95 µm	/
MIN -320		 Sa= 0,11 µm; Sq=0,15 µm; St=2,21 µm; Sp=0,83 µm; Sv=1,39 µm	λ = 1,647 0 mg $\frac{S_P}{S_{P0}} = 1,05$ $\frac{S_v}{S_{v0}} = 1,46$
PAO-320		 Sa=0,12 µm; Sq=0,16 µm; St=1,86 µm; Sp=0,81 µm; Sv=1,04 µm	λ = 1,521 2 mg $\frac{S_P}{S_{P0}} = 1,03$ $\frac{S_v}{S_{v0}} = 1,09$
ESTER-320		 Sa=0,18 µm; Sq=0,23 µm; St=2,43 µm; Sp=0,95 µm; Sv=1,48 µm	λ = 1,534 0 mg $\frac{S_P}{S_{P0}} = 1,20$ $\frac{S_v}{S_{v0}} = 1,56$

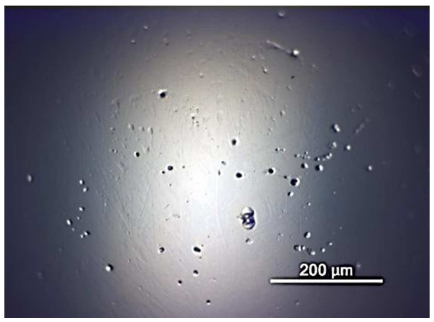
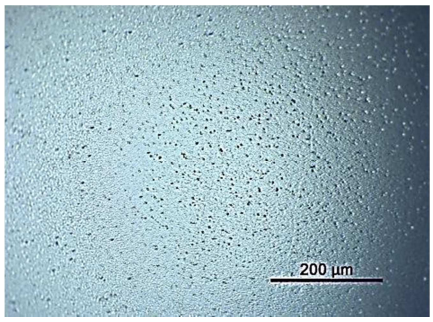
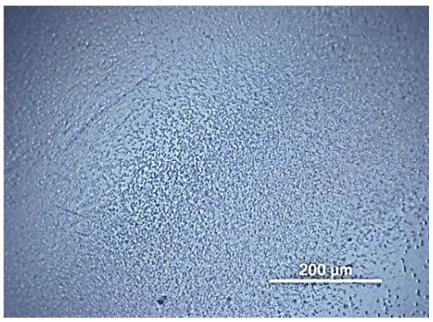
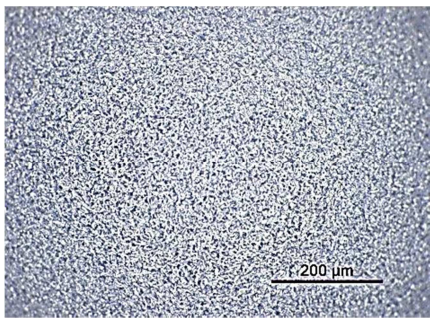
Lower Raceway (21 balls – 500rpm – 50h) – Contact Zone				
		Specific film thickness (λ) **Ferrometry**	**Operating temperature (°C)**	**Friction Torque** **Coefficient of friction**
NEW		/	/	/
MIN -320		λ = 1,647 d = 1 DL = 65,9 Ds = 33,7 CPUC = 99,6	θ_{oil} = 47,5 θ_{cham} = 24,4 $\Delta\theta_{oil-c}$ = 23,1 θ_{lab} = 19,1 $\Delta\theta_{oil-l}$ = 28,4	T = 283,51 Nmm μ_{Kelley} = 0,0749 μ_{CFT} = 0,0018 μ_{SL} = 0,066
PAO-320		λ = 1,521 d = 1 DL = 36,1 Ds = 14,8 CPUC = 50,9	θ_{oil} = 46,2 θ_{cham} = 25,0 $\Delta\theta_{oil-c}$ = 21,2 θ_{lab} = 19,5 $\Delta\theta_{oil-l}$ = 26,7	T = 272,75 Nmm μ_{Kelley} = 0,0743 μ_{CFT} = 0,0018 μ_{SL} = 0,059
ESTER-320		λ= 1,534 d = 1 DL = 97,2 Ds = 37,9 CPUC = 135,1	θ_{oil} = 46,5 θ_{cham} = 23,5 $\Delta\theta_{oil-c}$ = 23,0 θ_{lab} = 18,1 $\Delta\theta_{oil-l}$ = 28,4	T = 293,39 Nmm μ_{Kelley} = 0,0738 μ_{CFT} = 0,0019 μ_{SL} = 0,067

Balls (21 balls – 500rpm – 50h)	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

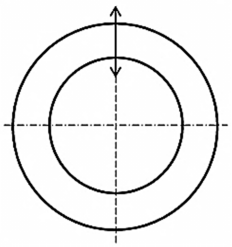
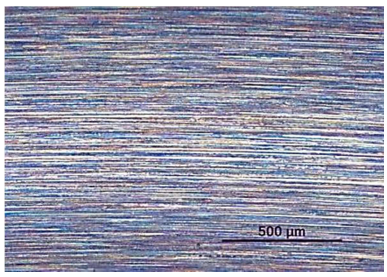
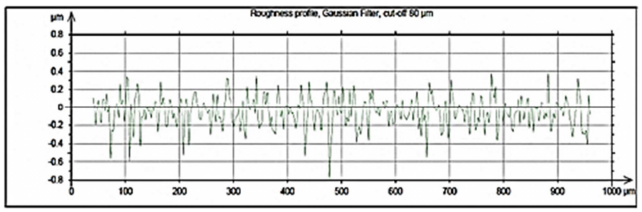
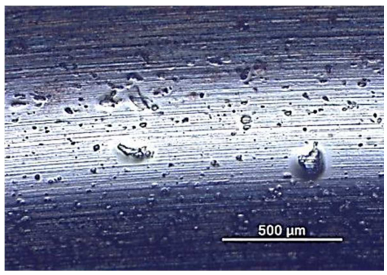
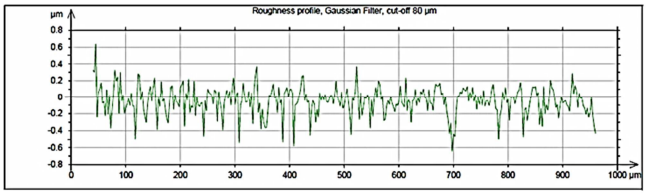
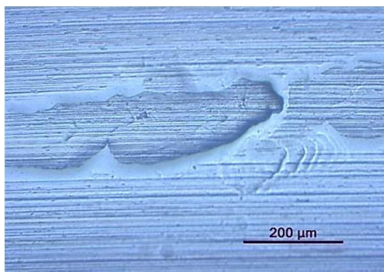
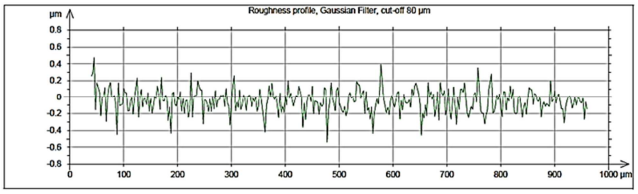
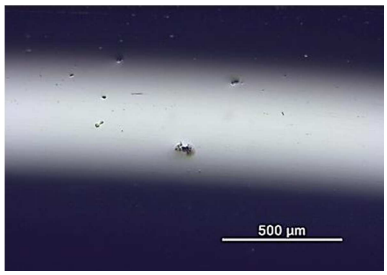
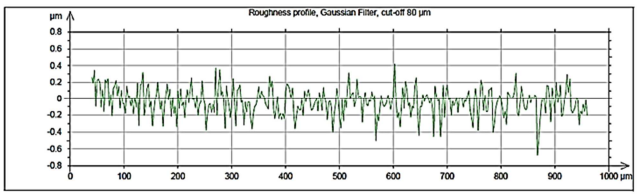
A.7. Comparison between the different oils for the test with TBB - 7 balls (first 50h)

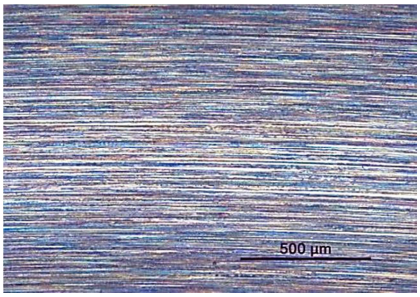
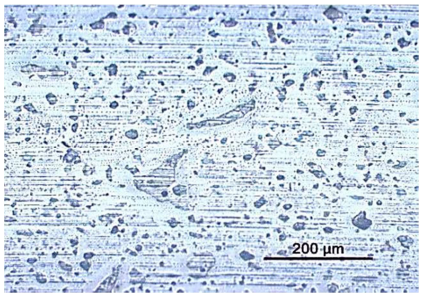
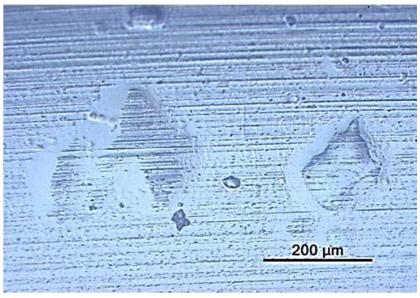
Upper Raceway (7 balls – 1200rpm – first 50h) – Contact Zone			
		Roughness profile direction 	**Specific film thickness** **Mass Loss** **Parameters for comparison**
NEW		 Sa=0,12 µm; Sq=0,16 µm; St=1,73 µm; Sp=0,79 µm; Sv=0,95 µm	/
MIN -320		 Sa=0,11 µm; Sq=0,14 µm; St=2,07 µm; Sp=0,80 µm; Sv=1,27 µm	λ = 0,910 1 mg $\frac{S_P}{S_{P0}} = 1,01$ $\frac{S_v}{S_{v0}} = 1,34$
PAO-320		 Sa=0,11 µm; Sq=0,14 µm; St=1,79 µm; Sp=0,84 µm; Sv=0,94 µm	λ = 1,192 0 mg $\frac{S_P}{S_{P0}} = 1,06$ $\frac{S_v}{S_{v0}} = 0,99$
ESTER-320		 Sa=0,11 µm; Sq=0,14 µm; St=1,85 µm; Sp=0,87 µm; Sv=0,98 µm	λ = 1,091 7 mg $\frac{S_P}{S_{P0}} = 1,10$ $\frac{S_v}{S_{v0}} = 1,03$

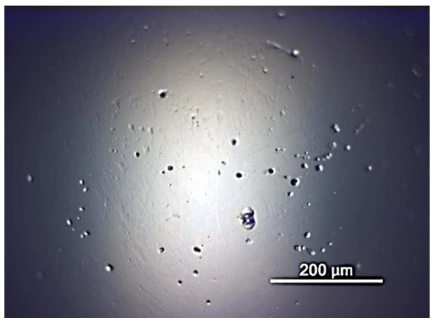
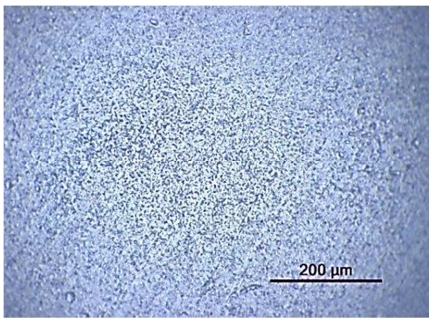
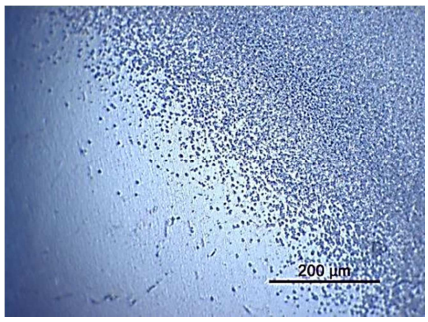
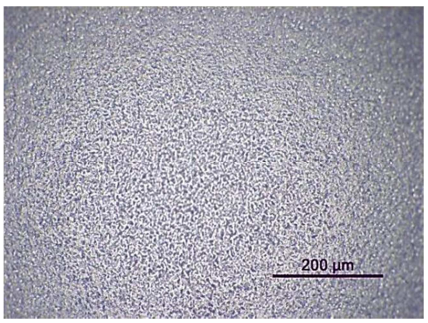
Lower Raceway (7 balls – 1200rpm – first 50h) – Contact Zone				
		Specific film thickness (λ) **Ferrometry**	**Operating temperature (°C)**	**Friction Torque** **Coefficient of friction**
NEW		/	/	/
MIN -320		λ = 0,910 d = 1 DL = 70,8 Ds = 23,1 CPUC = 93,9	$\theta_{oil} = 78,3$ $\theta_{cham} = 34,5$ $\Delta\theta_{oil-c} = 43,8$ $\theta_{lab} = 24,8$ $\Delta\theta_{oil-l} = 53,5$	T = 220,18 Nmm μ_{Kelley} = 0,073 μ_{CFT} = 0,0014
PAO-320		λ = 1,192 d = 1 DL = 63,7 Ds = 18,5 CPUC = 82,2	$\theta_{oil} = 70,1$ $\theta_{cham} = 33,1$ $\Delta\theta_{oil-c} = 37,0$ $\theta_{lab} = 23,5$ $\Delta\theta_{oil-l} = 46,6$	T = 240,50 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0016
ESTER-320		λ= 1,091 d = 0,01 DL = 112,0 Ds = 23,8 CPUC = 13580,0	$\theta_{oil} = 74,6$ $\theta_{cham} = 30,8$ $\Delta\theta_{oil-c} = 43,8$ $\theta_{lab} = 20,9$ $\Delta\theta_{oil-l} = 53,7$	T = 233,25 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0015

Balls (7 balls – 1200rpm – first 50h)	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

A.8. Comparison between the different oils for the test with TBB - 7 balls (second 50h)

Upper Raceway (7 balls – 1200rpm – second 50h) – Contact Zone			
		Roughness profile direction 	**Specific film thickness** **Mass Loss** **Parameters for comparison**
NEW		 Sa=0,12 µm; Sq=0,16 µm; St=1,73 µm; Sp=0,79 µm; Sv=0,95 µm	/
MIN -320		 Sa=0,14 µm; Sq=0,20 µm; St=3,73 µm; Sp=0,85 µm; Sv=2,88 µm	λ = 1,031 6 mg $\frac{S_P}{S_{P0}} = 1,08$ $\frac{S_v}{S_{v0}} = 3,04$
PAO-320		 Sa=0,11 µm; Sq=0,16 µm; St=3,77 µm; Sp=1,09 µm; Sv=2,68 µm	λ = 1,155 1 mg $\frac{S_P}{S_{P0}} = 1,38$ $\frac{S_v}{S_{v0}} = 2,82$
ESTER-320		 Sa=0,12 µm; Sq=0,16 µm; St=2,51 µm; Sp=1,22 µm; Sv=1,28 µm	λ = 1,191 3 mg $\frac{S_P}{S_{P0}} = 1,54$ $\frac{S_v}{S_{v0}} = 1,35$

Lower Raceway (7 balls – 1200rpm – second 50h) – Contact Zone				
		Specific film thickness (λ) **Ferrometry**	**Operating temperature (°C)**	**Friction Torque** **Coefficient of friction**
NEW		/	/	/
MIN -320		λ = 1,031 d = 0,01 DL = 38,2 Ds = 16,8 CPUC = 5500,0	$\theta_{oil} = 74,1$ $\theta_{cham} = 30,2$ $\Delta\theta_{oil-c} = 43,9$ $\theta_{lab} = 20,9$ $\Delta\theta_{oil-l} = 53,2$	T = 278,92 Nmm μ_{Kelley} = 0,072 μ_{CFT} = 0,0018
PAO-320		λ = 1,155 d = 0,1 DL = 29,7 Ds = 7,2 CPUC = 369,0	$\theta_{oil} = 71,3$ $\theta_{cham} = 32,2$ $\Delta\theta_{oil-c} = 39,1$ $\theta_{lab} = 22,7$ $\Delta\theta_{oil-l} = 48,6$	T = 240,50 Nmm μ_{Kelley} = 0,0695 μ_{CFT} = 0,0016 Due to a failure of wear, the test was stopped 5h after the starting.
ESTER-320		λ= 1,191 d = 0,01 DL = 71,9 Ds = 9,1 CPUC = 8100,0	$\theta_{oil} = 71,1$ $\theta_{cham} = 32,1$ $\Delta\theta_{oil-c} = 39,0$ $\theta_{lab} = 23,9$ $\Delta\theta_{oil-l} = 47,2$	T = 219,11 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0014

Balls (7 balls – 1200rpm – second 50h)	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

A.9. Analysis of Lubricants - Ferrometry and Analytical Ferrography - TBB

Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	17-18 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas Mineral 320 /
Nº de páginas: Data:	7 04/04/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante Mineral 320, resultantes de ensaios de Rolamentos Axiais de Esferas (21) na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
Run-In	2	X	X
48H	48	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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CLIENTE: ***INEGI***
MORADA: Porto
DATA: 28/03/11

ENSAIO: Rolamentos Axiais de Esferas
Ref. ÓLEO: Mineral 320

IDENTIFICAÇÃO							
Amostra nº:	Run-In	48H					
Data amostra:	Mar-11	Mar-11					
Análise nº:	17/11	18/11					
Ciclos/Máquina:	-	-					
Ciclos/Óleo:	-	-					
FERROMETRIA							
d:	1	1					
DL:	146,7	65,9					
DS:	65,5	33,7					
CPUC:	212,2	99,6					
ISUC:	1,7E+04	3,2E+03					
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Índice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							

DIAGNÓSTICO:

LEGENDA			
DL - Índice de partículas grandes			Não existe
DS - Índice de partículas pequenas		f	Fraco
CPUC - Concentração de partículas de d		M	Médio
ISUC - Índice de severidade de desgast		F	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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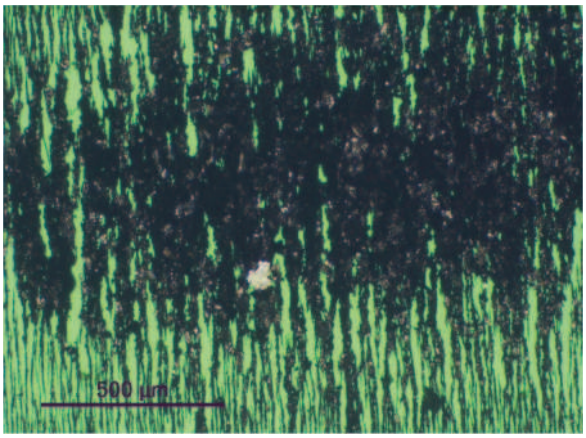
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Mineral 320 - Running In
DATA: 28/02/11	

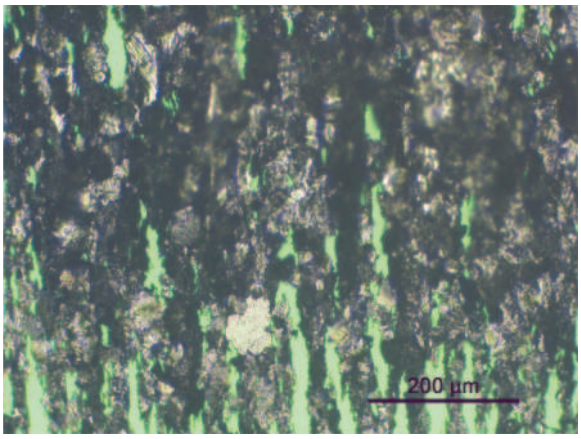
Fotografia 1



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

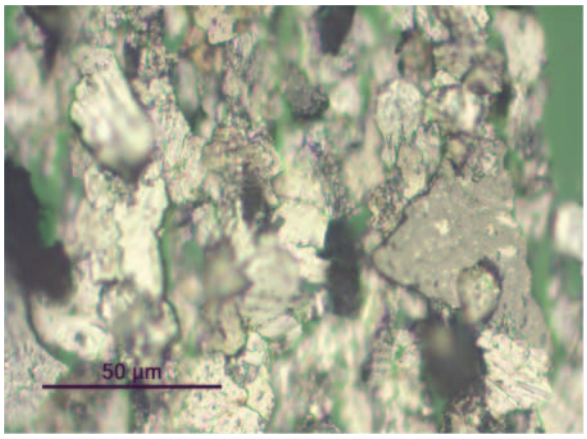
Fotografia 2



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões.

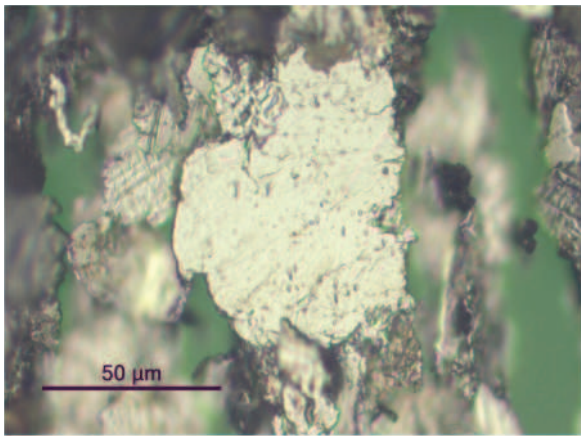
Fotografia 3



Ampliação: x 1000 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Presença de muitas partículas ferrosas de grandes dimensões, algumas severamente oxidadas..

Fotografia 4



Ampliação: x 1000 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de grandes dimensões, típica de desgaste de fadiga e partículas ferrosas de menores dimensões, mas oxidadas.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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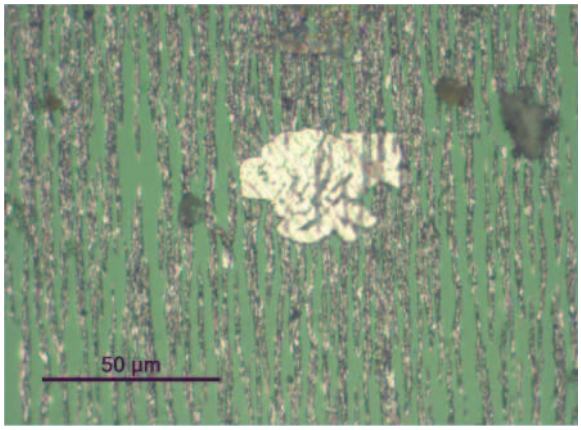
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais Esferas (21)
MORADA: Porto	Ref. ÓLEO: Mineral 320 - Running In
DATA: 28/03/11	

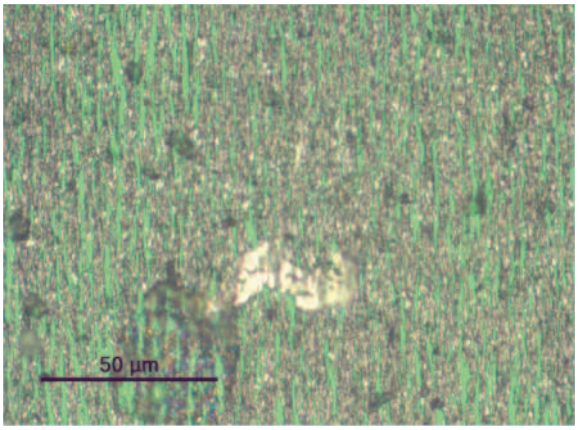
Fotografia 5



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas dimensões e de uma partícula não ferrosa (metal branco).

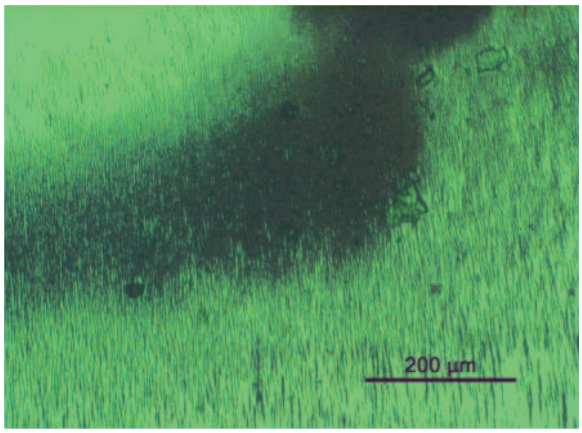
Fotografia 6



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas dimensões e de uma partícula não ferrosa (metal branco).

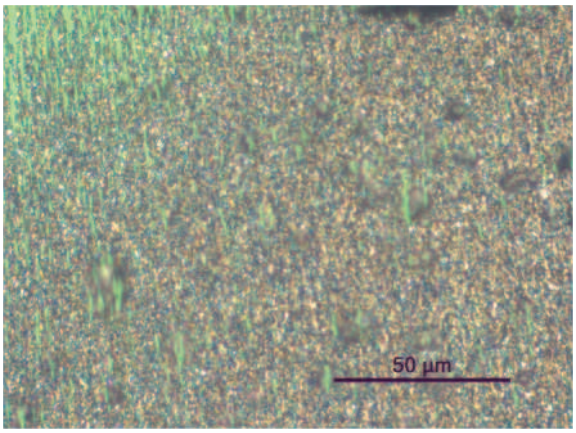
Fotografia 7



Ampliação: x 200 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Partículas ferrosas de muito pequenas dimensões, típicas de desgaste de corrosão.

Fotografia 8



Ampliação: x 1000 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Ampliação da Fotografia 7.
Note-se a elevada concentração de partículas de muito pequenas dimensões, que são típicas de um desgaste de corrosão das superfícies ferrosas pelo lubrificante.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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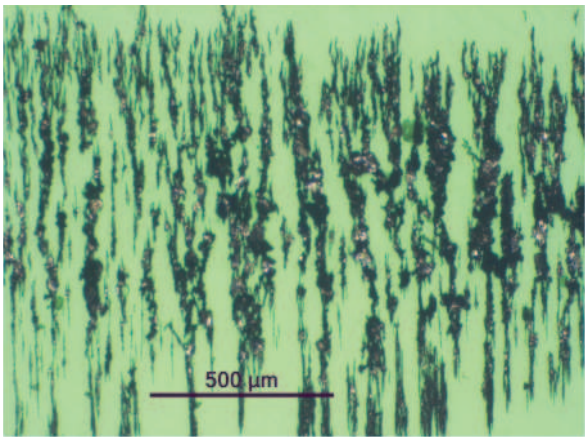
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais Esferas (21)
MORADA: Porto	Ref. ÓLEO: Mineral 320 - 48H
DATA: 28/03/11	

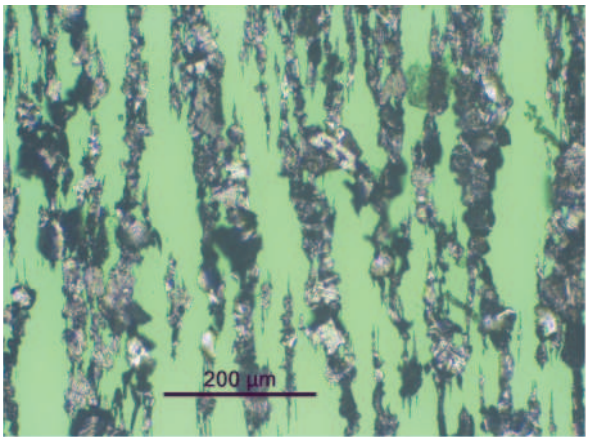
Fotografia 9



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões

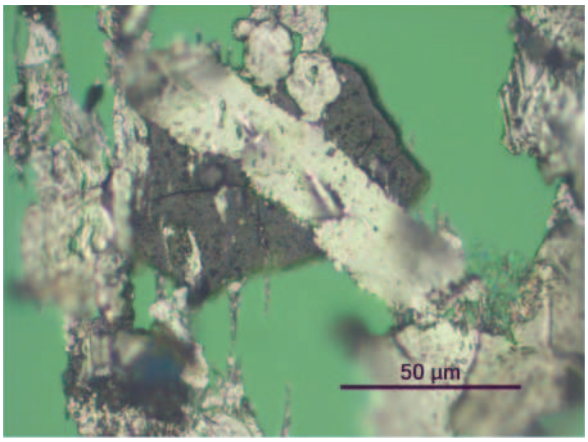
Fotografia 10



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Presença de partículas ferrosas de pequenas e grandes dimensões.

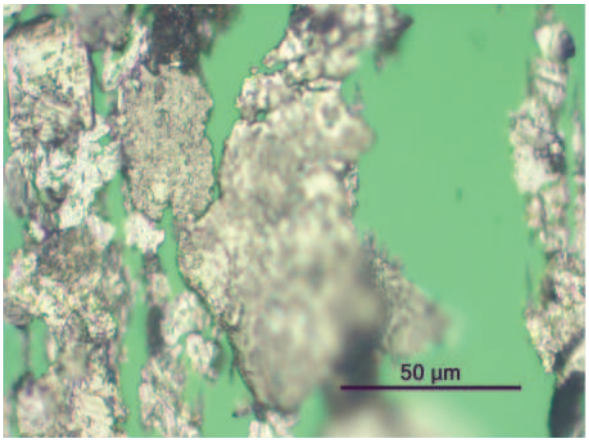
Fotografia 11



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Presença de muitas partículas ferrosas de grandes dimensões, algumas severamente oxidadas.

Fotografia 12



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Presença de muitas partículas ferrosas de grandes dimensões, algumas oxidadas.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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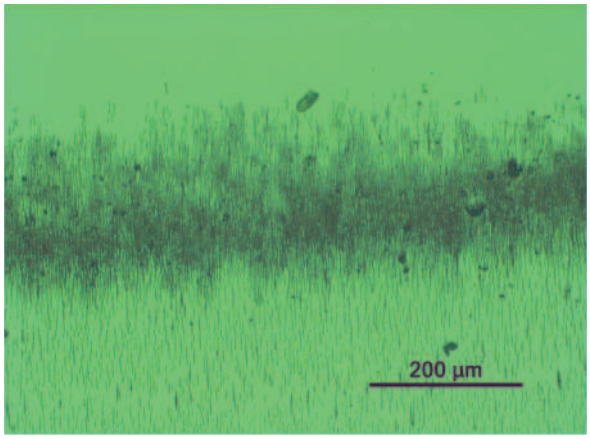
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais Esferas (21)
MORADA: Porto	Ref. ÓLEO: Mineral 320 - 48 H
DATA: 28/03/11	

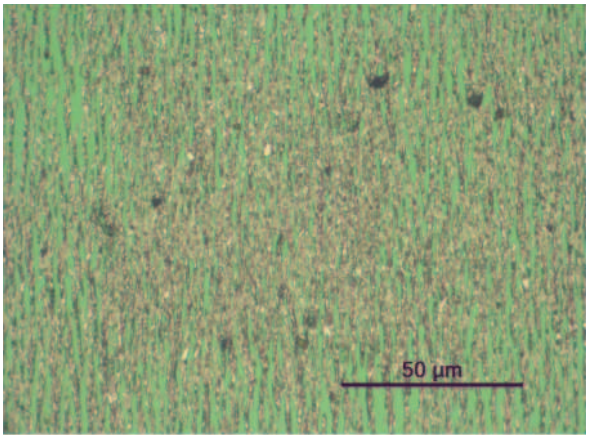
Fotografia 13



Ampliação: x 200 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Partículas ferrosas de muito pequenas dimensões, típicas de desgaste de corrosão.

Fotografia 14



Ampliação: x 1000 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Ampliação da Fotografia 13. Elevada concentração de partículas de pequenas dimensões, típicas de desgaste de corrosão, mas em menor concentração do que na amostra "Running In".

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	15-16 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas PAO 320 /
Nº de páginas: Data:	7 05/04/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante PAO 320, resultantes de ensaios de Rolamentos Axiais de Esferas (21) na Máquina de Quatro Esferas, para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
Run-In	2	X	X
48H	48	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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CLIENTE: ***INEGI***
MORADA: Porto
DATA: 28/03/11

ENSAIO: Rol. Axiais de Esferas (21)
Ref. ÓLEO: PAO 320

IDENTIFICAÇÃO							
Amostra nº:	Run-In	48H					
Data amostra:	Fev-11	Fev-11					
Análise nº:	15/11	16/11					
Ciclos/Máquina:	-	-					
Ciclos/Óleo:	-	-					
FERROMETRIA							
d:	1	1					
DL:	130,1	36,1					
DS:	55,8	14,8					
CPUC:	185,9	50,9					
ISUC:	1,4E+04	1,1E+03					
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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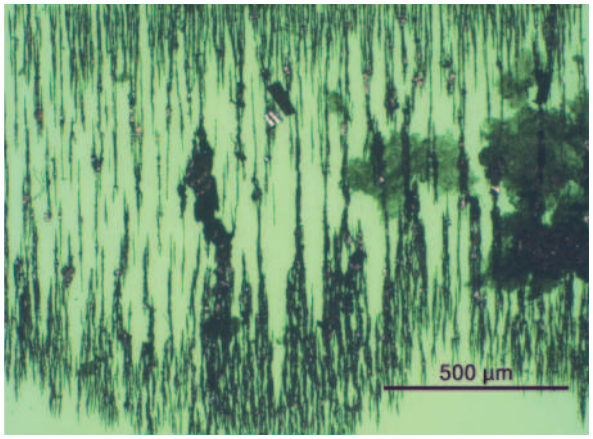
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (21)
MORADA: Porto	Ref. ÓLEO: PAO 320 Running In
DATA: 28/03/11	

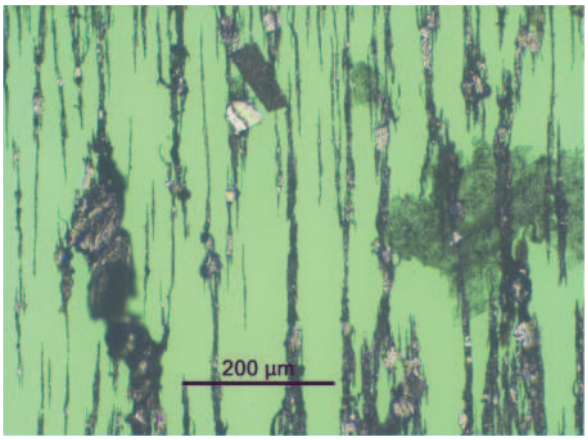
Fotografia 1



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

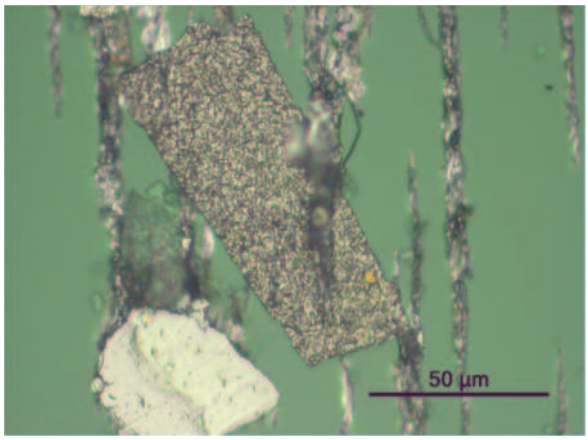
Fotografia 2



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões. Presença de alguns contaminantes externos.

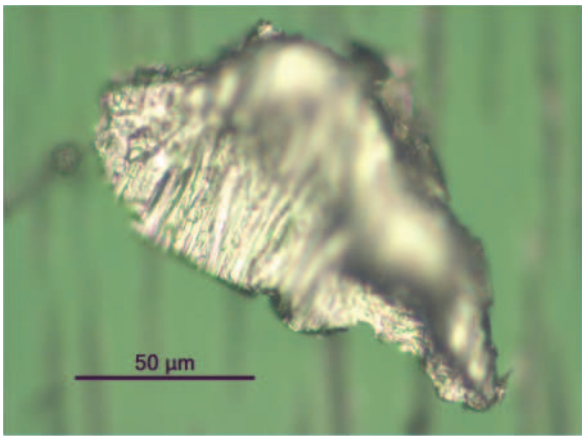
Fotografia 3



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Presença de algumas partículas de grandes dimensões e outras bastante oxidadas.

Fotografia 4



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula não ferrosa (metal branco) de grandes dimensões.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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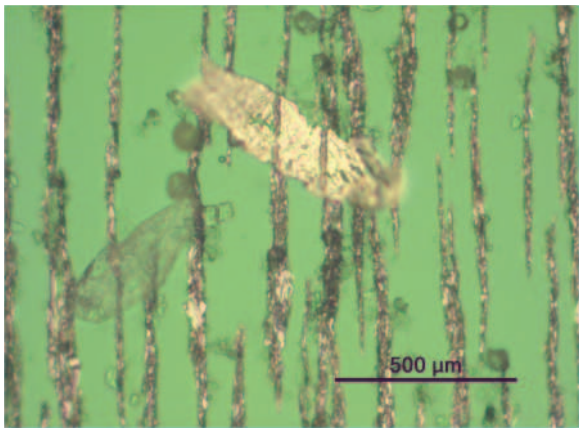
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (21)
MORADA: Porto	Ref. ÓLEO: PAO 320 Running In
DATA: 28/03/11	

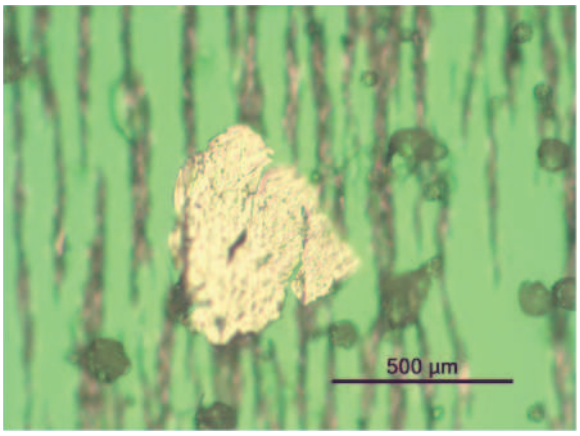
Fotografia 5



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas dimensões e de uma partícula não ferrosa (metal branco).

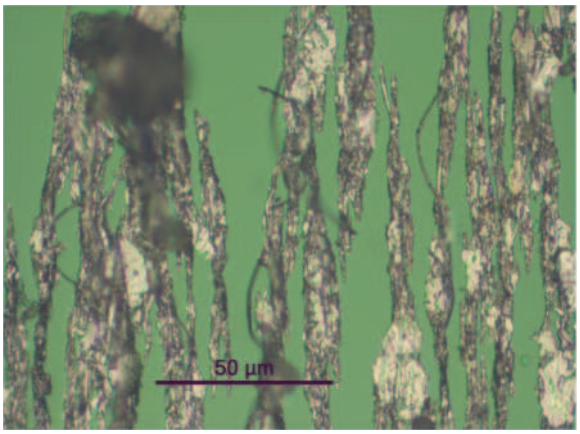
Fotografia 6



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas dimensões e de uma partícula não ferrosa (metal branco). Presença de alguns contaminantes de forma esférica.

Fotografia 7



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partículas ferrosas de desgaste de pequenas e médias dimensões. Note-se a presença significativa de partículas muito finas e compridas, resultantes de desgaste de corte.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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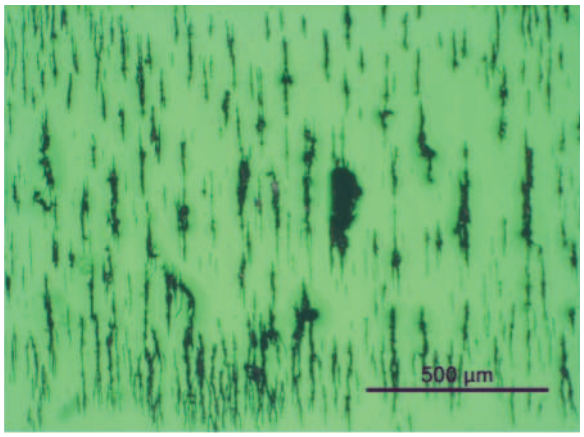
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (21)
MORADA: Porto	Ref. ÓLEO: PAO 320 48H
DATA: 28/03/11	

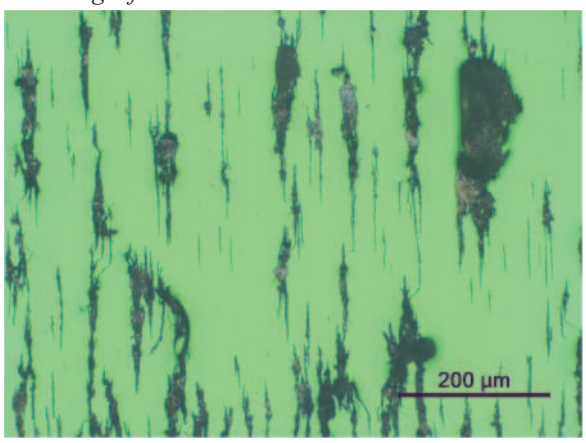
Fotografia 8



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

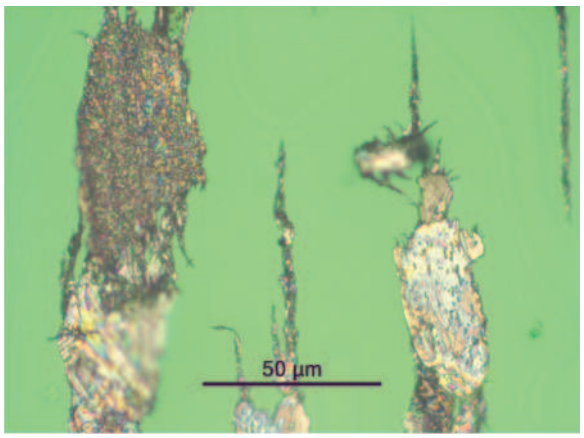
Fotografia 9



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 8.. Presença de partículas ferrosas de pequenas e grandes dimensões.

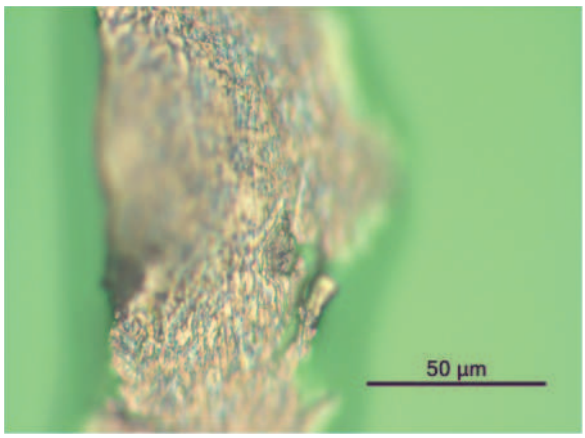
Fotografia 10



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Partículas ferrosas de grandes dimensões, algumas severamente oxidadas.

Fotografia 11



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Partícula ferrosa de grandes dimensões e oxidada.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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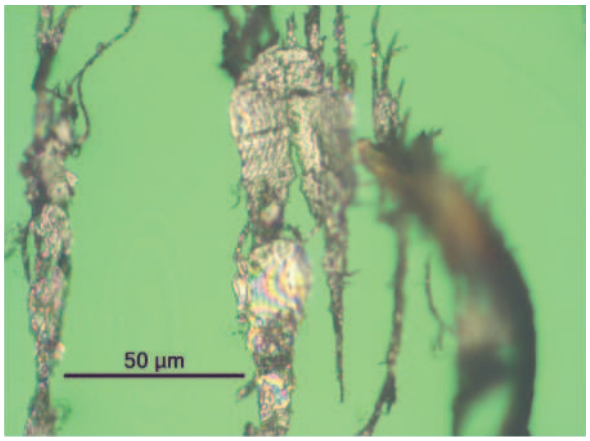
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (21)
MORADA: Porto	Ref. ÓLEO: PAO 320 48H
DATA: 28/03/11	

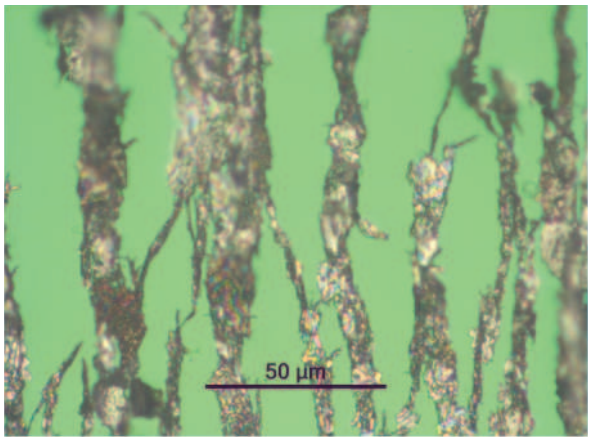
Fotografia 12



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Partículas ferrosas de desgaste de pequenas e médias dimensões. Note-se a presença significativa de partículas muito finas e compridas, resultantes de desgaste de corte.

Fotografia 13



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Partículas ferrosas de desgaste de pequenas e médias dimensões. Note-se a presença significativa de partículas muito finas e compridas, resultantes de desgaste de corte.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	21-22 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas (21) Ester 320 /
Nº de páginas: Data:	7 06/04/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante Ester 320, resultantes de ensaios de Rolamentos Axiais de Esferas (21), na Máquina de 4 Esferas, para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
Running-In	2	X	X
48H	48	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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CLIENTE: ***INEGI***
MORADA: Porto
DATA: 04/04/11

ENSAIO: Rolamentos Axiais de Esferas
Ref. ÓLEO: Ester 320

IDENTIFICAÇÃO							
Amostra nº:	Run-In	48H					
Data amostra:	Mar-11	Mar-11					
Análise nº:	21/11	22/11					
Ciclos/Máquina:	-	-					
Ciclos/Óleo:	-	-					
FERROMETRIA							
d:	1	1					
DL:	165,4	97,2					
DS:	96,6	37,9					
CPUC:	262,0	135,1					
ISUC:	1,8E+04	8,0E+03					
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Índice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL -** Índice de partículas grandes		Não existe
	DS - Indice de partículas pequenas	**I**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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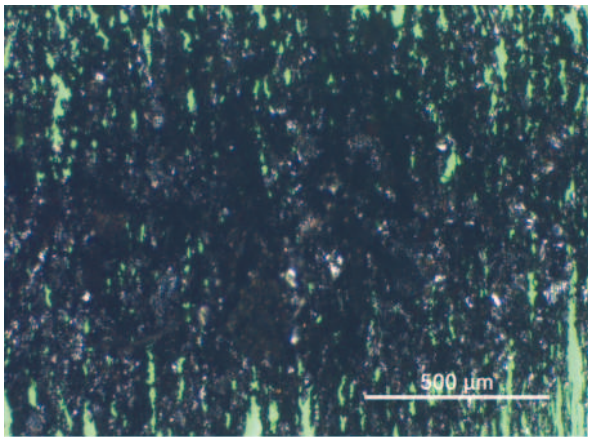
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 Running In
DATA: 04/04/11	

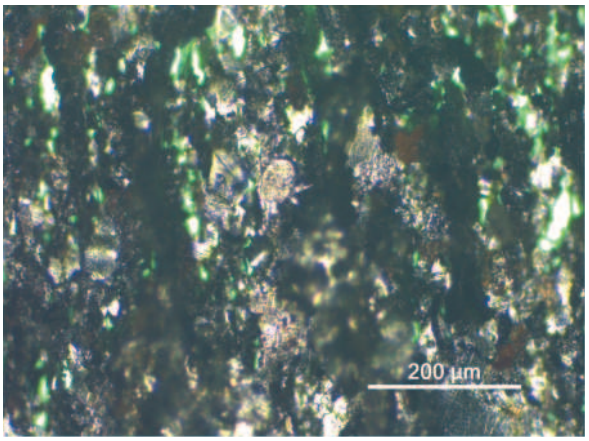
Fotografia 1



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença abundante de partículas ferrosas de pequenas e grandes dimensões.

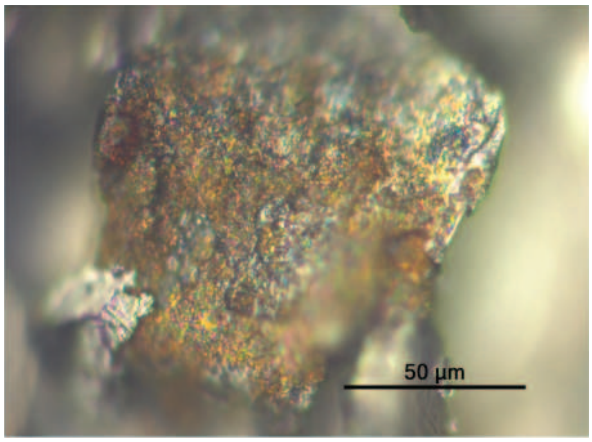
Fotografia 2



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença abundante de partículas ferrosas de pequenas e grandes dimensões, muitas delas oxidadas.

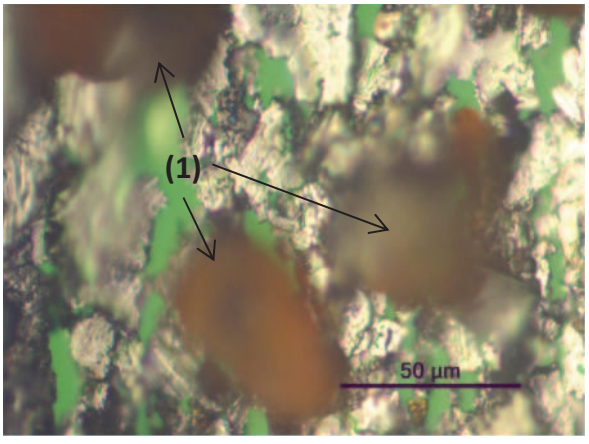
Fotografia 3



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.. Particula ferrosa de grandes dimensões e ligeiramente revestida por óxidos alaranjados.

Fotografia 4



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partículas ferrosas de desgaste de médias e grandes dimensões e de alguns óxidos de ferro laranja (1) (ferrugem).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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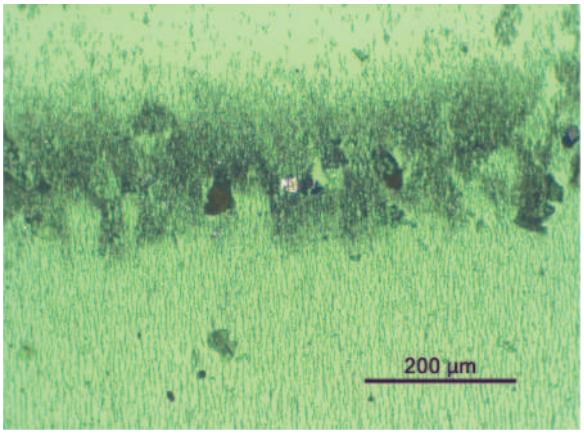
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 Running In
DATA: 04/04/11	

Fotografia 5

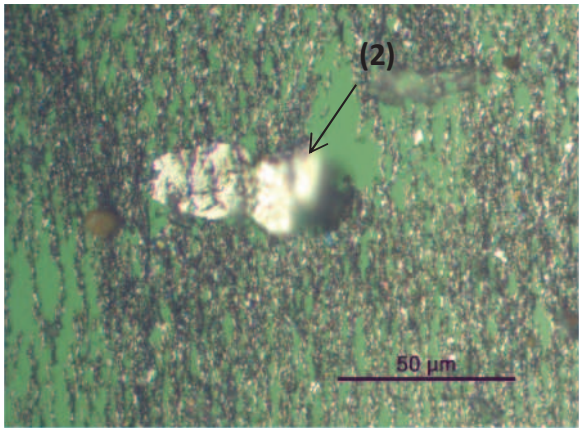


Ampliação: x 200 Diluição: 1

Localização: Saída Luz: Branca / Verde

Observações: Partículas ferrosas de pequenas dimensões típicas de desgaste de corrosão.

Fotografia 6



Ampliação: x 1000 Diluição: 1

Localização: Saida Luz: Branca / Verde

Observações: Ampliação da Fotografia 5. Partículas ferrosas de pequenas dimensões típicas de desgaste de corrosão. Presença de uma partícula não ferrosa de grandes dimensões (2).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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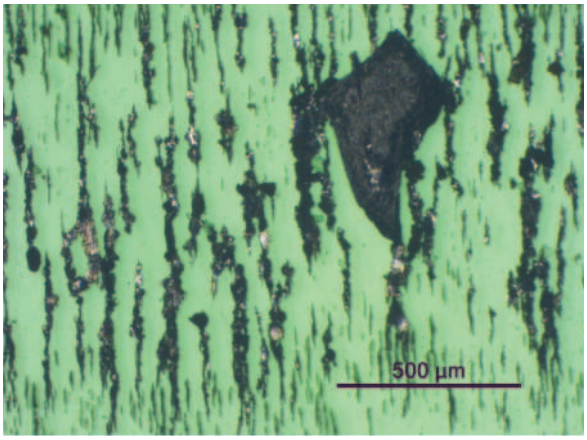
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 48H
DATA: 04/04/11	

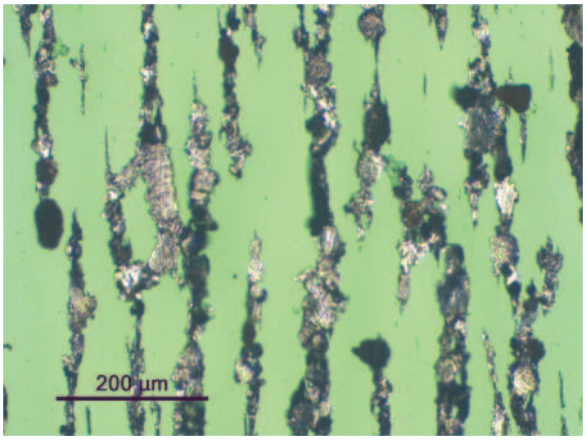
Fotografia 9



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

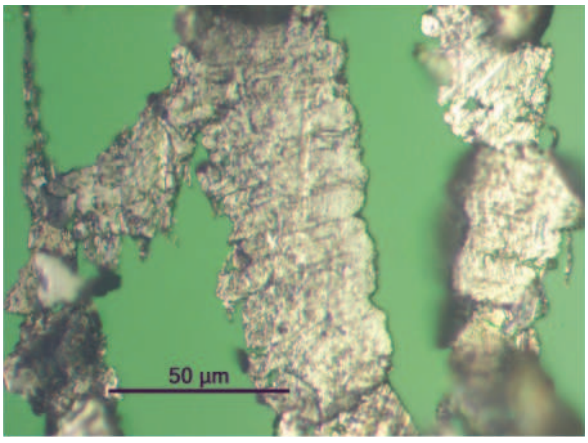
Fotografia 10



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 9.
Presença de partículas de pequenas e grandes dimensões.

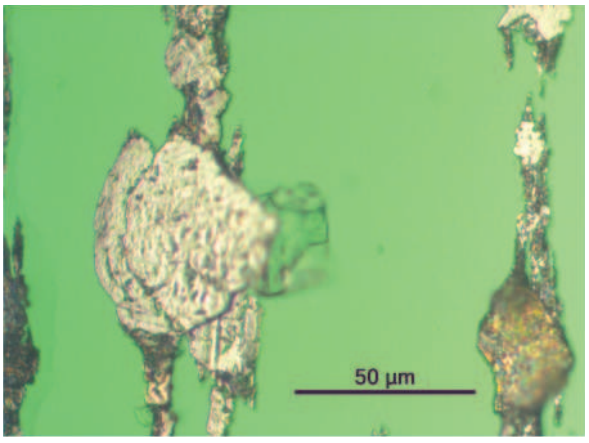
Fotografia 11



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10.
Partículas de desgaste de grandes dimensões.

Fotografia 12



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10.
Partículas de desgaste de grandes dimensões.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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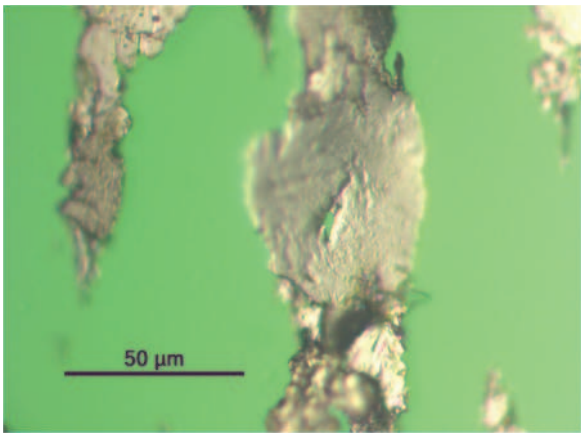
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 48H
DATA: 04/04/11	

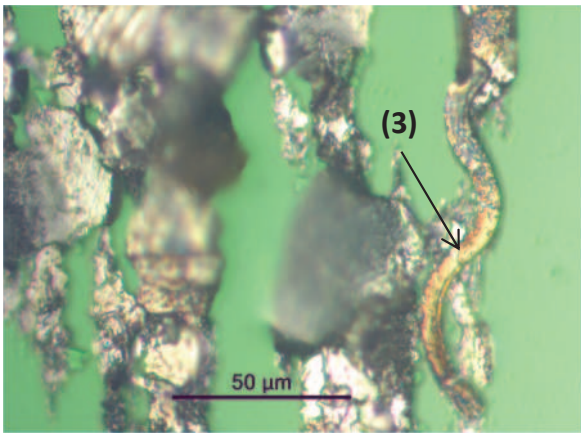
Fotografia 13



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Partícula de desgaste de grandes dimensões, típica de desgaste de fadiga.

Fotografia 14



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Partículas de desgaste de grandes dimensões, algumas severamente oxidadas e outras de desgaste de corte (3).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	39 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas (7 Esf.) Mineral 320 /
Nº de páginas: Data:	5 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de uma amostra de óleo lubrificante Mineral 320, resultantes de ensaios de Rolamentos Axiais de Esferas (7) na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50H	50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

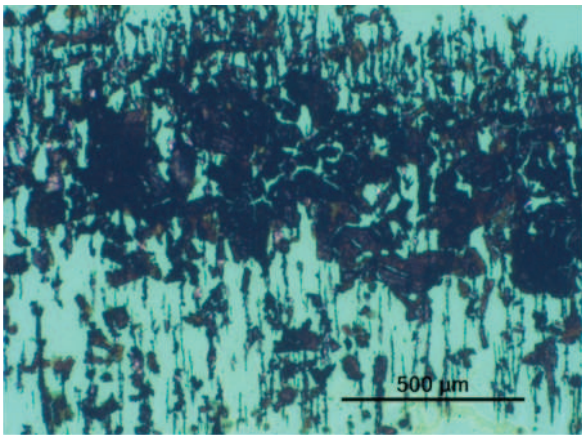
	CLIENTE: ***INEGI***		ENSAIO: Rol. Axiais de Esferas (7Esf)				
	MORADA: Porto		Ref. ÓLEO: Mineral 320				
	DATA: 10/06/11						
IDENTIFICAÇÃO							
Amostra nº:	50H						
Data amostra:	Mai-11						
Análise nº:	39/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	1						
DL:	70,8						
DS:	23,1						
CPUC:	93,9						
ISUC:	4,5E+03						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA			
	DL - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7Esf)
MORADA: Porto	Ref. ÓLEO: Mineral 320
DATA: 10/06/11	

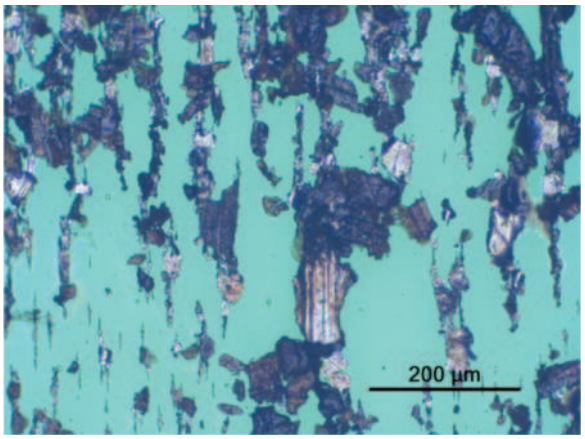
Fotografia 1



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença significativa de partículas de pequenas e grandes dimensões.

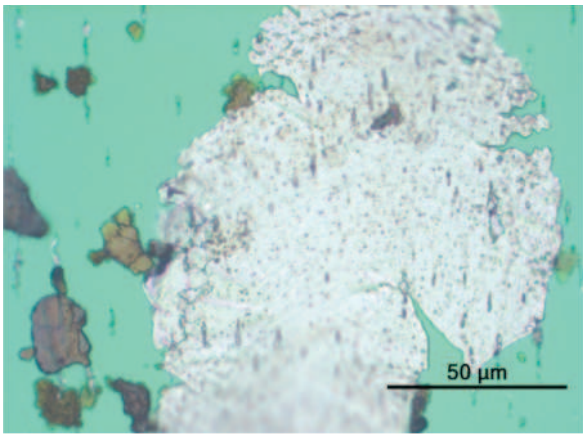
Fotografia 2



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões. Presença significativa de partículas de tonalidade escura, algumas alinhadas magnéticamente .

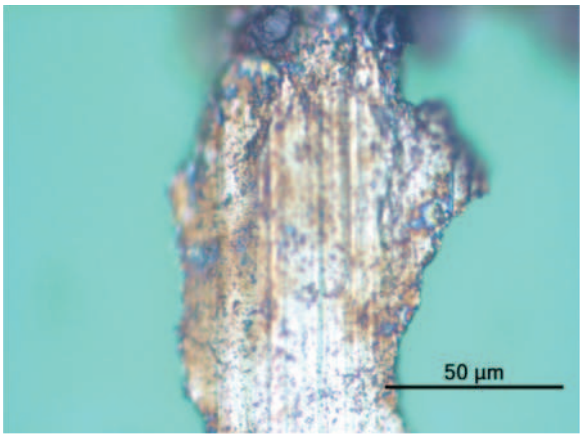
Fotografia 3



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de grandes dimensões, típica de desgaste de fadiga..

Fotografia 4



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de grandes dimensões, típica de desgaste de fadiga e ligeiramente oxidada.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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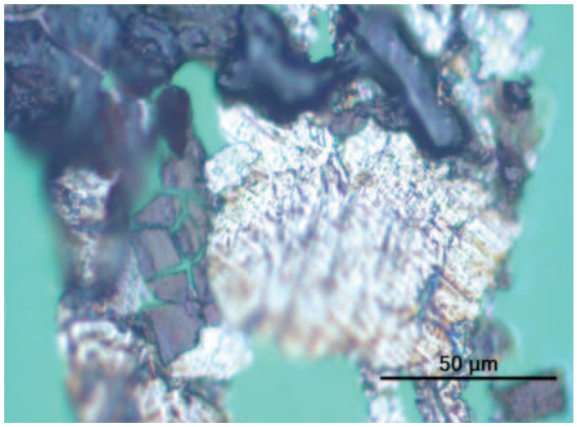
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7Esf)
MORADA: Porto	Ref. ÓLEO: Mineral 320
DATA: 10/06/11	

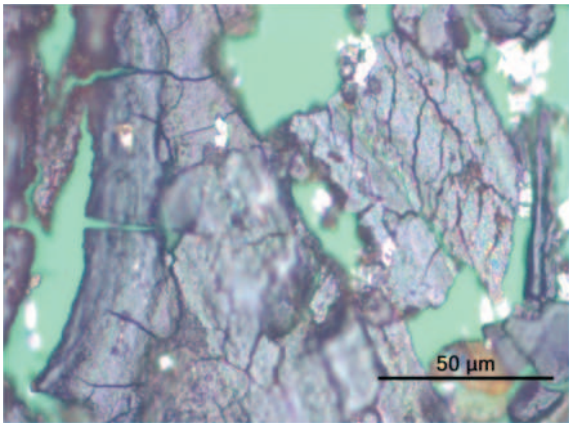
Fotografia 5



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.
Partícula ferrosa de desgaste de fadiga, de grandes dimensões e partículas de tonalidade negra.

Fotografia 6



Ampliação: x 1000 Diluição: 1
Localização: Meio Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.
Aspecto das partículas de tonalidade escura. Note-se a fissuração das partículas evidenciando a sua fragilidade, possivelmente por se encontrarem totalmente carbonizadas (?).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	69 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas (7 Esf) PAO 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de duas amostras de óleo lubrificante PAO 320, resultantes de ensaios de Rolamentos Axiais de Esferas (7 Esf.) na Máquina de Quatro Esferas, para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50H	50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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	CLIENTE: ***INEGI***			ENSAIO: Rol. Axiais de Esferas (7Esf)			
	MORADA: Porto			Ref. ÓLEO: PAO 320			
	DATA: 09/06/11						
IDENTIFICAÇÃO							
Amostra nº:	50H						
Data amostra:	Mai-11						
Análise nº:	69/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	1						
DL:	63,7						
DS:	18,5						
CPUC:	82,2						
ISUC:	3,7E+03						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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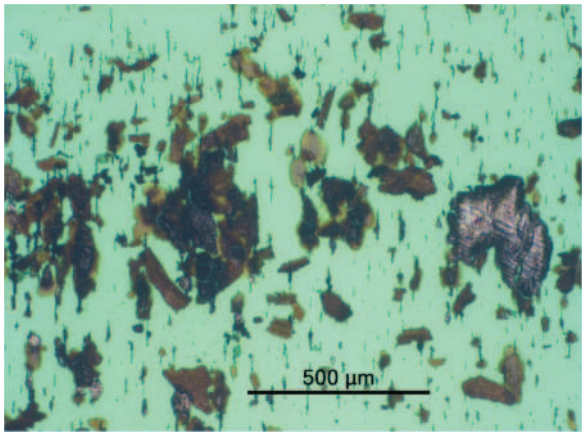
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7Esf)
MORADA: Porto	Ref. ÓLEO: PAO 320 50H
DATA: 09/06/11	

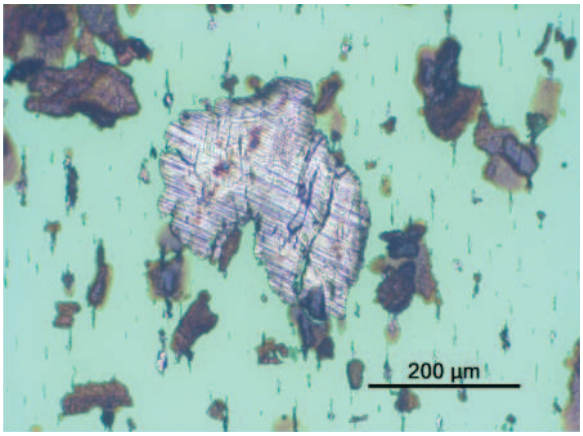
Fotografia 1



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e algumas de muito grandes dimensões. Partículas de tonalidade castanha, não metálicas e de grandes dimensões.

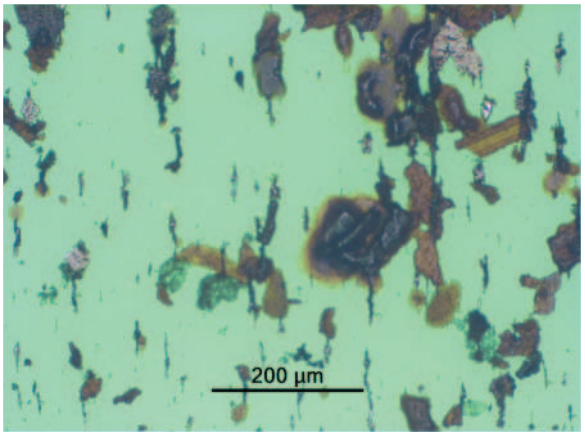
Fotografia 2



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Partícula ferrosa de grandes dimensões, com marcas de escorregamento.

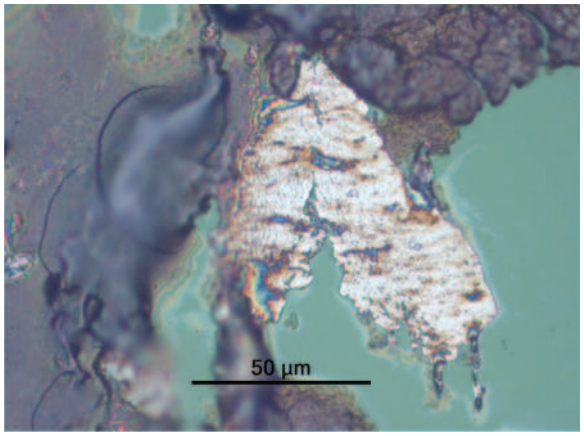
Fotografia 3



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partículas de grandes dimensões não metálicas de tonalidade castanha.

Fotografia 4



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de grandes dimensões, típica de desgaste de fadiga envolvida nas partículas não metálicas que sugerem ser um tipo de resina.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	65 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas (7 Esf.) Ester 320 50H /
Nº de páginas: Data:	7 09/10/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante Ester 320, resultantes de ensaios de Rolamentos Axiais de Esferas (7 Esf.), na Máquina de 4 Esferas, para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50	50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

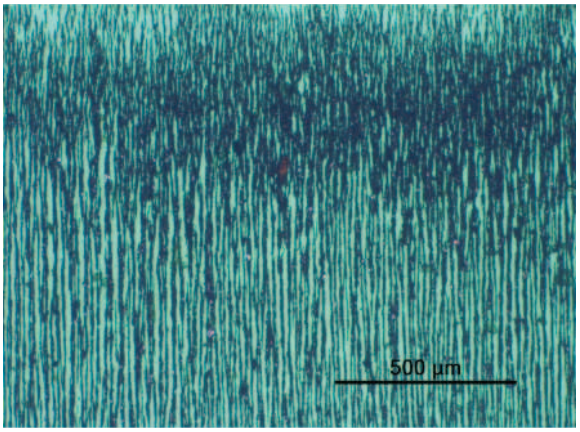
	CLIENTE: ***INEGI***			ENSAIO: Rol. Axiais de Esferas (7 Esf.)			
	MORADA: Porto			Ref. ÓLEO: Ester 320 50H			
	DATA: 09/06/11						
IDENTIFICAÇÃO							
Amostra nº:	50						
Data amostra:	Mai-11						
Análise nº:	65/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,01						
DL:	112,0						
DS:	23,8						
CPUC:	13580,0						
ISUC:	1,2E+08						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Índice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA			
	DL - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**I**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7 Esf.)
MORADA: Porto	Ref. ÓLEO: Ester 320 50+50H
DATA: 09/06/11	

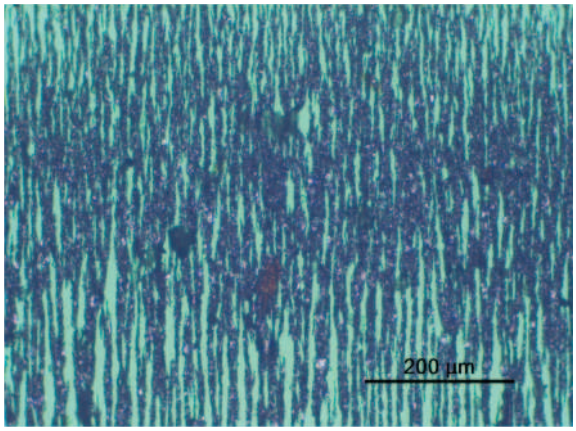
Fotografia 1



Ampliação: x 100 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Presença abundante de partículas ferrosas de pequenas e algumas de grandes dimensões.

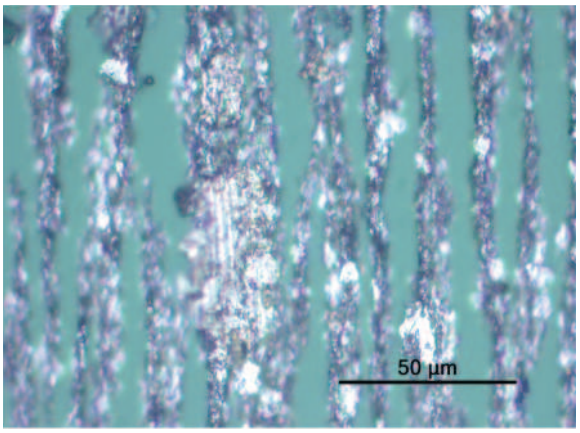
Fotografia 2



Ampliação: x 200 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença abundante de partículas ferrosas de pequenas e algumas de grandes dimensões.

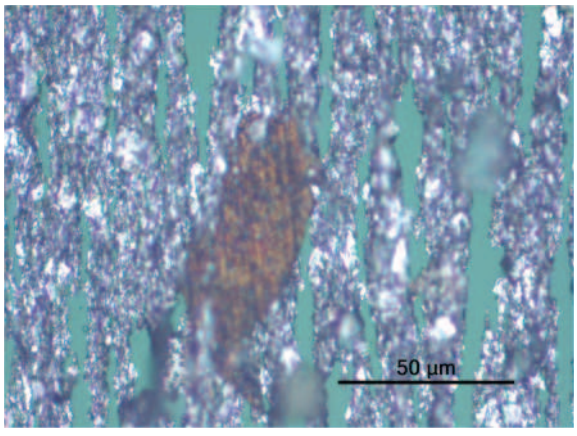
Fotografia 3



Ampliação: x 1000 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.. Particulas ferrosas de desgaste de pequenas e grandes dimensões.

Fotografia 4



Ampliação: x 1000 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Particulas ferrosas de desgaste de pequenas dimensões. Presença de uma partícula de grandes dimensões com tonalidade castanha.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	49 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas (7 Esf.) Mineral 320 (50+50H) /
Nº de páginas: Data:	5 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de uma amostra de óleo lubrificante Mineral 320, resultantes de ensaios de Rolamentos Axiais de Esferas (7) na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50+50H	50+50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

	CLIENTE: ***INEGI***			ENSAIO: Rol. Axiais de Esferas (7Esf)			
	MORADA: Porto			Ref. ÓLEO: Mineral 320			
	DATA: 09/06/11						
IDENTIFICAÇÃO							
Amostra nº:	50+50H						
Data amostra:	Mai-11						
Análise nº:	49/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,01						
DL:	38,2						
DS:	16,8						
CPUC:	5500,0						
ISUC:	1,2E+07						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**I**	Fraco
	CPUC - Concentração de partículas de des	**M**	Médio
	ISUC - Índice de severidade de desgaste	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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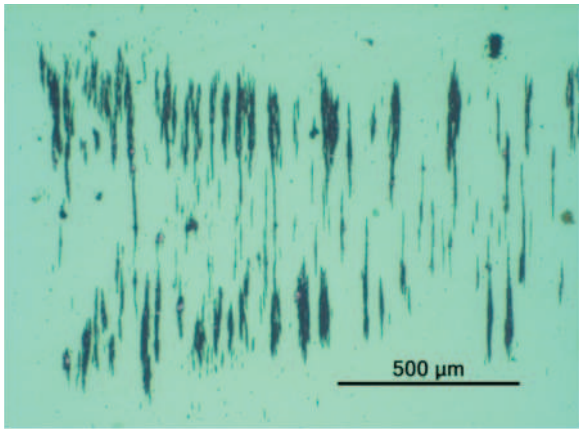
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7Esf)
MORADA: Porto	Ref. ÓLEO: Mineral 320 (50+50H) d=0,01
DATA: 09/06/11	

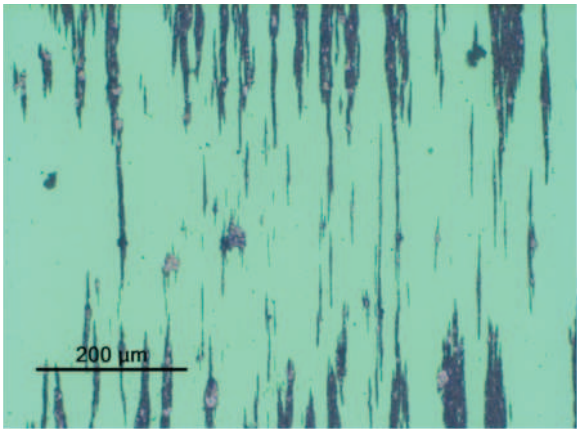
Fotografia 1



Ampliação: x 100 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Presença significativa de partículas de pequenas dimensões.

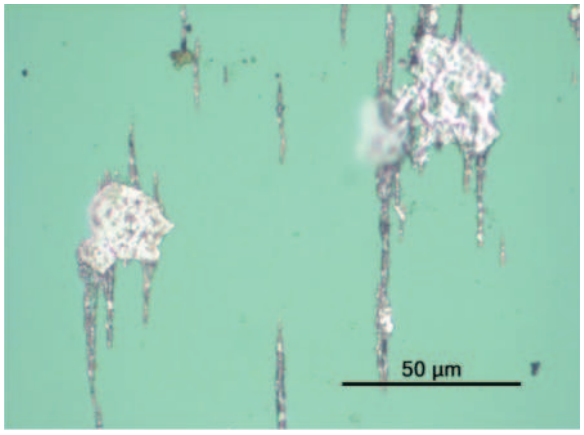
Fotografia 2



Ampliação: x 200 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas dimensões e algumas de maiores dimensões.

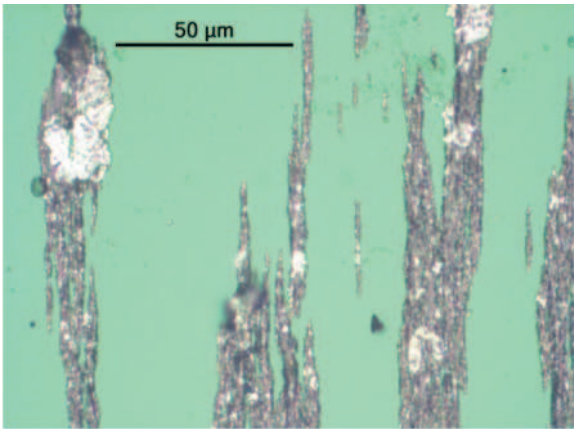
Fotografia 3



Ampliação: x 1000 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partículas ferrosas de grandes dimensões, típicas de desgaste de fadiga..

Fotografia 4



Ampliação: x 1000 Diluição: 0, 01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partículas ferrosas de pequenaas dimensões e algumas de grandes dimensões.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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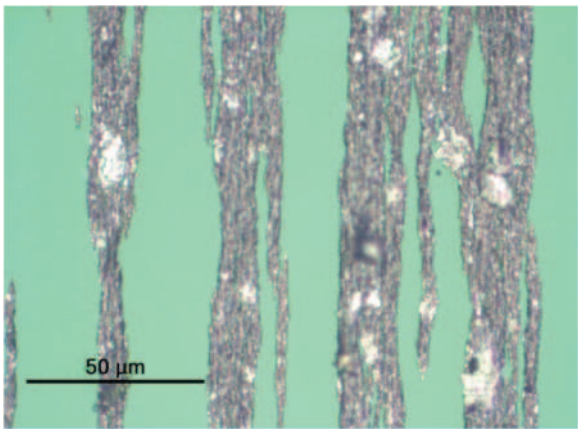
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7Esf)
MORADA: Porto	Ref. ÓLEO: Mineral 320
DATA: 09/06/11	

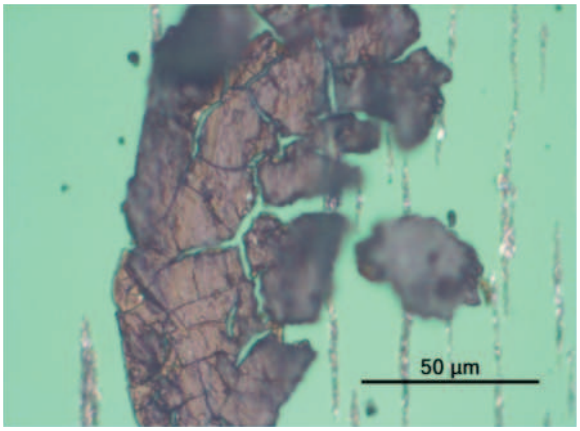
Fotografia 5



Ampliação: x 1000 Diluição: 0,0 1
Localização: Nucleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.
Partículas ferrosas de pequenaas dimensões.

Fotografia 6



Ampliação: x 1000 Diluição: 0,01
Localização: Meio Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.
Partícula de tonalidade escura, de grandes dimensões e totalmente fragmentada.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	71 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas (7 Esf) PAO 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de duas amostras de óleo lubrificante PAO 320, resultantes de ensaios de Rolamentos Axiais de Esferas (7 Esf.) na Máquina de Quatro Esferas, para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50+50	50+50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***
MORADA: Porto
DATA: 09/06/11

ENSAIO: Rol. Axiais de Esferas (7Esf)
Ref. ÓLEO: PAO 320 50+50H (Vib.)

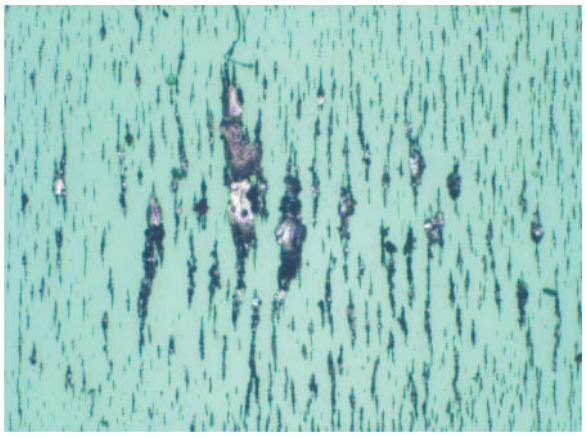
IDENTIFICAÇÃO							
Amostra nº:	50+50						
Data amostra:	Mai-11						
Análise nº:	71/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,1						
DL:	29,7						
DS:	7,2						
CPUC:	369,0						
ISUC:	8,3E+04						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA			
	DL - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7Esf)
MORADA: Porto	Ref. ÓLEO: PAO 320 50+50H
DATA: 09/06/11	

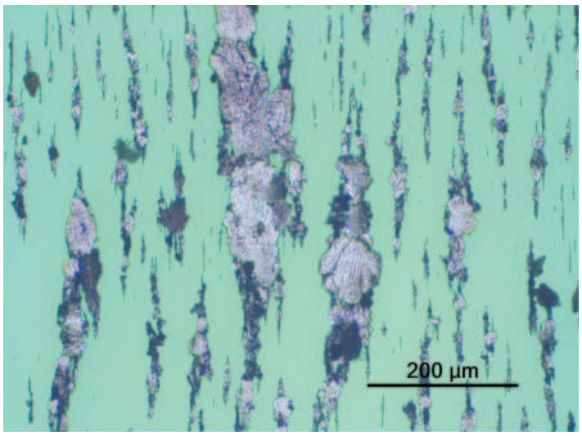
Fotografia 1



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

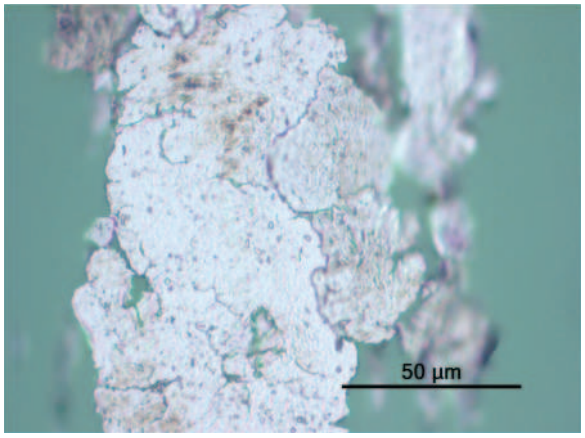
Fotografia 2



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Partículas ferrosas de grandes dimensões, algumas oxidadas termicamente.

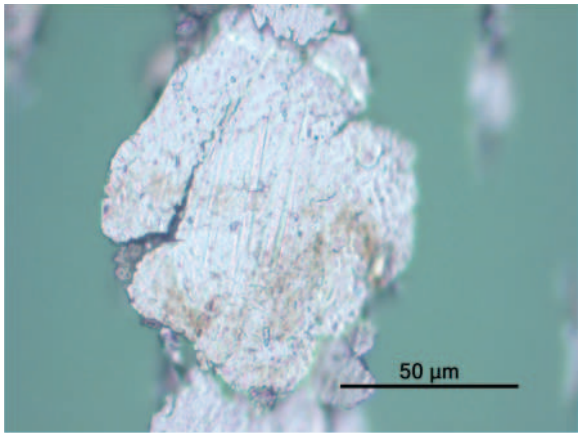
Fotografia 3



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de desgaste de fadiga de grandes dimensões.

Fotografia 4



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de desgaste de fadiga de grandes dimensões.
.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	50 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Esferas (7 Esf.) Ester 320 /
Nº de páginas: Data:	7 09/10/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante Ester 320, resultantes de ensaios de Rolamentos Axiais de Esferas (7 Esf.), na Máquina de 4 Esferas, para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50+50	50+50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***
MORADA: Porto
DATA: 09/06/11

ENSAIO: Rol. Axiais de Esferas (7 Esf.)
Ref. ÓLEO: Ester 320 50+50+50H

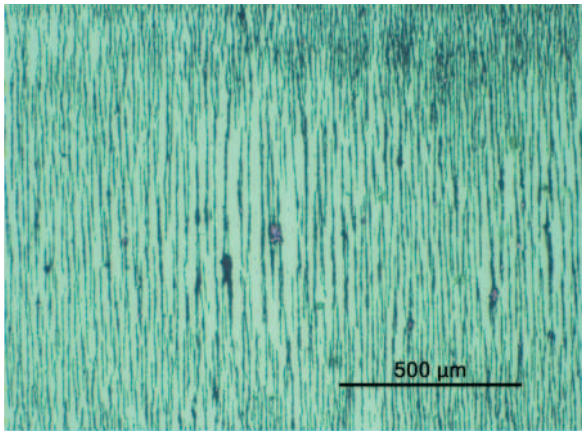
IDENTIFICAÇÃO							
Amostra nº:	50+50						
Data amostra:	Mai-11						
Análise nº:	50/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,01						
DL:	71,9						
DS:	9,1						
CPUC:	8100,0						
ISUC:	5,1E+07						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA			
	DL - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Esferas (7 Esf.)
MORADA: Porto	Ref. ÓLEO: Ester 320 50+50H
DATA: 09/06/11	

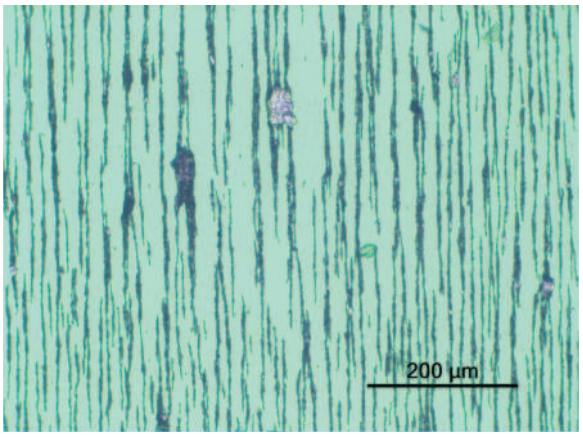
Fotografia 1



Ampliação: x 100 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Presença abundante de partículas ferrosas de pequenas e algumas de grandes dimensões.

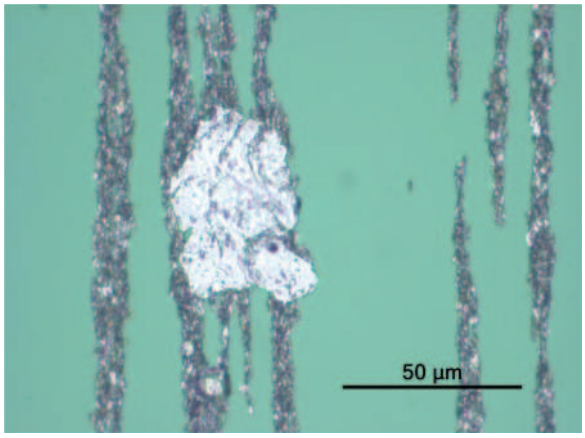
Fotografia 2



Ampliação: x 200 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença abundante de partículas ferrosas de pequenas e algumas de grandes dimensões.

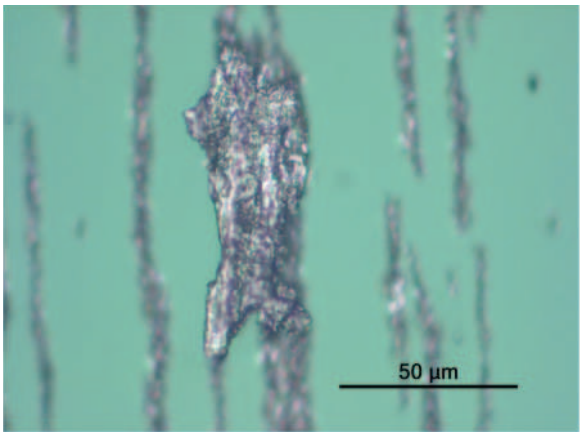
Fotografia 3



Ampliação: x 1000 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.. Particula ferrosa de desgaste de fadiga de grandes dimensões.

Fotografia 4



Ampliação: x 1000 Diluição: 0,01
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Particula ferrosa de desgaste de grandes dimensões e oxidada termicamente.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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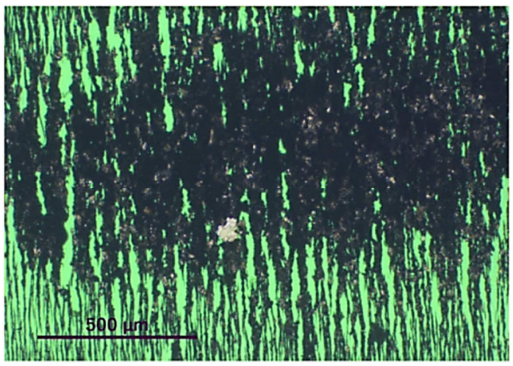
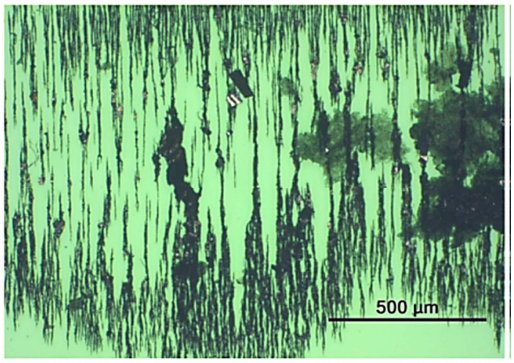
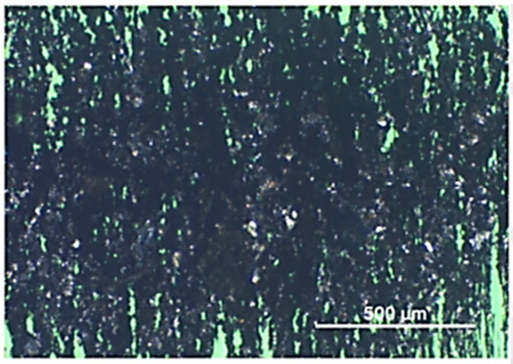
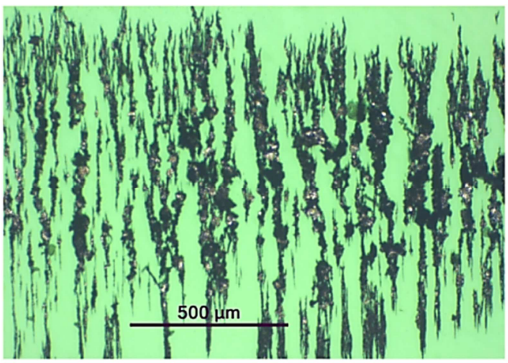
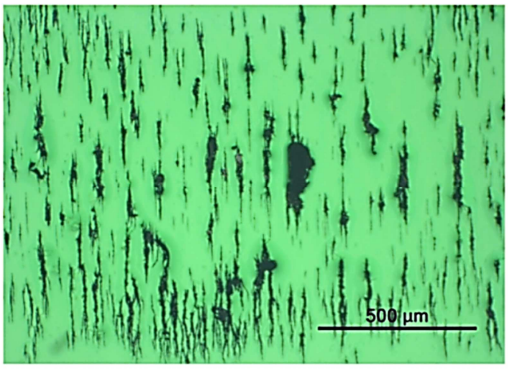
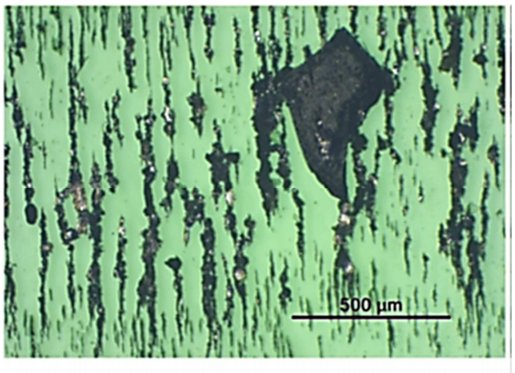
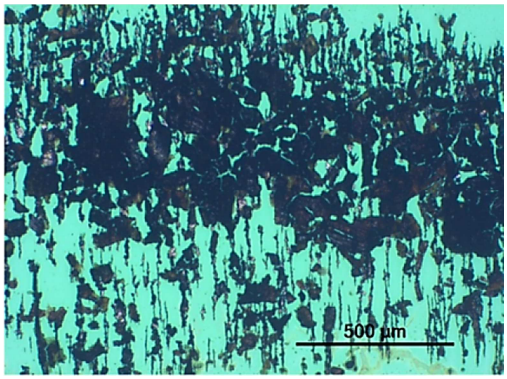
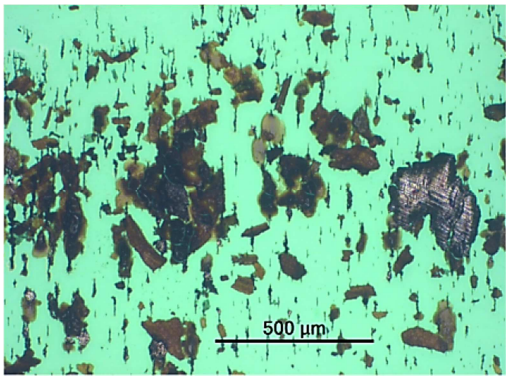
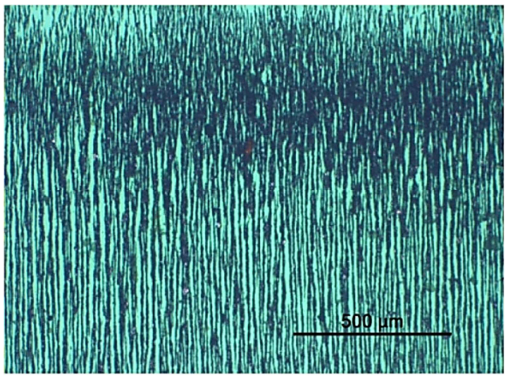
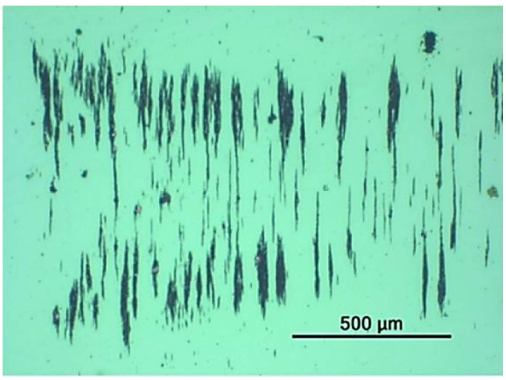
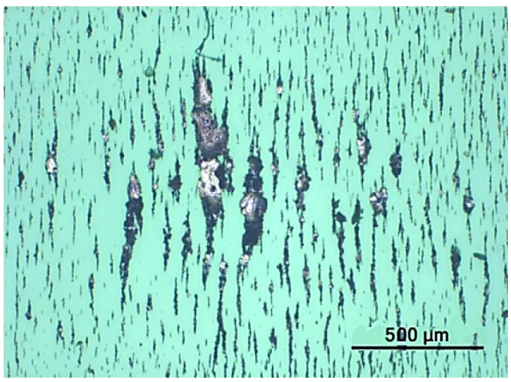
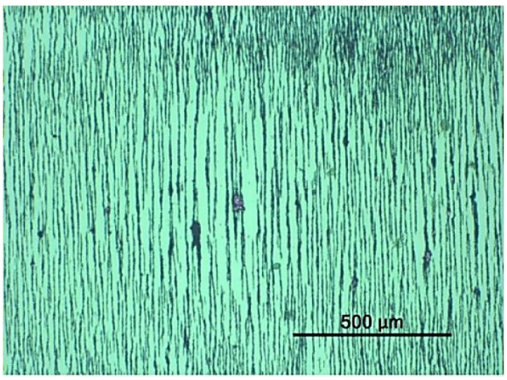
A.10. Ferrometry and Analytical Ferrography - TBB - comparison

Analysis of Lubricants – Analytical Ferrography and Ferrometry		
	Thrust ball bearings (21 balls)	**RUN-IN**
MIN - 320		d = 1 DL = 146,6 DS = 65,5 CPUC = 212,2 ISUC = 1,7E+04
PAO - 320		d = 1 DL = 130,1 DS = 55,8 CPUC = 185,9 ISUC = 1,4E+04
ESTER - 320		d = 1 DL = 165,4 Ds = 96,6 CPUC = 262,0 ISUC = 1,8E+04

Analysis of Lubricants – Analytical Ferrography and Ferrometry		
	Thrust ball bearing (21 balls)	**Wear (48h)**
MIN - 320		d = 1 DL = 65,9 DS = 33,7 CPUC = 99,6 ISUC = 3,2E+03
PAO - 320		d = 1 DL = 36,1 DS = 14,8 CPUC = 50,9 ISUC = 1,1E+03
ESTER - 320		d = 1 DL = 97,2 Ds = 37,9 CPUC = 135,1 ISUC = 8,0E+03

Analysis of Lubricants – Analytical Ferrography and Ferrometry		
	Thrust ball bearing SKF 51107	**Wear (7 balls – first 50h)**
MIN - 320		d = 1 DL = 70,8 DS = 23,1 CPUC = 93,9 ISUC = 4,5E+03
PAO - 320		d = 1 DL = 63,7 DS = 18,5 CPUC = 82,2 ISUC = 3,7E+03
ESTER - 320		d = 0,01 DL = 112,0 Ds = 23,8 CPUC = 13580,0 ISUC = 1,2E+08

Analysis of Lubricants – Analytical Ferrography and Ferrometry		
	Thrust ball bearing SKF 51107	**Wear (7 balls – second 50h)**
MIN - 320		d = 0,01 DL = 38,2 DS = 16,8 CPUC = 5500,0 ISUC = 1,2E+07
PAO - 320		d = 0,1 DL = 29,7 DS = 7,2 CPUC = 369,0 ISUC = 8,3E+04 **Due to a wear failure (spalling), the test was stopped 5h after the starting.**
ESTER - 320		d = 0,01 DL = 71,9 Ds = 9,1 CPUC = 8100,0 ISUC = 5,1E+07

A.11. Test data sheet for TRB 81107 TN with 20 rollers (mass loss, photographs of the surfaces and topography)

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (50h)	**Brand Oil**	Repsol
Bearing :	Axial Roller (20 rolls)	**Base Oil**	Mineral
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Super Tauro FND 320

Reference Bearing-initiation	
weighings	**Average**
77,048	77,048
77,048	
77,048	
Reference Bearing-end	
weighings	**Average**
77,049	77,049
77,049	
77,049	

Cage-initiation	
weighings	**Average**
17,741	17,741
17,741	
17,741	
Cage-end	
weighings	**Average**
17,697	17,697
17,697	
17,697	

Bearing-initiation	
weighings	**Average**
73,742	73,742
73,742	
73,742	
Bearing-end	
weighings	**Average**
73,698	73,698
73,698	
73,698	

Date

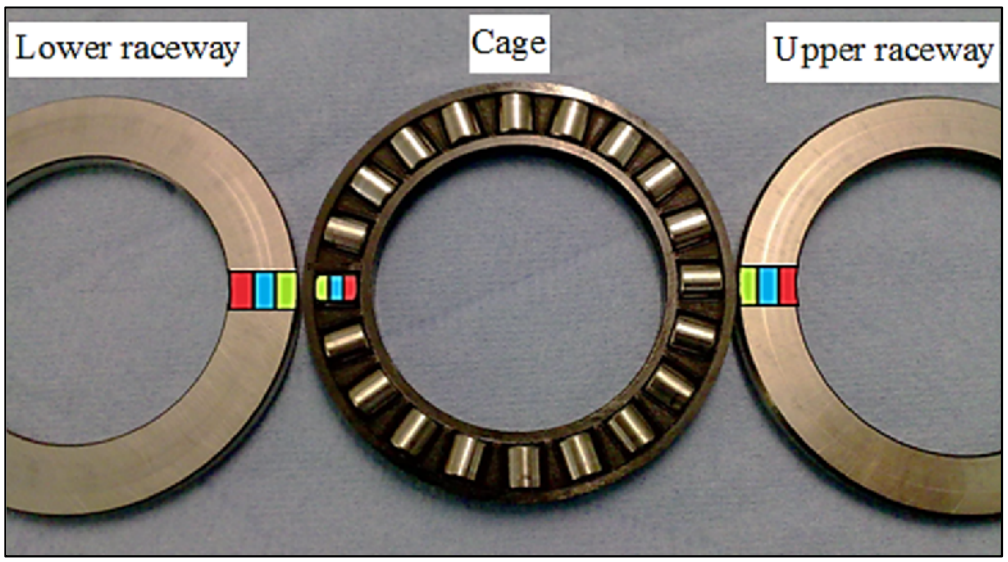
Initiation: **16-02-2011**

End: **18-02-2011**

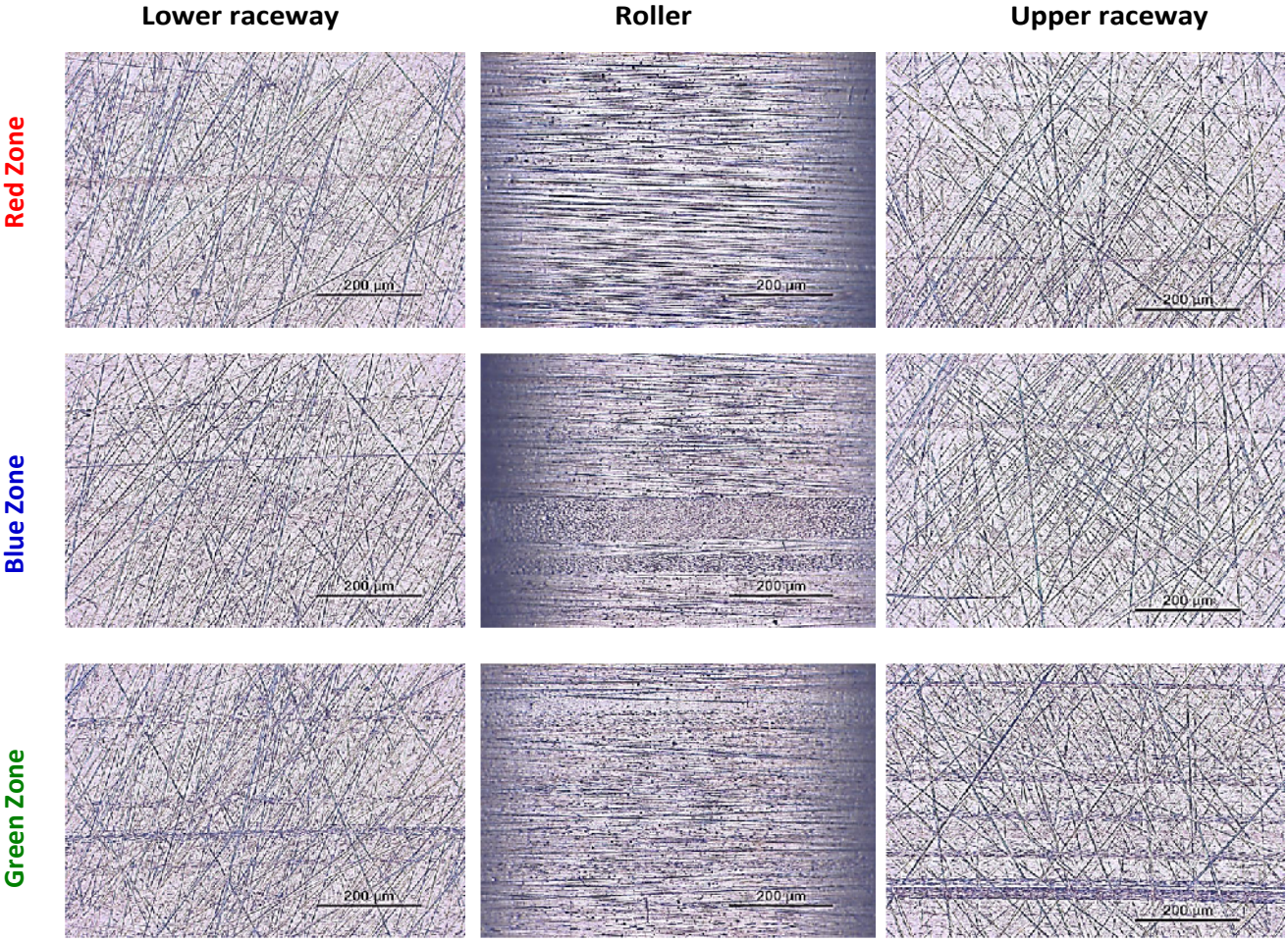
Mass loss	
45	mg

Identification of different contact zones

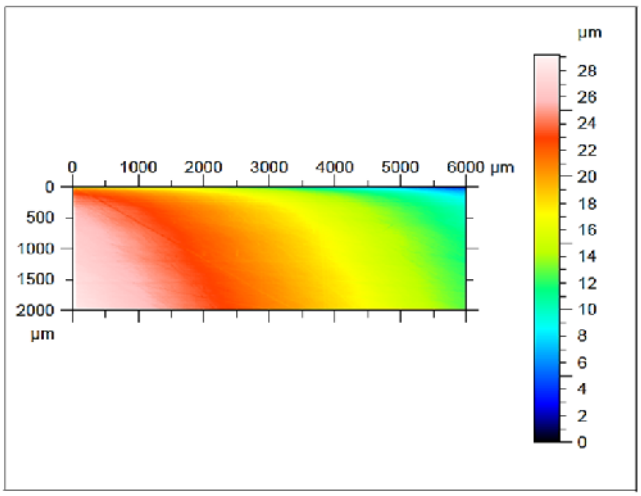
Scheme of the different contact zones analyzed

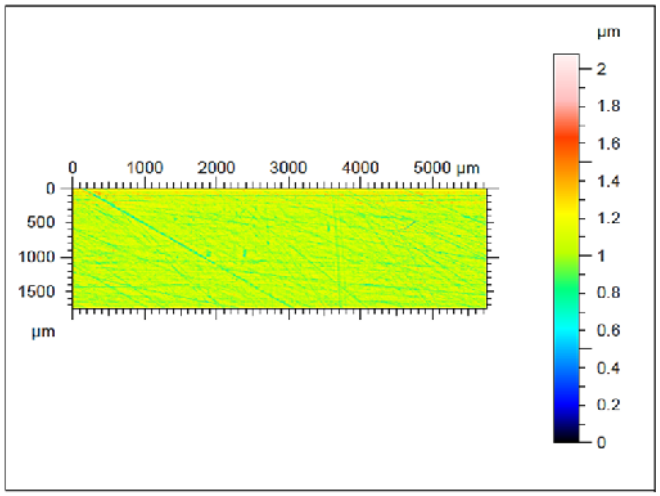


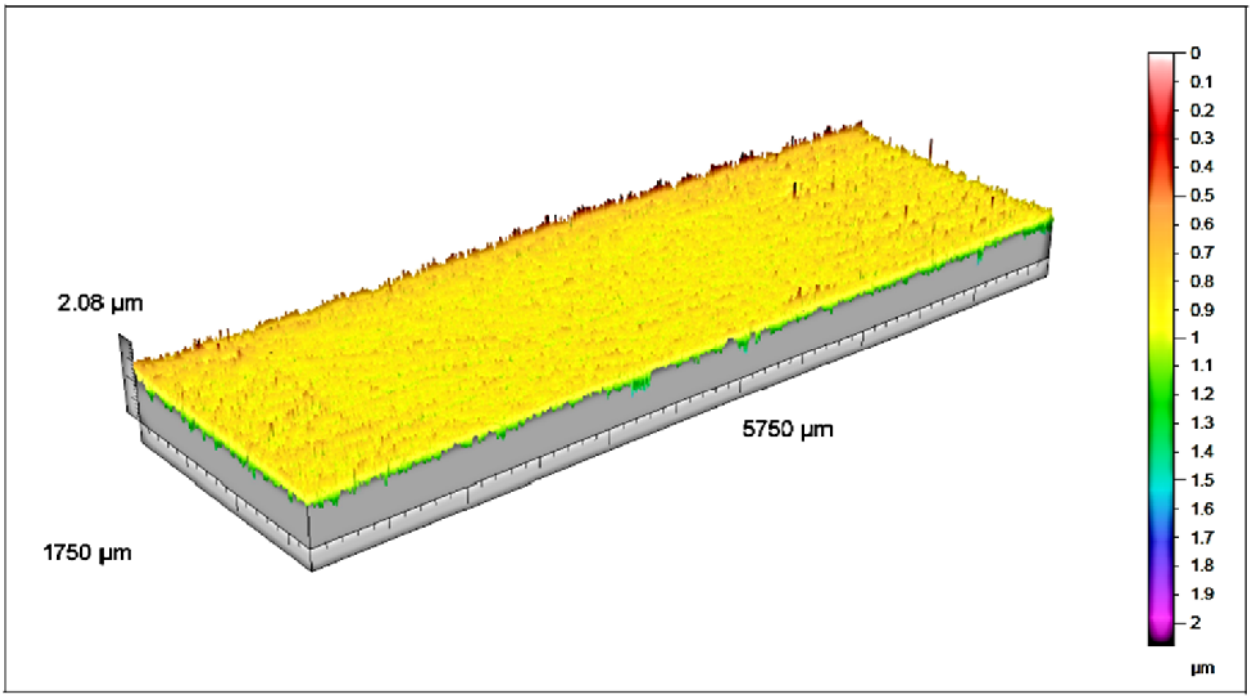
Brand Oil Repsol
Base Oil Mineral
Oil Ref. Super Tauro FND 320

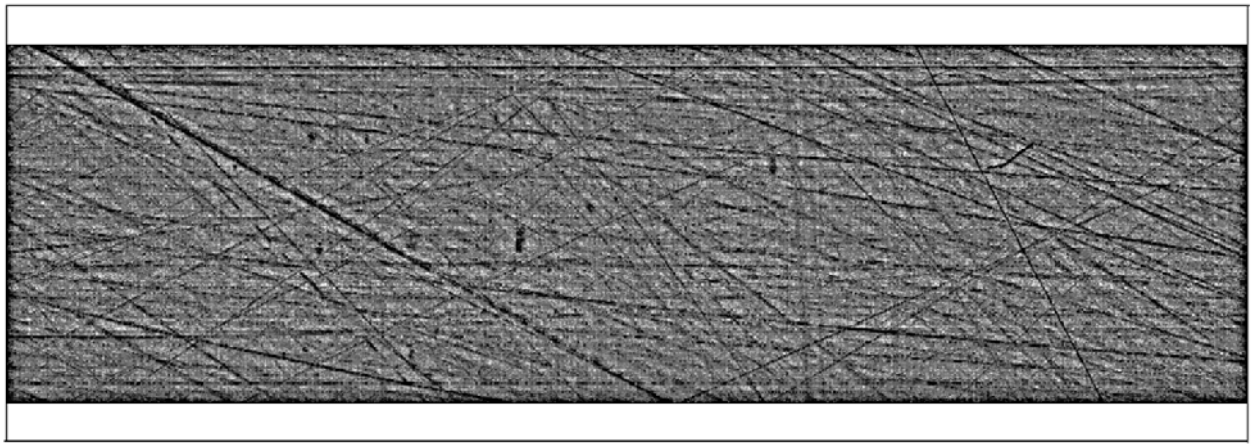


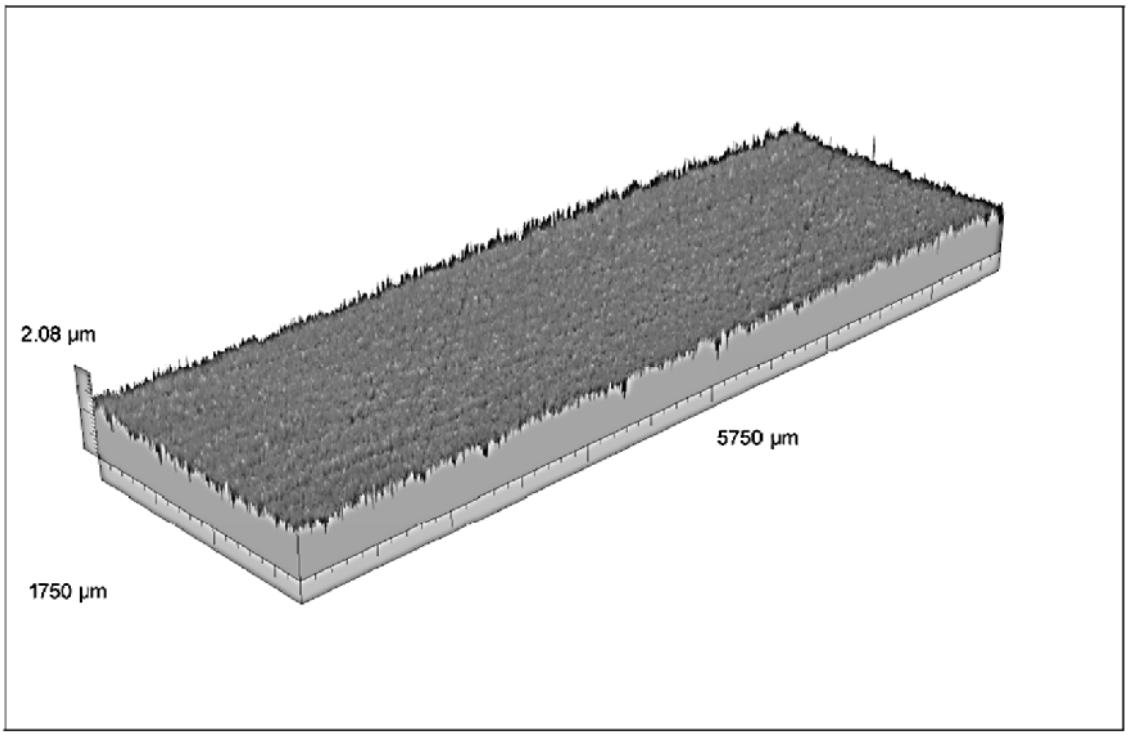
Topography, Gaussian Filter, 250 µm









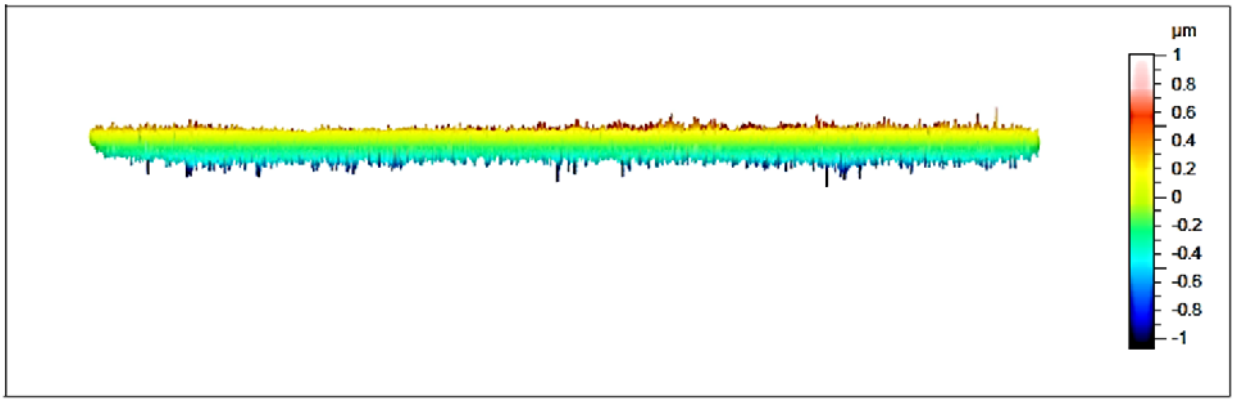


Parameters calculated on the surface D-AR-min > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

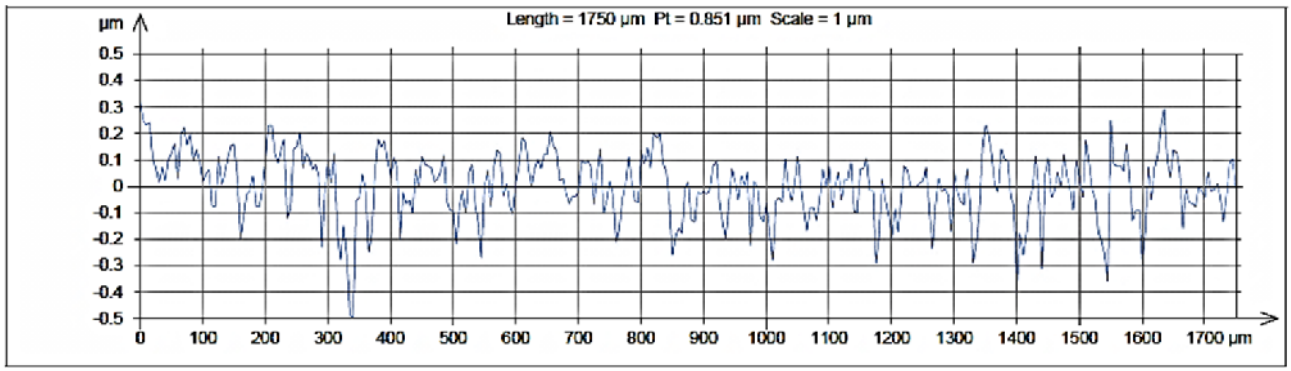
Amplitude Parameters

Sa	= 0.0929 µm
Sq	= 0.12 µm
Sp	= 1.01 µm
Sv	= 1.07 µm
St	= 2.08 µm
Ssk	= -0.0172
Sku	= 4.18
Sz	= 2.08 µm



Profiles in the circumferential direction

Profile outside the contact zone:



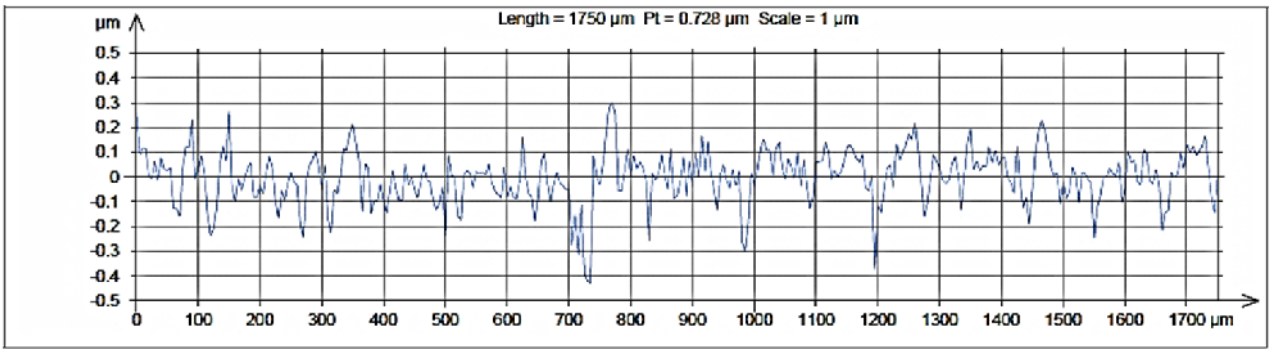
Parameters calculated on the profile D-AR-min
Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.079 µm
Rq	=	0.0974 µm
Rz	=	0.441 µm
Rt	=	0.641 µm
Rp	=	0.184 µm
Rv	=	0.257 µm
Rsk	=	-0.678
Rku	=	4.39

Profile in the area of effect of board (Red Zone)



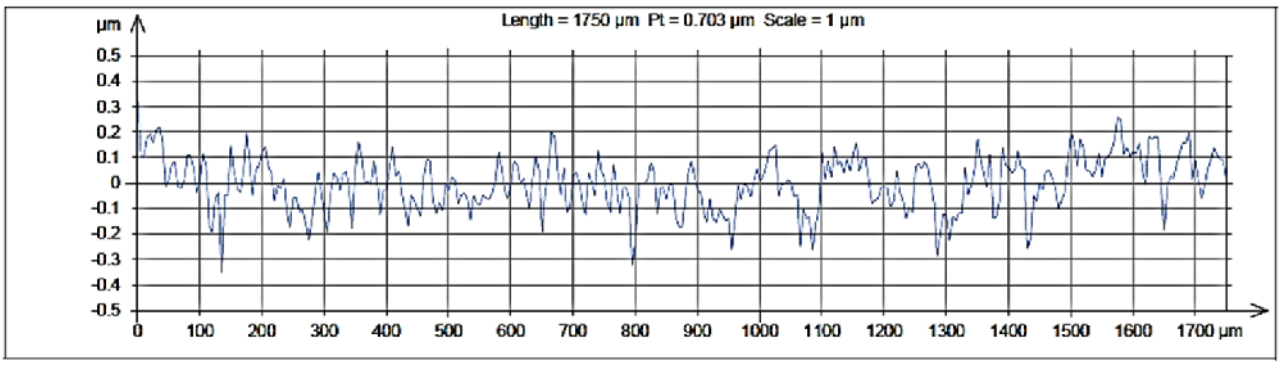
Parameters calculated on the profile D-AR-min
Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0693 µm
Rq	=	0.0925 µm
Rz	=	0.474 µm
Rt	=	0.662 µm
Rp	=	0.194 µm
Rv	=	0.28 µm
Rsk	=	-0.657
Rku	=	5.59

Profile in the contact zone (Blue Zone)



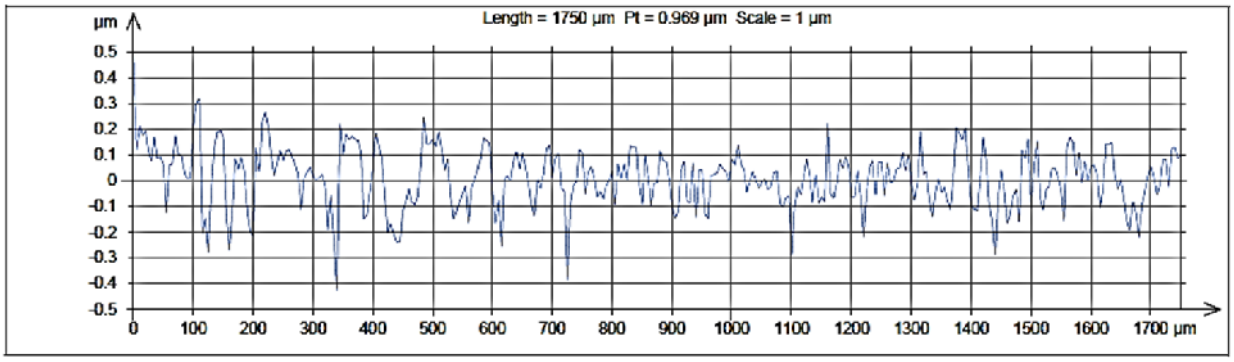
Parameters calculated on the profile D-AR-min
Extracted profile

* Parameters calculated as average value of all sampling lengths
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0647 µm
Rq	=	0.0801 µm
Rz	=	0.374 µm
Rt	=	0.429 µm
Rp	=	0.162 µm
Rv	=	0.212 µm
Rsk	=	-0.342
Rku	=	3.19

Profile in the outer zone (Green zone)



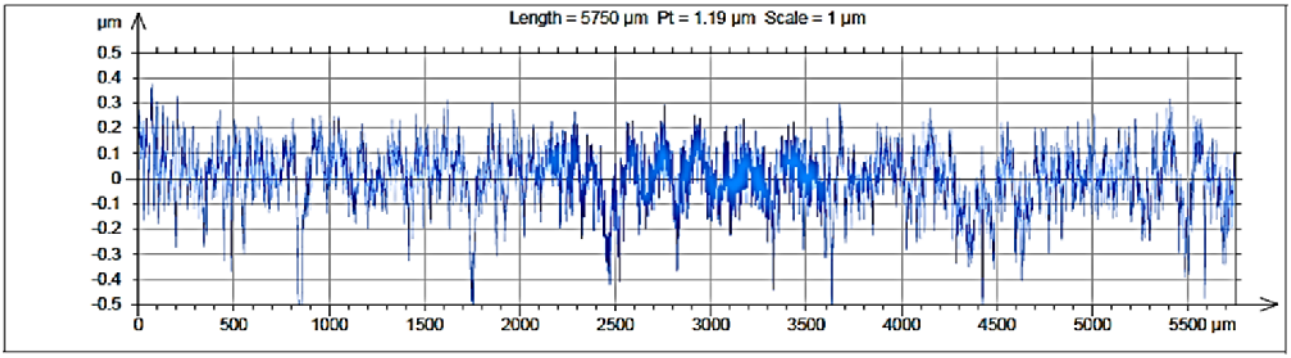
Parameters calculated on the profile D-AR-min :
Roughness, Gaussian Filter, 250 µm

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0748 µm
Rq	=	0.0937 µm
Rz	=	0.413 µm
Rt	=	0.528 µm
Rp	=	0.169 µm
Rv	=	0.244 µm
Rsk	=	-0.459
Rku	=	3.81

Profiles in the radial direction

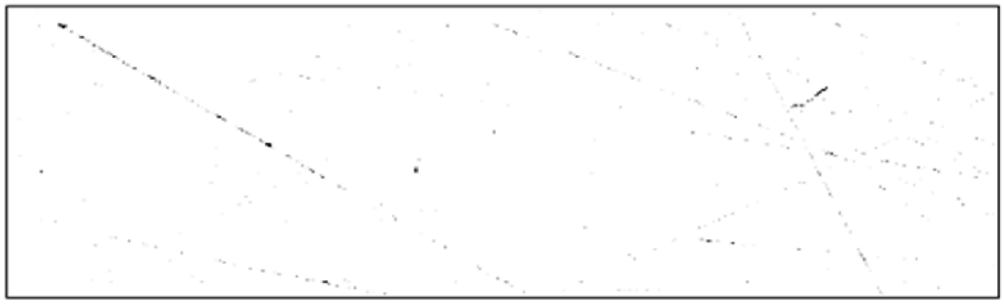


Parameters calculated on the profile D-AR-min

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.0752 µm
Rq	= 0.0974 µm
Rz	= 0.544 µm
Rt	= 1 µm
Rp	= 0.237 µm
Rv	= 0.307 µm
Rsk	= -0.976
Rku	= 6.84



	■	□
Area (%)	0.092	99.9
Volume of void (%)	0.012	66
Volume of material (%)	100	34
Volume of void (µm³/µm2)	6.79e-005	0.997
Volume of material (µm³/µm2)	0.567	0.513
Mean thickness of void (µm)	6.79e-005	0.997
Mean thickness of material (µm)	0.567	0.513

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (50h)	**Brand Oil**	Repsol
Bearing :	Thrust roller bearings (20 rolls)	**Base Oil**	PAO
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Super Tauro Synthetic 320

Reference Bearing-initiation	
weighings	**Average**
77,051	77,049
77,048	
77,048	
Reference Bearing-close	
weighings	**Average**
77,050	77,049
77,049	
77,048	

Cage-initiation	
weighings	**Average**
17,736	17,736
17,736	
17,736	
Cage-end	
weighings	**Average**
17,696	17,697
17,698	
17,697	

Runway up-initiation	
weighings	**Average**
29,697	29,697
29,697	
29,697	
Runway up-end	
weighings	**Average**
29,698	29,698
29,697	
29,698	

Runway lower-initiation	
weighings	**Average**
26,378	26,378
26,379	
26,378	
Runway lower-end	
weighings	**Average**
26,379	26,379
26,378	
26,379	

Bearing-initiation	
weighings	**Average**
73,810	73,810
73,810	
73,810	
Bearing-end	
weighings	**Average**
73,772	73,771
73,771	
73,771	

Date

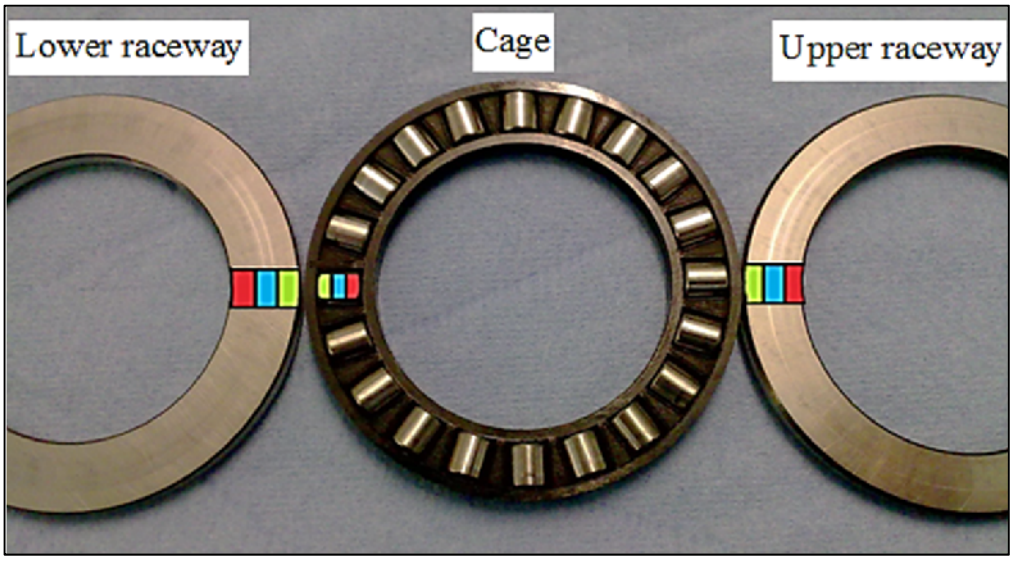
Initiation: **21-02-2011**

End: **23-02-2011**

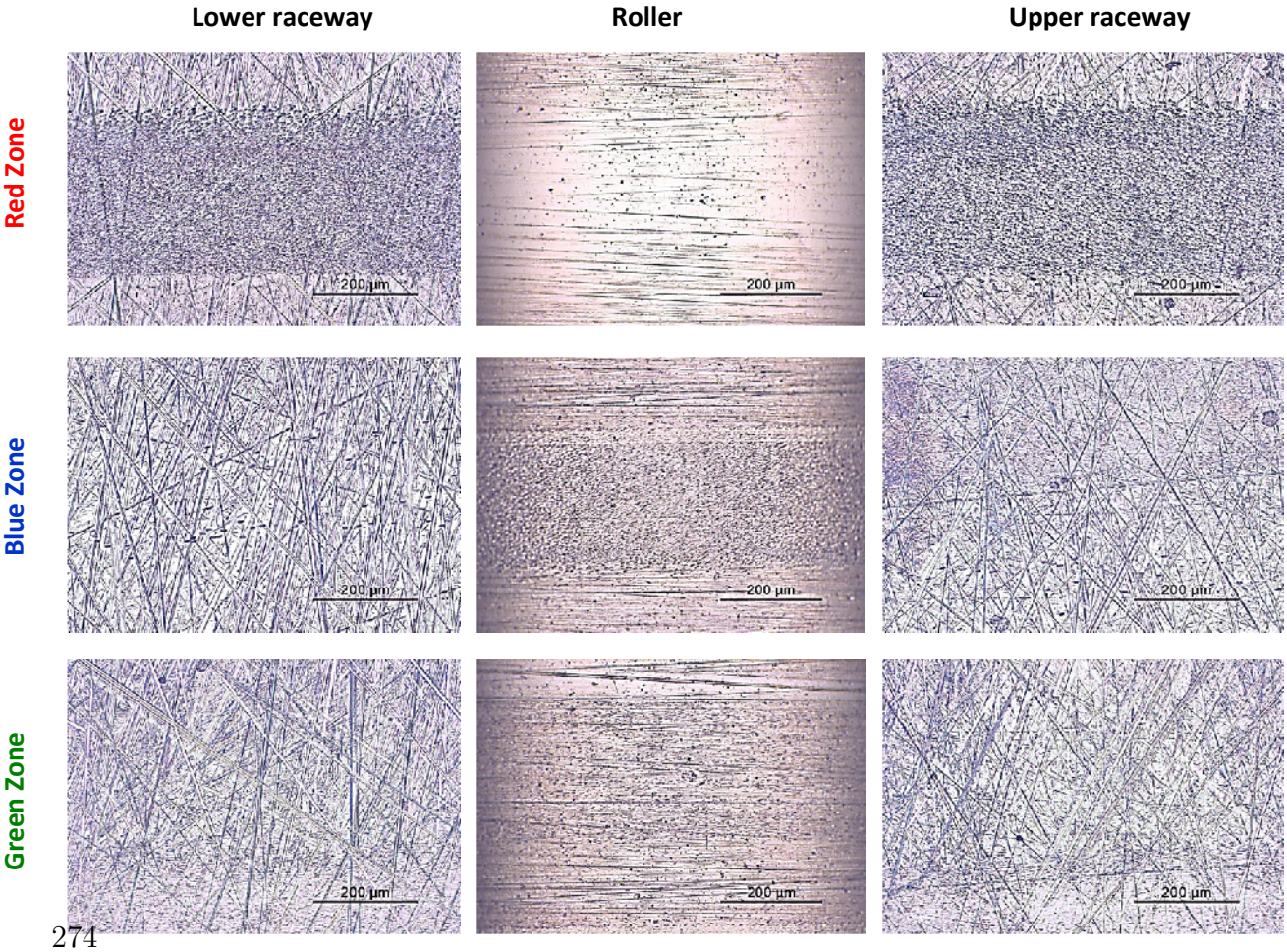
Mass loss	
39	mg

Identification of different contact zones

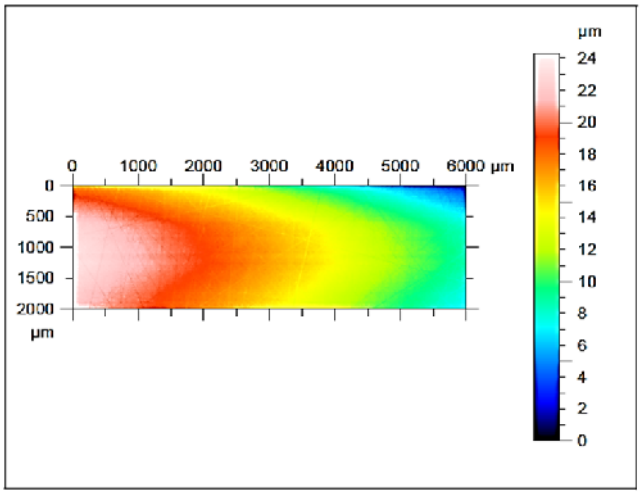
Scheme of the different contact zones analyzed

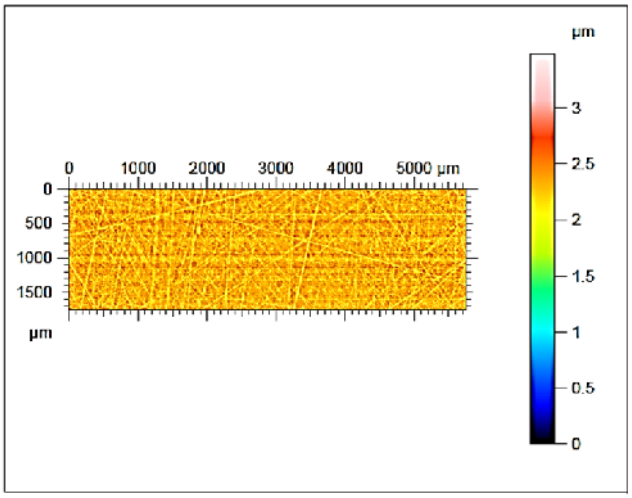


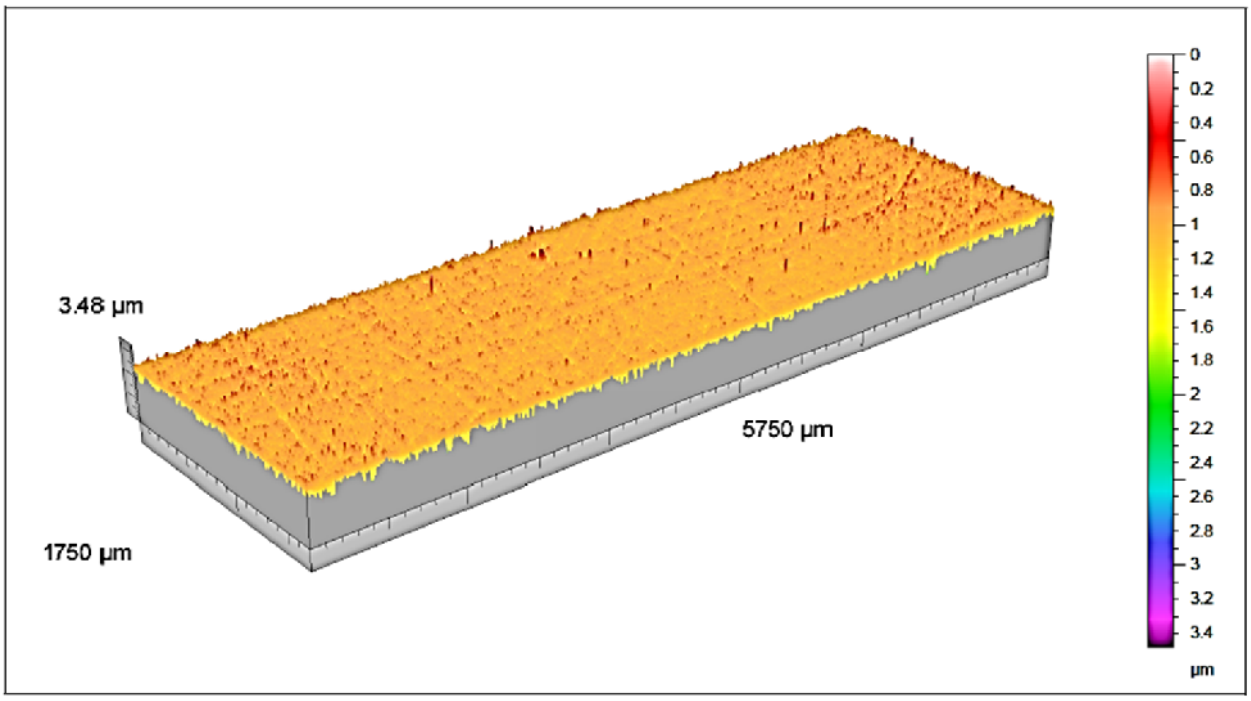
Brand Oil	Repsol
Base Oil	PAO
Oil Ref.	Super Tauro Synthetic 320

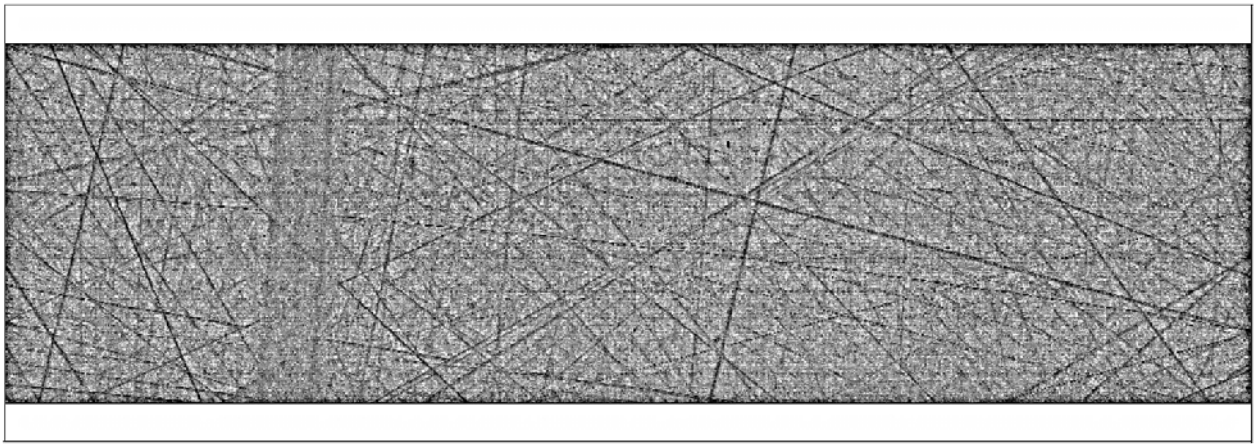


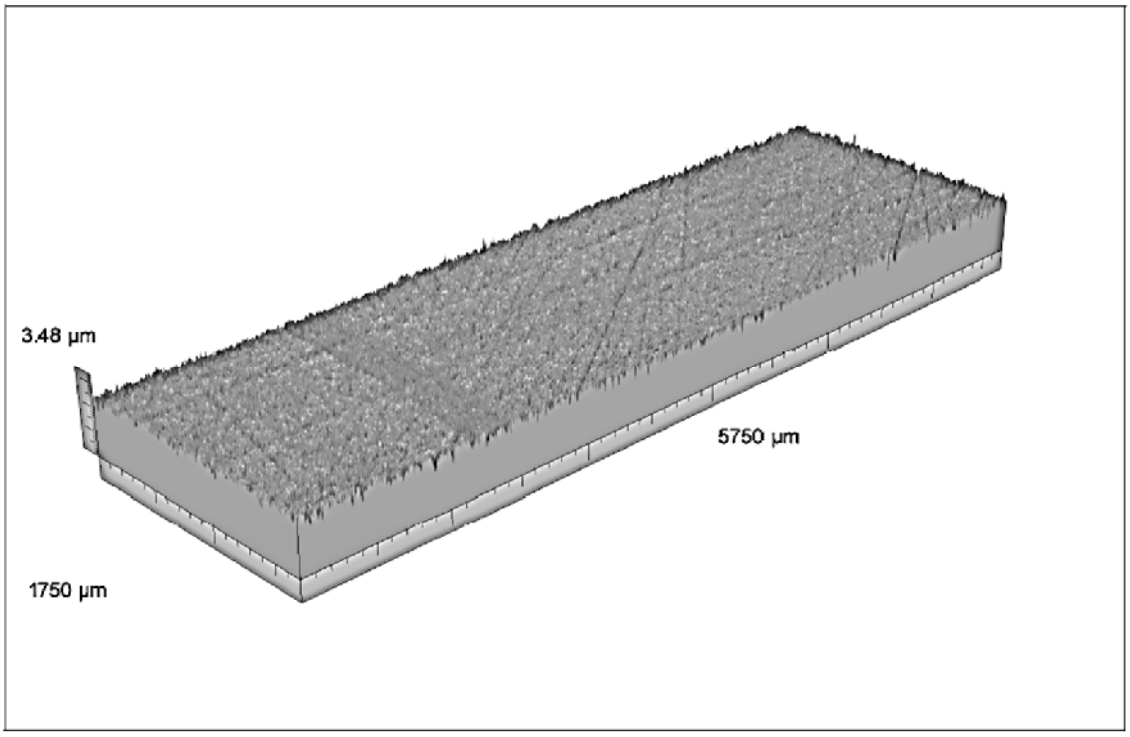
Topography, Gaussian Filter, 250 µm









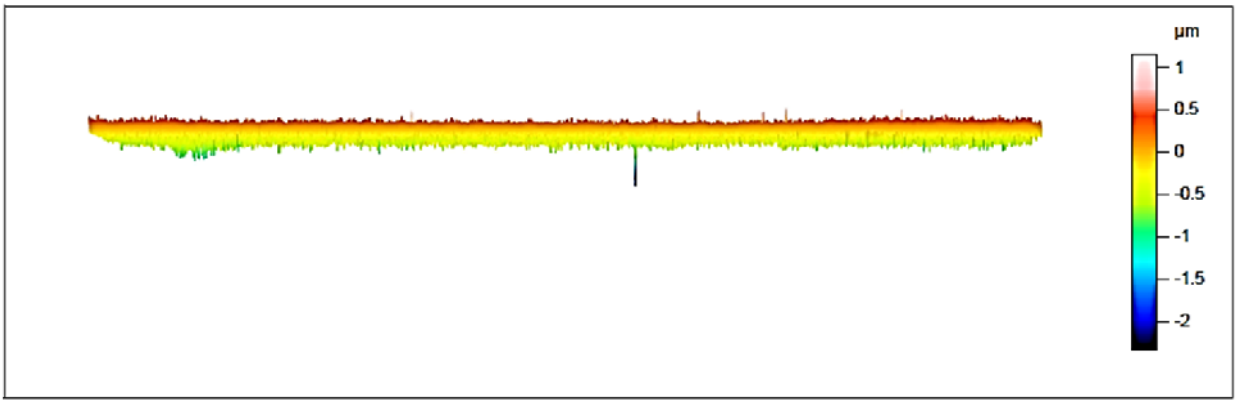


Parameters calculated on the surface D-AR-pao > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

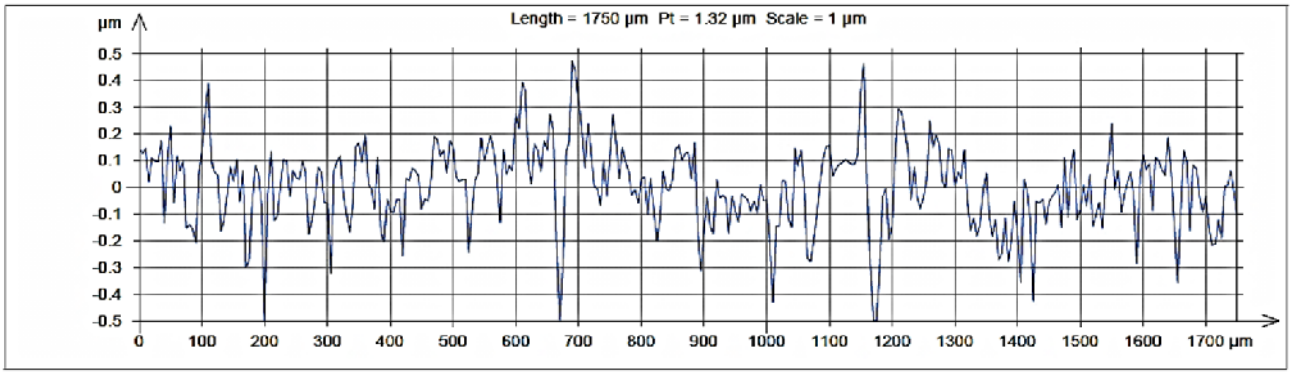
Amplitude Parameters

Sa	=	0.103 µm
Sq	=	0.132 µm
Sp	=	1.15 µm
Sv	=	2.33 µm
St	=	3.48 µm
Ssk	=	-0.37
Sku	=	4.34
Sz	=	3.48 µm



Profiles in the circumferential direction

Profile outside the contact zone:



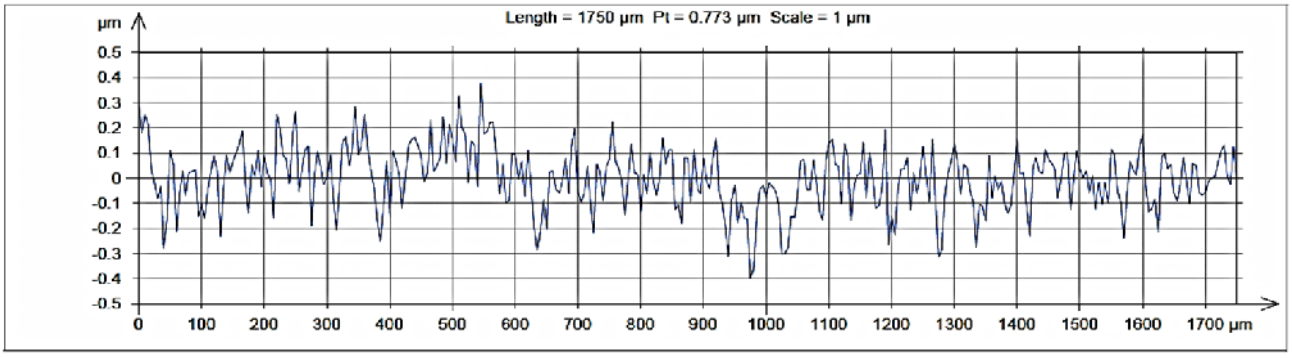
Parameters calculated on the profile D-AR-pao
Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0988 µm
Rq	=	0.137 µm
Rz	=	0.751 µm
Rt	=	1.18 µm
Rp	=	0.27 µm
Rv	=	0.481 µm
Rsk	=	-1.6
Rku	=	10.3

Profile in the area of effect of board (Red Zone)



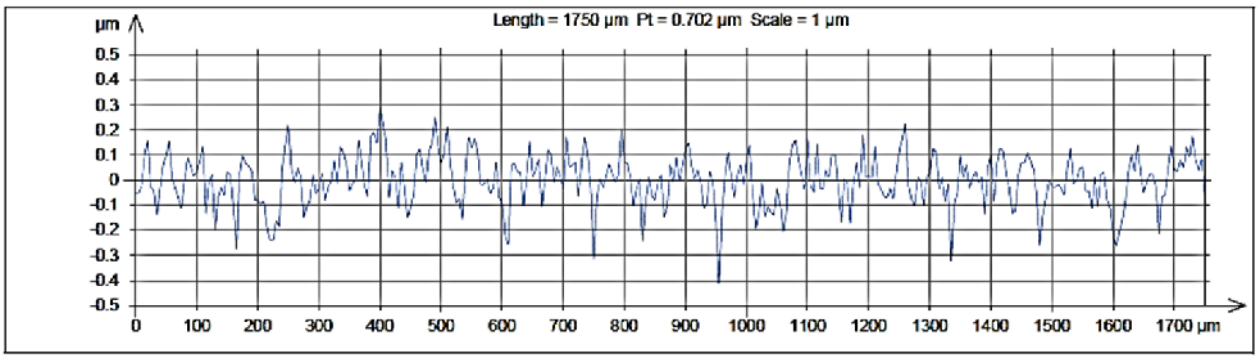
Parameters calculated on the profile D-AR-pao
Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0771 µm
Rq	=	0.0968 µm
Rz	=	0.438 µm
Rt	=	0.471 µm
Rp	=	0.195 µm
Rv	=	0.243 µm
Rsk	=	-0.399
Rku	=	2.92

Profile in the contact zone (Blue Zone)



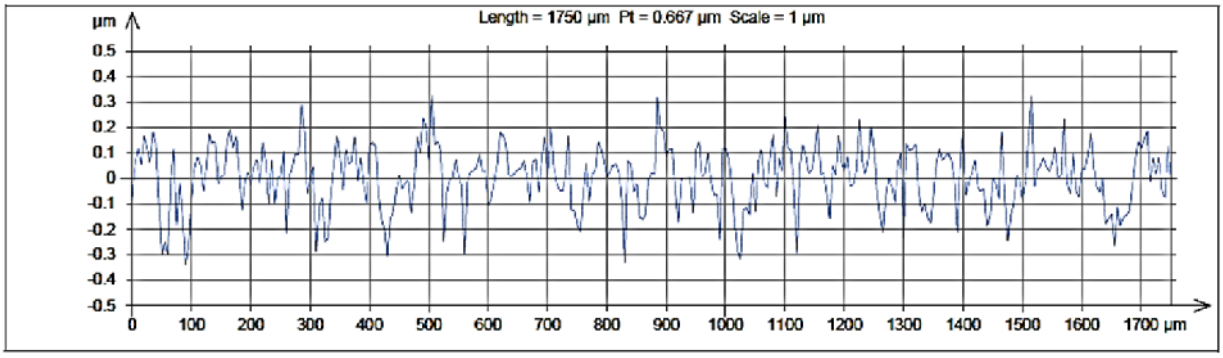
Parameters calculated on the profile D-AR-pao
Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0702 µm
Rq	=	0.0905 µm
Rz	=	0.47 µm
Rt	=	0.59 µm
Rp	=	0.201 µm
Rv	=	0.269 µm
Rsk	=	-0.408
Rku	=	3.94

Profile in the outer zone (Green zone)



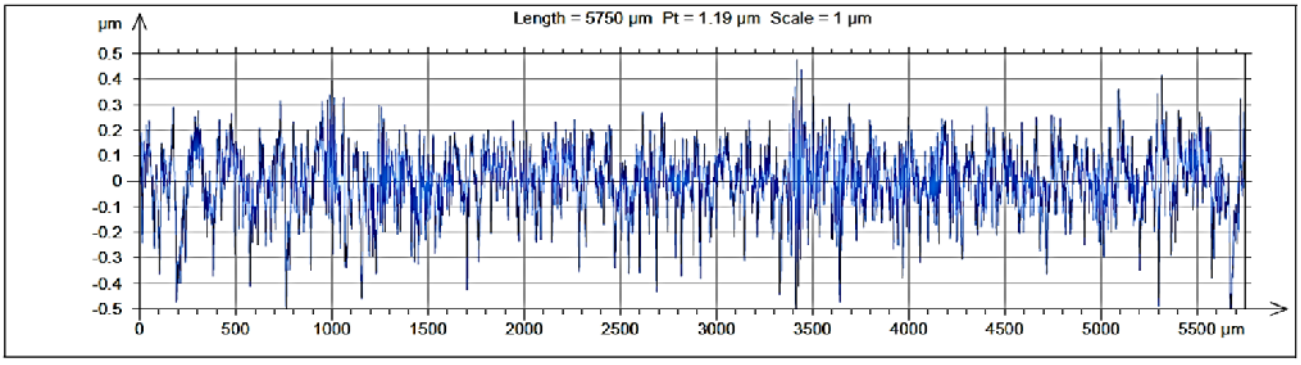
Parameters calculated on the profile D-AR-pao > ... > Roughness, Gaussian Filter, 250 µm

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0802 µm
Rq	=	0.101 µm
Rz	=	0.452 µm
Rt	=	0.561 µm
Rp	=	0.21 µm
Rv	=	0.242 µm
Rsk	=	-0.301
Rku	=	2.95

Profiles in the radial direction

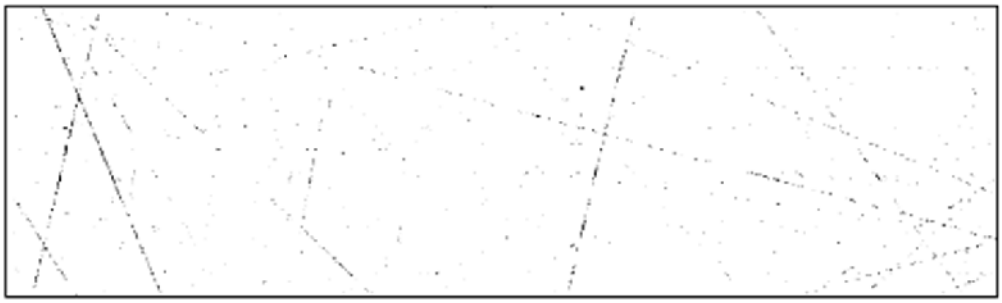


Parameters calculated on the profile D-AR-pao

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.0939 µm
Rq	= 0.119 µm
Rz	= 0.641 µm
Rt	= 1.13 µm
Rp	= 0.275 µm
Rv	= 0.366 µm
Rsk	= -0.494
Rku	= 4.2



	■	□
Area (%)	0.2	99.8
Volume of void (%)	0.0101	69.1
Volume of material (%)	100	30.9
Volume of void (µm³/µm2)	0.000185	1.14
Volume of material (µm³/µm2)	1.83	0.51
Mean thickness of void (µm)	0.000185	1.14
Mean thickness of material (µm)	1.83	0.51

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (50h)	**Brand Oil**	Fuchs
Bearing :	Thrust roller bearings (20 rolls)	**Base Oil**	Ester
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Gearmaster ECO 320

Reference Bearing-initiation	
weighings	**Average**
77,050	77,049
77,049	
77,049	
Reference Bearing-close	
weighings	**Average**
77,050	77,051
77,051	
77,051	

Cage-initiation	
weighings	**Average**
17,715	17,715
17,715	
17,714	
Cage-end	
weighings	**Average**
17,684	17,684
17,684	
17,685	

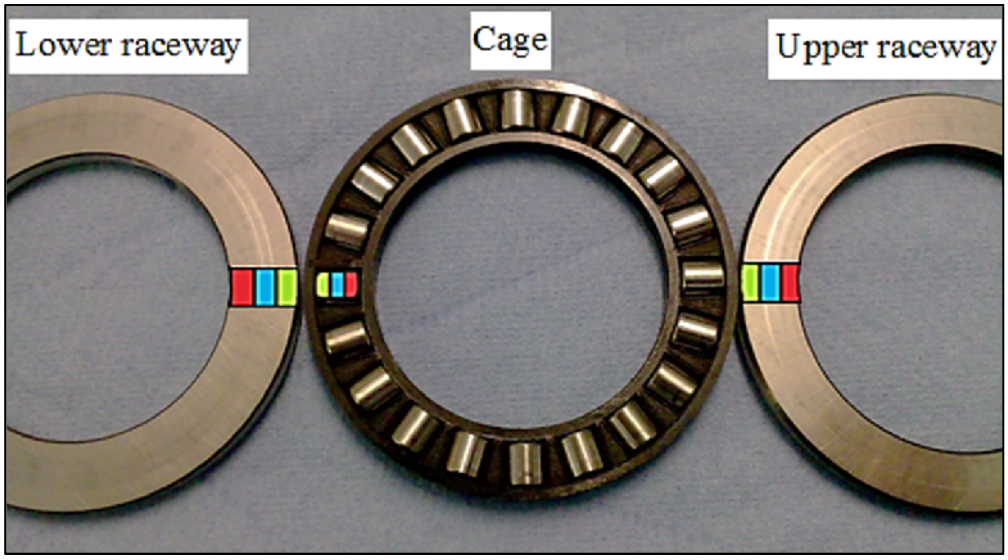
Bearing-initiation	
weighings	**Average**
73,754	73,754
73,754	
73,755	
Bearing-end	
weighings	**Average**
73,725	73,725
73,726	
73,724	

Date
Initiation: 23-02-2011
End: 26-02-2011

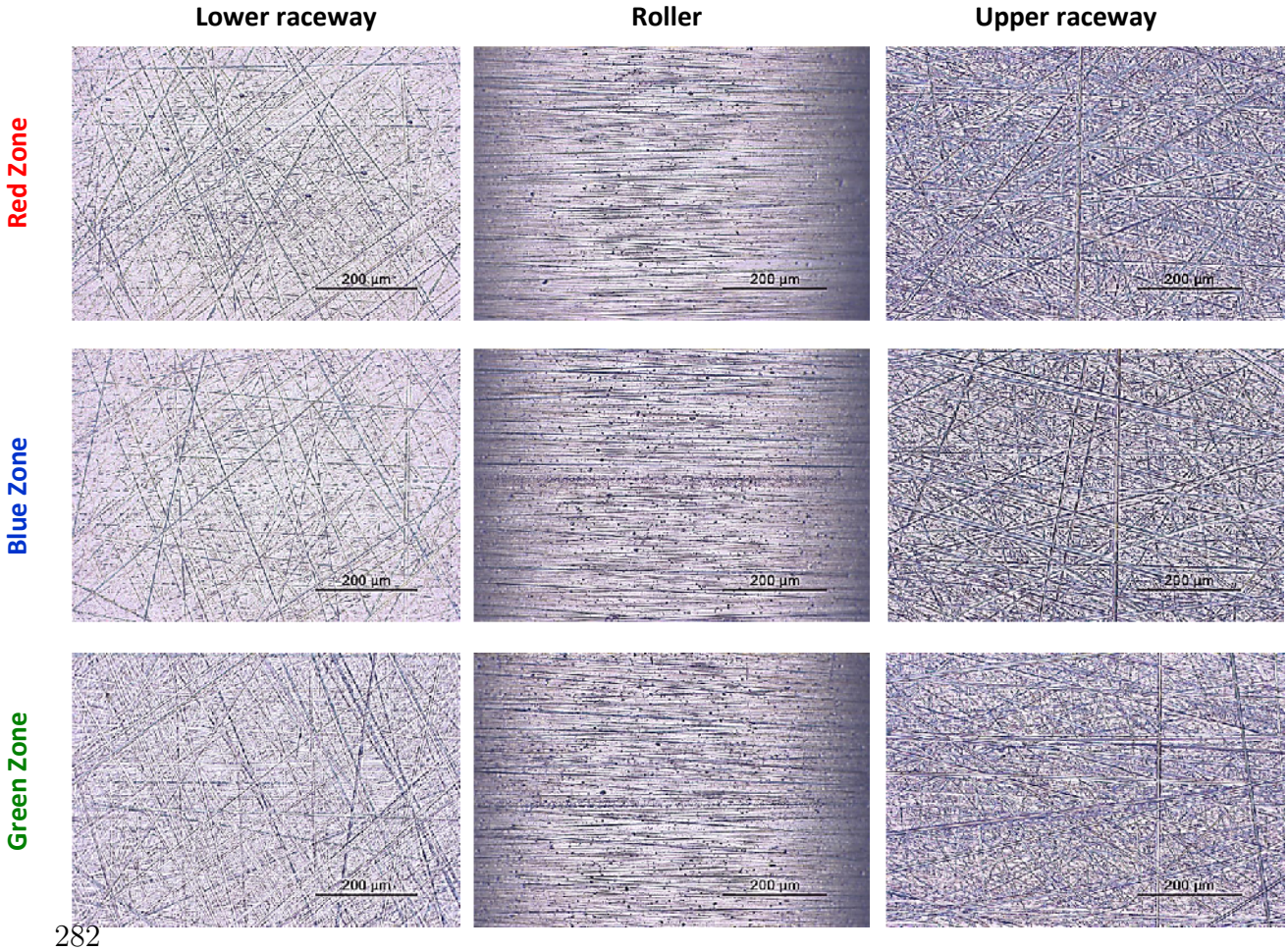
Mass loss	
31	mg

Identification of different contact zones

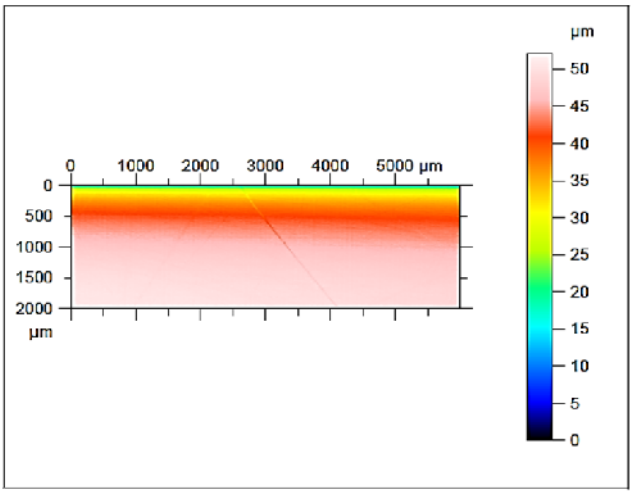
Scheme of the different contact zones analyzed

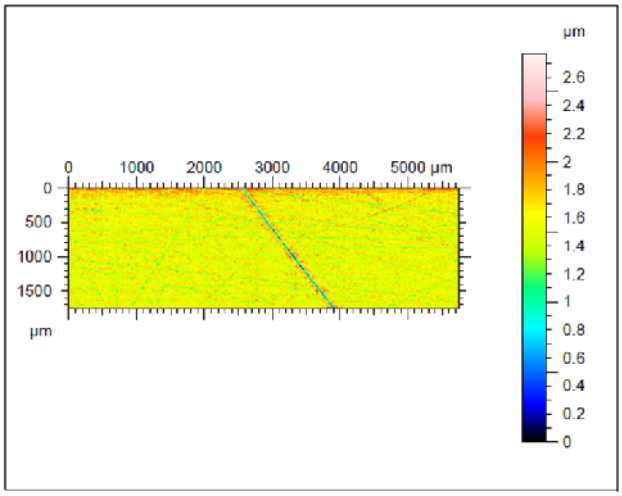


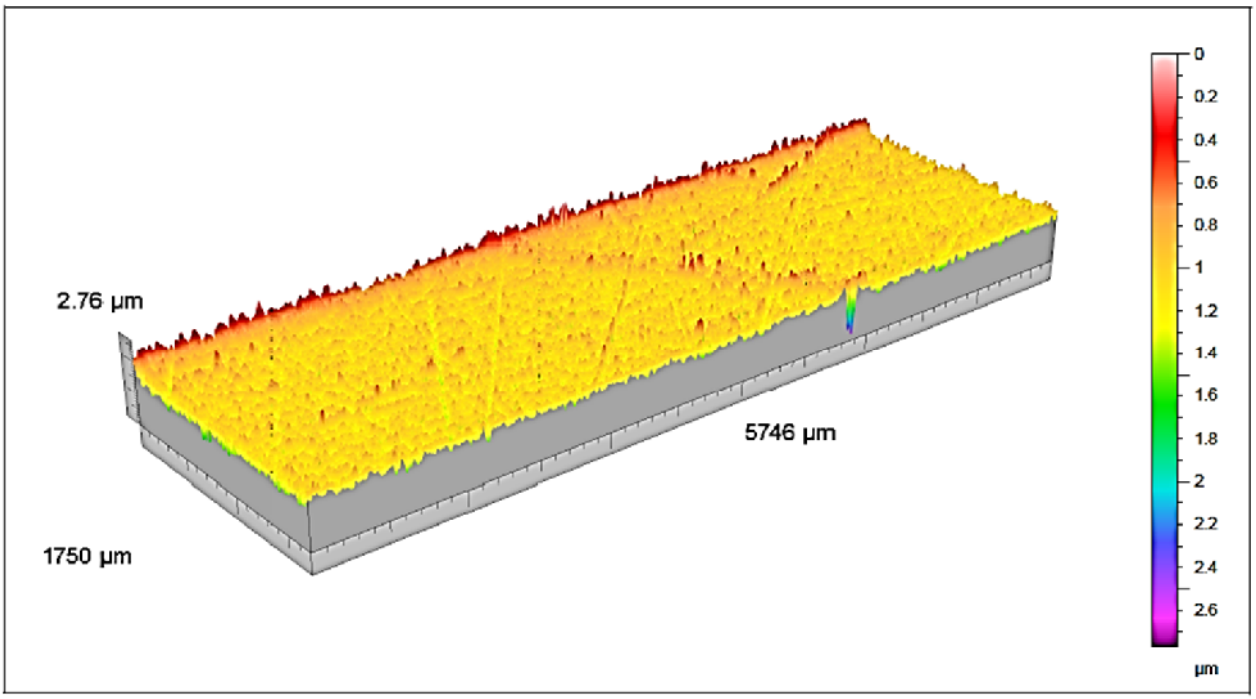
Brand Oil Fuchs
Base Oil Ester
Oil Ref. Gearmaster ECO 320

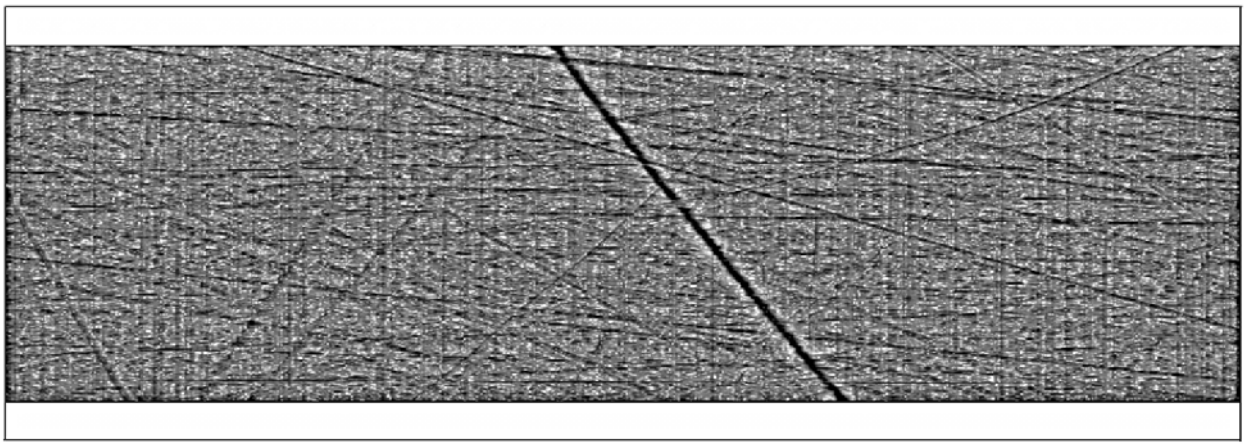


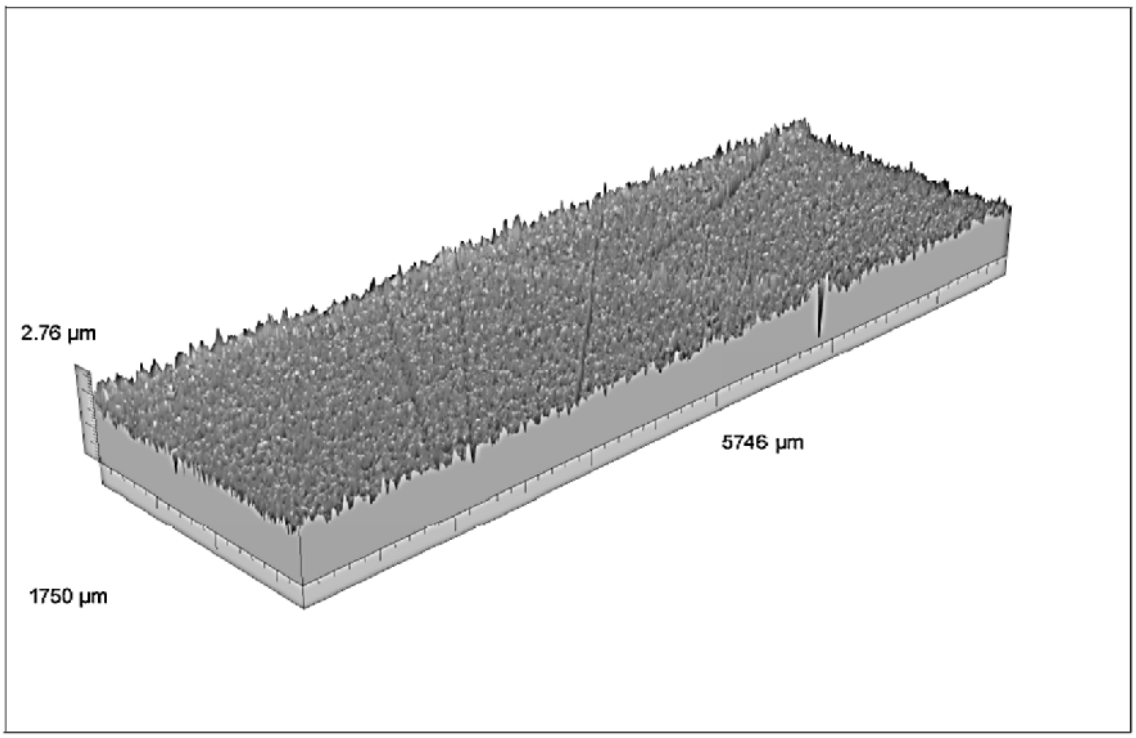
Topography, Gaussian Filter, 250 µm









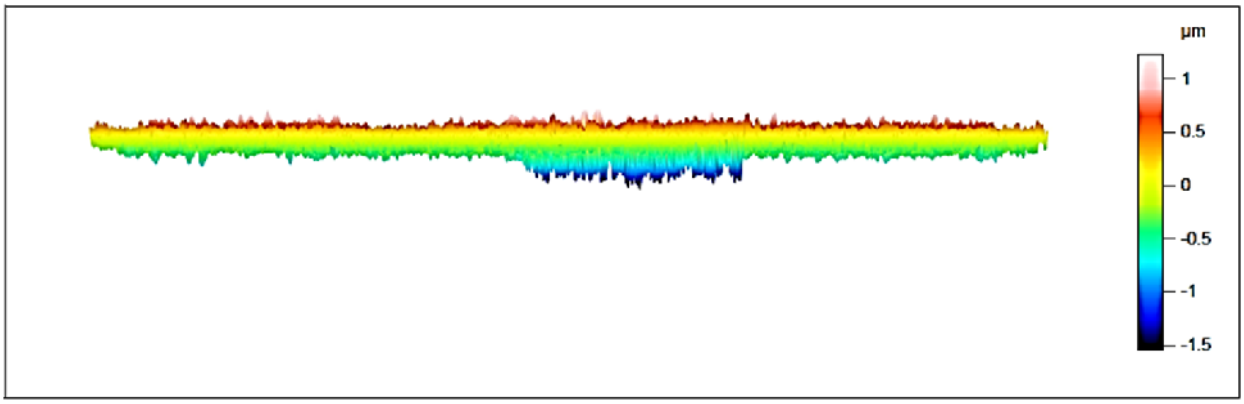


Parameters calculated on the surface D-AR-est > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

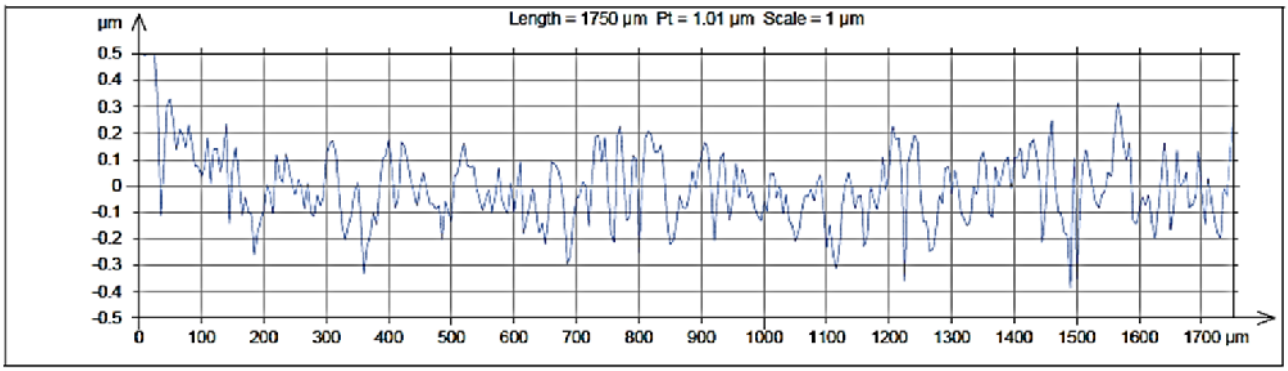
Amplitude Parameters

Sa	=	0.136 µm
Sq	=	0.187 µm
Sp	=	1.23 µm
Sv	=	1.54 µm
St	=	2.77 µm
Ssk	=	0.629
Sku	=	6.91
Sz	=	2.77 µm



Profiles in the circumferential direction

Profile outside the contact zone:



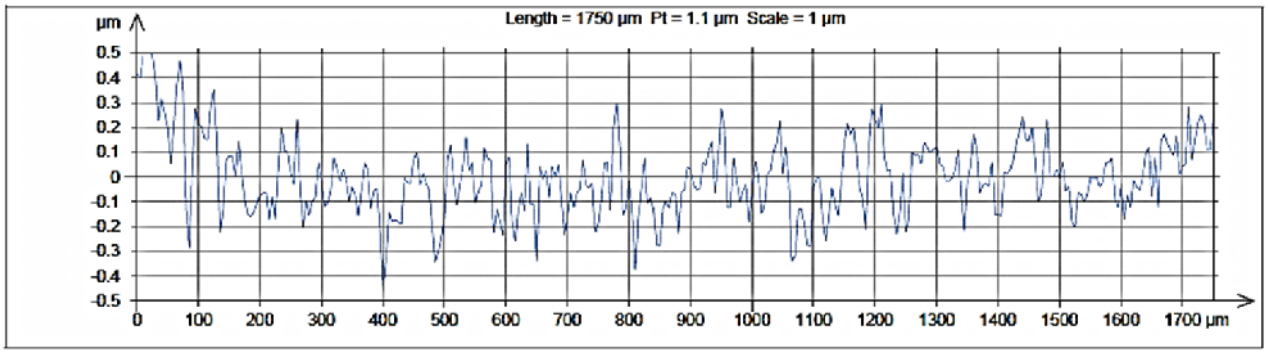
Parameters calculated on the profile D-AR-est
Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0807 µm
Rq	=	0.0994 µm
Rz	=	0.405 µm
Rt	=	0.627 µm
Rp	=	0.187 µm
Rv	=	0.218 µm
Rsk	=	-0.217
Rku	=	2.7

Profile in the area of effect of board (Red Zone)



Parameters calculated on the profile D-AR-est

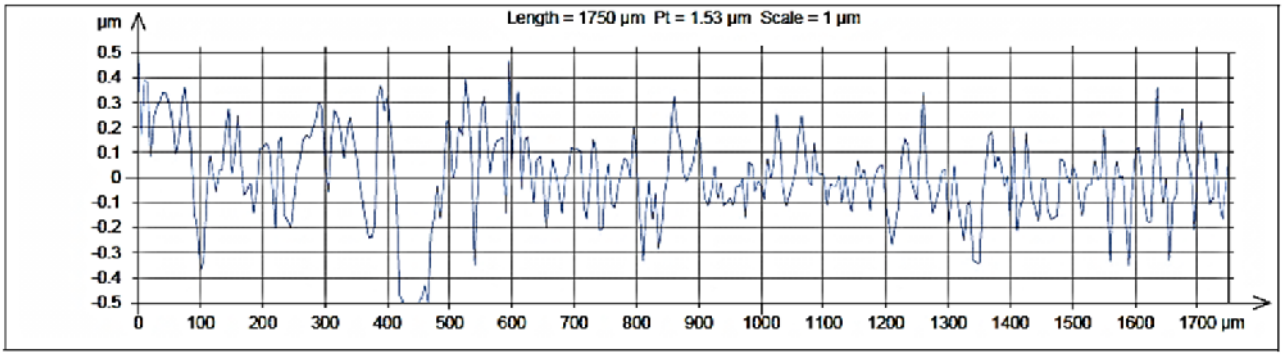
Extracted profile

```
* Parameters calculated as average value of all sampling lengths
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.0909 µm
   Rq     = 0.112 µm
   Rz     = 0.498 µm
   Rt     = 0.633 µm
   Rp     = 0.244 µm
   Rv     = 0.254 µm
   Rsk    = -0.118
   Rku    = 2.82
```

Profile in the contact zone (Blue Zone)



Parameters calculated on the profile D-AR-est

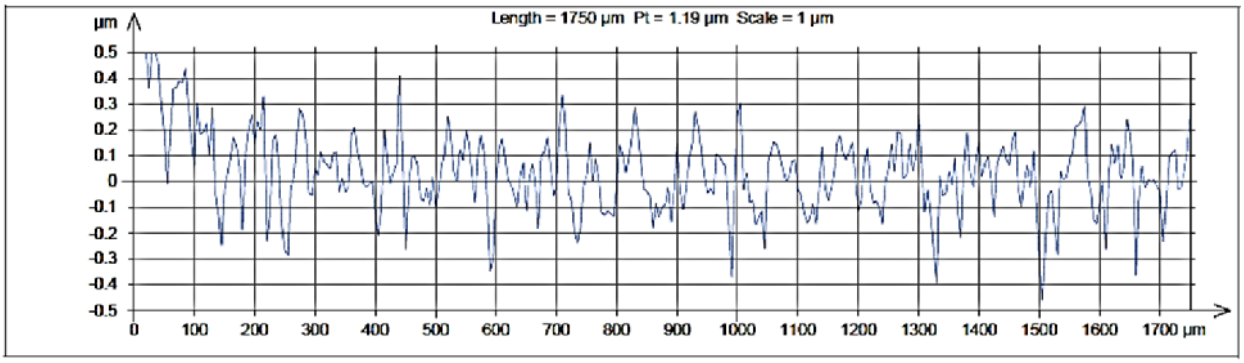
Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.113 µm
   Rq     = 0.143 µm
   Rz     = 0.624 µm
   Rt     = 1.2 µm
   Rp     = 0.303 µm
   Rv     = 0.322 µm
   Rsk    = -1.04
   Rku    = 9.76
```

Profile in the outer zone (Green zone)



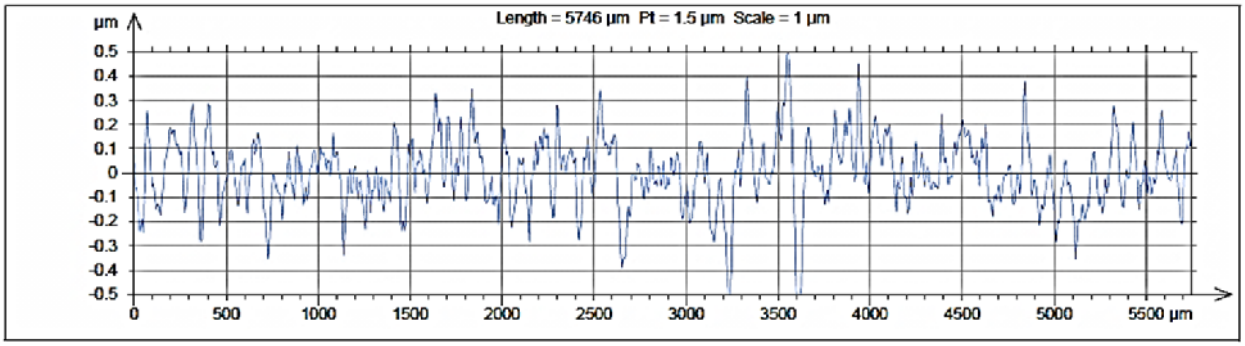
Parameters calculated on the profile D-AR-est > ... > Roughness, Gaussian Filter, 250 µm

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.0952 µm
   Rq     = 0.119 µm
   Rz     = 0.549 µm
   Rt     = 0.658 µm
   Rp     = 0.246 µm
   Rv     = 0.303 µm
   Rsk    = -0.376
   Rku    = 3.1
```

Profiles in the radial direction

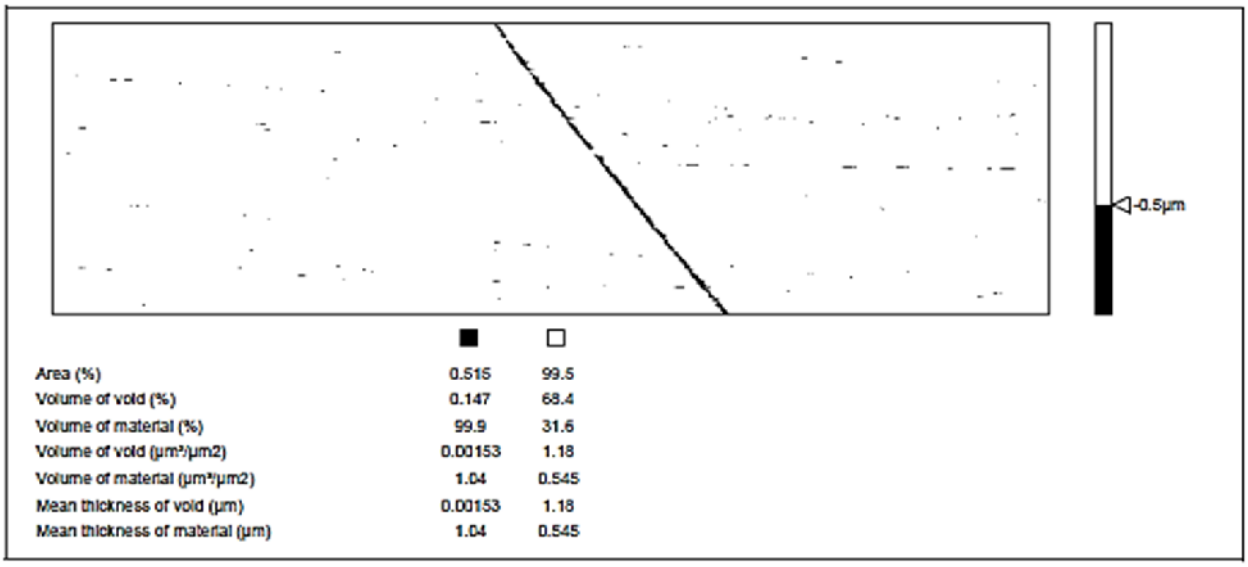


Parameters calculated on the profile D-AR-est

* Parameters calculated as average value of all sampling lengths
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0846 µm
Rq	=	0.106 µm
Rz	=	0.439 µm
Rt	=	1.22 µm
Rp	=	0.208 µm
Rv	=	0.231 µm
Rsk	=	-1.32
Rku	=	13.9



	■	□
Area (%)	0.515	99.5
Volume of void (%)	0.147	68.4
Volume of material (%)	99.9	31.6
Volume of void (µm³/µm2)	0.00153	1.18
Volume of material (µm³/µm2)	1.04	0.545
Mean thickness of void (µm)	0.00153	1.18
Mean thickness of material (µm)	1.04	0.545

A.12. Test data sheet for TRB 81107 TN with 10 rollers - first 50h (mass loss, photographs of the surfaces and topography)

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (10 rolls - 50h)	**Brand Oil**	Repsol
Bearing :	Thrust roller bearings (10 rolls)	**Base Oil**	Mineral
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Super Tauro FND 320

Reference Bearing-initiation	
weighings	**Average**
77,051	77,051
77,051	
77,051	
Reference Bearing-end	
weighings	**Average**
77,049	77,050
77,050	
77,050	

Cage-initiation	
weighings	**Average**
10,169	10,169
10,169	
10,168	
Cage-end	
weighings	**Average**
10,136	10,136
10,136	
10,136	

Bearing-initiation	
weighings	**Average**
66,534	66,534
66,534	
66,535	
Bearing-end	
weighings	**Average**
66,503	66,503
66,503	
66,503	

Date

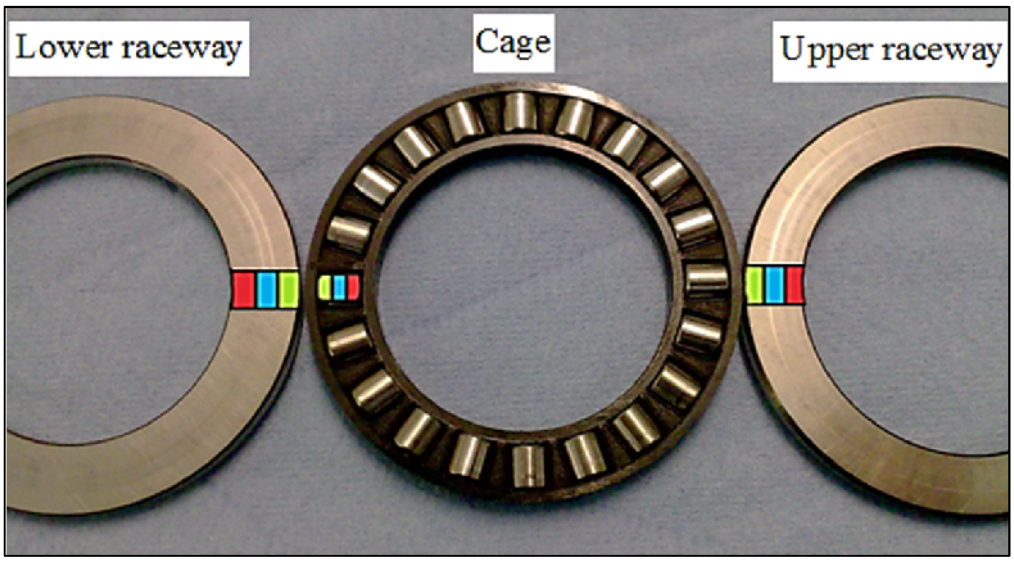
Initiation: **11-05-2011**

End: **13-05-2011**

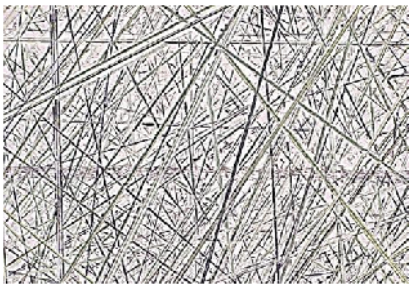
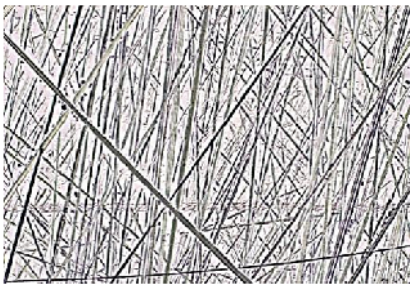
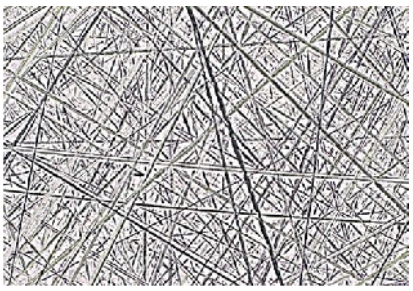
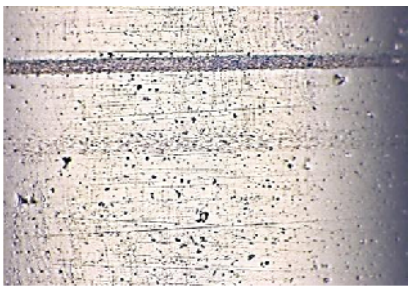
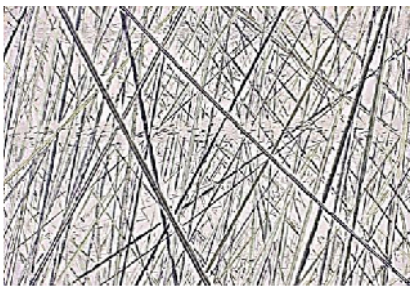
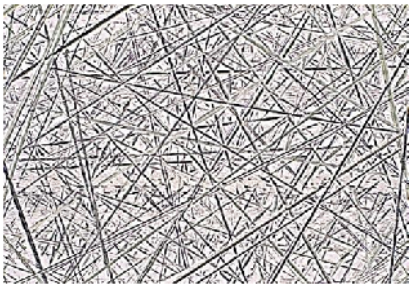
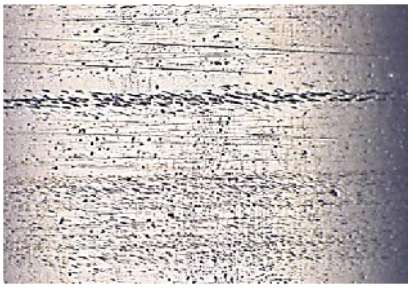
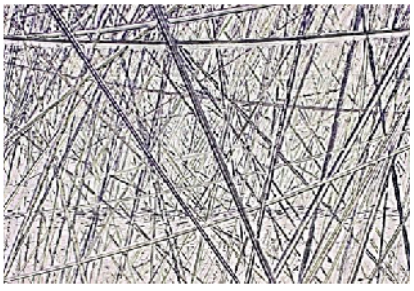
Mass loss	
30	mg

Identification of different contact zones

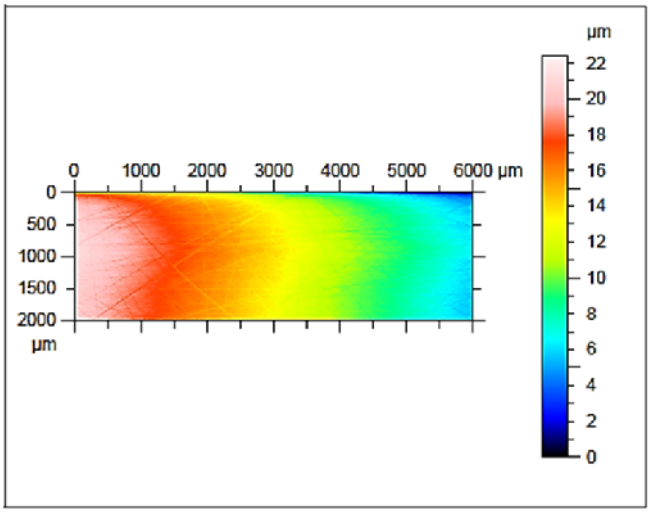
Scheme of the different contact zones analyzed

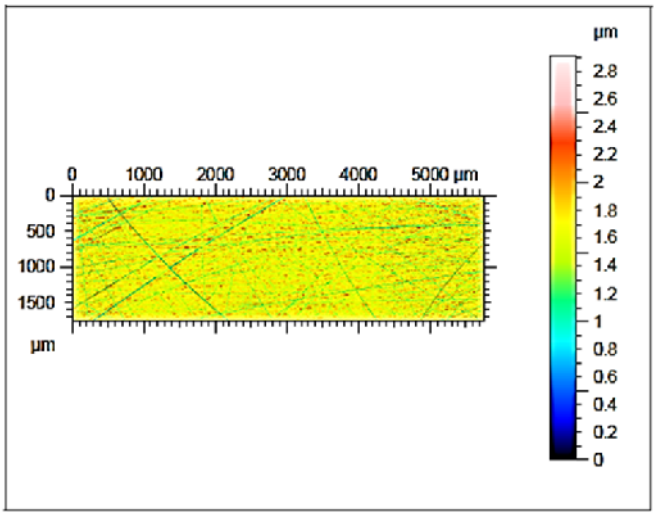


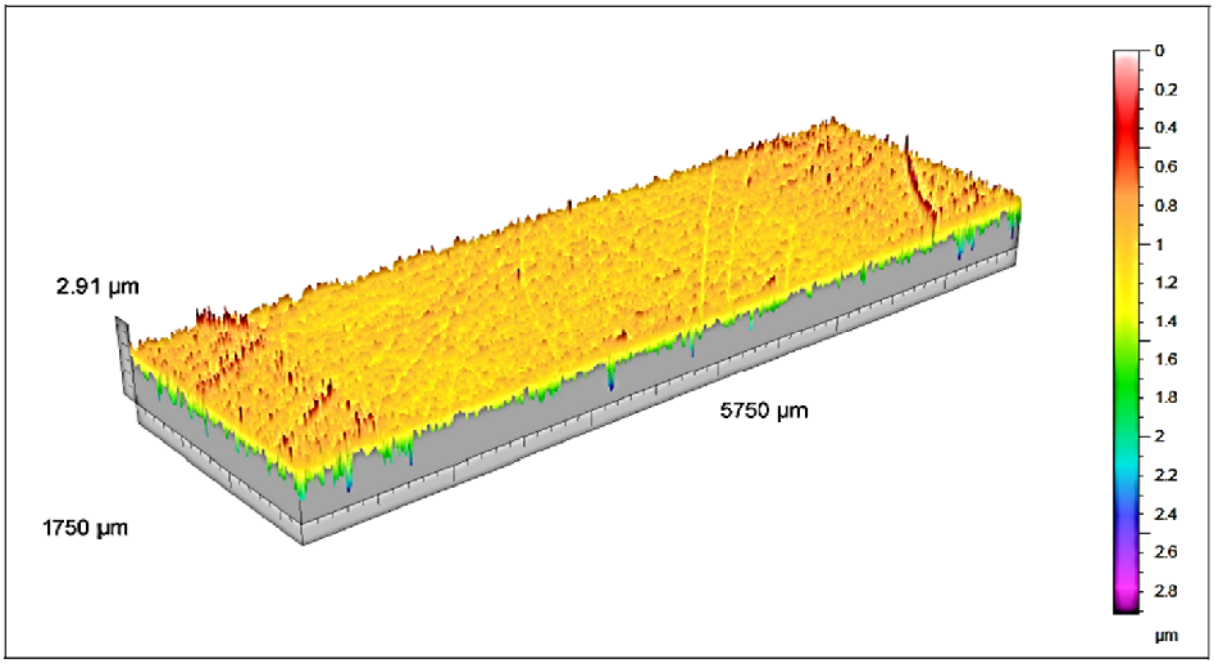
Brand Oil Repsol
Base Oil Mineral
Oil Ref. Super Tauro FND 320

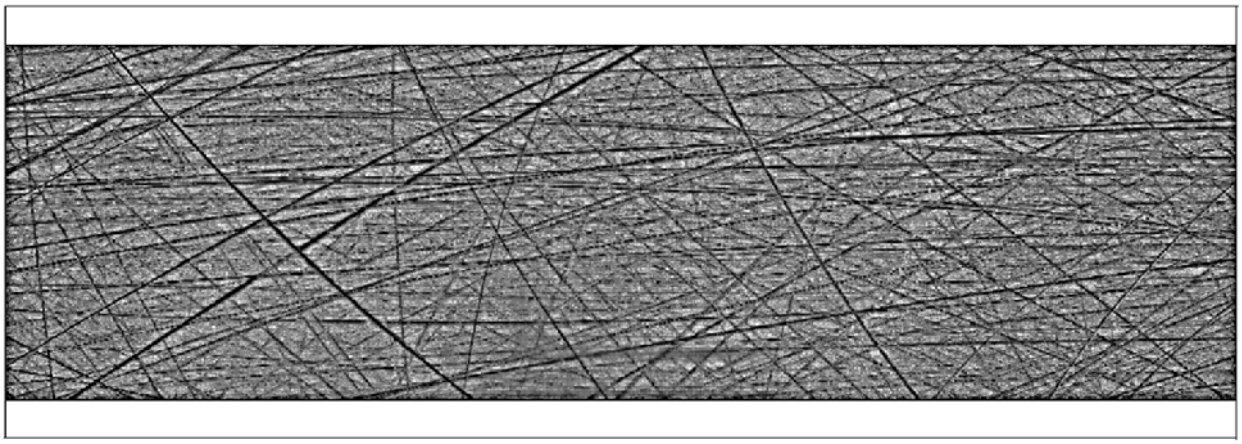
	Lower raceway	Roller	Upper raceway
Red Zone			
Blue Zone			
Green Zone			

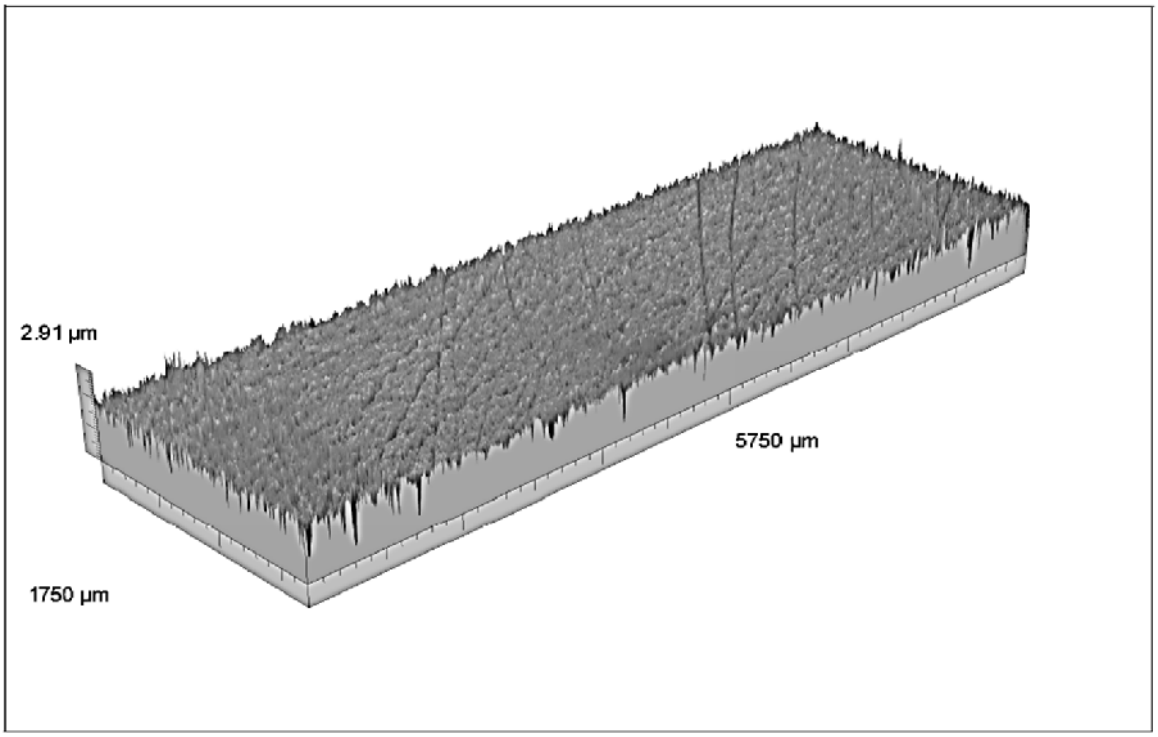
Topography, Gaussian Filter, 250 µm









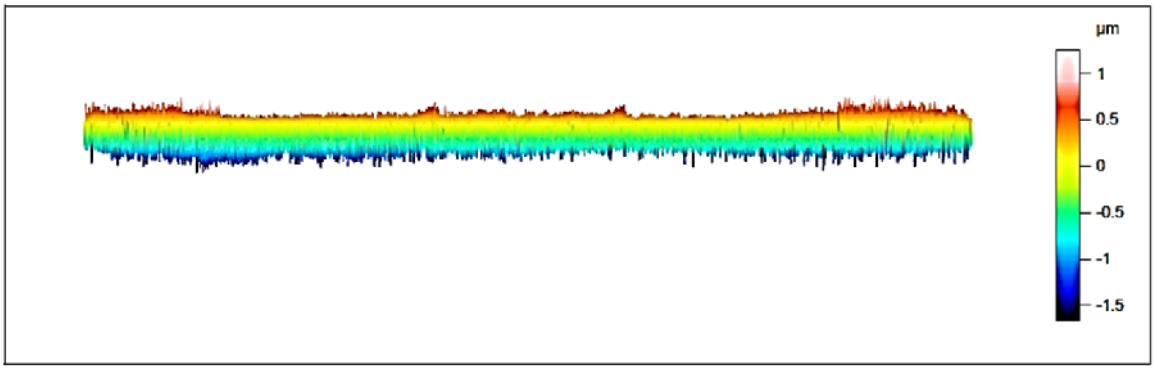


Parameters calculated on the surface AR_MIN320_10rolos_50h > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

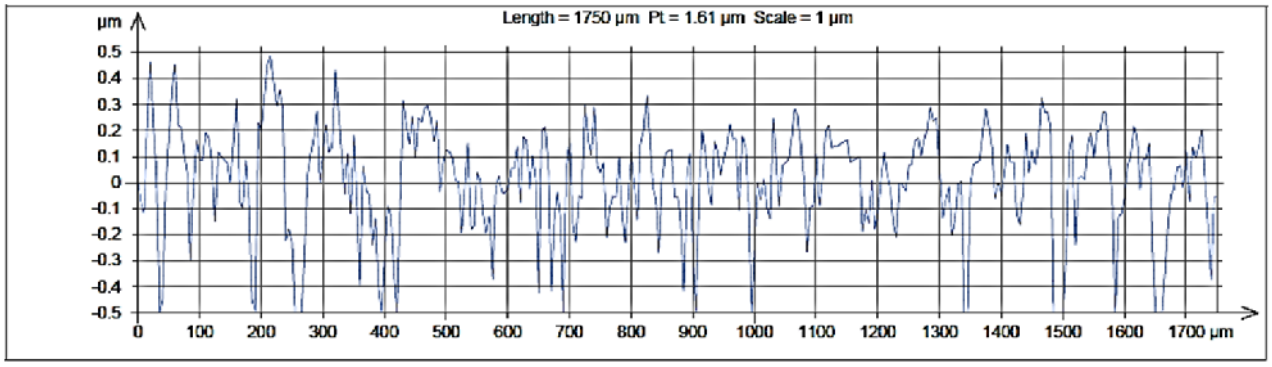
Amplitude Parameters

Sa	= 0.169 µm
Sq	= 0.223 µm
Sp	= 1.25 µm
Sv	= 1.66 µm
St	= 2.91 µm
Ssk	= -0.808
Sku	= 4.93
Sz	= 2.91 µm



Profiles in the circumferential direction

Profile outside the contact zone:



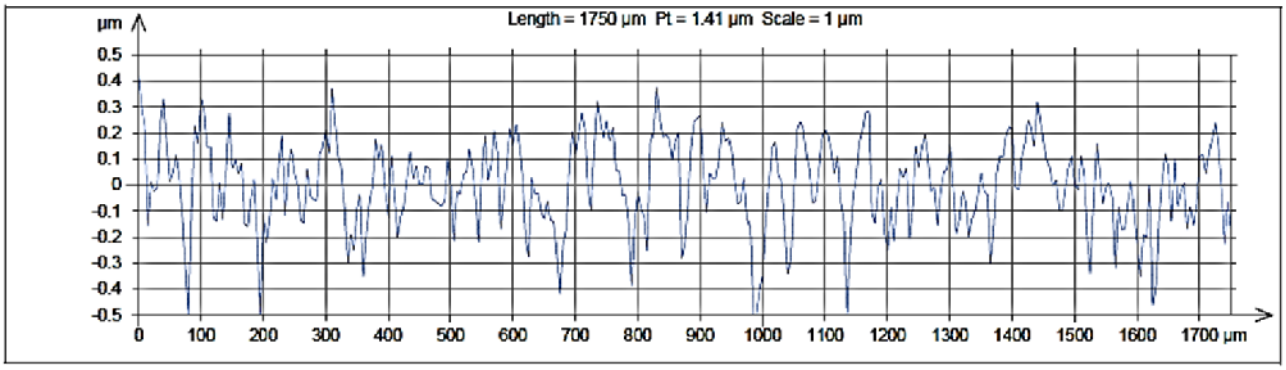
Parameters calculated on the profile AR_MIN320_10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.141 µm
Rq	= 0.185 µm
Rz	= 0.887 µm
Rt	= 1.5 µm
Rp	= 0.297 µm
Rv	= 0.59 µm
Rsk	= -1.39
Rku	= 7.91

Profile in the area of effect of board (Red Zone)



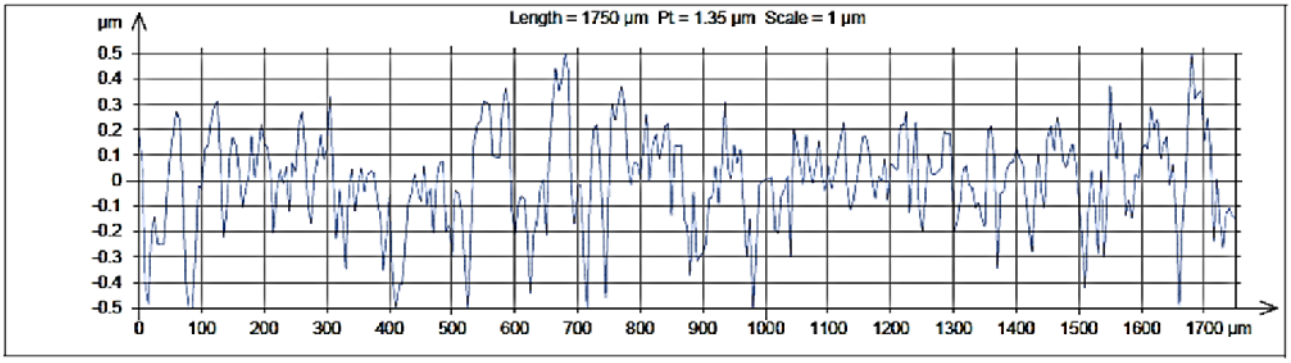
Parameters calculated on the profile AR_MIN320_10rolos_50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.121 µm
   Rq     = 0.152 µm
   Rz     = 0.707 µm
   Rt     = 1.15 µm
   Rp     = 0.262 µm
   Rv     = 0.445 µm
   Rsk    = -1.26
   Rku    = 6.98
```

Profile in the contact zone (Blue Zone)



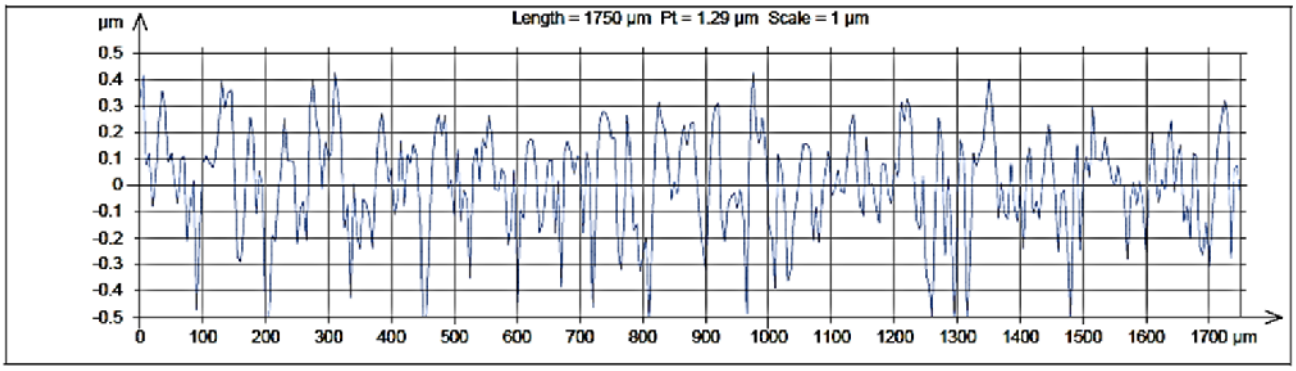
Parameters calculated on the profile AR_MIN320_10rolos_50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.125 µm
   Rq     = 0.157 µm
   Rz     = 0.762 µm
   Rt     = 1.07 µm
   Rp     = 0.327 µm
   Rv     = 0.435 µm
   Rsk    = -0.436
   Rku    = 4.45
```

Profile in the outer zone (Green zone)



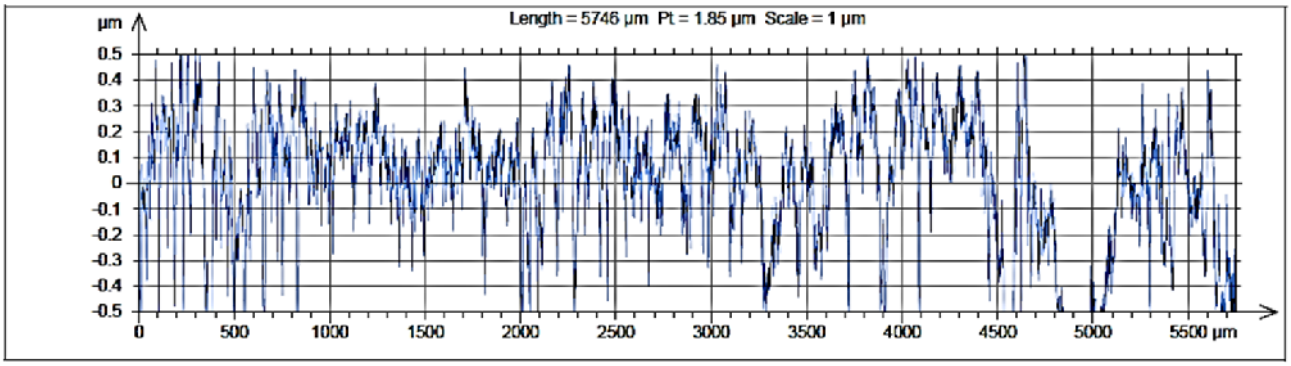
Parameters calculated on the profile AR_MIN320_10rolos_50h > ... > Roughness, Gaussian Filter, 250 µm

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.152 µm
Rq	=	0.19 µm
Rz	=	0.86 µm
Rt	=	1.07 µm
Rp	=	0.33 µm
Rv	=	0.53 µm
Rsk	=	-0.616
Rku	=	3.66

Profiles in the radial direction

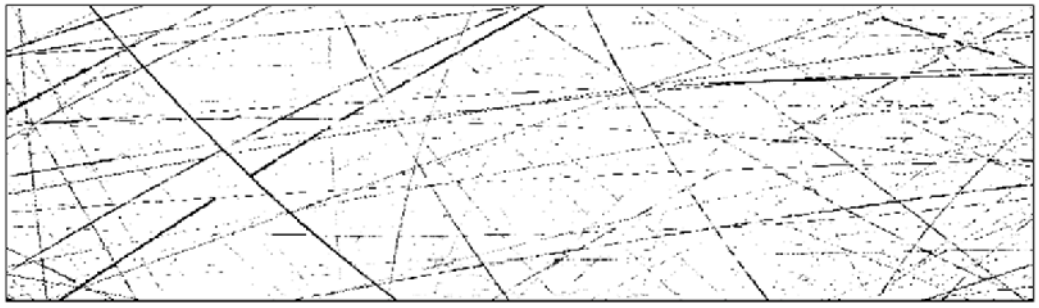


Parameters calculated on the profile AR_MIN320_10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.129 µm
Rq	= 0.168 µm
Rz	= 0.872 µm
Rt	= 1.95 µm
Rp	= 0.324 µm
Rv	= 0.549 µm
Rsk	= -1.5
Rku	= 10.1



	■	□
Area (%)	2.91	97.1
Volume of void (%)	0.429	70.7
Volume of material (%)	99.6	29.3
Volume of void (µm³/µm2)	0.00497	1.24
Volume of material (µm³/µm2)	1.15	0.513
Mean thickness of void (µm)	0.00497	1.24
Mean thickness of material (µm)	1.15	0.513

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (10 rolls - 50h)	**Brand Oil**	Repsol
Bearing :	Thrust roller bearings (10 rolls)	**Base Oil**	PAO
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Super Tauro Synthetic 320

Reference Bearing-initiation	
weighings	**Average**
77,051	77,050
77,049	
77,050	
Reference Bearing-close	
weighings	**Average**
77,050	77,050
77,050	
77,050	

Cage-initiation	
weighings	**Average**
10,200	10,200
10,200	
10,200	
Cage-end	
weighings	**Average**
10,164	10,164
10,164	
10,164	

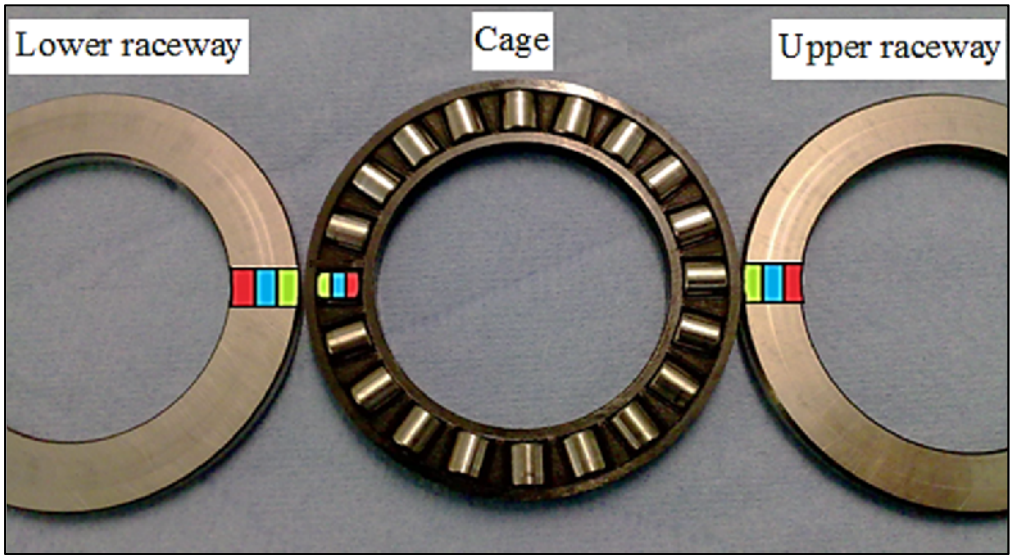
Bearing-initiation	
weighings	**Average**
66,484	66,484
66,484	
66,484	
Bearing-end	
weighings	**Average**
66,447	66,448
66,448	
66,448	

Date
Initiation: **16-05-2011**
End: **18-05-2011**

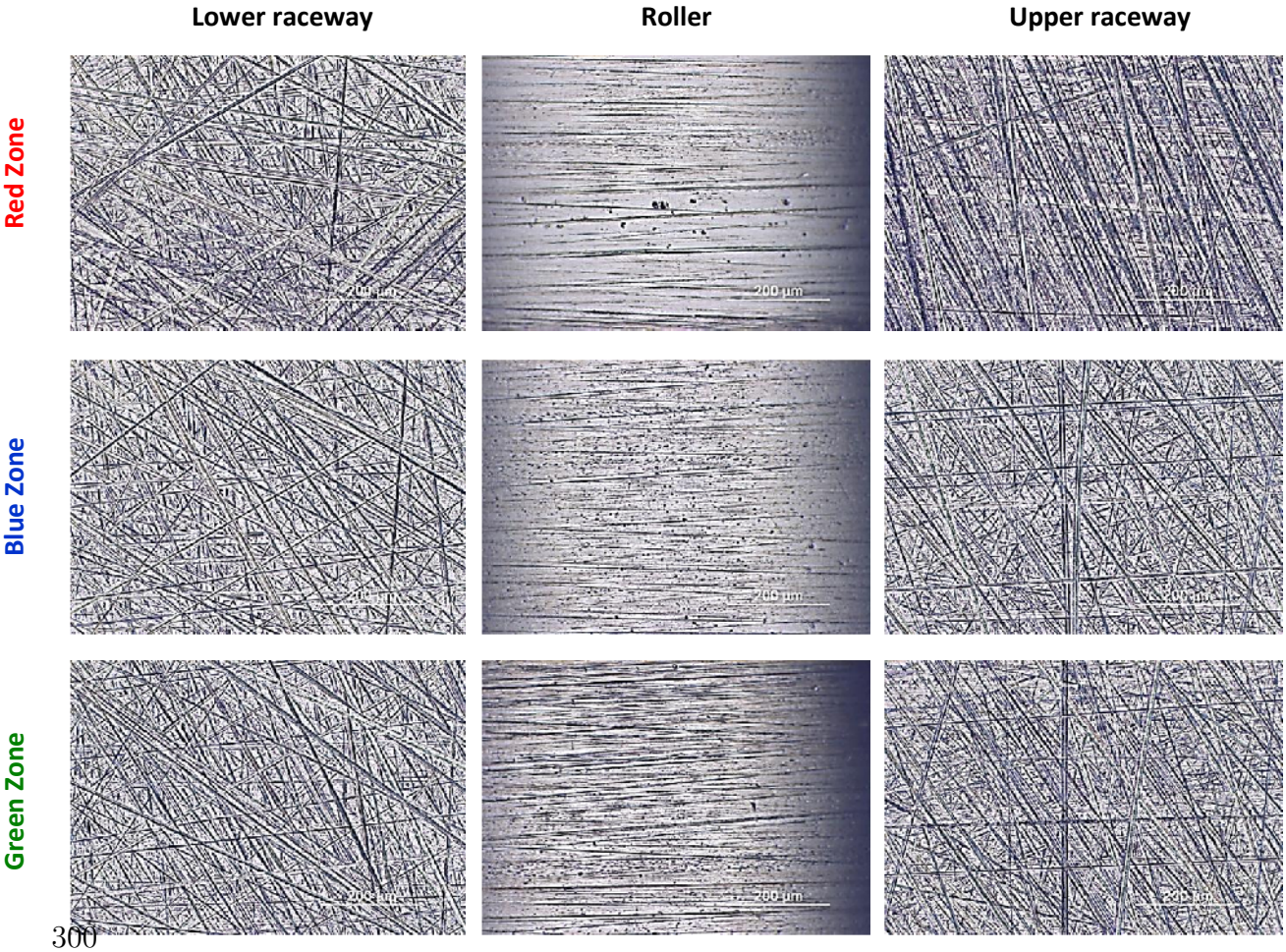
Mass loss	
36	mg

Identification of different contact zones

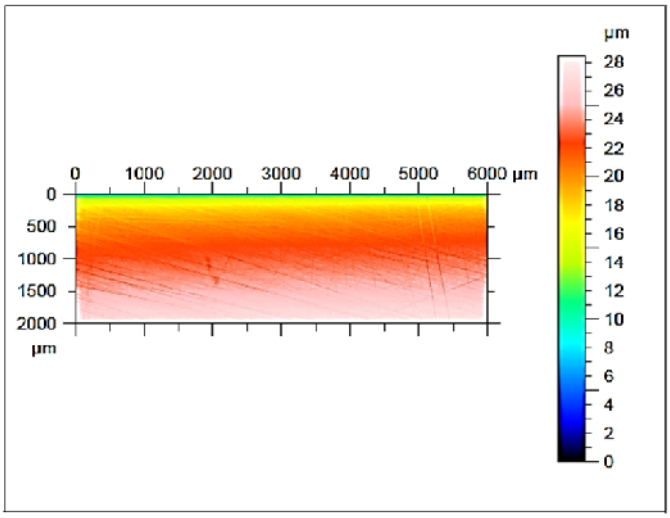
Scheme of the different contact zones analyzed

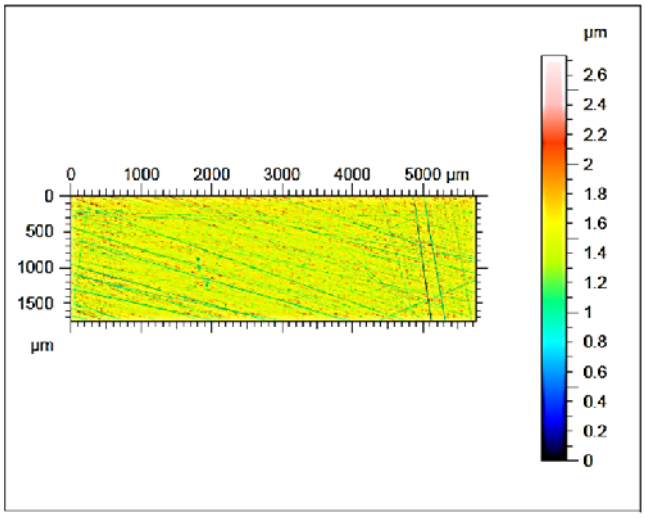


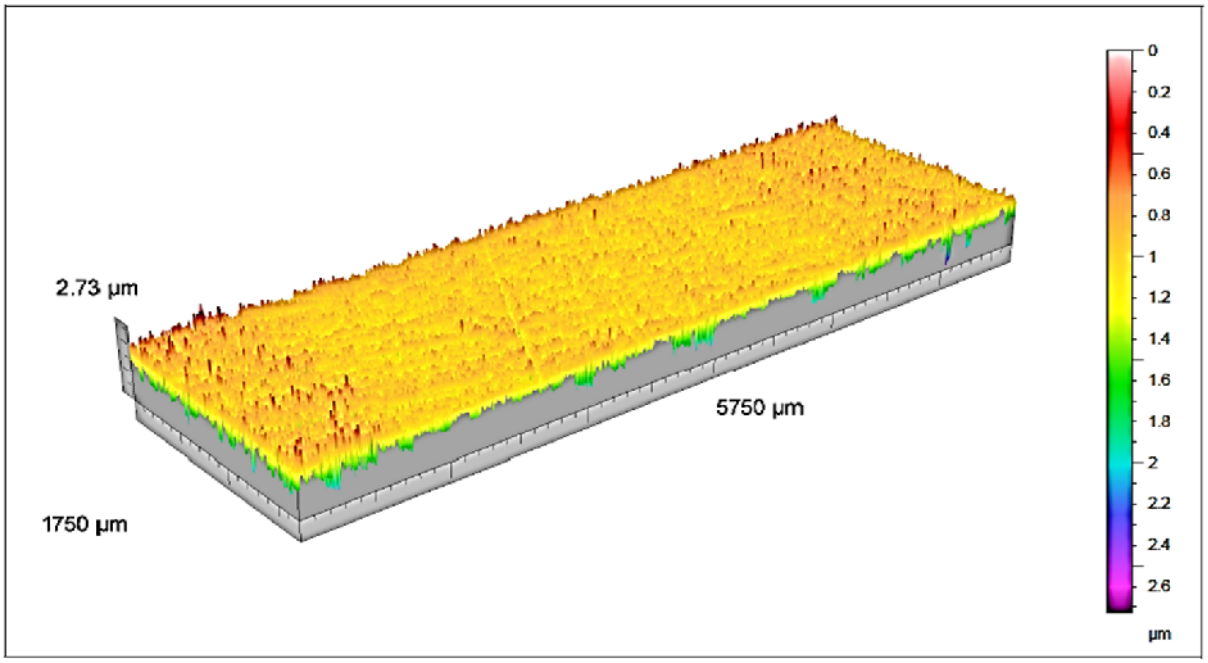
Brand Oil	Repsol
Base Oil	PAO
Oil Ref.	Super Tauro Synthetic 320

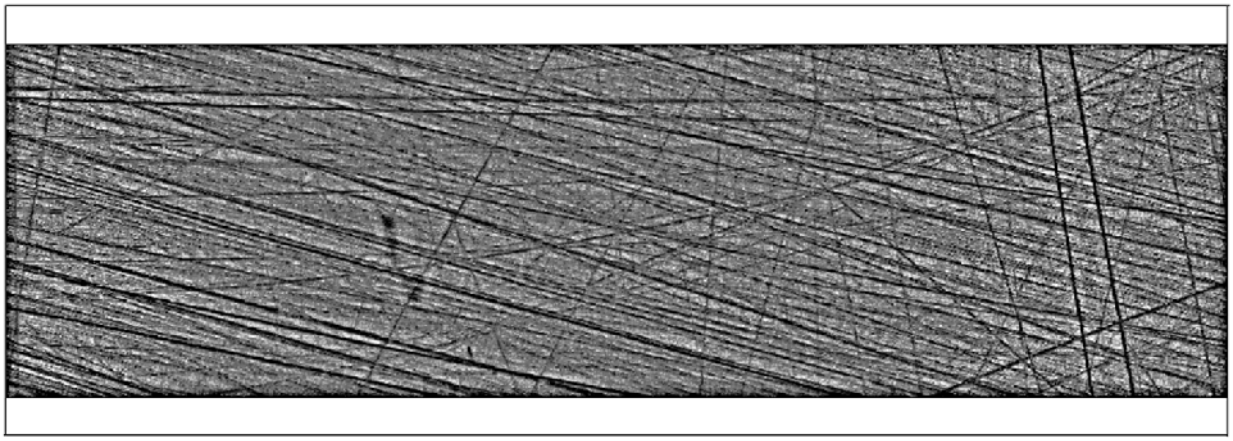


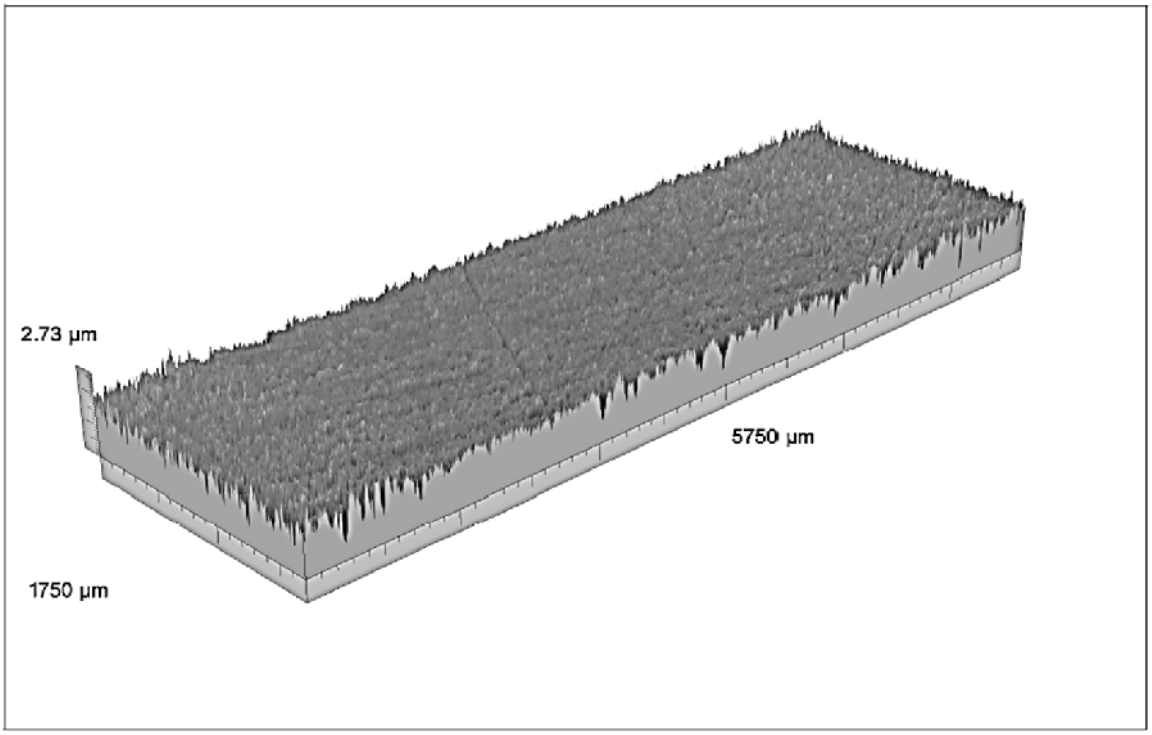
Topography, Gaussian Filter, 250 µm









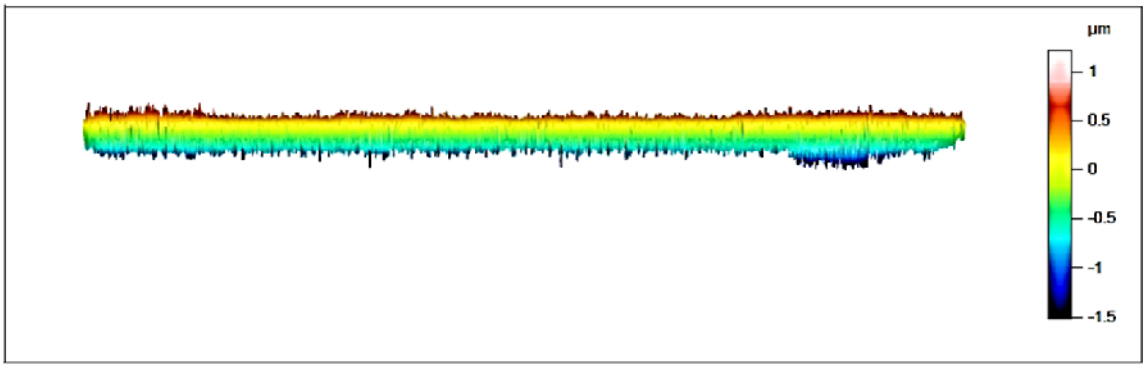


Parameters calculated on the surface AR_PAO320_10rolos_50h > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

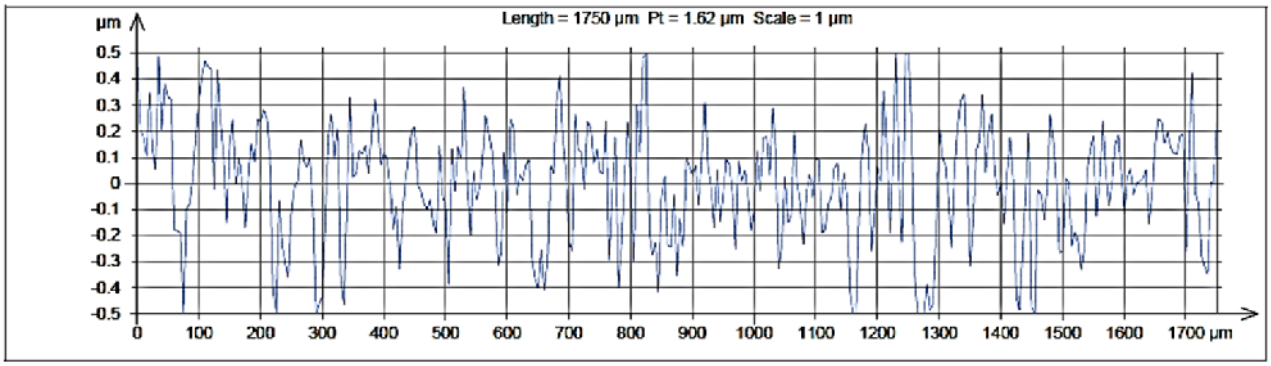
Amplitude Parameters

Sa	=	0.162 µm
Sq	=	0.208 µm
Sp	=	1.21 µm
Sv	=	1.51 µm
St	=	2.73 µm
Ssk	=	-0.37
Sku	=	4.01
Sz	=	2.73 µm



Profiles in the circumferential direction

Profile outside the contact zone:



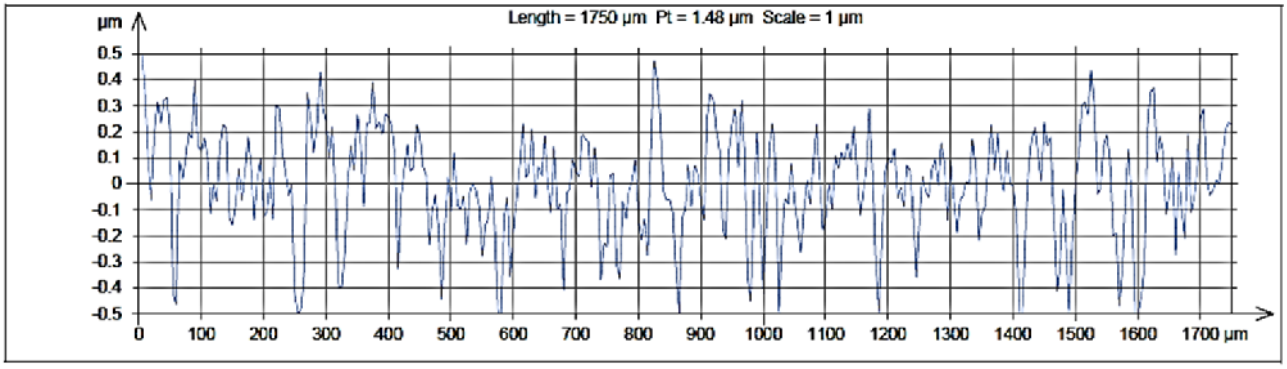
Parameters calculated on the profile AR_PAO320_10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.153 µm
Rq	= 0.189 µm
Rz	= 0.787 µm
Rt	= 1.26 µm
Rp	= 0.394 µm
Rv	= 0.393 µm
Rsk	= -0.215
Rku	= 4.35

Profile in the area of effect of board (Red Zone)



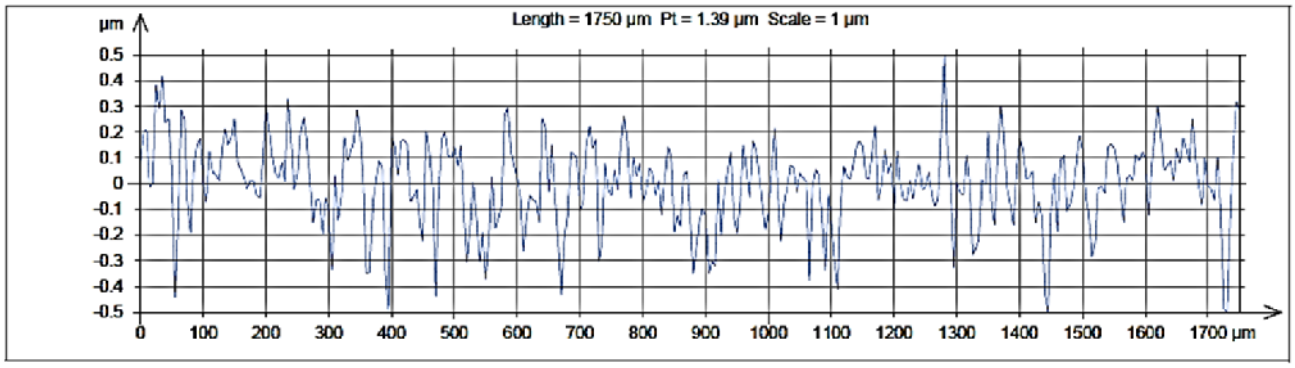
Parameters calculated on the profile AR_PAO320_10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.128 µm
Rq	= 0.166 µm
Rz	= 0.811 µm
Rt	= 1.06 µm
Rp	= 0.322 µm
Rv	= 0.489 µm
Rsk	= -0.689
Rku	= 4.29

Profile in the contact zone (Blue Zone)



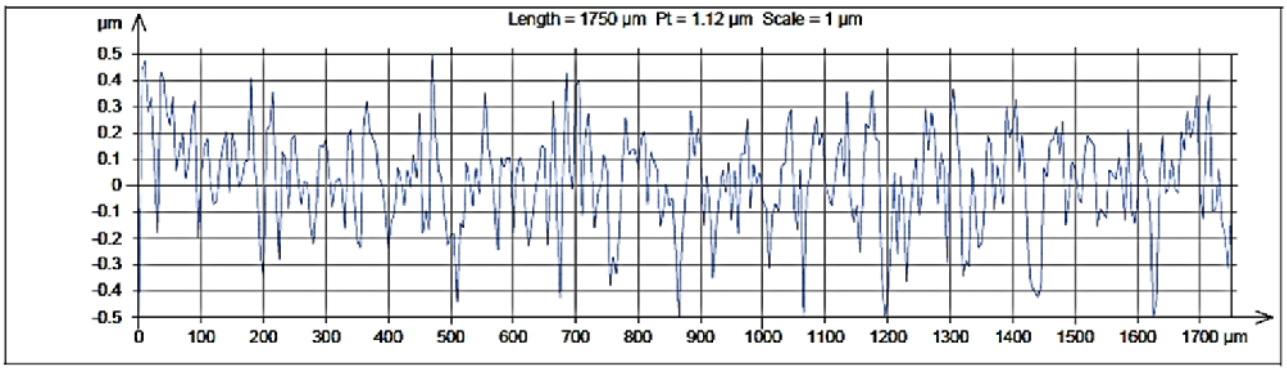
Parameters calculated on the profile AR_PAO320_10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.107 µm
Rq	= 0.136 µm
Rz	= 0.65 µm
Rt	= 0.969 µm
Rp	= 0.295 µm
Rv	= 0.354 µm
Rsk	= -0.348
Rku	= 3.52

Profile in the outer zone (Green zone)



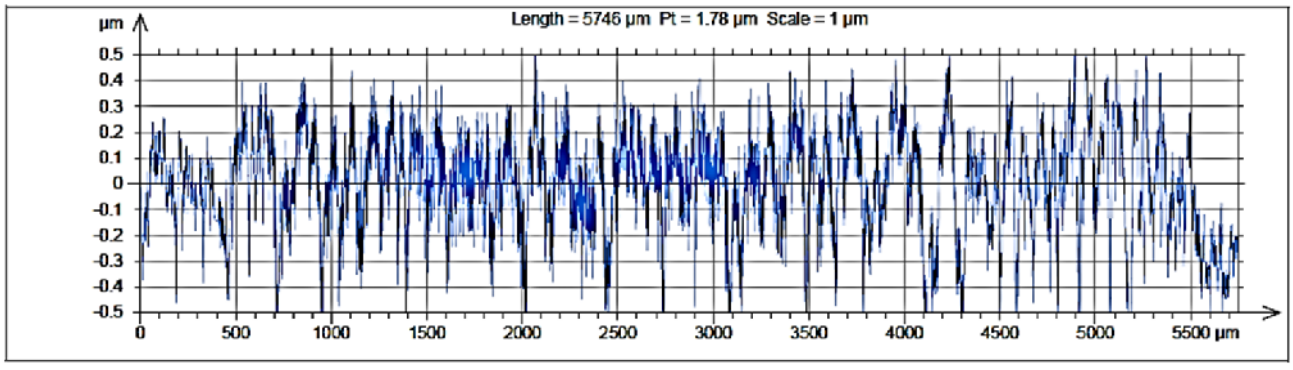
Parameters calculated on the profile AR_PAO320_10rolos_50h > ... > Roughness, Gaussian Filter, 250 µm

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.127 µm
Rq	=	0.161 µm
Rz	=	0.777 µm
Rt	=	0.985 µm
Rp	=	0.329 µm
Rv	=	0.449 µm
Rsk	=	-0.369
Rku	=	3.57

Profiles in the radial direction

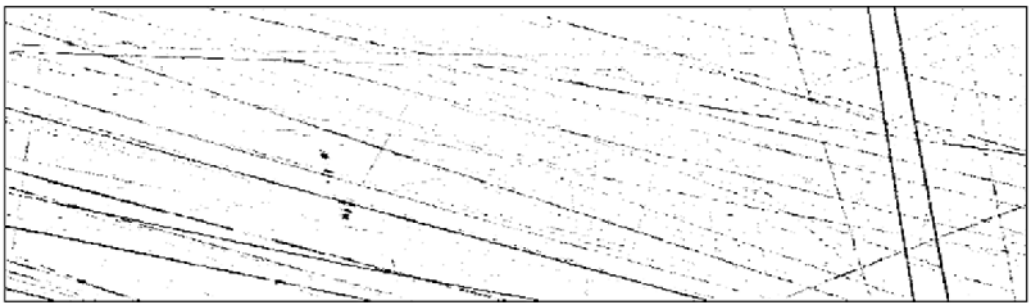


Parameters calculated on the profile AR_PAO320_10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.13 µm
Rq	= 0.165 µm
Rz	= 0.892 µm
Rt	= 1.81 µm
Rp	= 0.368 µm
Rv	= 0.524 µm
Rsk	= -0.973
Rku	= 6.29



	■	□
Area (%)	1.81	98.2
Volume of void (%)	0.235	69.7
Volume of material (%)	99.8	30.3
Volume of void (µm³/µm2)	0.00239	1.19
Volume of material (µm³/µm2)	1.01	0.52
Mean thickness of void (µm)	0.00239	1.19
Mean thickness of material (µm)	1.01	0.52

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (10 rolls - 50h)	**Brand Oil**	Fuchs
Bearing :	Thrust roller bearings (10 rolls)	**Base Oil**	Ester
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Gearmaster ECO 320

Reference Bearing-initiation	
weighings	**Average**
77,047	77,048
77,049	
77,049	
Reference Bearing-close	
weighings	**Average**
77,048	77,048
77,047	
77,048	

Cage-initiation	
weighings	**Average**
10,164	10,164
10,164	
10,164	
Cage-end	
weighings	**Average**
10,134	10,133
10,133	
10,133	

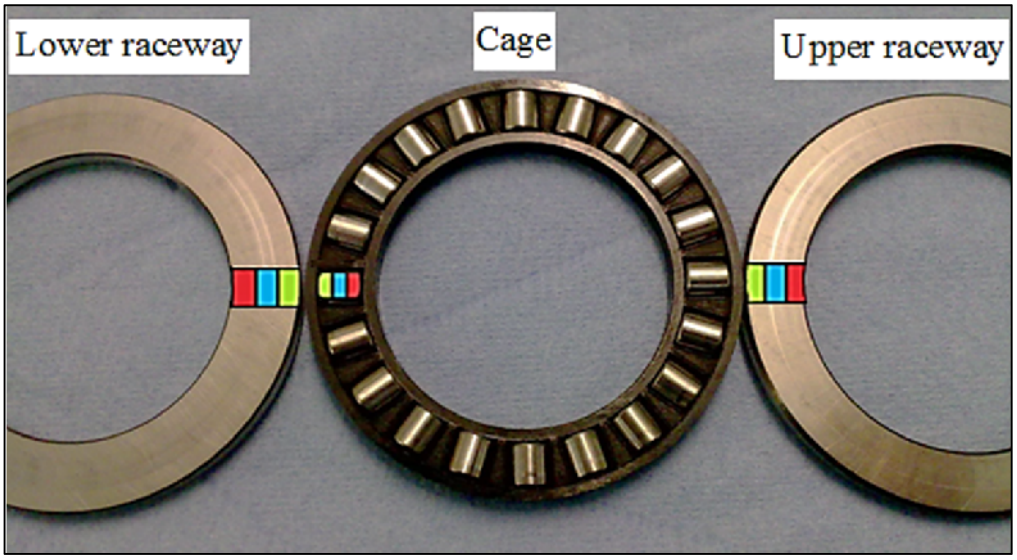
Bearing-initiation	
weighings	**Average**
66,517	66,517
66,518	
66,517	
Bearing-end	
weighings	**Average**
66,486	66,486
66,486	
66,486	

Date
Initiation: **18-05-2011**
End: **20-05-2011**

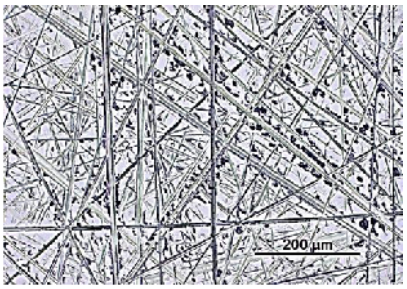
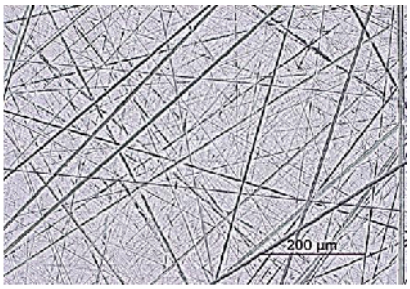
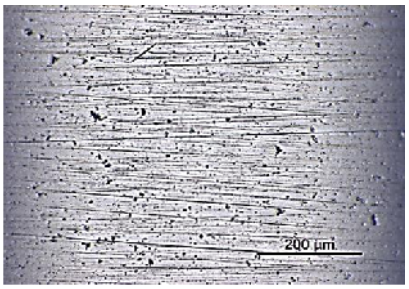
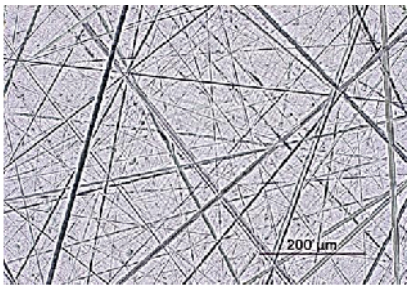
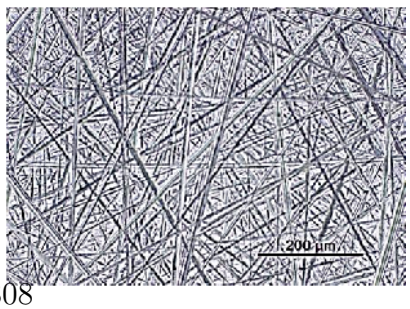
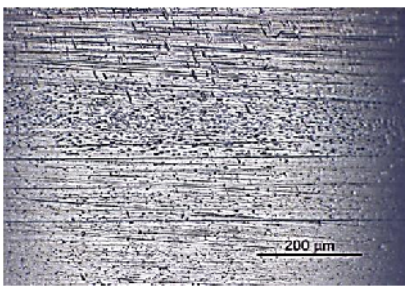
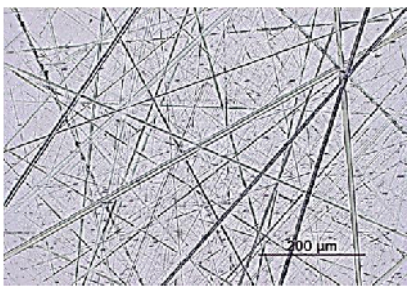
Mass loss	
31	mg

Identification of different contact zones

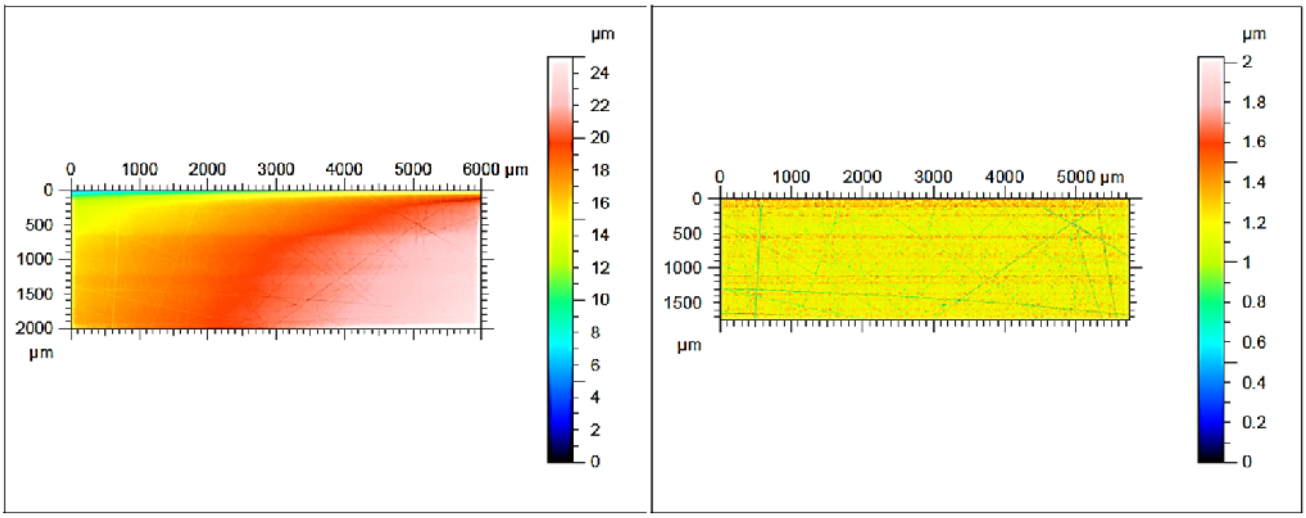
Scheme of the different contact zones analyzed

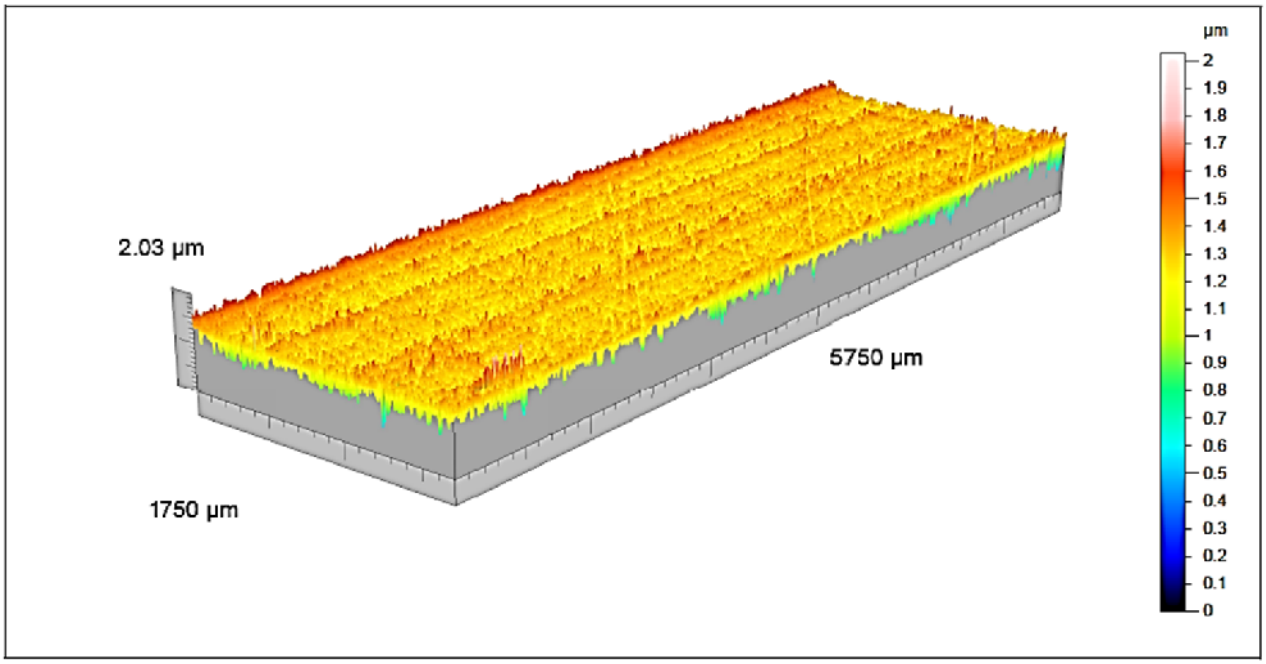


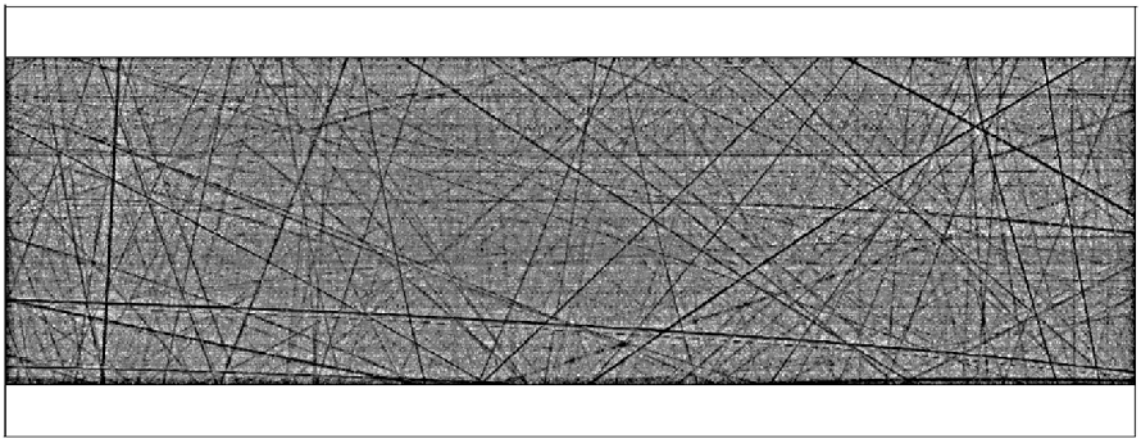
Brand Oil Fuchs
Base Oil Ester
Oil Ref. Gearmaster ECO 320

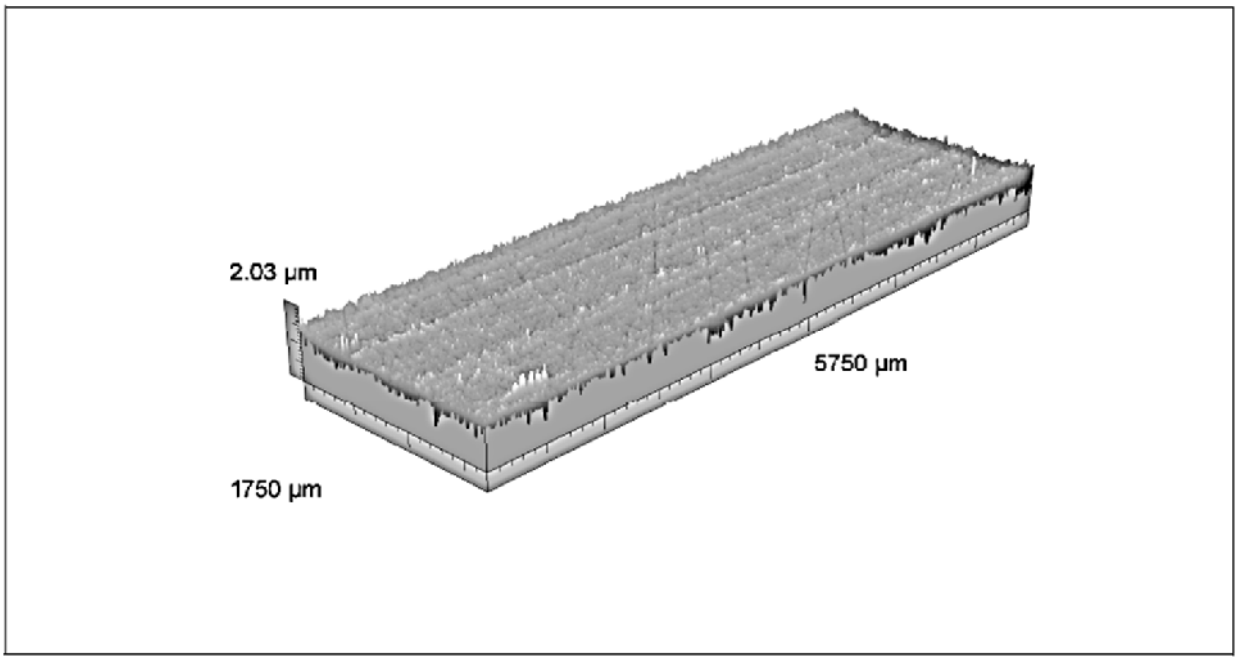
	Lower raceway	Roller	Upper raceway
Red Zone			
Blue Zone			
Green Zone			

Topography, Gaussian Filter, 250 µm







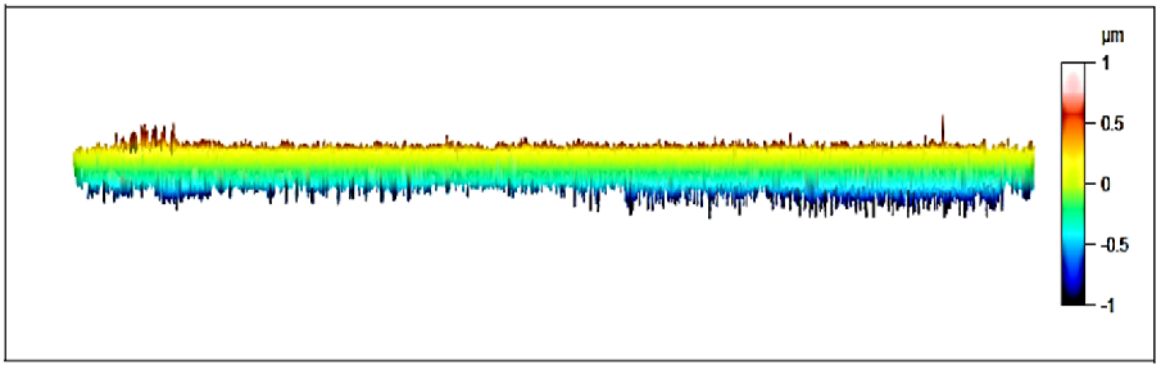


Parameters calculated on the surface AR_ESTER320_10rolos_50h > ... > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

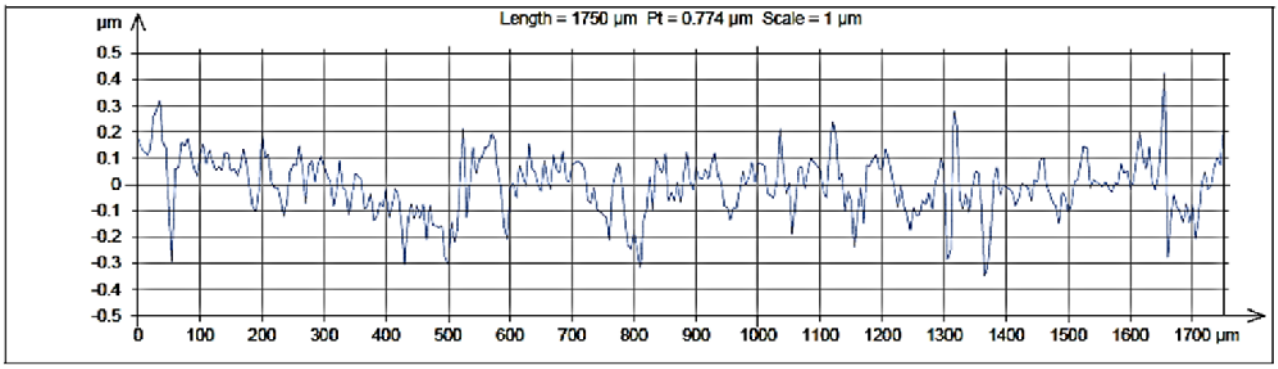
Amplitude Parameters

Sa	=	0.0915 µm
Sq	=	0.122 µm
Sp	=	0.844 µm
Sv	=	1.18 µm
St	=	2.03 µm
Ssk	=	-0.347
Sku	=	5.43
Sz	=	2.03 µm



Profiles in the circumferential direction

Profile outside the contact zone:



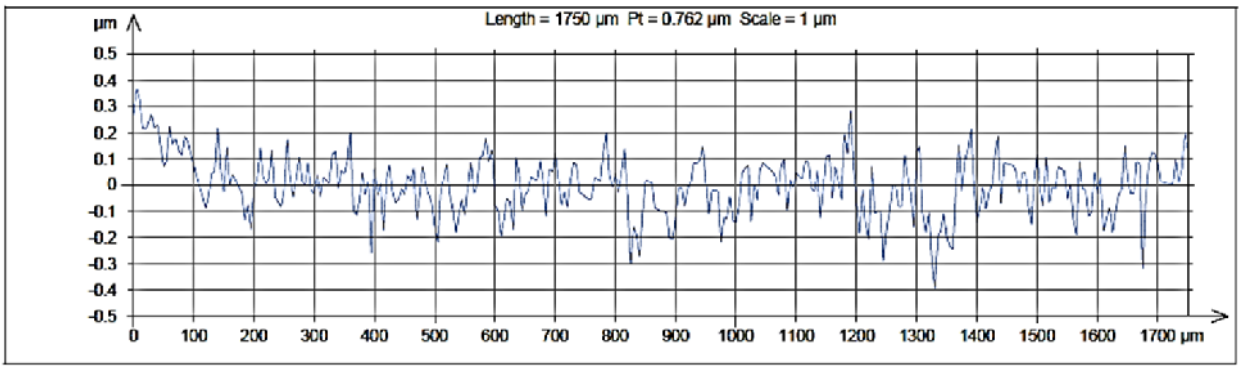
Parameters calculated on the profile AR_ESTER320_ 10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0661 µm
Rq	=	0.0842 µm
Rz	=	0.398 µm
Rt	=	0.58 µm
Rp	=	0.191 µm
Rv	=	0.206 µm
Rsk	=	-0.283
Rku	=	4.2

Profile in the area of effect of board (Red Zone)



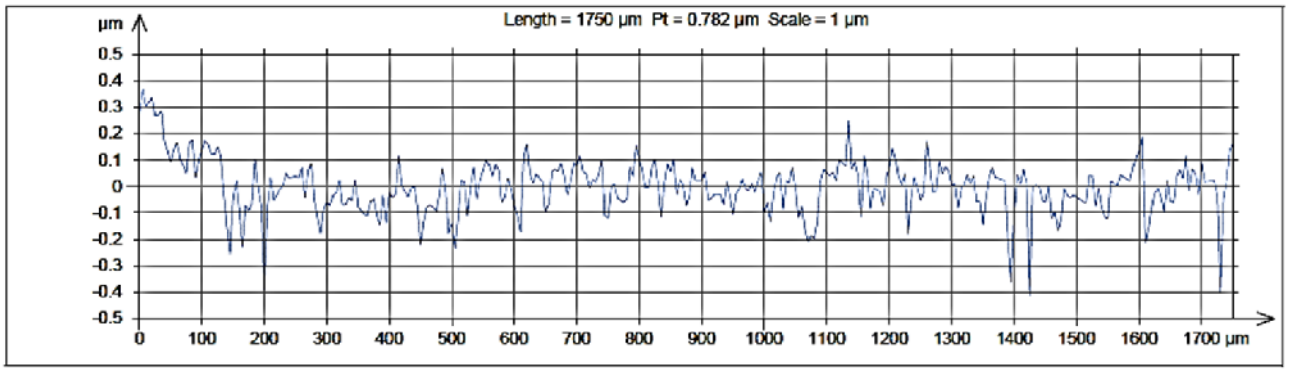
Parameters calculated on the profile AR_ESTER320_ 10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0665 µm
Rq	=	0.0838 µm
Rz	=	0.38 µm
Rt	=	0.491 µm
Rp	=	0.186 µm
Rv	=	0.194 µm
Rsk	=	-0.0442
Rku	=	3.44

Profile in the contact zone (Blue Zone)



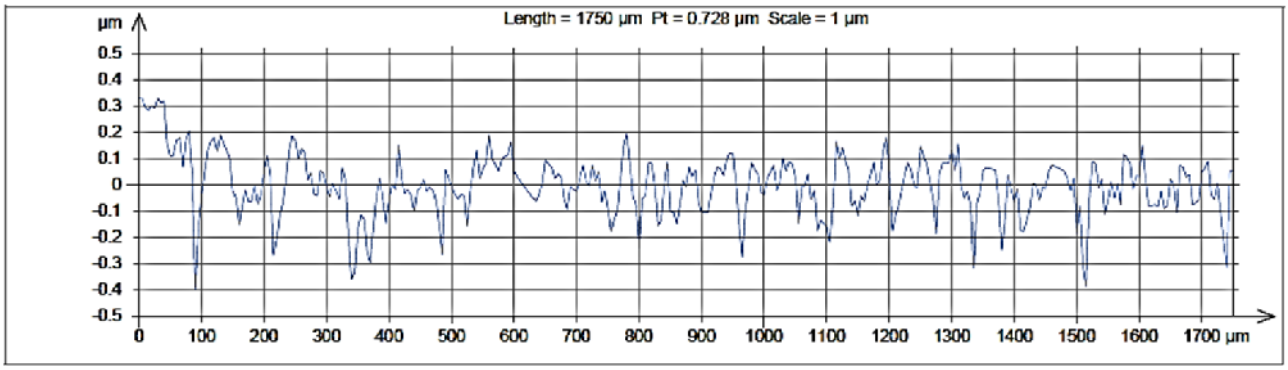
Parameters calculated on the profile AR_ESTER320_ 10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0539 µm
Rq	=	0.0689 µm
Rz	=	0.335 µm
Rt	=	0.472 µm
Rp	=	0.142 µm
Rv	=	0.194 µm
Rsk	=	-0.855
Rku	=	4.15

Profile in the outer zone (Green zone)



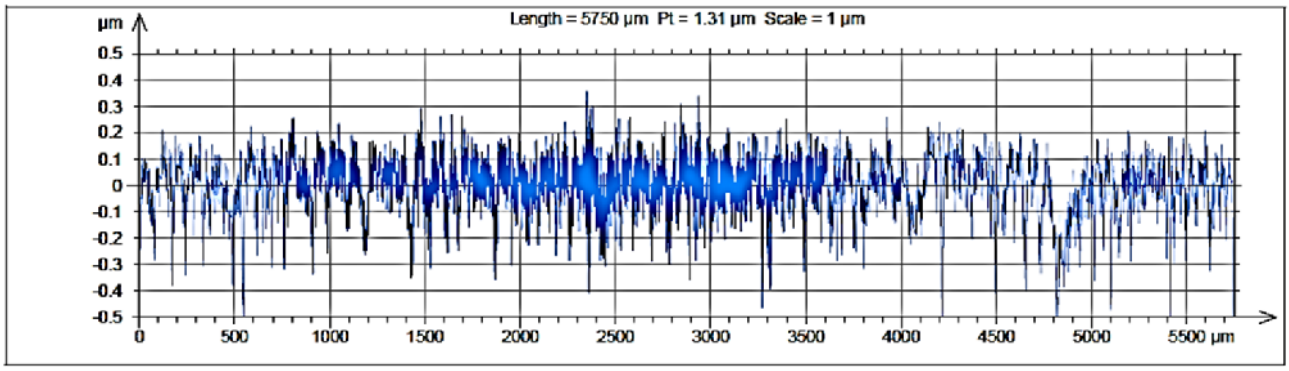
Parameters calculated on the profile AR_ESTER320_ 10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0687 µm
Rq	=	0.0848 µm
Rz	=	0.385 µm
Rt	=	0.482 µm
Rp	=	0.169 µm
Rv	=	0.216 µm
Rsk	=	-0.563
Rku	=	3.35

Profiles in the radial direction

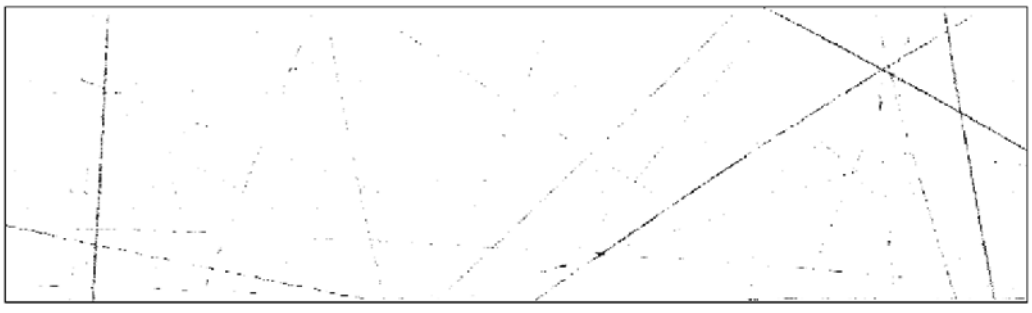


Parameters calculated on the profile AR_ESTER320_ 10rolos_50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.0717 µm
Rq	=	0.0939 µm
Rz	=	0.541 µm
Rt	=	0.888 µm
Rp	=	0.205 µm
Rv	=	0.336 µm
Rsk	=	-1.06
Rku	=	5.7



	■	□
Area (%)	0.24	99.8
Volume of void (%)	0.0375	61.6
Volume of material (%)	100	38.4
Volume of void (µm³/µm2)	0.000256	0.828
Volume of material (µm³/µm2)	0.684	0.516
Mean thickness of void (µm)	0.000256	0.828
Mean thickness of material (µm)	0.684	0.516

A.13. Test data sheet for TRB 81107 TN with 10 rollers - second 50h (mass loss, photographs of the surfaces and topography)

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (10 rolls - 50h+50h)	**Brand Oil**	Repsol
Bearing :	Thrust roller bearings (10 rolls)	**Base Oil**	Mineral
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Super Tauro FND 320

Reference Bearing-initiation	
weighings	**Average**
77,049	77,050
77,050	
77,050	
Reference Bearing-end	
weighings	**Average**
77,049	77,049
77,048	
77,049	

Cage-initiation	
weighings	**Average**
10,136	10,136
10,136	
10,136	
Cage-end	
weighings	**Average**
10,136	10,136
10,137	
10,136	

Bearing-initiation	
weighings	**Average**
66,503	66,503
66,503	
66,503	
Bearing-end	
weighings	**Average**
66,500	66,501
66,502	
66,501	

Date

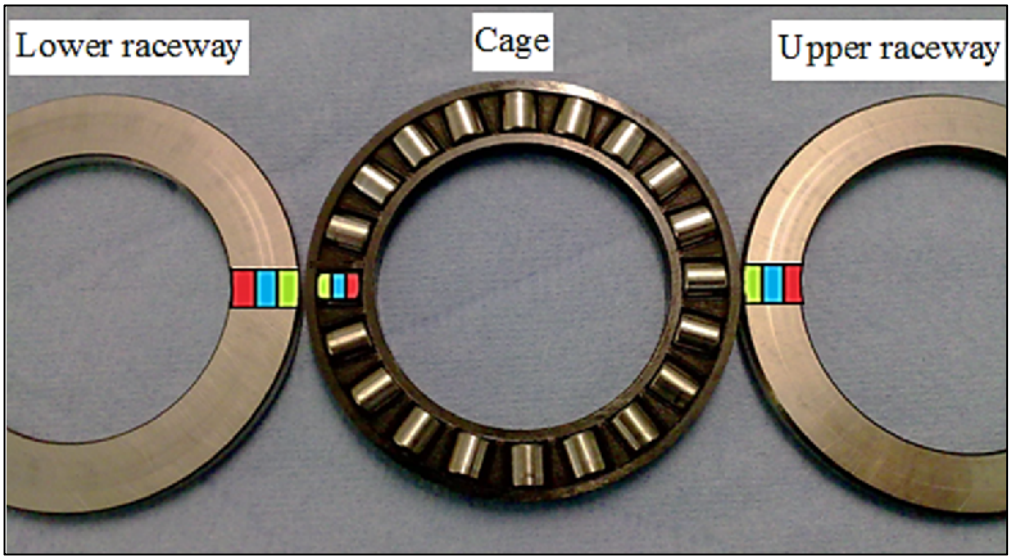
Initiation: **23-05-2011**

End: **25-05-2011**

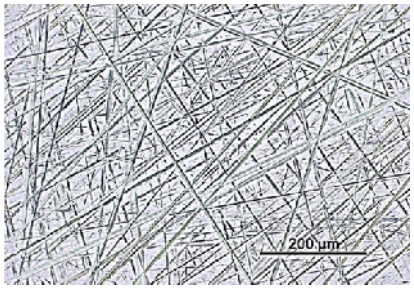
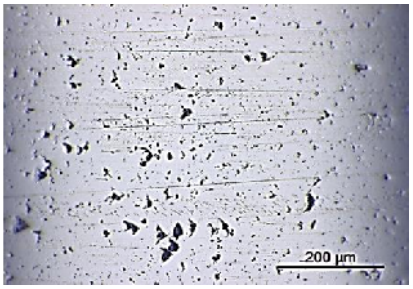
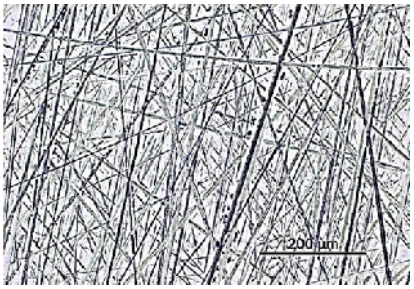
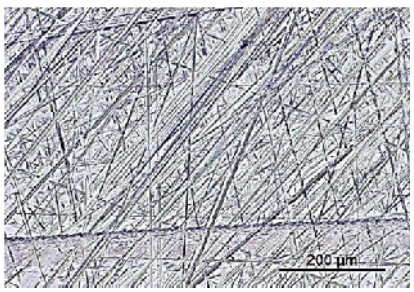
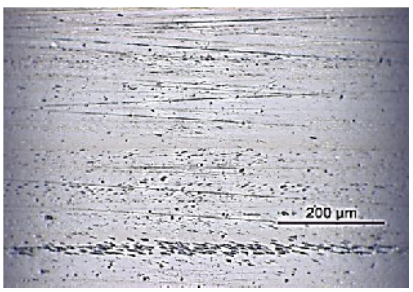
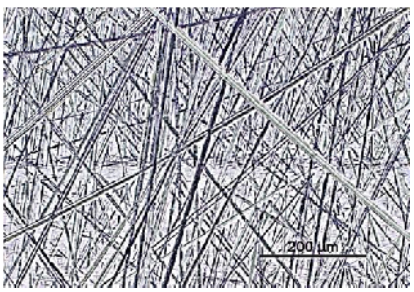
Mass loss	
1	mg

Identification of different contact zones

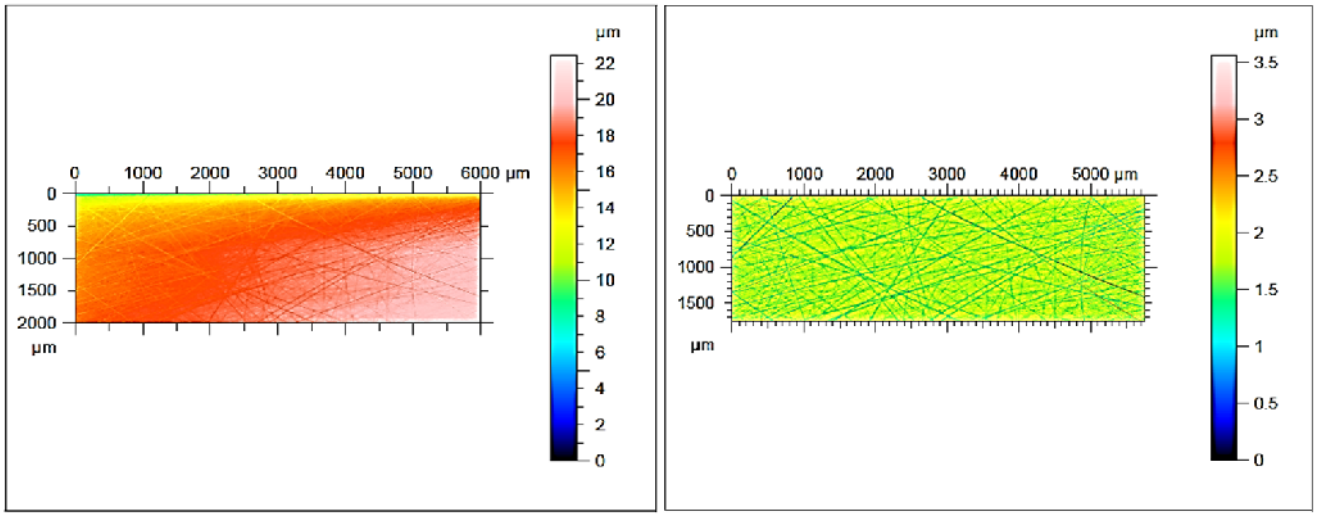
Scheme of the different contact zones analyzed

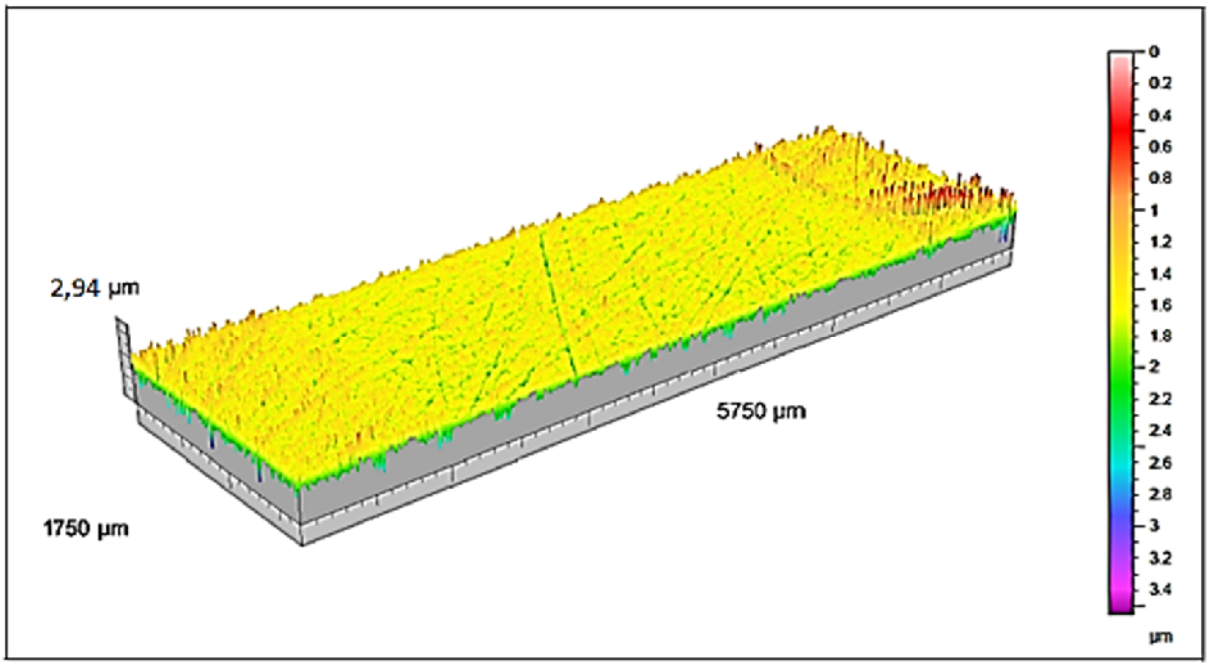


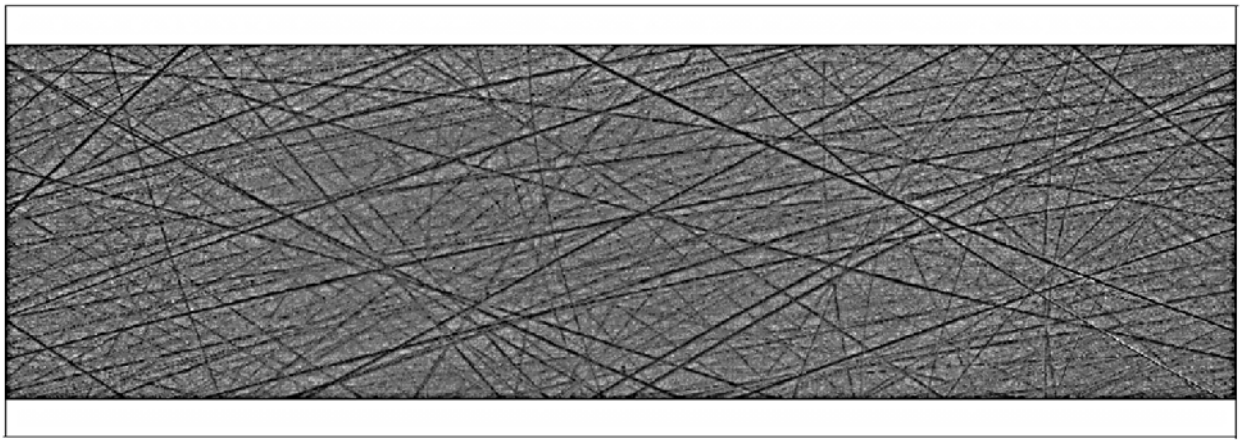
Brand Oil Repsol
Base Oil Mineral
Oil Ref. Super Tauro FND 320

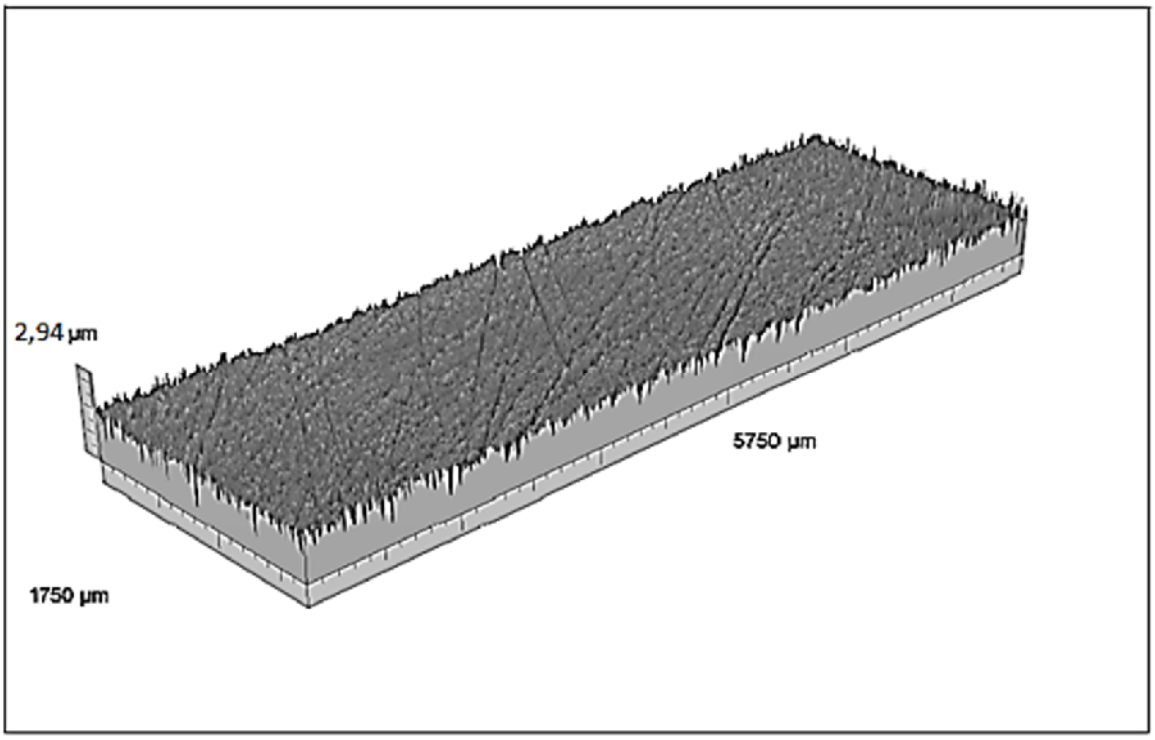
	Lower raceway	Roller	Upper raceway
Red Zone			
Blue Zone			
Green Zone			

Topography, Gaussian Filter, 250 µm







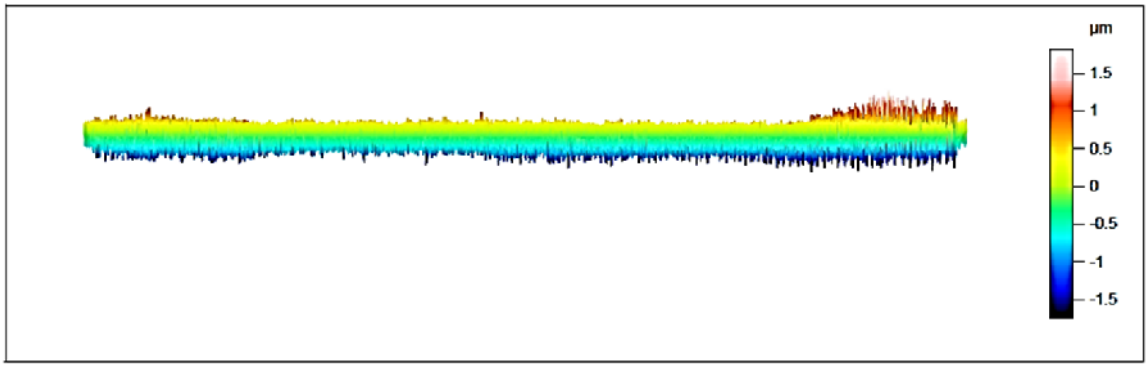


Parameters calculated on the surface AR_MIN320_10rolos_50h+50h

Sz, Sds and Ssc parameters are defined according to ISO standard.

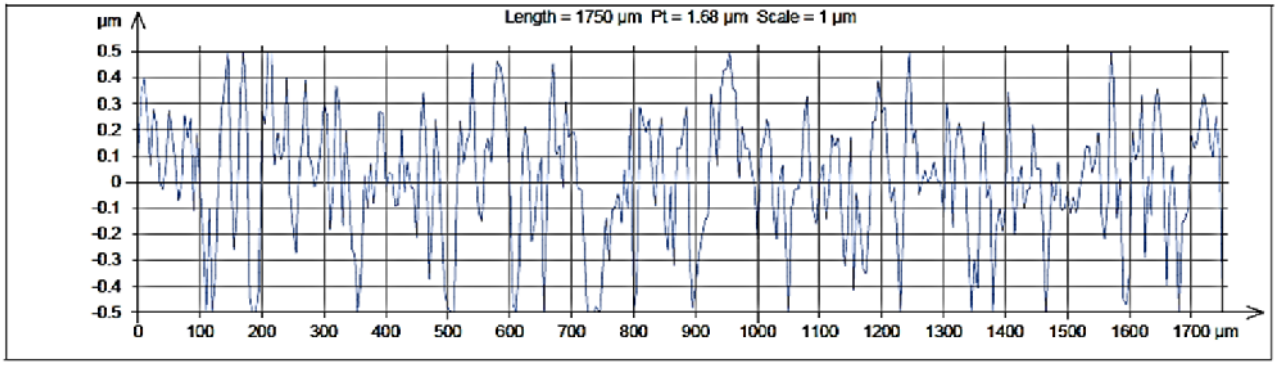
Amplitude Parameters

Sa	=	0.143 µm
Sq	=	0.205 µm
Sp	=	1.19 µm
Sv	=	1.75 µm
St	=	2.94 µm
Ssk	=	-0.966
Sku	=	5.71
Sz	=	2.94 µm



Profiles in the circumferential direction

Profile outside the contact zone:



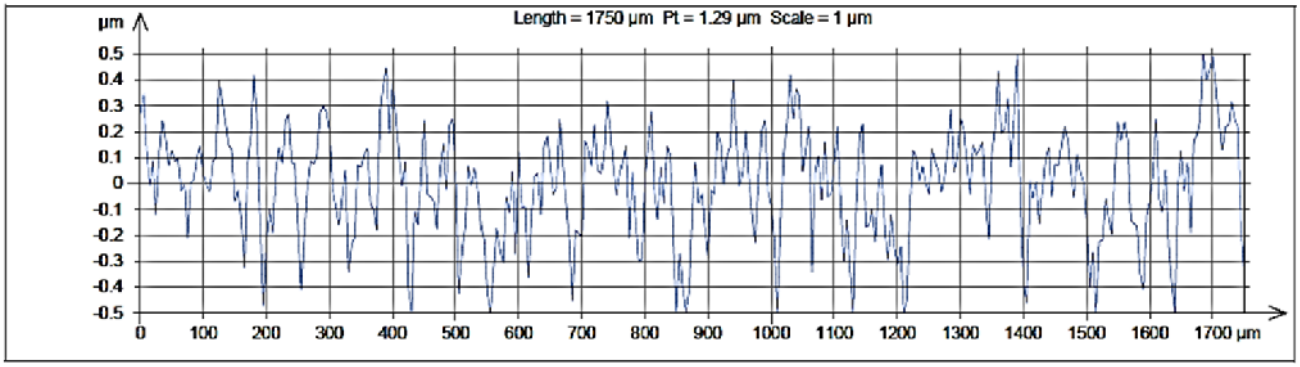
Parameters calculated on the profile AR_MIN320_10rolos_50h+50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.187 µm
Rq	=	0.238 µm
Rz	=	1.06 µm
Rt	=	1.59 µm
Rp	=	0.422 µm
Rv	=	0.638 µm
Rsk	=	-0.785
Rku	=	4.49

Profile in the area of effect of board (Red Zone)



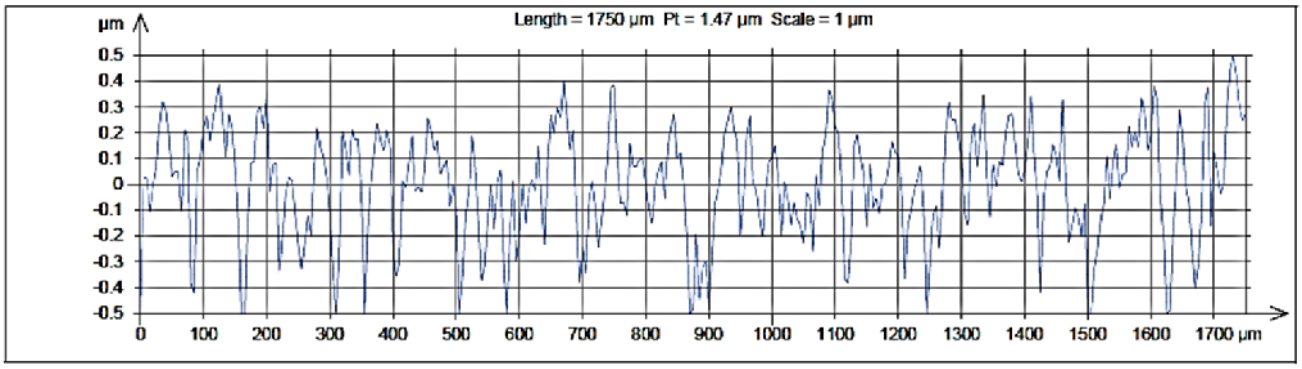
Parameters calculated on the profile AR_MIN320_10rolos_50h+50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.142 µm
   Rq     = 0.182 µm
   Rz     = 0.854 µm
   Rt     = 1.04 µm
   Rp     = 0.351 µm
   Rv     = 0.503 µm
   Rsk    = -0.517
   Rku    = 3.41
```

Profile in the contact zone (Blue Zone)



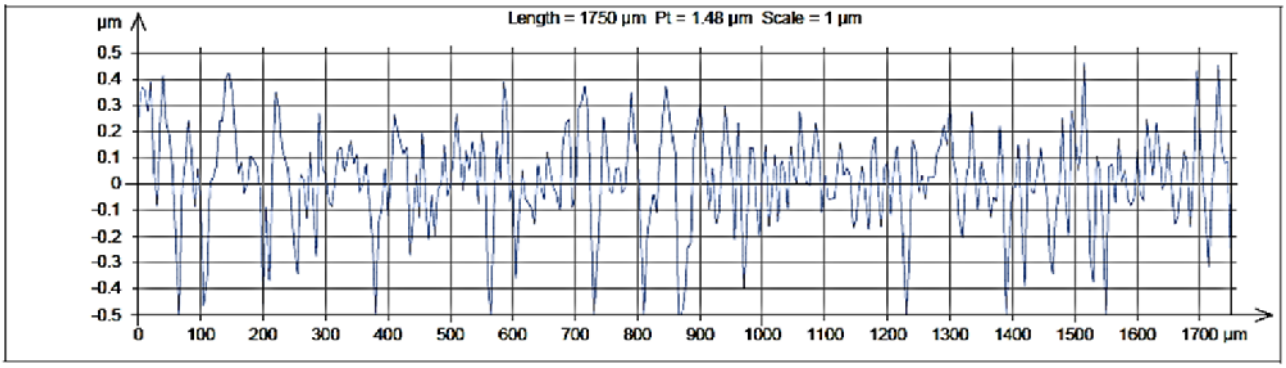
Parameters calculated on the profile AR_MIN320_10rolos_50h+50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.149 µm
   Rq     = 0.188 µm
   Rz     = 0.859 µm
   Rt     = 1.15 µm
   Rp     = 0.301 µm
   Rv     = 0.558 µm
   Rsk    = -0.867
   Rku    = 4.46
```

Profile in the outer zone (Green zone)



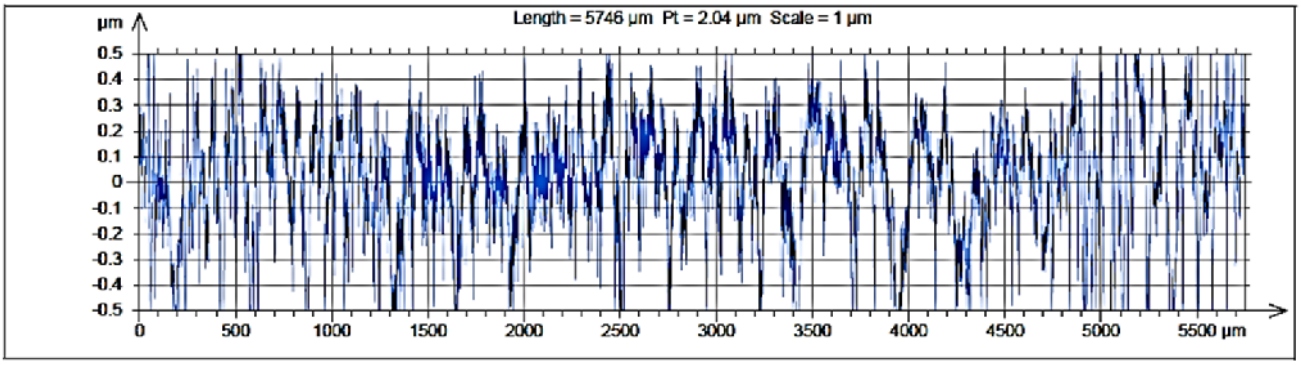
Parameters calculated on the profile AR_MIN320_10rolos_50h+50h > ... > Roughness, Gaussian Filter, 250 µm

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	=	0.127 µm
Rq	=	0.174 µm
Rz	=	0.891 µm
Rt	=	1.33 µm
Rp	=	0.326 µm
Rv	=	0.565 µm
Rsk	=	-1.35
Rku	=	7.81

Profiles in the radial direction

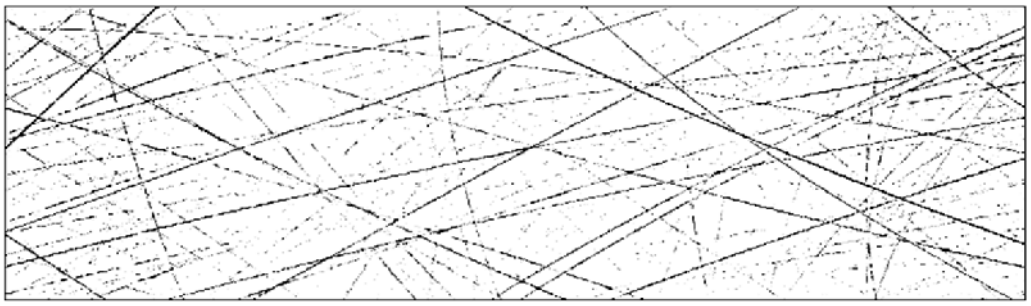


Parameters calculated on the profile AR_MIN320_10rolos_50h+50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.158 µm
Rq	= 0.204 µm
Rz	= 1.1 µm
Rt	= 1.82 µm
Rp	= 0.428 µm
Rv	= 0.67 µm
Rsk	= -1.09
Rku	= 6.08



	■	□
Area (%)	3.11	96.9
Volume of void (%)	0.417	77.6
Volume of material (%)	99.6	22.4
Volume of void (µm³/µm2)	0.00516	1.8
Volume of material (µm³/µm2)	1.23	0.517
Mean thickness of void (µm)	0.00516	1.8
Mean thickness of material (µm)	1.23	0.517

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (10 rolls - 50h+50h)	**Brand Oil**	Repsol
Bearing :	Thrust roller bearings (10 rolls)	**Base Oil**	PAO
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Super Tauro Synthetic 320

Reference Bearing-initiation	
weighings	**Average**
77,050	77,050
77,050	
77,050	
Reference Bearing-close	
weighings	**Average**
77,048	77,049
77,049	
77,049	

Cage-initiation	
weighings	**Average**
10,164	10,164
10,164	
10,164	
Cage-end	
weighings	**Average**
10,163	10,163
10,163	
10,164	

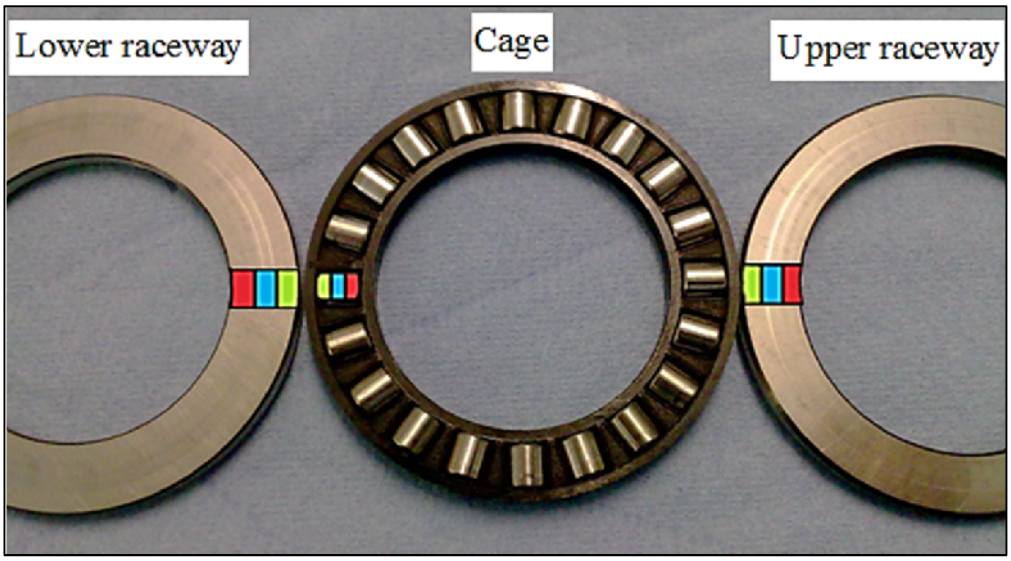
Bearing-initiation	
weighings	**Average**
66,447	66,448
66,448	
66,448	
Bearing-end	
weighings	**Average**
66,447	66,447
66,448	
66,447	

Date
Initiation: **25-05-2011**
End: **27-05-2011**

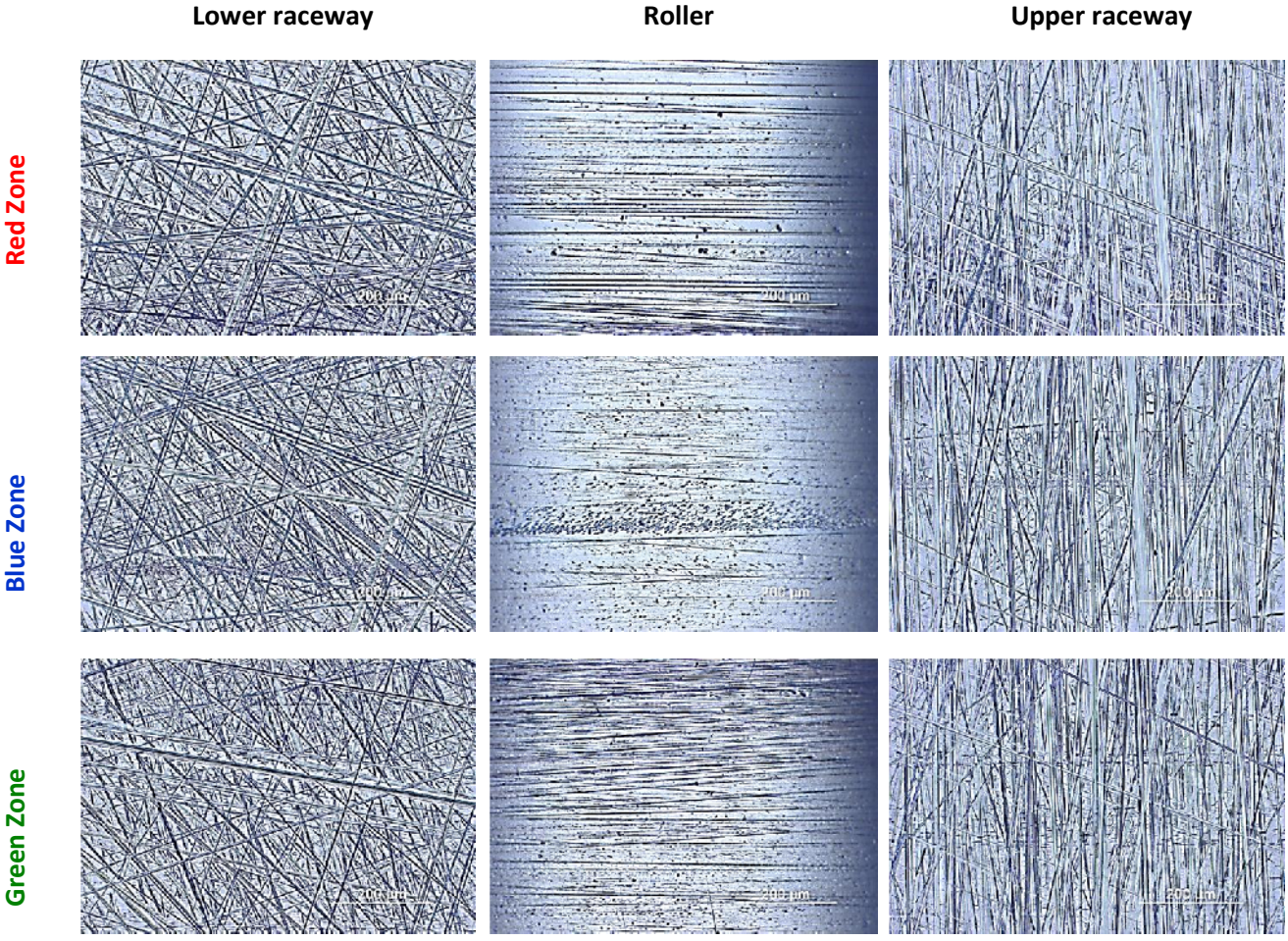
Mass loss	
0	mg

Identification of different contact zones

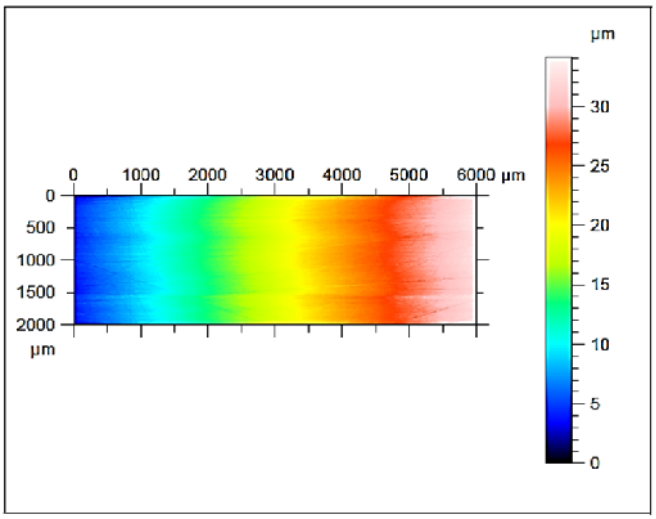
Scheme of the different contact zones analyzed

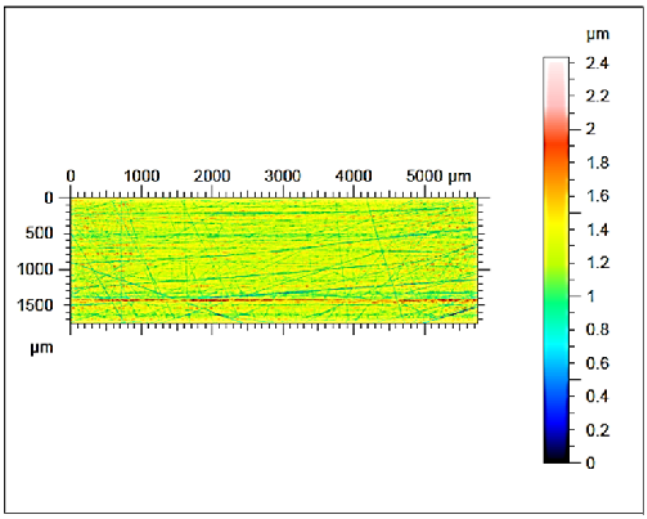


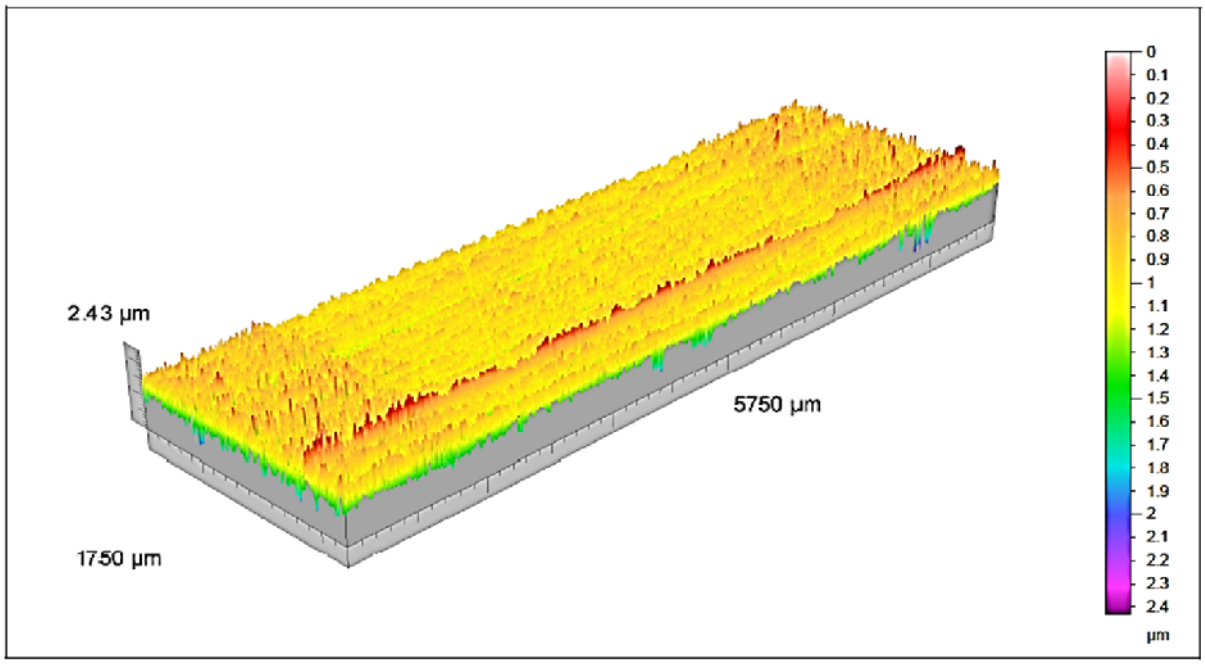
Brand Oil	Repsol
Base Oil	PAO
Oil Ref.	Super Tauro Synthetic 320

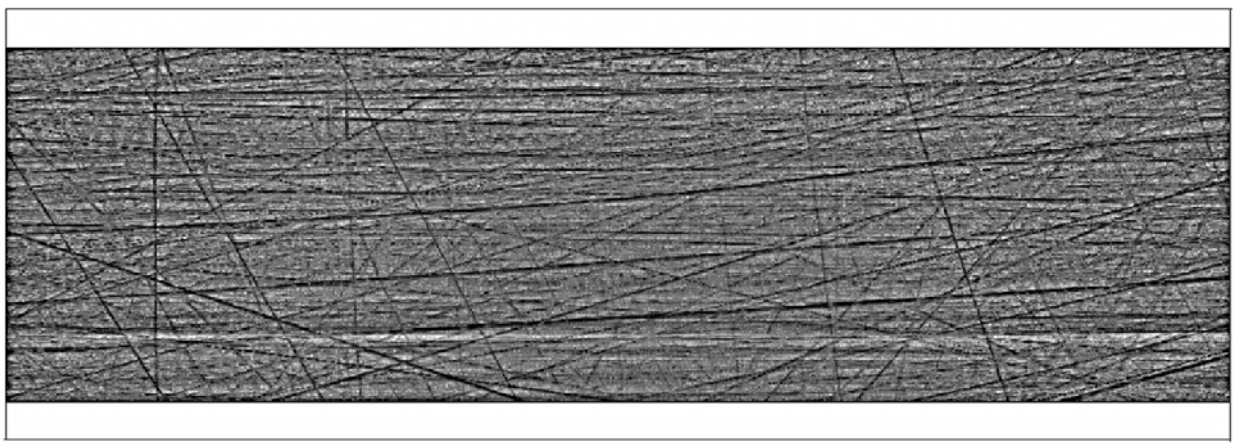


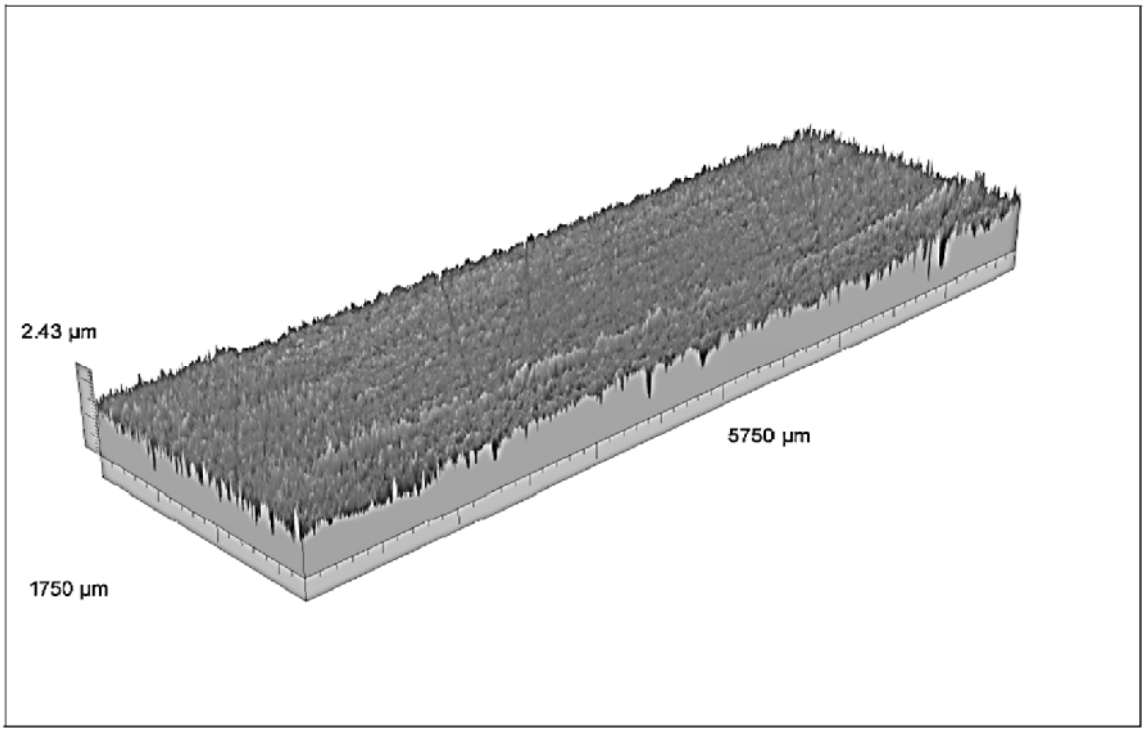
Topography, Gaussian Filter, 250 µm









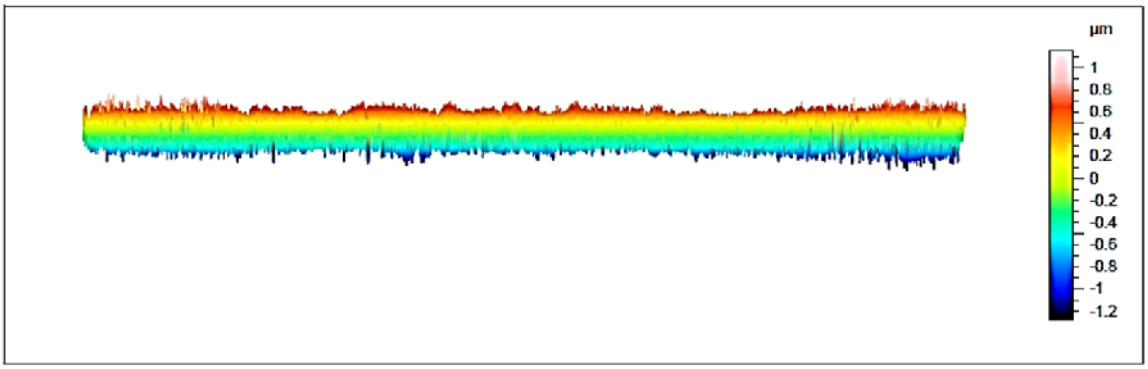


Parameters calculated on the surface AR_PAO320 _10rolos_50h+50h > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

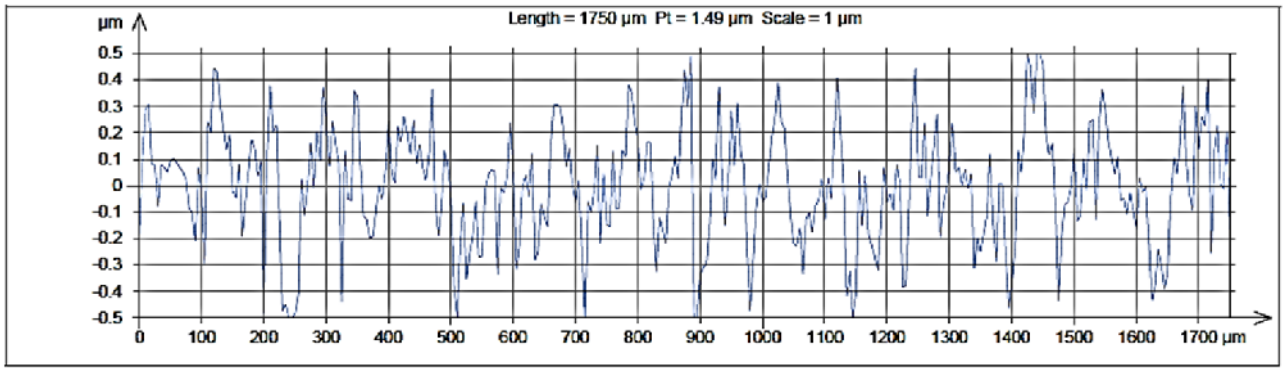
Amplitude Parameters

Sa	= 0.148 µm
Sq	= 0.192 µm
Sp	= 1.15 µm
Sv	= 1.28 µm
St	= 2.43 µm
Ssk	= -0.252
Sku	= 4.04
Sz	= 2.43 µm



Profiles in the circumferential direction

Profile outside the contact zone:



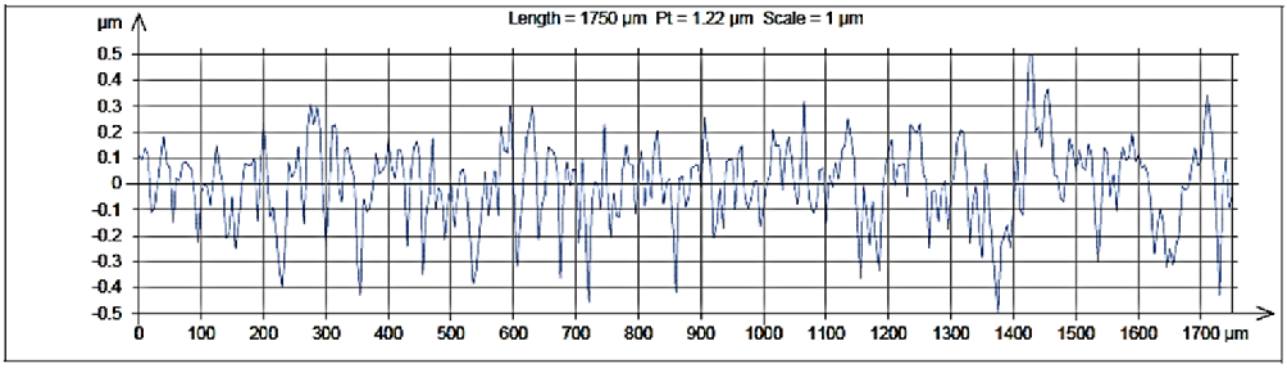
Parameters calculated on the profile AR_PAO320_10rolos_50h+50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.15 µm
Rq	= 0.188 µm
Rz	= 0.862 µm
Rt	= 1.24 µm
Rp	= 0.373 µm
Rv	= 0.489 µm
Rsk	= -0.431
Rku	= 3.21

Profile in the area of effect of board (Red Zone)



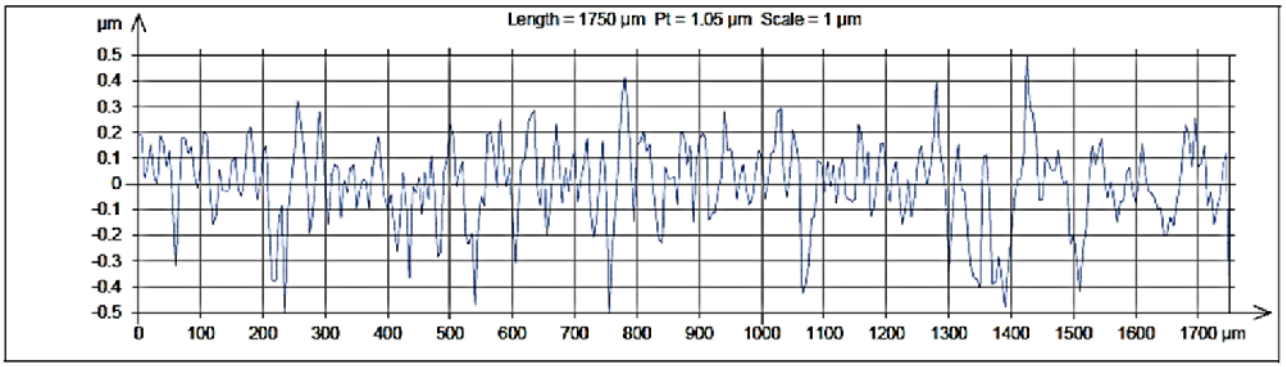
Parameters calculated on the profile AR_PAO320_10rolos_50h+50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.106 µm
   Rq     = 0.133 µm
   Rz     = 0.574 µm
   Rt     = 0.97 µm
   Rp     = 0.246 µm
   Rv     = 0.328 µm
   Rsk    = -0.618
   Rku    = 3.35
```

Profile in the contact zone (Blue Zone)



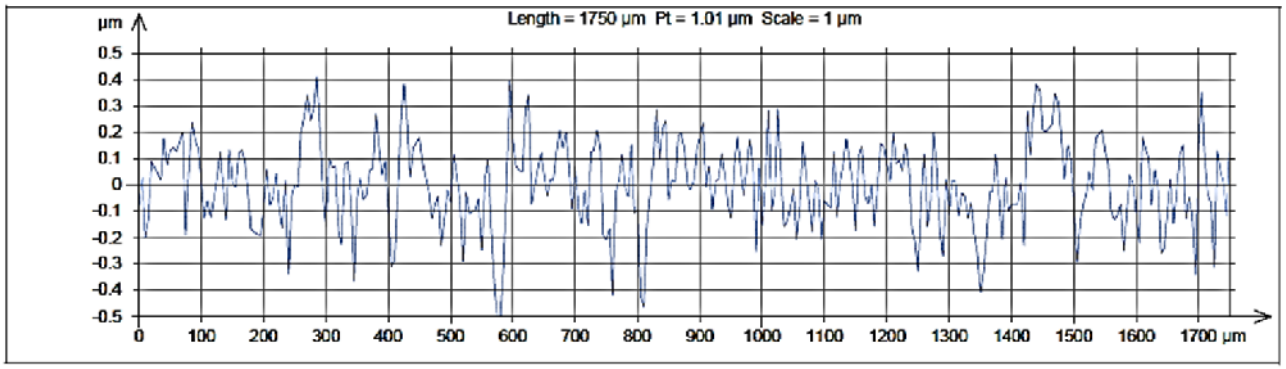
Parameters calculated on the profile AR_PAO320_10rolos_50h+50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.11 µm
   Rq     = 0.141 µm
   Rz     = 0.681 µm
   Rt     = 0.922 µm
   Rp     = 0.298 µm
   Rv     = 0.383 µm
   Rsk    = -0.526
   Rku    = 3.31
```

Profile in the outer zone (Green zone)



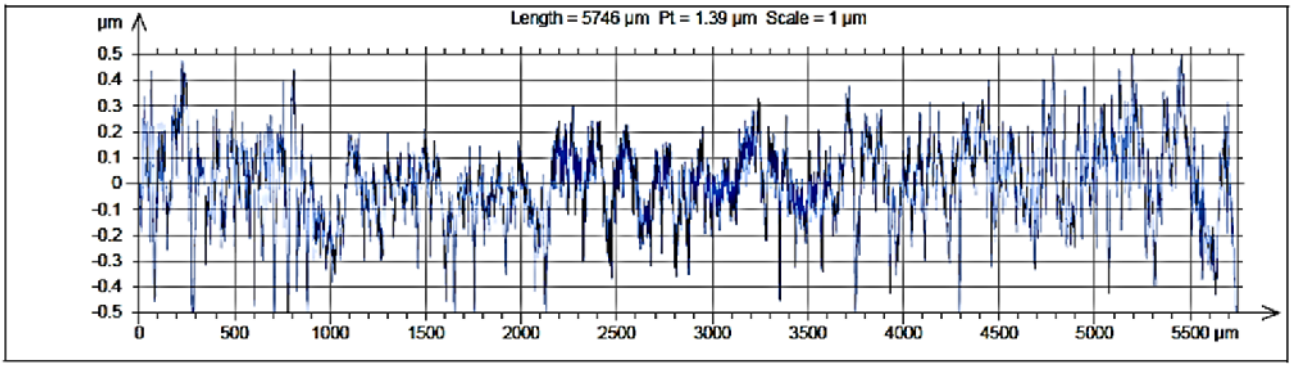
Parameters calculated on the profile AR_PAO320_10rolos_50h+50h > ... >
Roughness, Gaussian Filter, 250 µm

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.104 µm
   Rq     = 0.134 µm
   Rz     = 0.622 µm
   Rt     = 0.868 µm
   Rp     = 0.267 µm
   Rv     = 0.355 µm
   Rsk    = -0.565
   Rku    = 4.39
```

Profiles in the radial direction

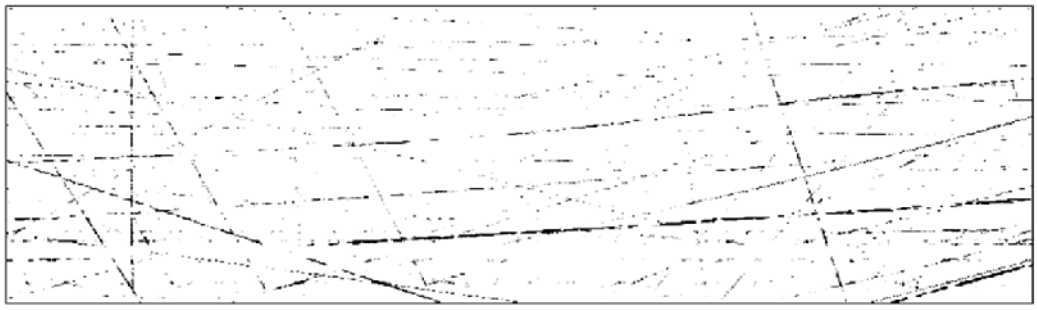


Parameters calculated on the profile AR_PAO320_10rolos_50h+50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.0962 µm
   Rq     = 0.124 µm
   Rz     = 0.679 µm
   Rt     = 1.26 µm
   Rp     = 0.267 µm
   Rv     = 0.413 µm
   Rsk    = -0.988
   Rku    = 6.9
```



	■	□
Area (%)	1.14	98.9
Volume of void (%)	0.157	69.4
Volume of material (%)	99.8	30.6
Volume of void (µm³/µm2)	0.00122	1.15
Volume of material (µm³/µm2)	0.774	0.505
Mean thickness of void (µm)	0.00122	1.15
Mean thickness of material (µm)	0.774	0.505

Power loss in thrust ball and roller bearings lubricated with "WindMill Gear Oils"

TEST DATA SHEET

Test Tipe:	Wear (10 rolls - 50h+50h)	**Brand Oil**	Fuchs
Bearing :	Thrust roller bearings (10 rolls)	**Base Oil**	Ester
Bearing Ref.	SKF 81107 TN	**Oil Ref.**	Gearmaster ECO 320

Reference Bearing-initiation	
weighings	**Average**
77,048	77,048
77,047	
77,048	
Reference Bearing-close	
weighings	**Average**
77,048	77,048
77,048	
77,048	

Cage-initiation	
weighings	**Average**
10,134	10,133
10,133	
10,133	
Cage-end	
weighings	**Average**
10,131	10,131
10,131	
10,131	

Bearing-initiation	
weighings	**Average**
66,486	66,486
66,486	
66,486	
Bearing-end	
weighings	**Average**
66,484	66,484
66,484	
66,484	

Date

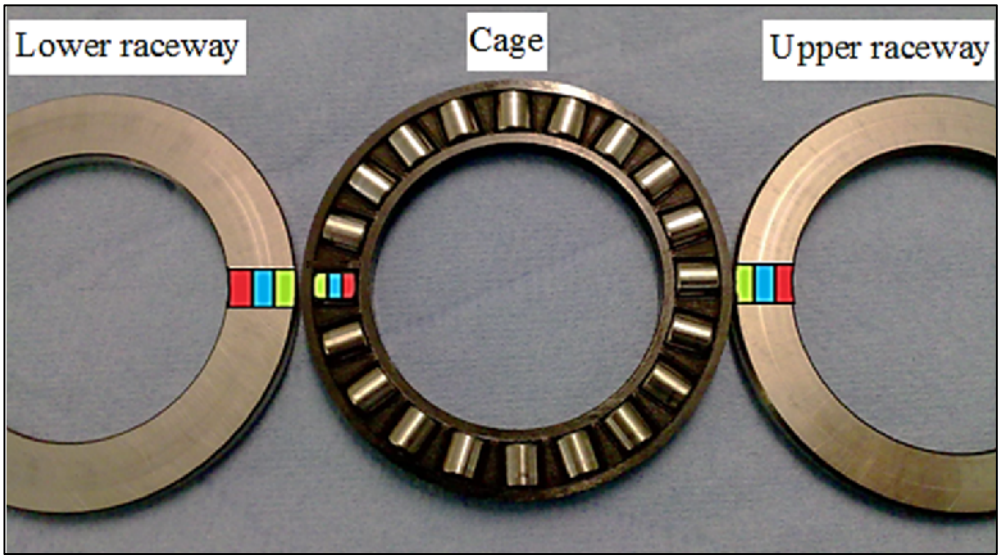
Initiation: **30-05-2011**

End: **01-06-2011**

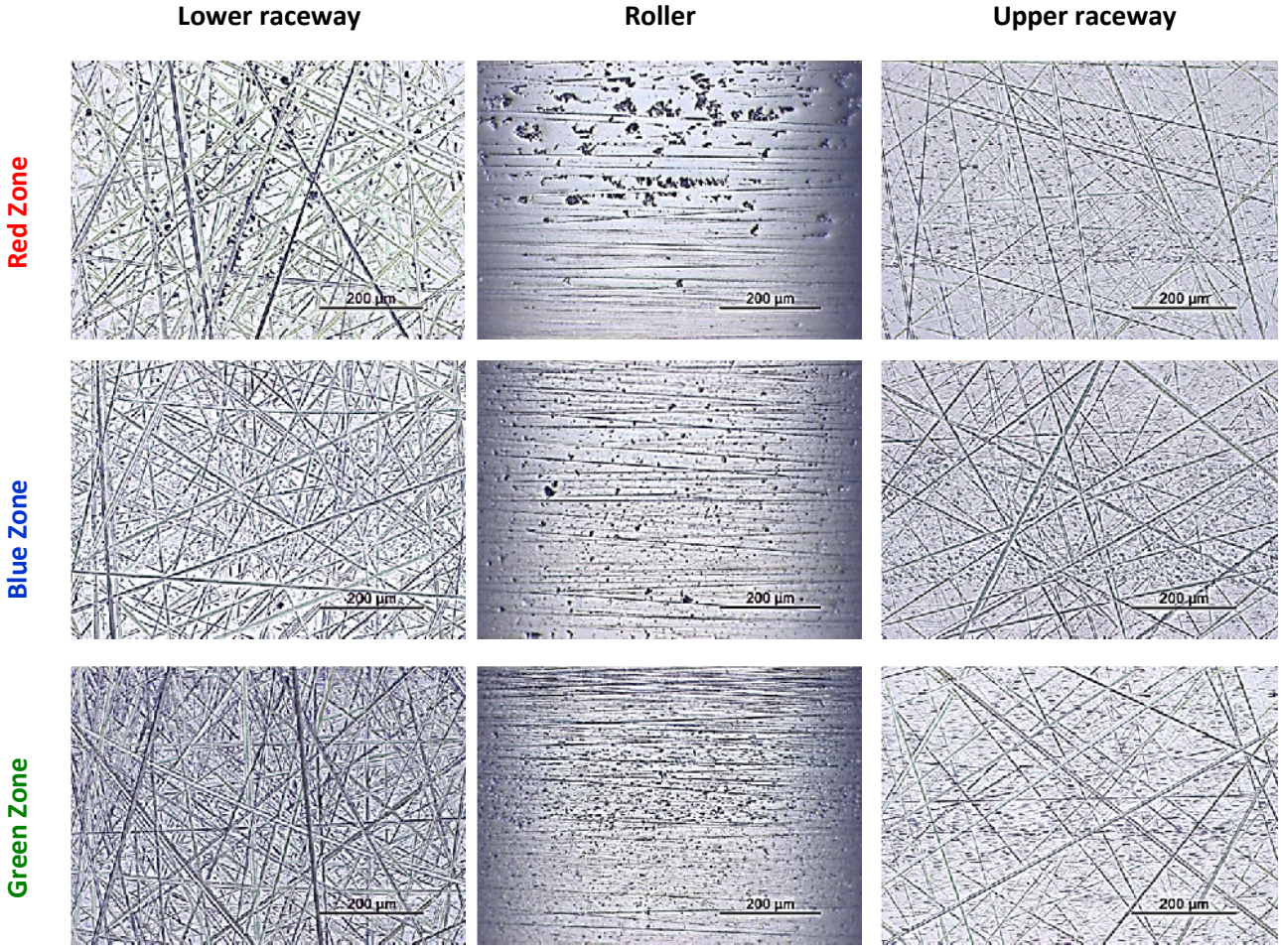
Mass loss	
2	mg

Identification of different contact zones

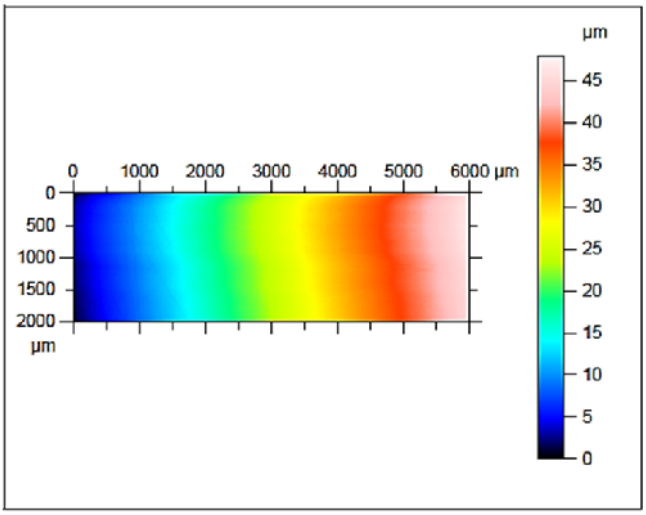
Scheme of the different contact zones analyzed

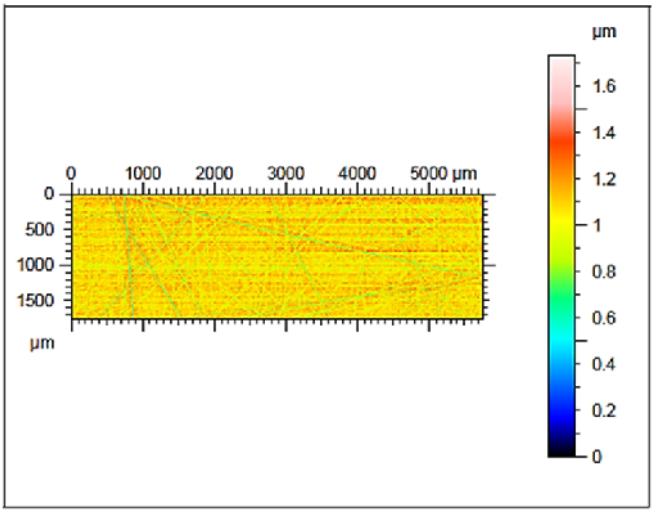


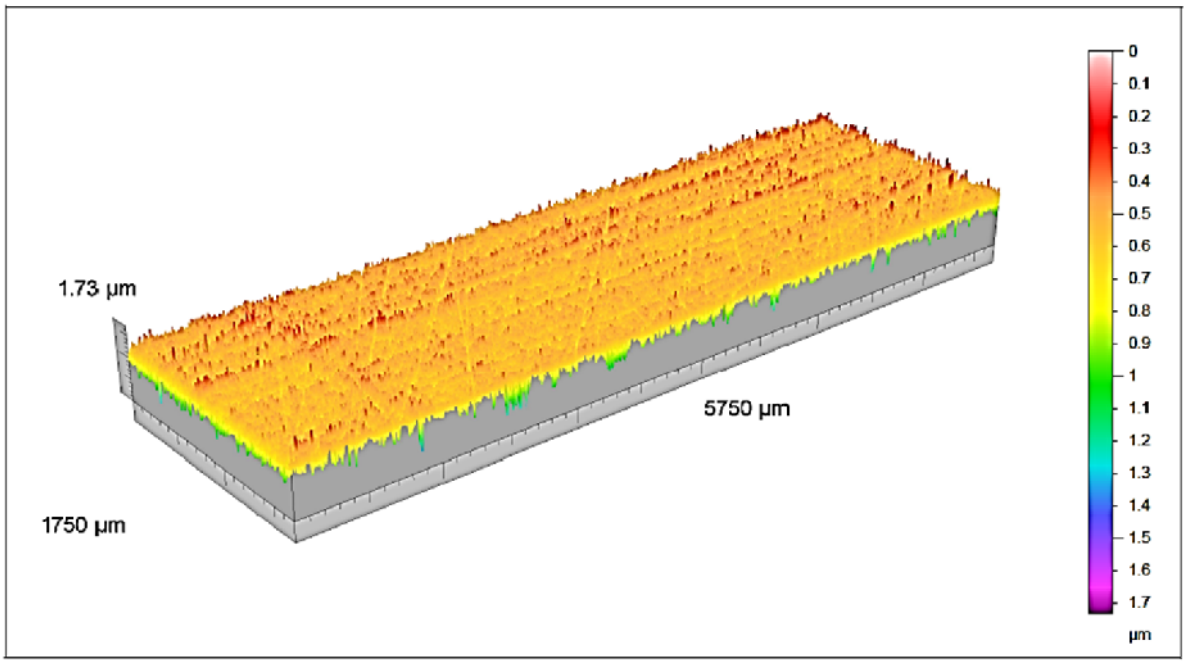
Brand Oil	Fuchs
Base Oil	Ester
Oil Ref.	Gearmaster ECO 320

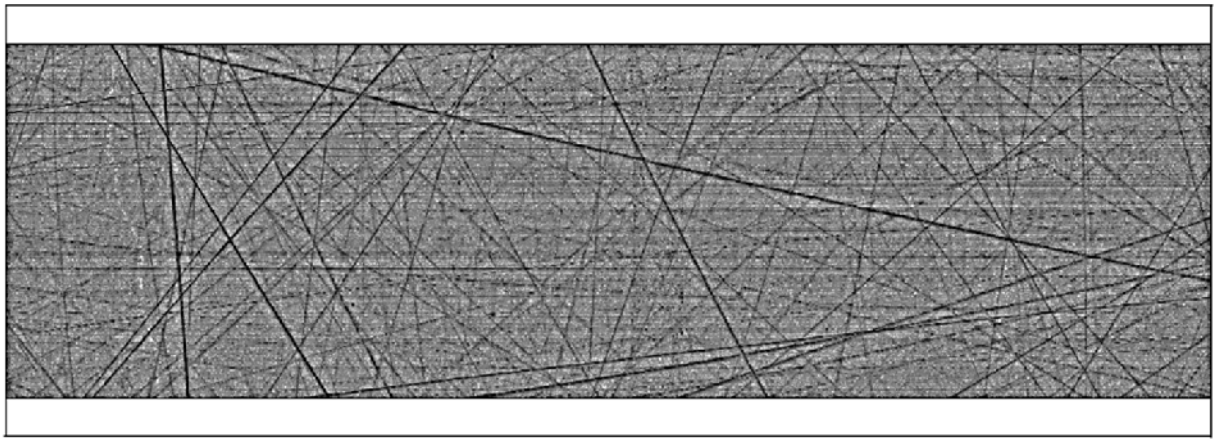


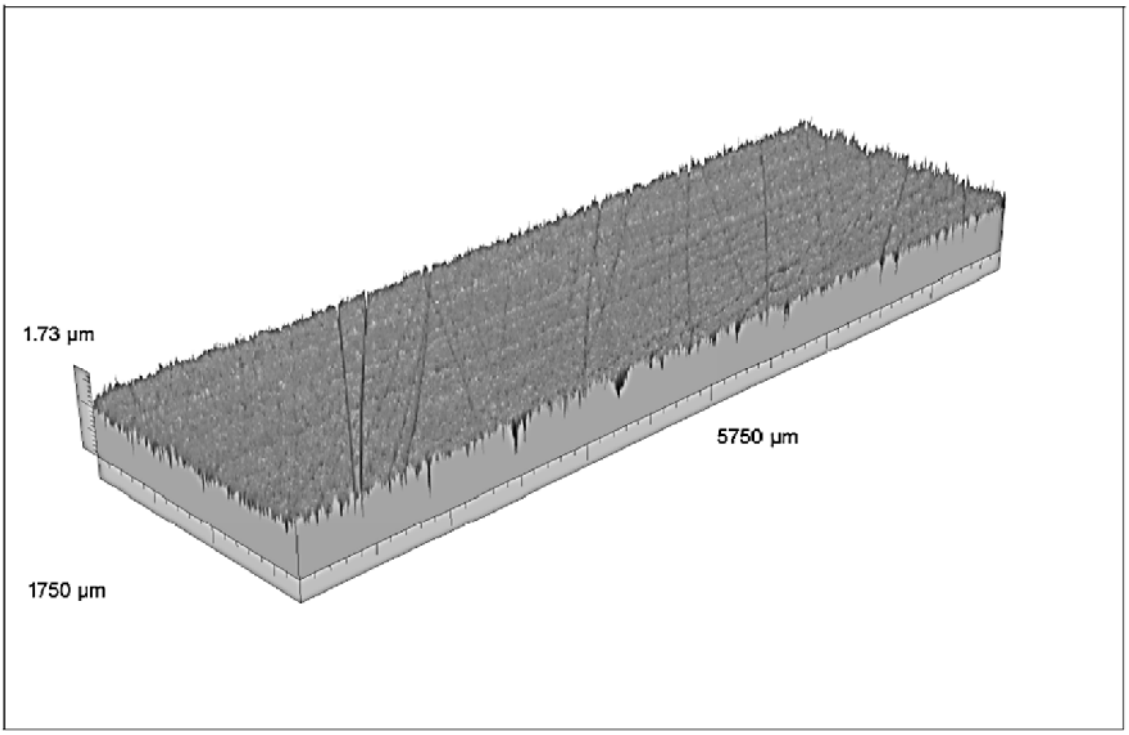
Topography, Gaussian Filter, 250 µm









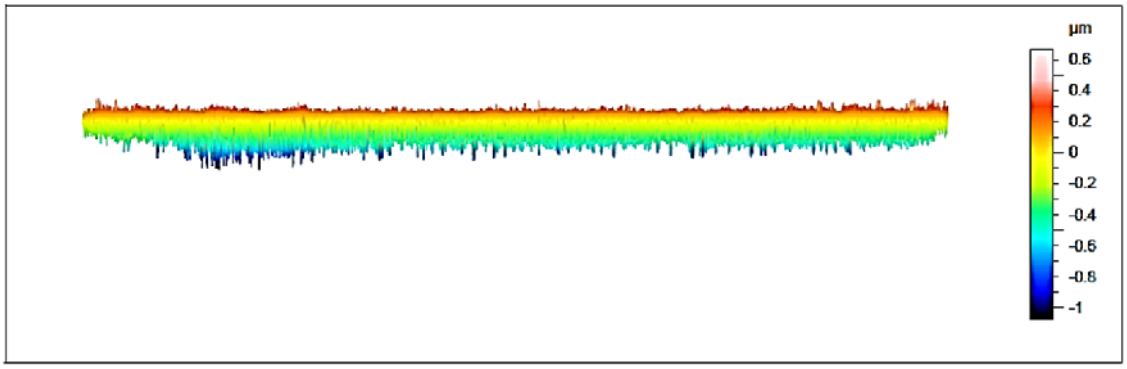


Parameters calculated on the surface AR_ESTER320_10rolos_50h+50h > Roughness, Gaussian Filter, 250 µm

Sz, Sds and Ssc parameters are defined according to ISO standard.

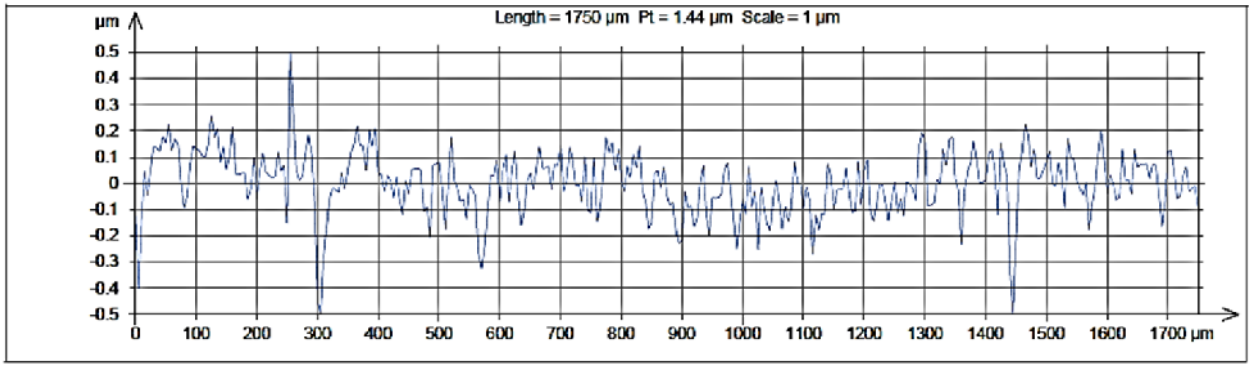
Amplitude Parameters

Sa	=	0.0858 µm
Sq	=	0.114 µm
Sp	=	0.664 µm
Sv	=	1.07 µm
St	=	1.73 µm
Ssk	=	-0.786
Sku	=	5.65
Sz	=	1.73 µm



Profiles in the circumferential direction

Profile outside the contact zone:



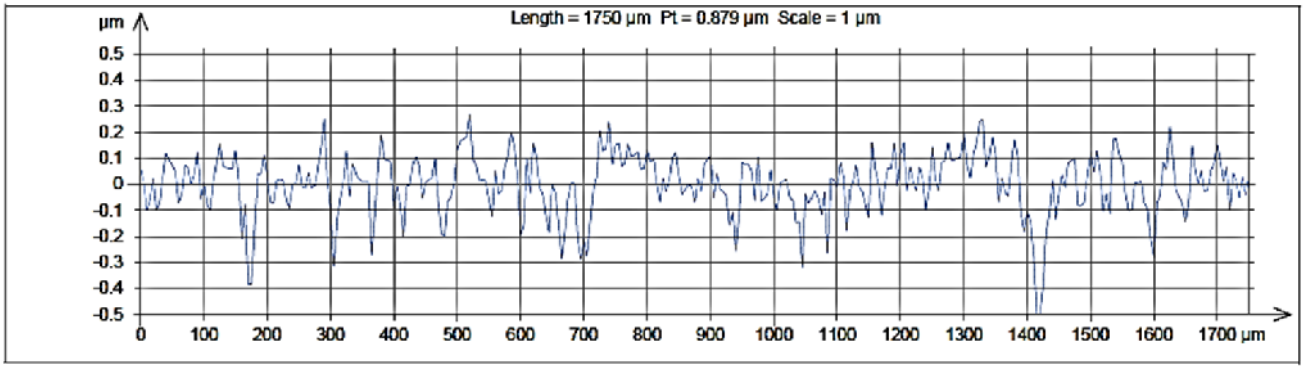
Parameters calculated on the profile AR_ESTER320_10rolos_50h+ 50h > ... > Extracted profile

* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

Ra	= 0.0702 µm
Rq	= 0.0981 µm
Rz	= 0.524 µm
Rt	= 1.2 µm
Rp	= 0.19 µm
Rv	= 0.334 µm
Rsk	= -3.11
Rku	= 28.3

Profile in the area of effect of board (Red Zone)



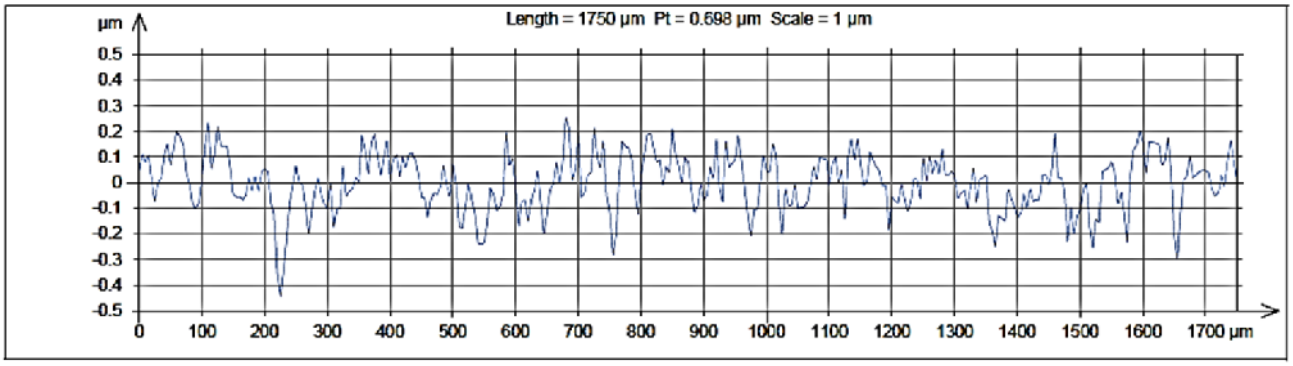
Parameters calculated on the profile AR_ESTER320_10rolos_50h+ 50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.0705 µm
   Rq     = 0.0917 µm
   Rz     = 0.412 µm
   Rt     = 0.682 µm
   Rp     = 0.181 µm
   Rv     = 0.231 µm
   Rsk    = -0.58
   Rku    = 4.16
```

Profile in the contact zone (Blue Zone)



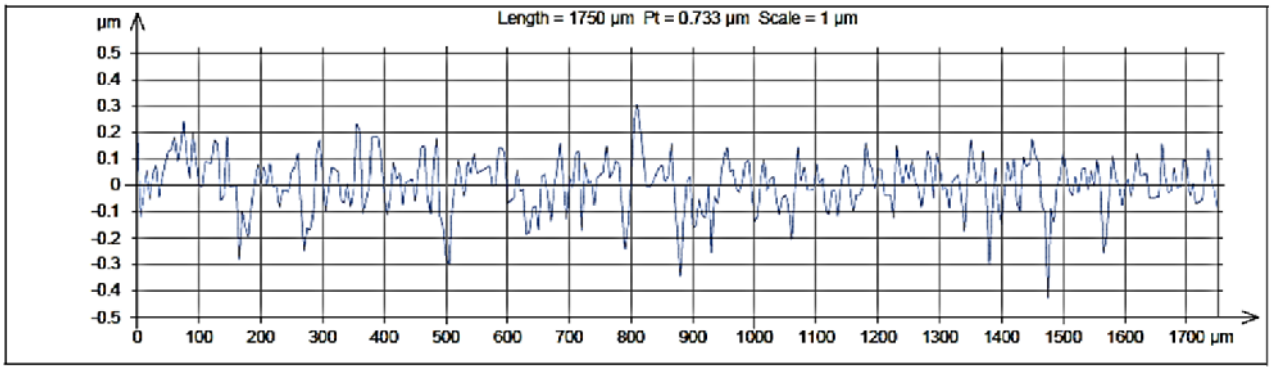
Parameters calculated on the profile AR_ESTER320_10rolos_50h+ 50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.0677 µm
   Rq     = 0.0849 µm
   Rz     = 0.395 µm
   Rt     = 0.557 µm
   Rp     = 0.165 µm
   Rv     = 0.23 µm
   Rsk    = -0.641
   Rku    = 4.18
```

Profile in the outer zone (Green zone)



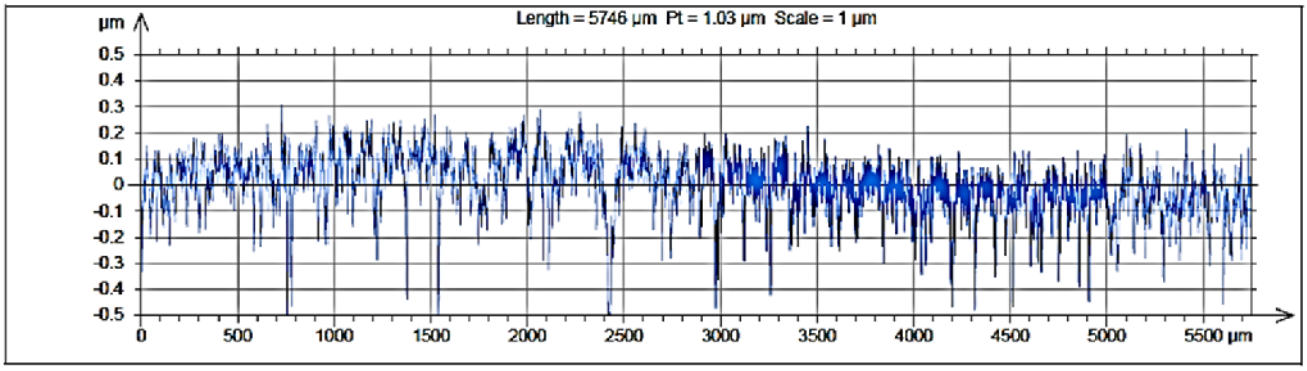
Parameters calculated on the profile AR_ESTER320_10rolos_50h+50h > ... > Roughness, Gaussian Filter, 250 µm

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

Roughness Parameters, Gaussian filter, 250 µm

   Ra     = 0.0681 µm
   Rq     = 0.0876 µm
   Rz     = 0.42 µm
   Rt     = 0.572 µm
   Rp     = 0.173 µm
   Rv     = 0.247 µm
   Rsk    = -0.542
   Rku    = 4
```

Profiles in the radial direction

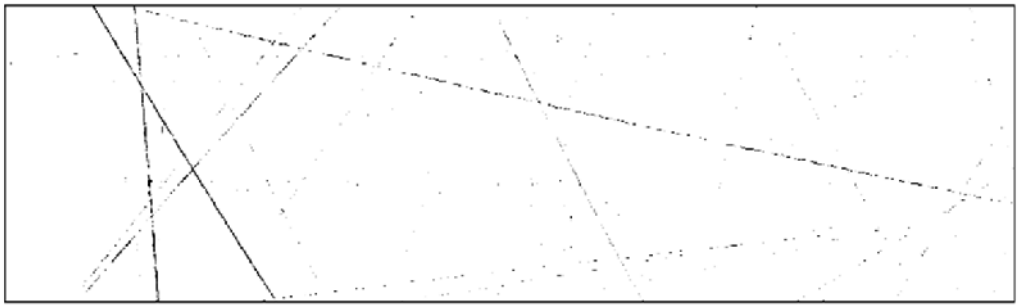


Parameters calculated on the profile AR_ESTER320_10rolos_50h+50h > ... > Extracted profile

```
* Parameters calculated as average value of all sampling lengths.
* A microroughness filtering is used, with a ratio of 2.5 µm.

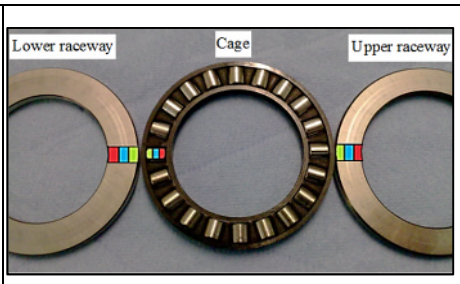
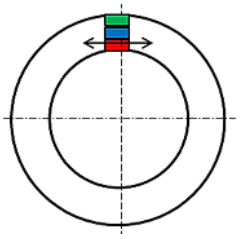
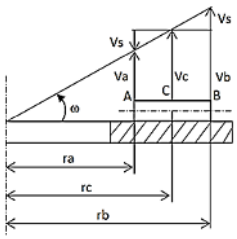
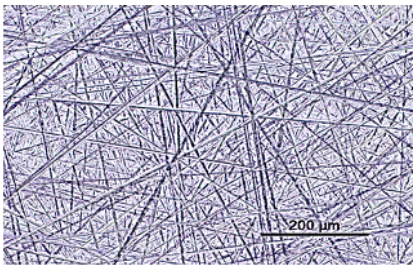
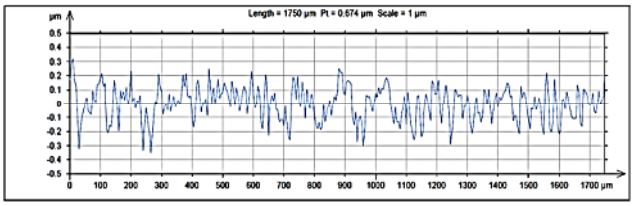
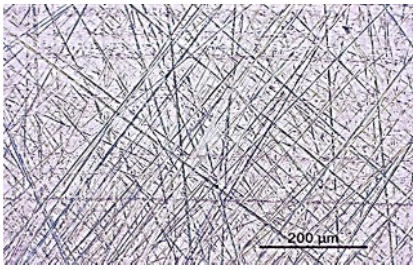
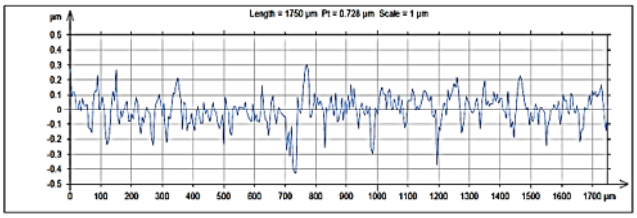
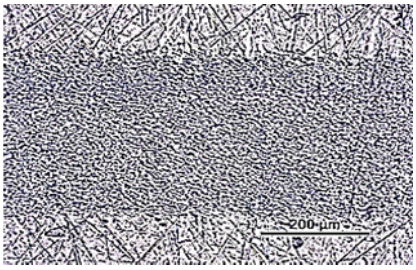
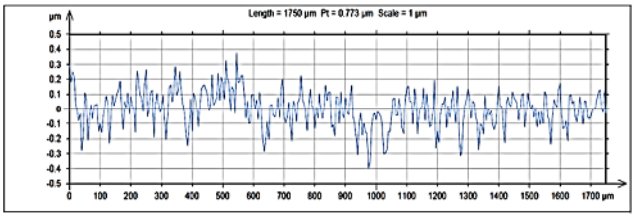
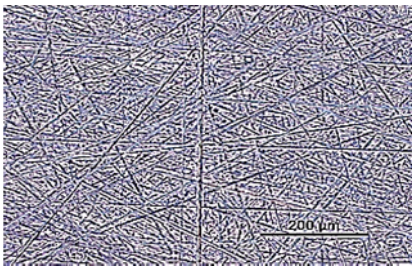
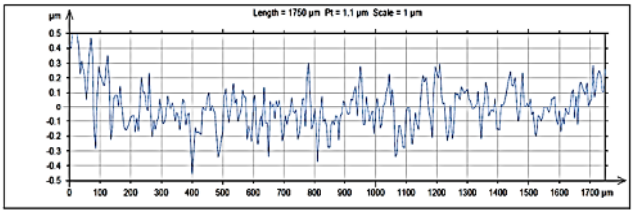
Roughness Parameters, Gaussian filter, 250 µm

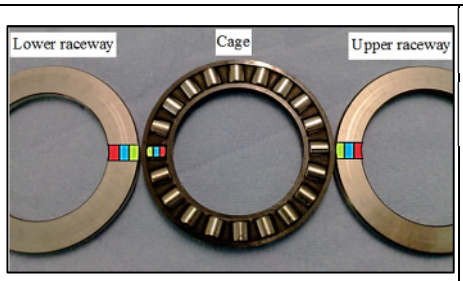
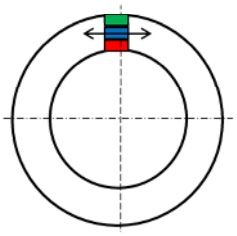
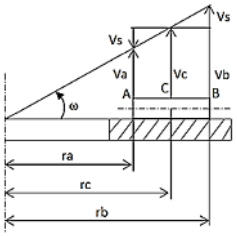
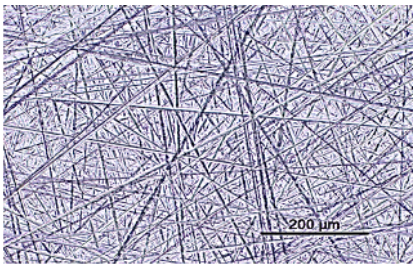
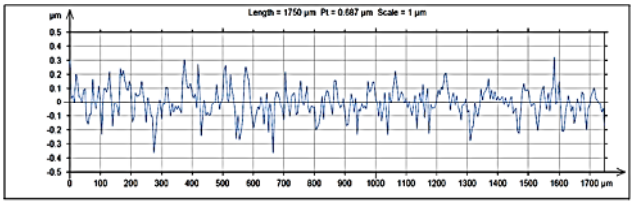
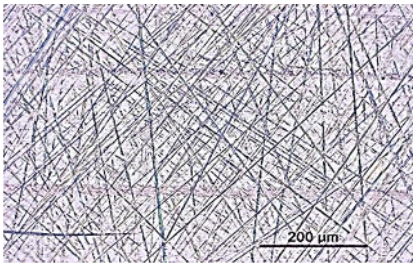
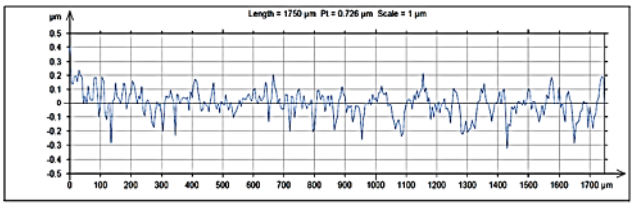
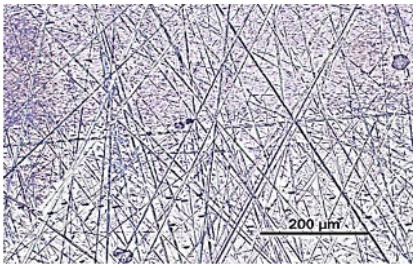
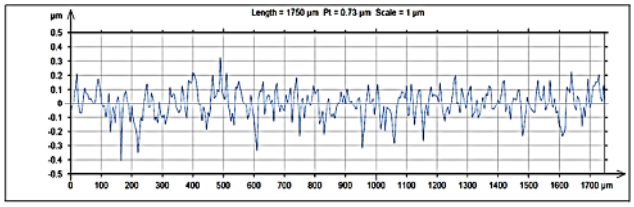
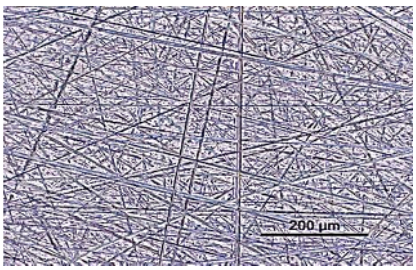
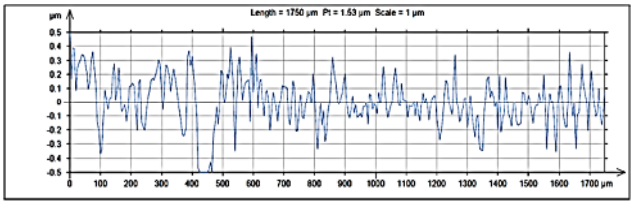
   Ra     = 0.0667 µm
   Rq     = 0.0902 µm
   Rz     = 0.531 µm
   Rt     = 0.969 µm
   Rp     = 0.179 µm
   Rv     = 0.352 µm
   Rsk    = -1.61
   Rku    = 8.57
```



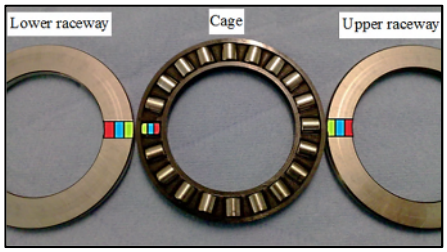
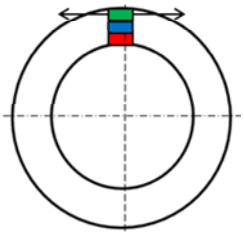
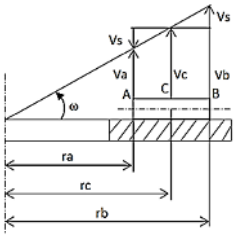
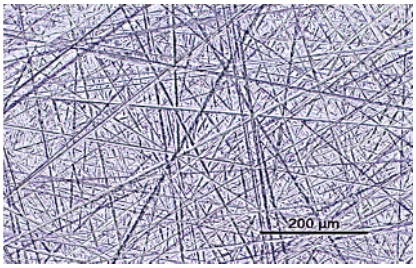
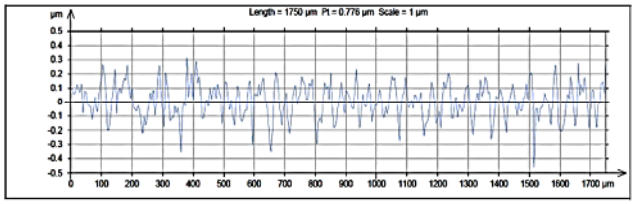
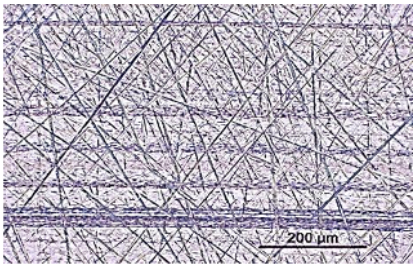
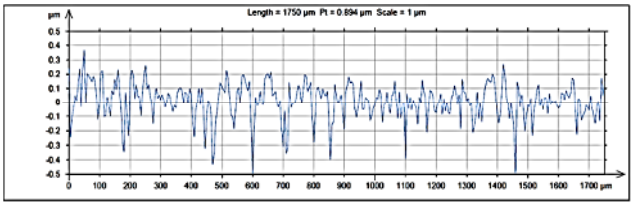
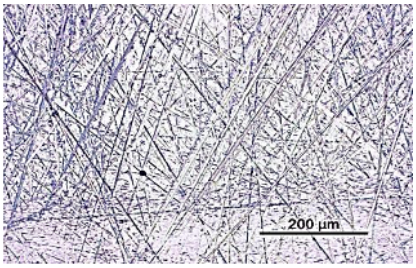
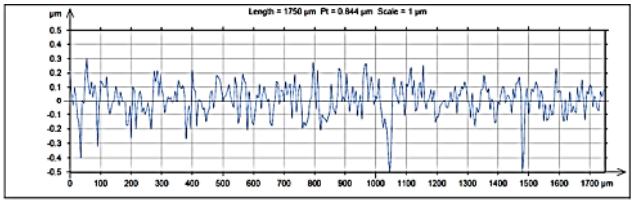
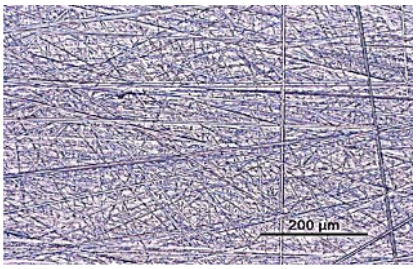
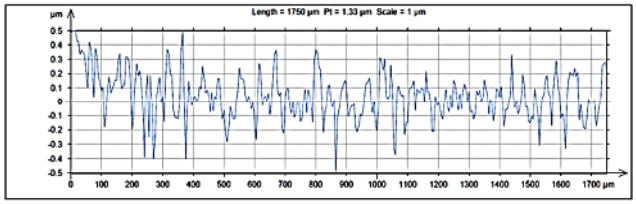
	■	□
Area (%)	0.239	99.8
Volume of void (%)	0.0403	56.6
Volume of material (%)	100	43.4
Volume of void (µm³/µm2)	0.000229	0.658
Volume of material (µm³/µm2)	0.568	0.505
Mean thickness of void (µm)	0.000229	0.658
Mean thickness of material (µm)	0.568	0.505

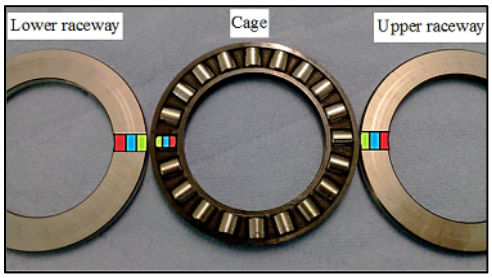
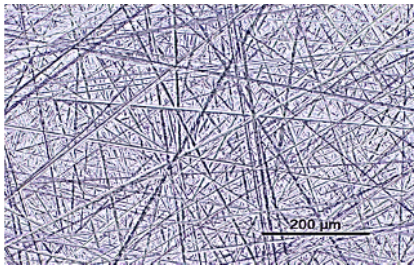
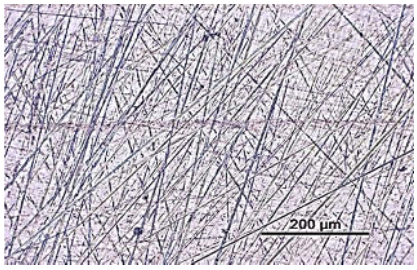
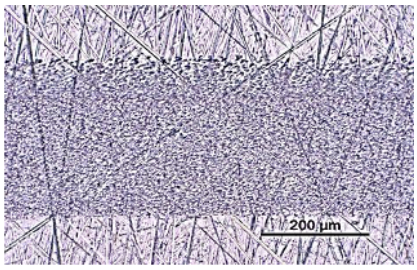
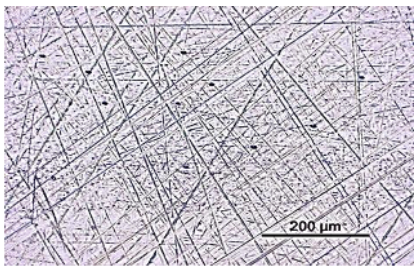
A.14. Comparison between the different oils for the test with TRB - 20 rollers

Upper Raceway (20 rollers) - Red Zone (effect of board)				
		Roughness profile direction 	Velocity profile 	**Specific film thickness** **Mass Loss** **Parameters for comparison**
NEW		 Sa=0,09 µm; Sq=0,12 µm; St=2,29 µm; Sp=1,39 µm;Sv=0,90 µm		/
MIN -320		 Sa=0,09 µm; Sq=0,12 µm; St= 2,08 µm; Sp=1,01 µm; Sv=1,07 µm		λ =1,549 45 mg $\frac{S_P}{S_{P0}} = 0,73$ $\frac{S_V}{S_{V0}} = 1,19$
PAO-320		 Sa=0,10 µm; Sq=0,13 µm; St=3,48 µm; Sp=1,15 µm; Sv=2,33 µm		λ = 1,609 39 mg $\frac{S_P}{S_{P0}} = 0,83$ $\frac{S_V}{S_{V0}} = 2,59$
ESTER-320		 Sa=0,14 µm; Sq=0,19 µm; St=2,77 µm; Sp=1,23 µm; Sv=1,54 µm		λ = 1,443 31 mg $\frac{S_P}{S_{P0}} = 0,88$ $\frac{S_V}{S_{V0}} = 1,71$

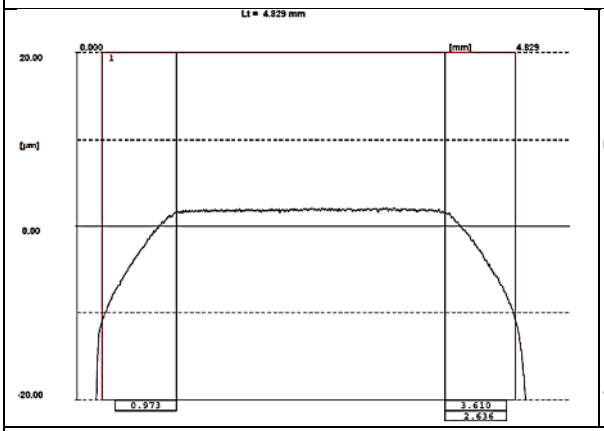
Upper Raceway (20 rollers) - Blue Zone (contact zone)				
		Roughness profile direction 	Velocity profile 	**Specific film thickness** **Mass Loss** **Parameters for comparison**
NEW		 Sa=0,095 µm; Sq=0,12 µm; St=2,29 µm; Sp=1,39 µm; Sv=0,90 µm	/
MIN -320		 Sa=0,09 µm; Sq=0,12 µm; St= 2,08 µm; Sp=1,01 µm; Sv=1,07 µm	λ = 1,549 45 mg $\frac{S_P}{S_{P0}}$ =0,73 $\frac{S_V}{S_{V0}}$ =1,19
PAO-320		 Sa=0,10 µm; Sq=0,13 µm; St=3,48 µm; Sp=1,15 µm; Sv=2,33 µm	λ = 1,609 39 mg $\frac{S_P}{S_{P0}}$ = 0,83 $\frac{S_V}{S_{V0}}$ = 2,59
ESTER-320		 Sa=0,14 µm; Sq=0,19 µm; St=2,77 µm; Sp=1,23 µm; Sv=1,54 µm	λ = 1,443 31 mg $\frac{S_P}{S_{P0}}$ =0,88 $\frac{S_V}{S_{V0}}$ = 1,71

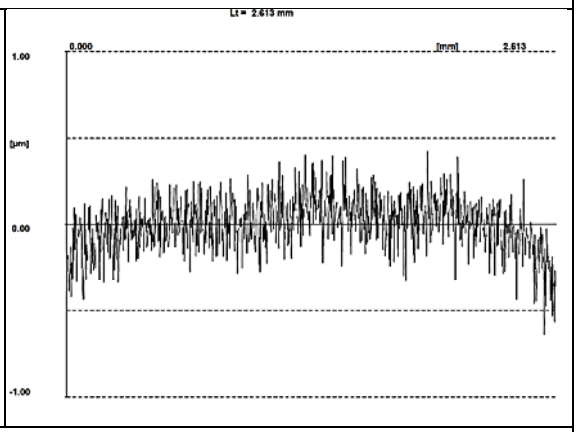
Upper Raceway (20 rollers) - Green Zone

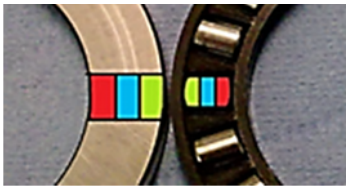
		Roughness profile direction	Velocity profile	Specific film thickness Mass Loss Parameters for comparison
				
NEW		 Sa=0,09 µm; Sq=0,12 µm; St=2,29 µm; Sp=1,39 µm;Sv=0,90 µm	/
MIN -320		 Sa=0,09 µm; Sq=0,12 µm; St= 2,08 µm; Sp=1,01 µm; Sv=1,07 µm	λ = 1,549 45 mg $\frac{S_P}{S_{P0}}$ =0,73 $\frac{S_v}{S_{v0}}$ =1,19
PAO-320		 Sa=0,10 µm; Sq=0,13 µm; St=3,48 µm; Sp=1,15 µm; Sv=2,33 µm	λ = 1,609 39 mg $\frac{S_P}{S_{P0}}$ =0,83 $\frac{S_v}{S_{v0}}$ = 2,59
ESTER-320		 Sa=0,14 µm; Sq=0,19 µm; St=2,77 µm; Sp=1,23 µm; Sv=1,54 µm	λ = 1,443 31 mg $\frac{S_P}{S_{P0}}$ = 0,88 $\frac{S_v}{S_{v0}}$ = 1,71

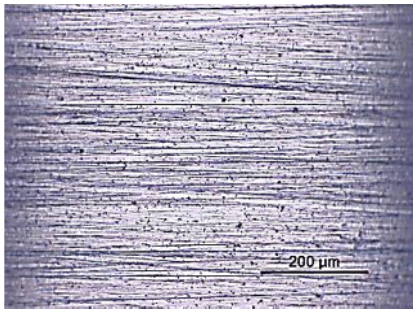
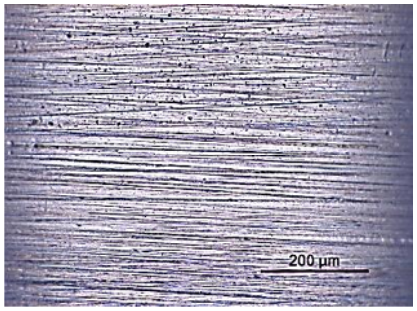
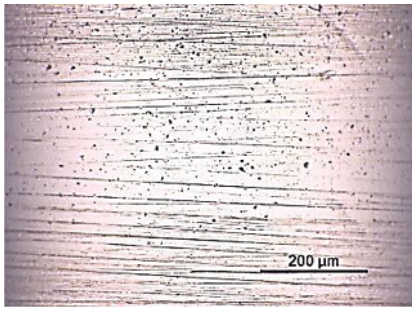
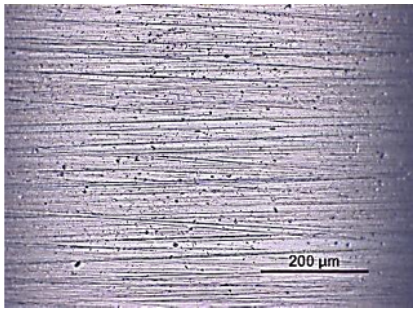
Lower Raceway (20 rollers) - Red Zone (effect of board)				
		**Specific film thickness (λ)** **Ferrometry**	**Operating temperature (°C)**	**Friction Torque** **Coefficient of friction**
NEW		/	/	/
MIN -320		λ=1,509 d = 1 DL = 58,7 Ds = 31,1 CPUC = 89,8	θ_{oil} = 60,0 θ_{cham} = 22,4 $\Delta\theta_{oil-c}$ = 37,6 θ_{lab} = 16,8 $\Delta\theta_{oil-l}$ = 43,2	T = 424,39 Nmm μ_{Kelley} = 0,072 μ_{CFT} = 0,0028 μ_{SL} = 0,0220
PAO-320		λ=1,609 d = 0,1 DL = 40,3 Ds = 18,5 CPUC = 588,0	θ_{oil} = 56,4 θ_{cham} = 25,8 $\Delta\theta_{oil-c}$ = 30,6 θ_{lab} = 18,0 $\Delta\theta_{oil-l}$ = 38,4	T = 451,97 Nmm μ_{Kelley} = 0,071 μ_{CFT} = 0,0030 μ_{SL} = 0,0213
ESTER-320		λ= 1,443 d=1 DL = 59,0 Ds = 21,4 CPUC = 80,4	θ_{oil} = 60,1 θ_{cham} = 24,0 $\Delta\theta_{oil-c}$ = 36,1 θ_{lab} = 16,9 $\Delta\theta_{oil-l}$ = 43,2	T = 448,04 Nmm μ_{Kelley} = 0,071 μ_{CFT} = 0,0030 μ_{SL} = 0,0220

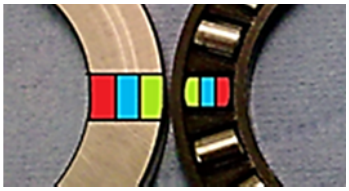
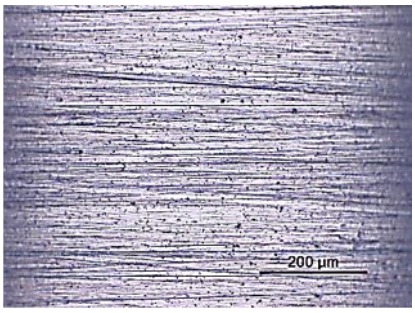
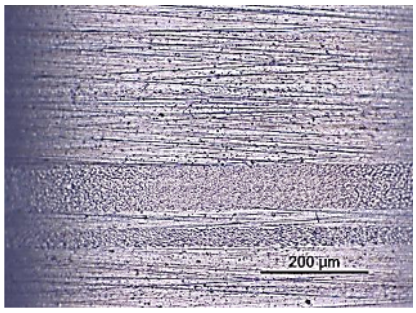
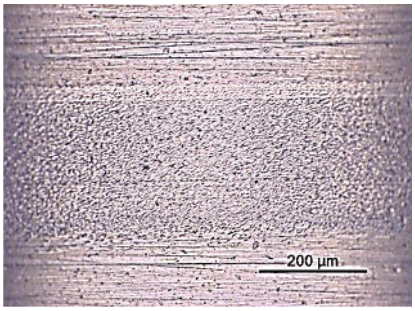
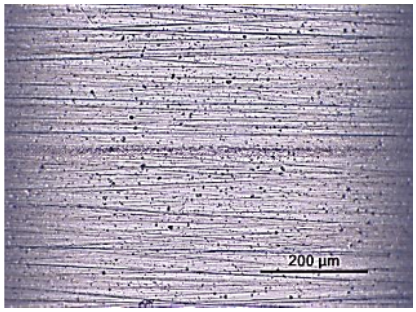
Rollers (20 Rollers) - Red Zone

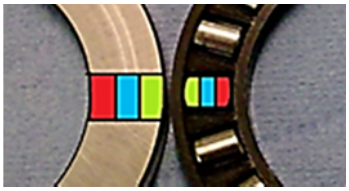
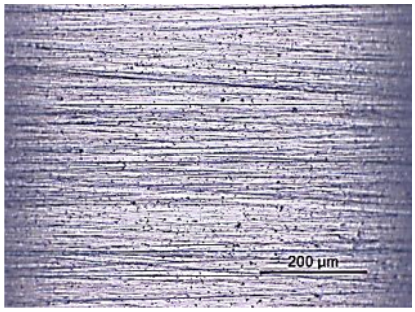
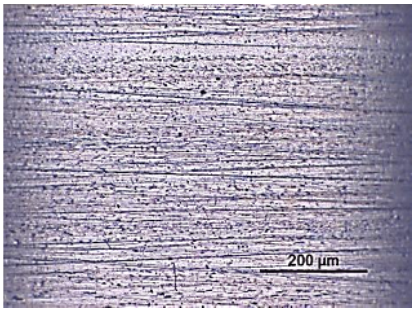
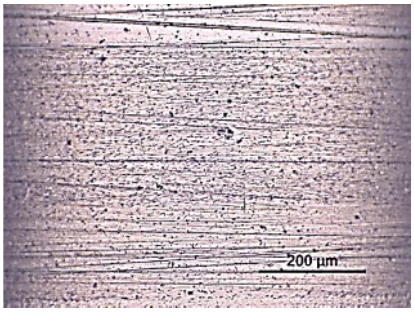
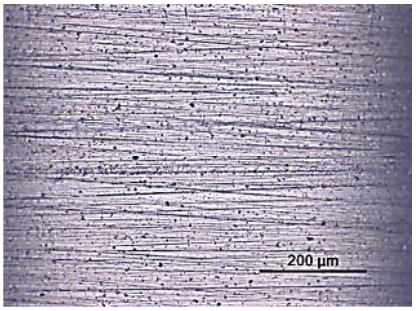






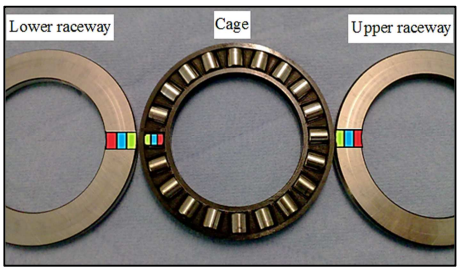
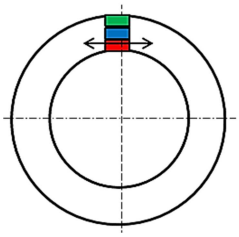
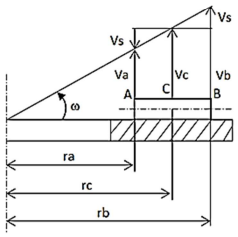
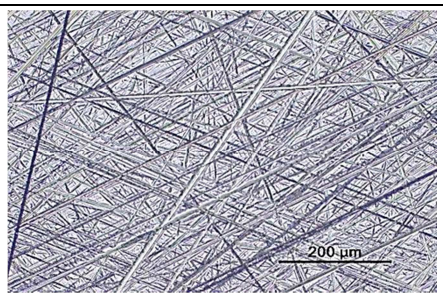
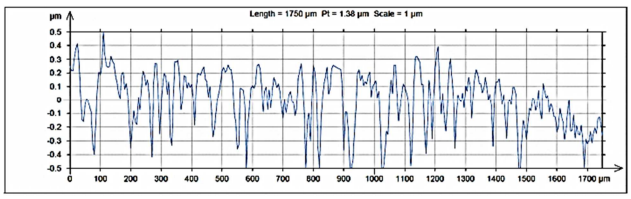
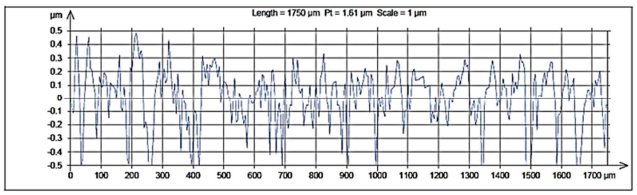
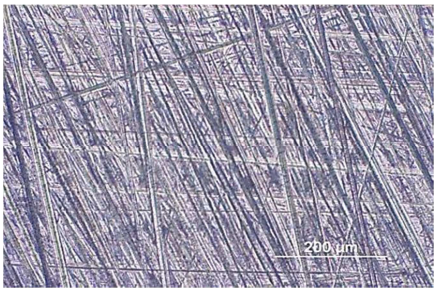
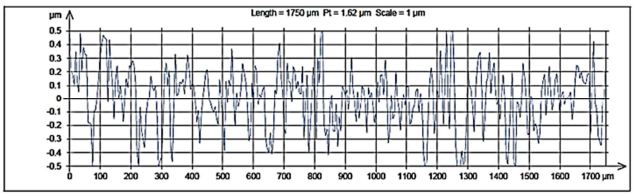
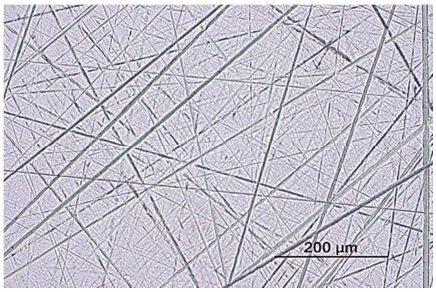
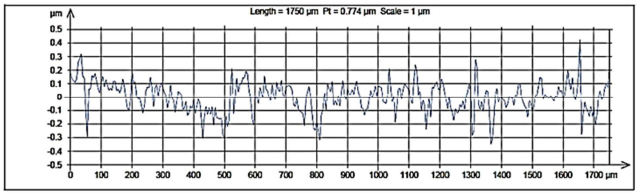
NEW	MIN-320
	
PAO-320	**ESTER-320**
	

Rollers (20 Rollers) - Blue Zone	
	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

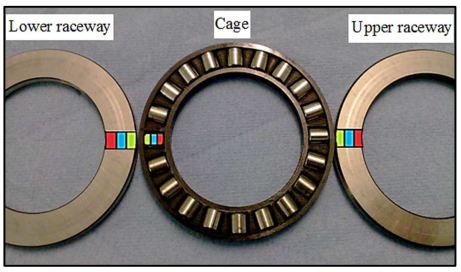
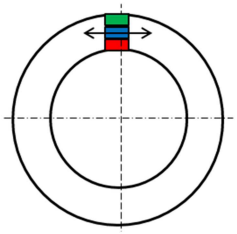
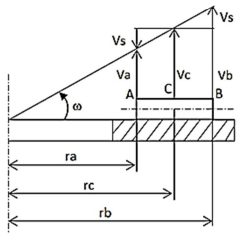
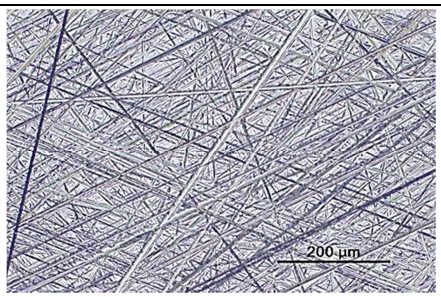
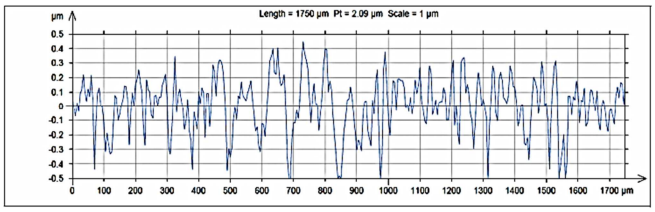
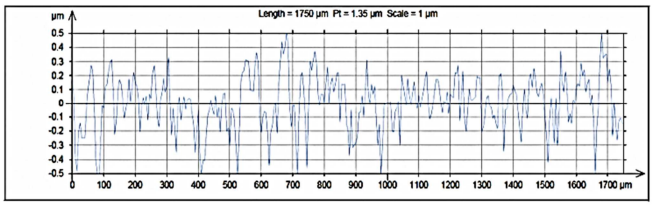
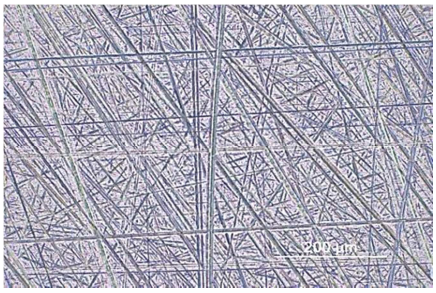
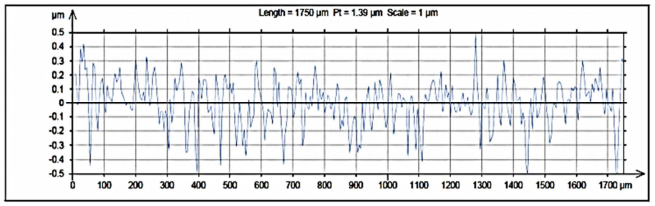
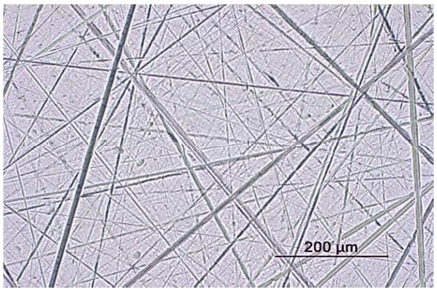
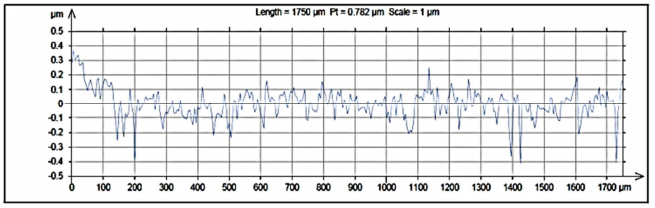
Rollers (20 Rollers) - Green Zone	
	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

A.15. Comparison between the different oils for the test with TRB - 10 rollers (first 50h)

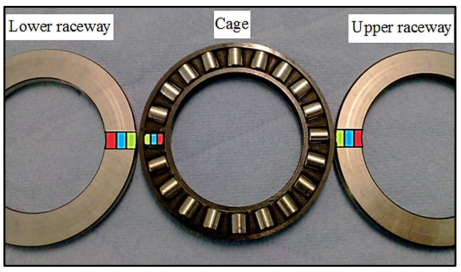
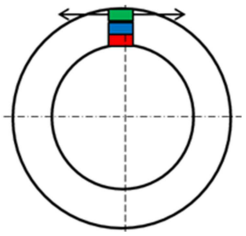
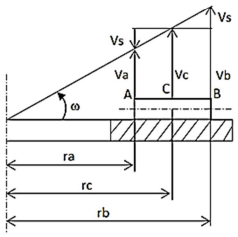
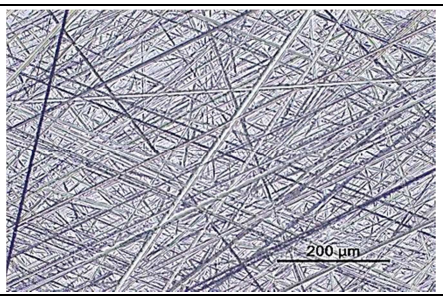
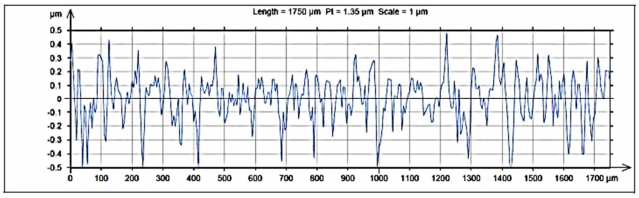
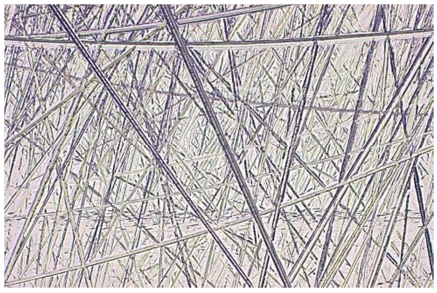
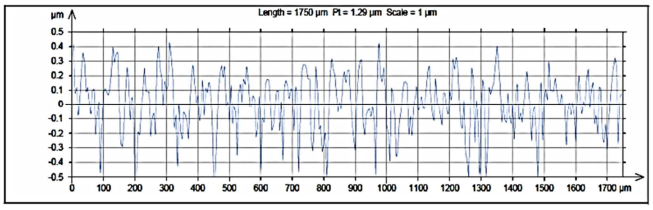
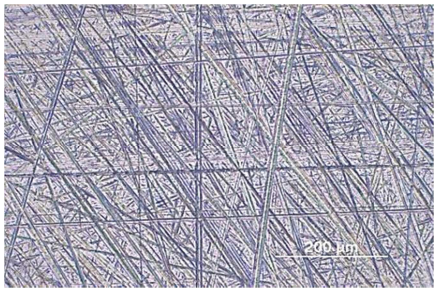
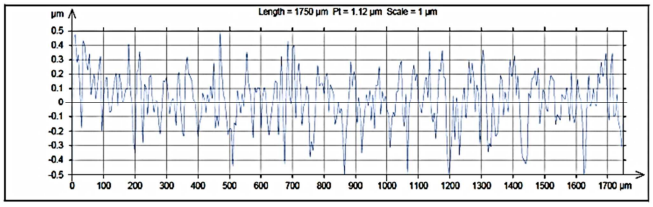
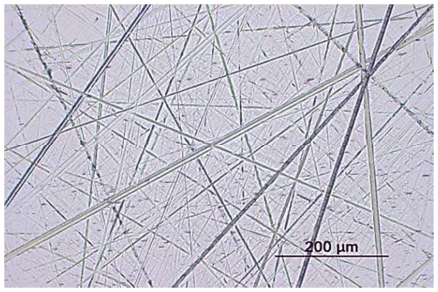
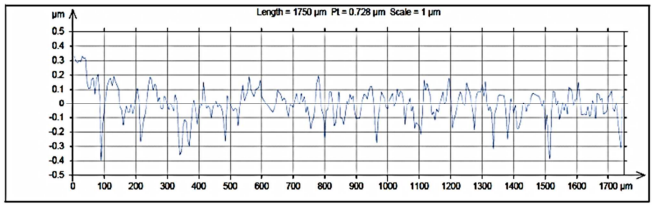
Upper Raceway (10 rollers – 100rpm – first 50h) - Red Zone (effect of board)

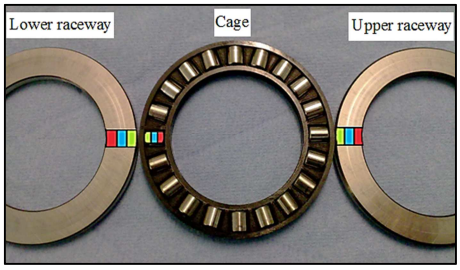
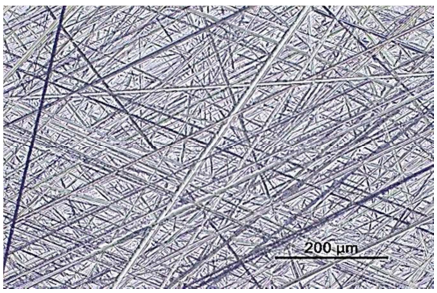
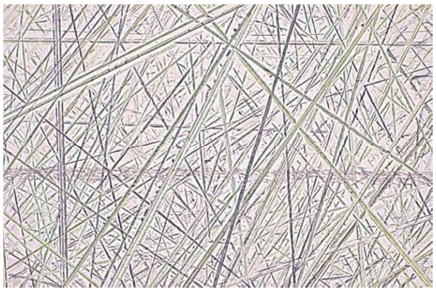
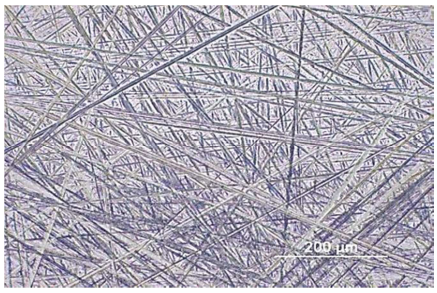
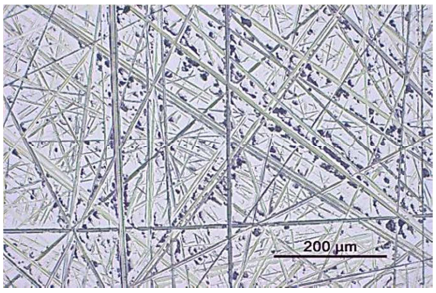
		Roughness profile direction	Velocity profile	**Specific film thickness** **Mass Loss** **Parameters for comparison**
				
NEW		 Sa=0,18 µm; Sq=0,23 µm; St=2,95 µm; Sp=0,92 µm; Sv=2,04 µm	/
MIN -320		 Sa=0,17 µm; Sq=0,22 µm; St=2,91 µm; Sp=1,25 µm; Sv=1,66 µm	λ =0,948 30 mg $\frac{S_P}{S_{P0}}$ =1,36 $\frac{S_V}{S_{V0}}$ = 0,81
PAO-320		 Sa=0,16 µm; Sq=0,21 µm; St=2,73 µm; Sp=1,21 µm; Sv=1,51 µm	λ = 1,374 36 mg $\frac{S_P}{S_{P0}}$ =1,32 $\frac{S_V}{S_{V0}}$ = 0,74
ESTER-320		 Sa=0,09 µm; Sq=0,12 µm; St=2,03 µm; Sp=0,84 µm; Sv=1,18 µm	λ = 1,364 31 mg $\frac{S_P}{S_{P0}}$ =0,91 $\frac{S_V}{S_{V0}}$ = 0,58

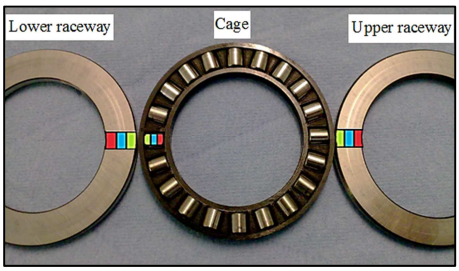
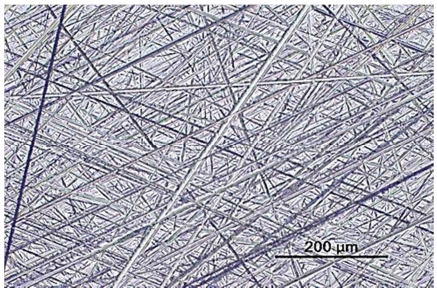
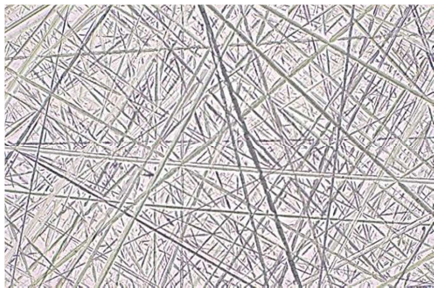
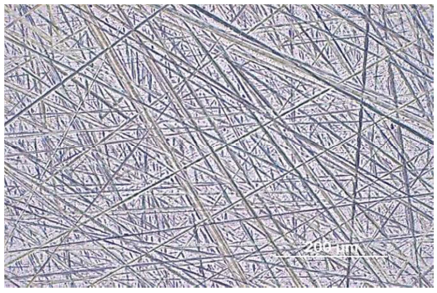
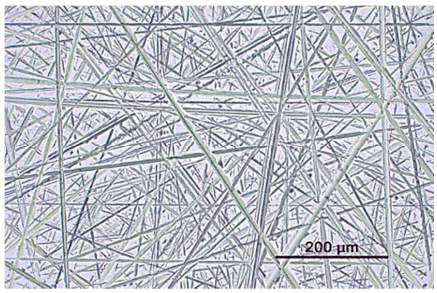
Upper Raceway (10 rollers – 100rpm – first 50h) - Blue Zone (contact zone)

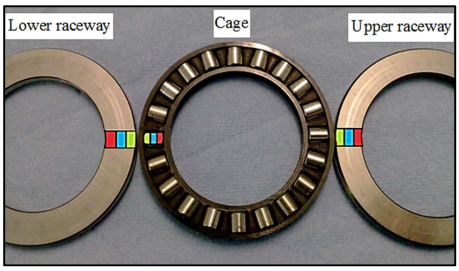
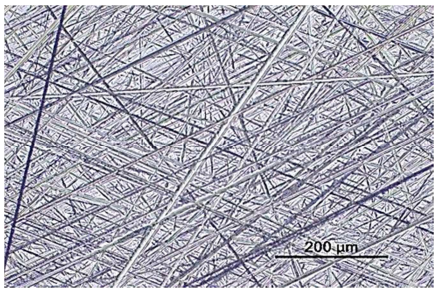
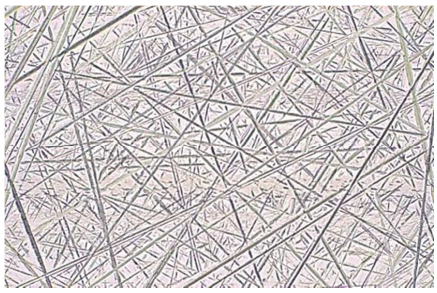
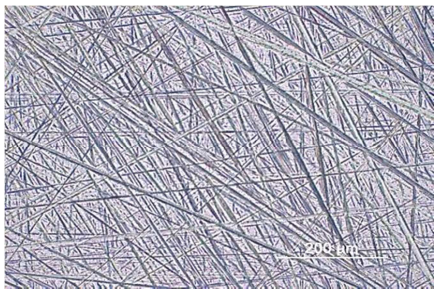
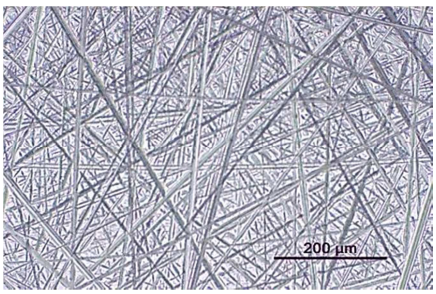
		Roughness profile direction 	Velocity profile 	**Specific film thickness** **Mass Loss** **Parameters for comparison**
NEW		 Sa=0,18 µm; Sq=0,23 µm; St=2,95 µm; Sp=0,92 µm; Sv=2,04 µm		/
MIN -320		 Sa=0,17 µm; Sq=0,22 µm; St=2,91 µm; Sp=1,25 µm; Sv=1,66 µm		λ =0,948 30 mg $\frac{S_P}{S_{P0}}$ =1,36 $\frac{S_v}{S_{v0}}$ = 0,81
PAO-320		 Sa=0,16 µm; Sq=0,21 µm; St=2,73 µm; Sp=1,21 µm; Sv=1,51 µm		λ = 1,374 36 mg $\frac{S_P}{S_{P0}}$ =1,32 $\frac{S_v}{S_{v0}}$ = 0,74
ESTER-320		 Sa=0,09 µm; Sq=0,12 µm; St=2,03 µm; Sp=0,84 µm; Sv=1,18 µm		λ = 1,364 31 mg $\frac{S_P}{S_{P0}}$ =0,91 $\frac{S_v}{S_{v0}}$ = 0,58

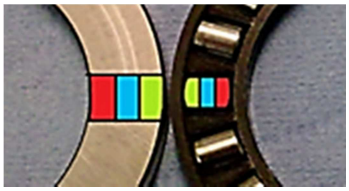
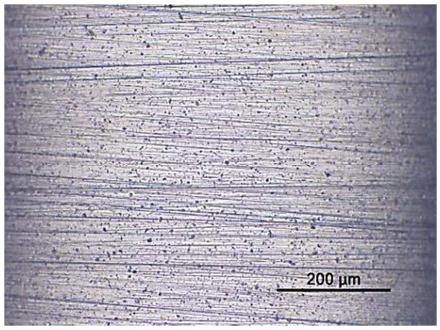
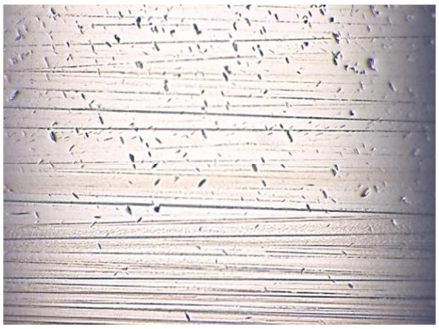
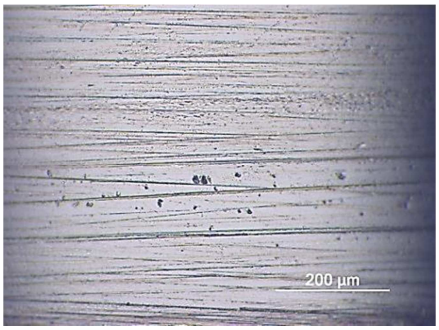
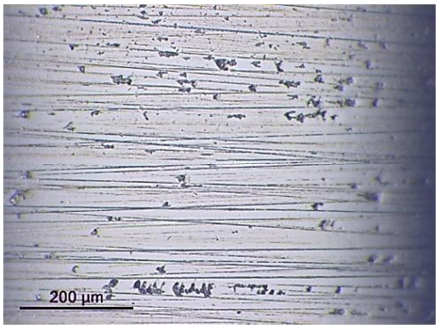
Upper Raceway (10 rollers – 100rpm – first 50h) - Green Zone

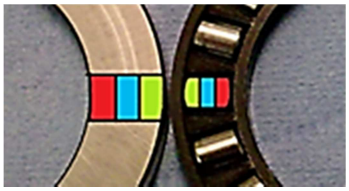
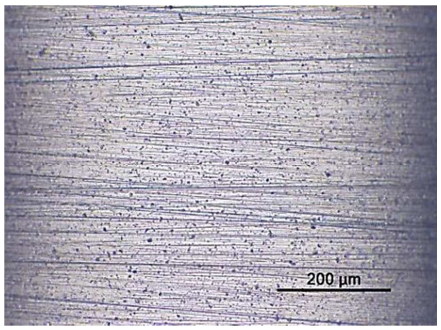
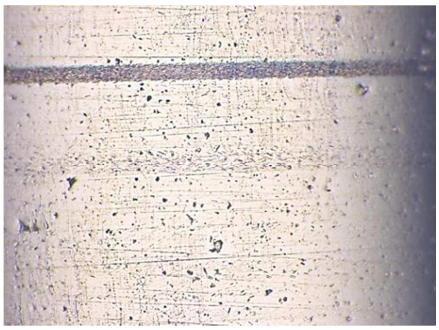
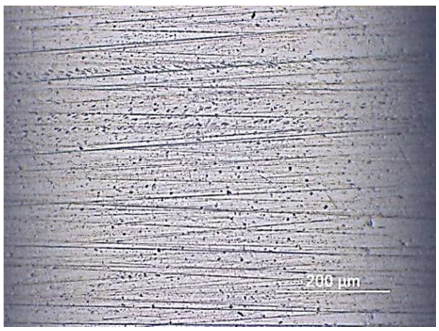
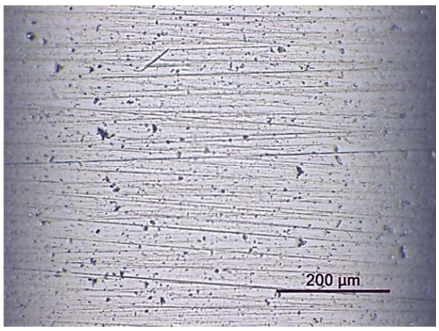
		Roughness profile direction	Velocity profile	Specific film thickness Mass Loss Parameters for comparison
				
NEW		 Sa=0,18 µm; Sq=0,23 µm; St=2,95 µm; Sp=0,92 µm; Sv=2,04 µm	/
MIN -320		 Sa=0,17 µm; Sq=0,22 µm; St=2,91 µm; Sp=1,25 µm; Sv=1,66 µm	λ =0,948 30 mg $\frac{S_P}{S_{P0}}$ =1,36 $\frac{S_V}{S_{V0}}$ = 0,81
PAO-320		 Sa=0,16 µm; Sq=0,21 µm; St=2,73 µm; Sp=1,21 µm; Sv=1,51 µm	λ = 1,374 36 mg $\frac{S_P}{S_{P0}}$ =1,32 $\frac{S_V}{S_{V0}}$ = 0,74
ESTER-320		 Sa=0,09 µm; Sq=0,12 µm; St=2,03 µm; Sp=0,84 µm; Sv=1,18 µm	λ = 1,364 31 mg $\frac{S_P}{S_{P0}}$ =0,91 $\frac{S_V}{S_{V0}}$ = 0,58

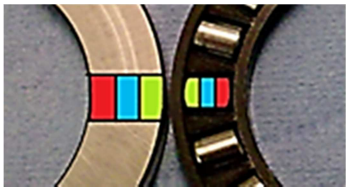
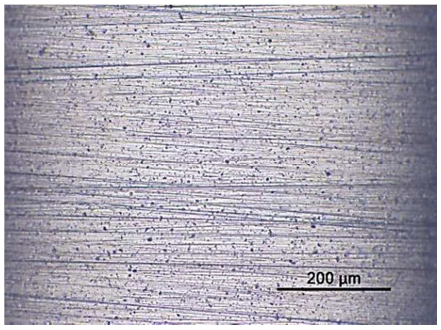
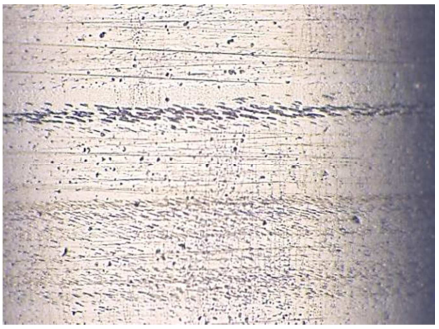
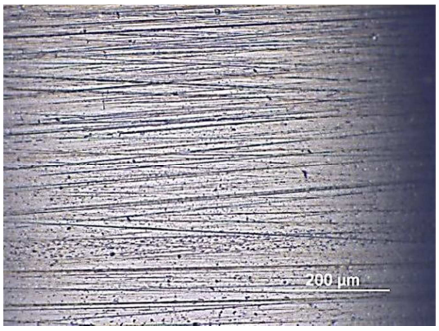
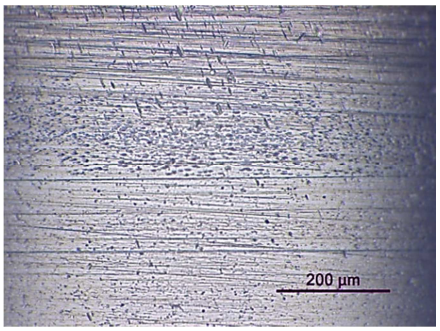
Lower Raceway (10 rollers – 100rpm – first 50h) - Red Zone (effect of board)				
		**Specific film thickness (λ)**	**Operating temperature (°C)**	**Friction Torque** **Coefficient of friction**
NEW		/	/	/
MIN -320		λ=0,948 d = 0,1 DL = 24,9 Ds = 5,1 CPUC = 300,0	$\theta_{oil} = 92,0$ $\theta_{cham} = 35,9$ $\Delta\theta_{oil-c} = 56,1$ $\theta_{lab} = 25,6$ $\Delta\theta_{oil-l} = 66,4$	T = 385,48 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0025
PAO-320		λ = 1,374 d = 0,1 DL = 26,9 Ds = 7,9 CPUC = 348,0	$\theta_{oil} = 79,8$ $\theta_{cham} = 33,1$ $\Delta\theta_{oil-c} = 46,7$ $\theta_{lab} = 24,3$ $\Delta\theta_{oil-l} = 55,5$	T = 332,34 Nmm μ_{Kelley} = 0,065 μ_{CFT} = 0,0022
ESTER-320		λ= 1,364 d = 1 DL = 54,4 Ds = 10,6 CPUC = 650,0	$\theta_{oil} = 80,7$ $\theta_{cham} = 33,3$ $\Delta\theta_{oil-c} = 47,4$ $\theta_{lab} = 24,8$ $\Delta\theta_{oil-l} = 55,9$	T = 337,46 Nmm μ_{Kelley} =0,064 μ_{CFT} = 0,0022

Lower Raceway (10 rollers – 100rpm – first 50h) - Blue Zone (contact zone)				
		**Specific film thickness (λ)**	**Operating temperature (°C)**	**Friction Torque** **Coefficient of friction**
NEW		/	/	/
MIN -320		λ=0,948 d = 0,1 DL = 24,9 Ds = 5,1 CPUC = 300,0	$\theta_{oil} = 92,0$ $\theta_{cham} = 35,9$ $\Delta\theta_{oil-c} = 56,1$ $\theta_{lab} = 25,6$ $\Delta\theta_{oil-l} = 66,4$	T = 385,48 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0025
PAO-320		λ = 1,374 d = 0,1 DL = 26,9 Ds = 7,9 CPUC = 348,0	$\theta_{oil} = 79,8$ $\theta_{cham} = 33,1$ $\Delta\theta_{oil-c} = 46,7$ $\theta_{lab} = 24,3$ $\Delta\theta_{oil-l} = 55,5$	T = 332,34 Nmm μ_{Kelley} = 0,065 μ_{CFT} = 0,0022
ESTER-320		λ= 1,364 d = 1 DL = 54,4 Ds = 10,6 CPUC = 650,0	$\theta_{oil} = 80,7$ $\theta_{cham} = 33,3$ $\Delta\theta_{oil-c} = 47,4$ $\theta_{lab} = 24,8$ $\Delta\theta_{oil-l} = 55,9$	T = 337,46 Nmm μ_{Kelley} =0,064 μ_{CFT} = 0,0022

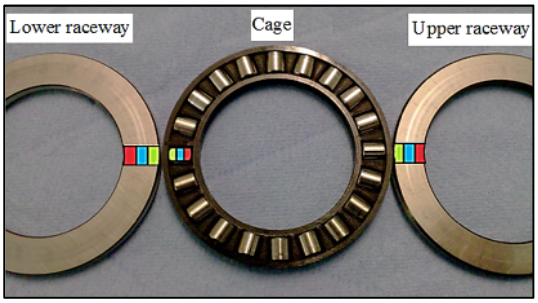
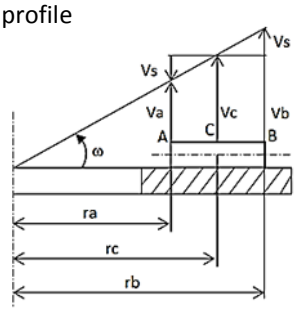
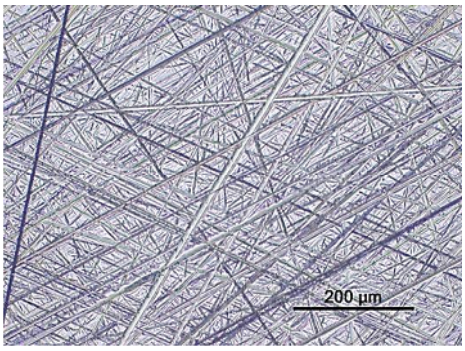
Lower Raceway (10 rollers – 100rpm – first 50h) - Green Zone				
		**Specific film thickness (λ)**	**Operating temperature (°C)**	**Friction Torque** **Coefficient of friction**
NEW		/	/	/
MIN -320		λ=0,948 d = 0,1 DL = 24,9 Ds = 5,1 CPUC = 300,0	$\theta_{oil} = 92,0$ $\theta_{cham} = 35,9$ $\Delta\theta_{oil-c} = 56,1$ $\theta_{lab} = 25,6$ $\Delta\theta_{oil-l} = 66,4$	T = 385,48 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0025
PAO-320		λ = 1,374 d = 0,1 DL = 26,9 Ds = 7,9 CPUC = 348,0	$\theta_{oil} = 79,8$ $\theta_{cham} = 33,1$ $\Delta\theta_{oil-c} = 46,7$ $\theta_{lab} = 24,3$ $\Delta\theta_{oil-l} = 55,5$	T = 332,34 Nmm μ_{Kelley} = 0,065 μ_{CFT} = 0,0022
ESTER-320		λ= 1,364 d = 1 DL = 54,4 Ds = 10,6 CPUC = 650,0	$\theta_{oil} = 80,7$ $\theta_{cham} = 33,3$ $\Delta\theta_{oil-c} = 47,4$ $\theta_{lab} = 24,8$ $\Delta\theta_{oil-l} = 55,9$	T = 337,46 Nmm μ_{Kelley} =0,064 μ_{CFT} = 0,0022

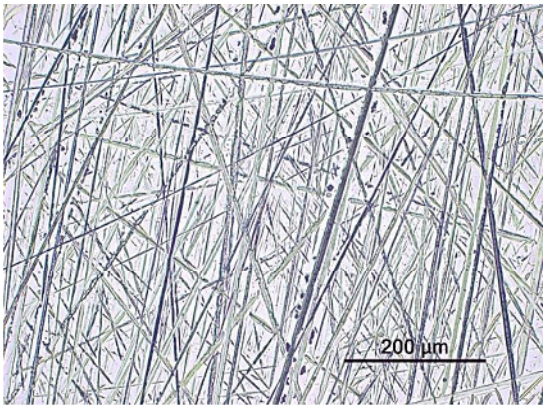
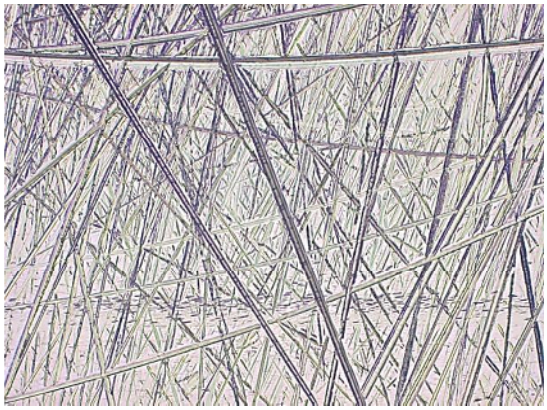
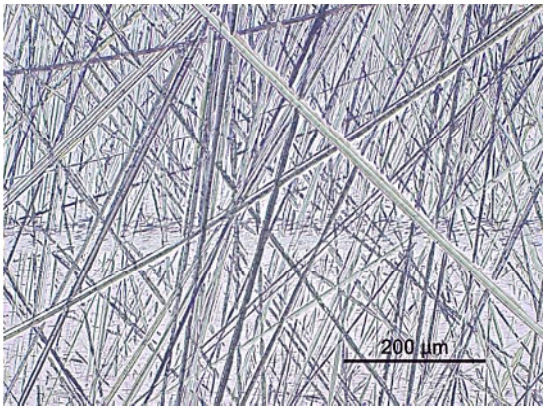
Rollers (10 rollers – 100rpm – first 50h) - Red Zone	
	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

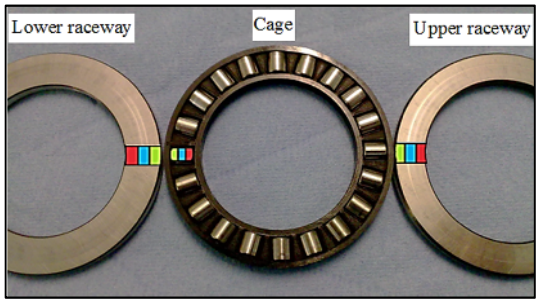
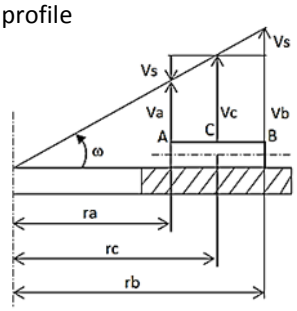
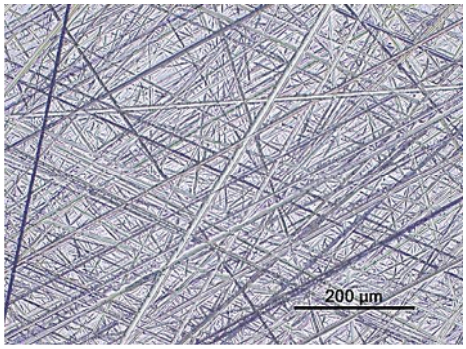
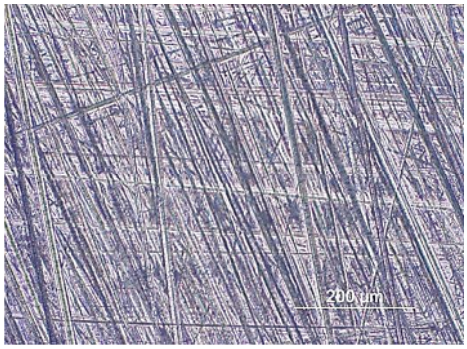
Rollers (10 rollers – 100rpm – first 50h) - Blue Zone	
	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

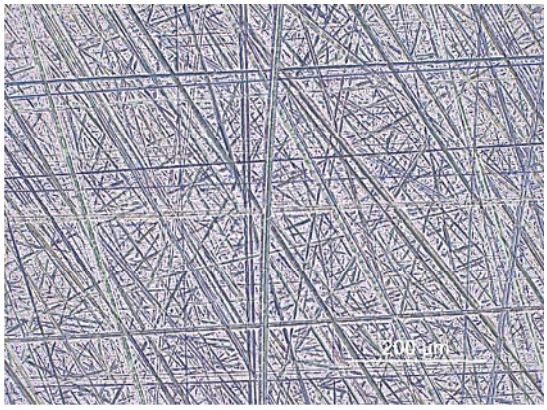
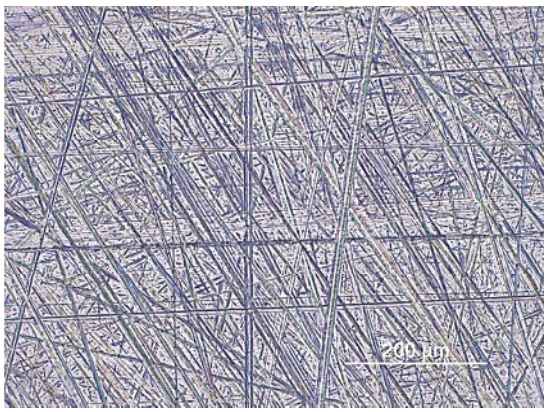
Rollers (10 rollers – 100rpm – first 50h) - Green Zone	
	
NEW	**MIN-320**
	
PAO-320	**ESTER-320**
	

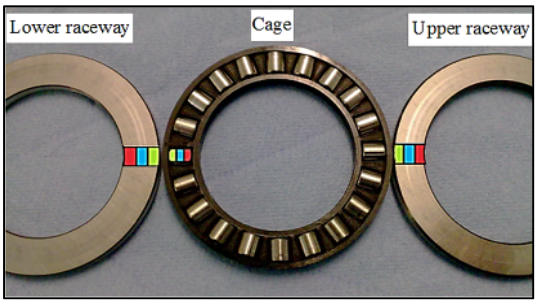
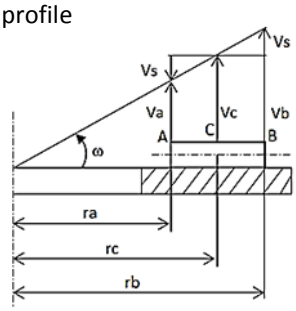
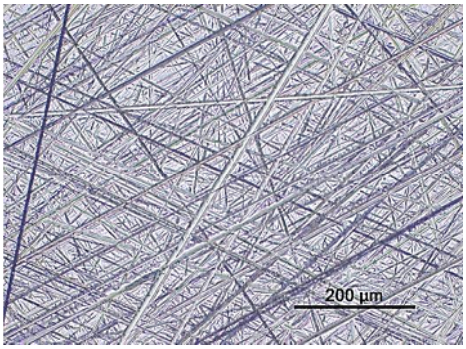
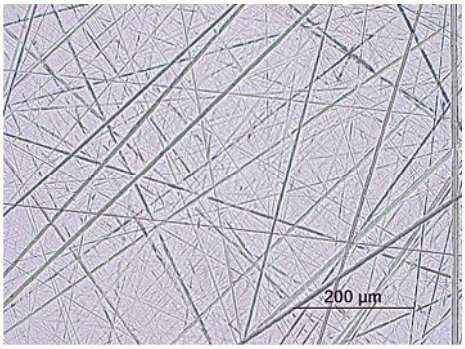
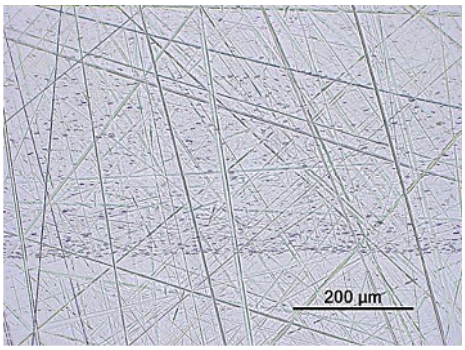
A.16. Comparison between the different oils for the test with TRB - 10 rollers (second 50h)

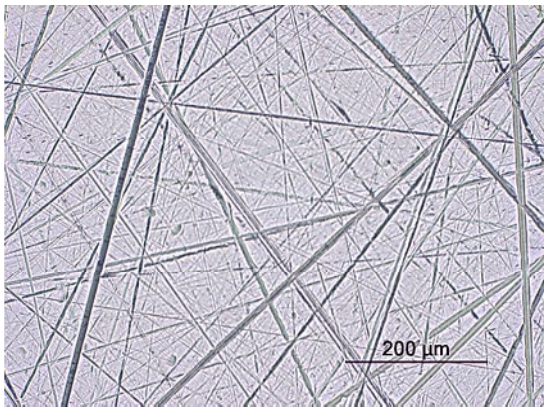
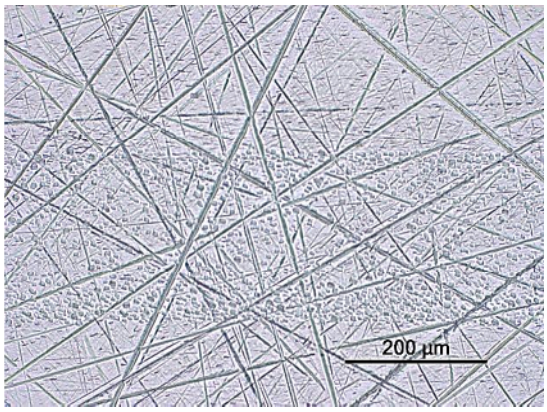
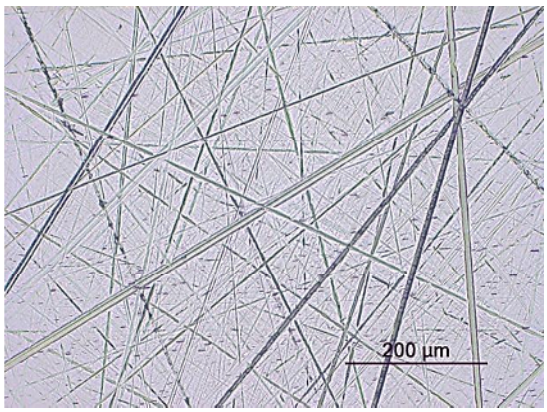
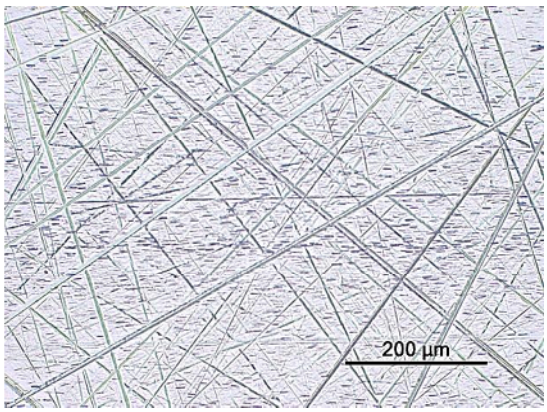
MIN 320 - Upper Raceway - Red Zone (comparison)				
		Velocity profile 		**Specific film thickness** **Mass Loss** **Parameters for comparison**
1000 rpm with 10rollers - 50h+50h				
NEW		Sa=0,18 µm; Sq=0,23 µm; St=2,95 µm; Sp=0,92 µm; Sv=2,04 µm	/	/
10rollers - first 50h		Sa= 0,17 µm; Sq=0,22 µm; St=2,91 µm; Sp=1,25 µm; Sv=1,66 µm T = 385,48 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0025	θ_{oil} = 92,0 θ_{cham} = 35,9 $\Delta\theta_{oil-c}$ = 56,1 θ_{lab} = 25,6 $\Delta\theta_{oil-l}$ = 66,4	λ = 0,948 30 mg $\frac{S_P}{S_{P0}}$ = 1,36 $\frac{S_V}{S_{V0}}$ = 0,81
10 rollers - second 50h		Sa= 0,14 µm; Sq=0,21 µm; St=2,94 µm; Sp=1,19 µm; Sv=1,7 5µm T = 401,77 Nmm μ_{Kelley} = 0,069 μ_{CFT} = 0,0026	θ_{oil} = 92,4 θ_{cham} = 37,4 $\Delta\theta_{oil-c}$ = 55,0 θ_{lab} = 26,9 $\Delta\theta_{oil-l}$ = 65,5	λ = 0,938 1 mg $\frac{S_P}{S_{P0}}$ = 1,29 $\frac{S_V}{S_{V0}}$ = 0,86

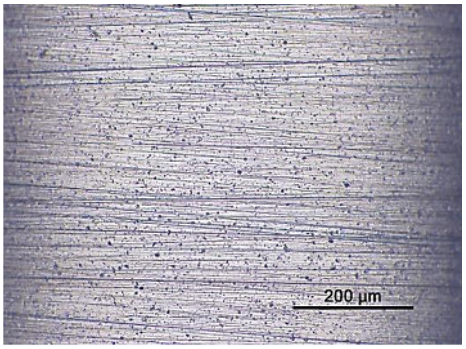
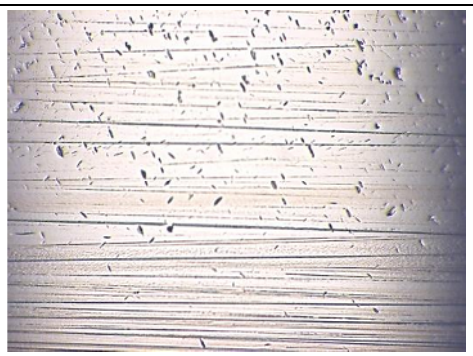
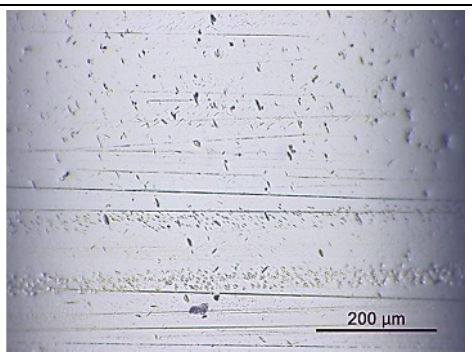
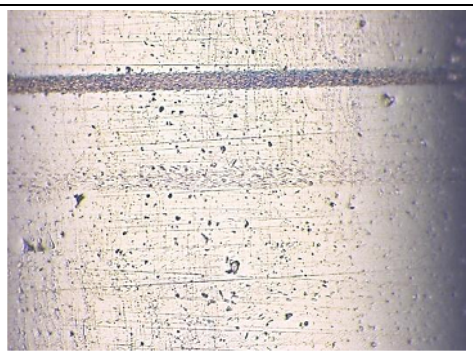
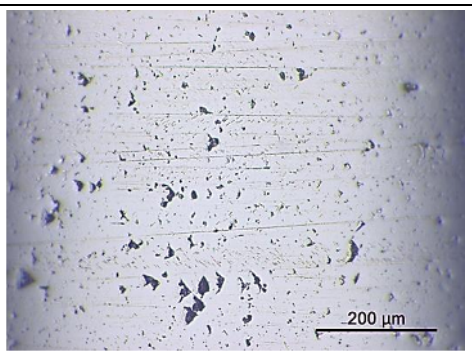
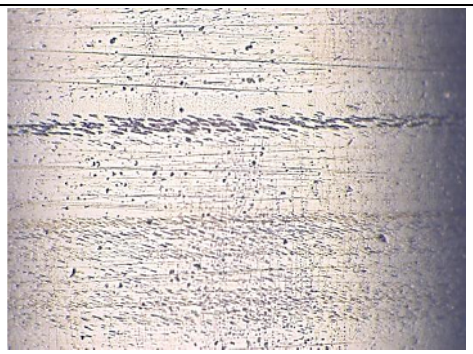
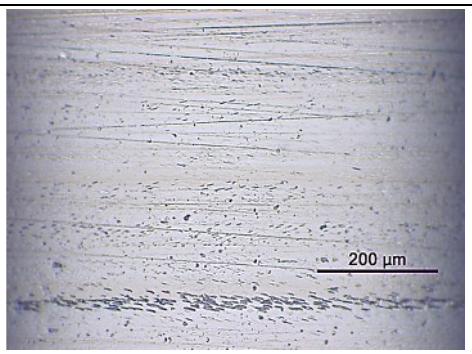
MIN-320	
Upper Raceway (1000 rpm with 10rollers - 50h+50h) - Blue Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	
Upper Raceway (1000 rpm with 10rollers - 50h+50h) - Green Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	

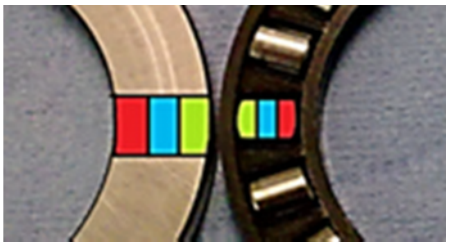
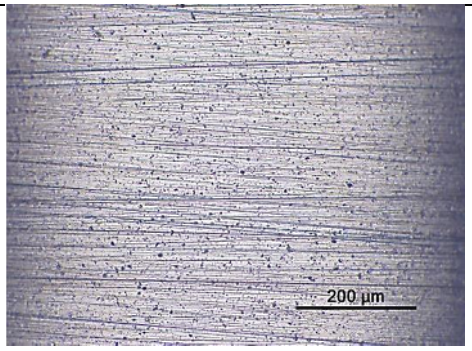
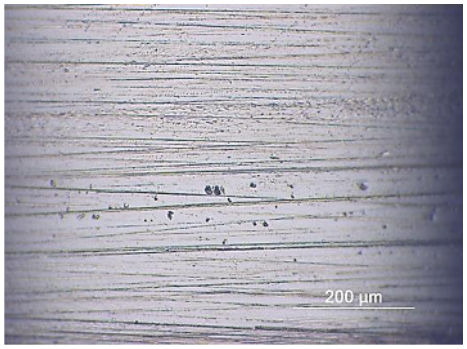
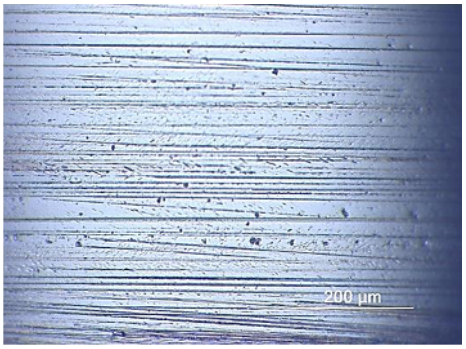
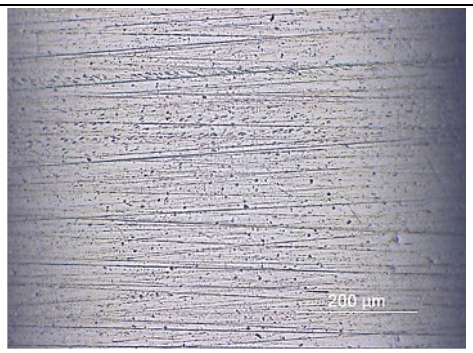
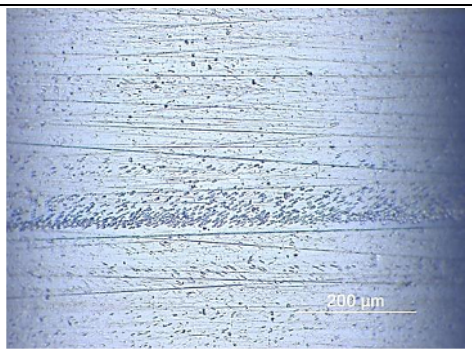
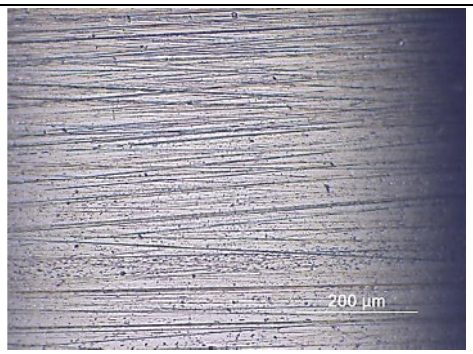
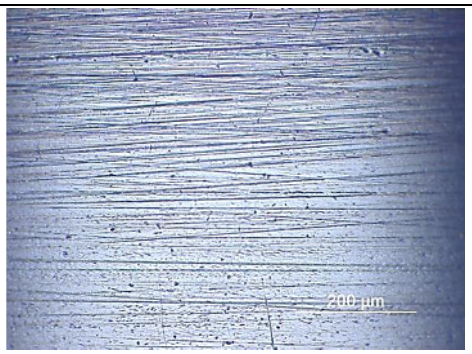
PAO 320 - Upper Raceway - Red Zone (comparison)				
		Velocity profile 		**Specific film thickness** **Mass Loss** **Parameters for comparison**
1000 rpm with 10rollers - 50h+50h				
NEW		Sa=0,18 µm; Sq=0,23 µm; St=2,95 µm; Sp=0,92 µm; Sv=2,04 µm	/	/
10rollers - first 50h		Sa=0,16 µm; Sq=0,21µm; St=2,73 µm; Sp=1,21 µm; Sv=1,51 µm T = 332,34 Nmm μ_{Kelley} = 0,065 μ_{CFT} = 0,0022	θ_{oil} = 79,8 θ_{cham} = 33,1 $\Delta\theta_{oil-c}$ = 46,7 θ_{lab} = 24,3 $\Delta\theta_{oil-l}$ = 55,5	λ = 1,374 36 mg $\frac{S_P}{S_{P0}}$ = 1,32 $\frac{S_v}{S_{v0}}$ = 0,74
10 rollers - second 50h		Sa=0,15 µm; Sq=1,15 µm; St=2,43 µm; Sp=1,15 µm; Sv=1,28 µm T = 308,69 Nmm μ_{Kelley} = 0,064 μ_{CFT} =0,0020	θ_{oil} = 77,2 θ_{cham} = 34,2 $\Delta\theta_{oil-c}$ = 43,0 θ_{lab} = 24,9 $\Delta\theta_{oil-l}$ = 52,3	λ = 1,470 0 mg $\frac{S_P}{S_{P0}}$ = 1,25 $\frac{S_v}{S_{v0}}$ = 0,63

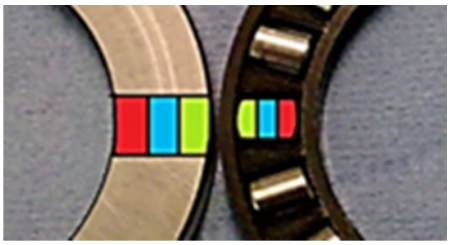
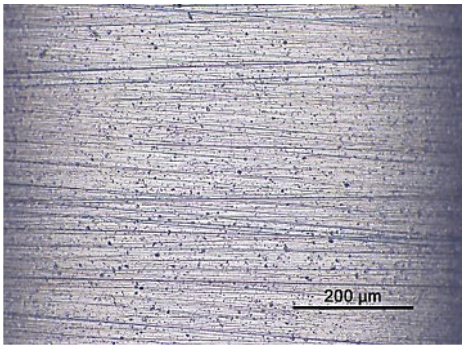
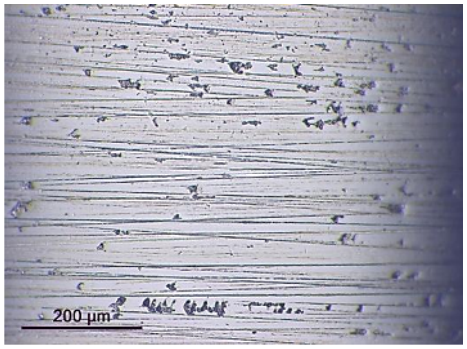
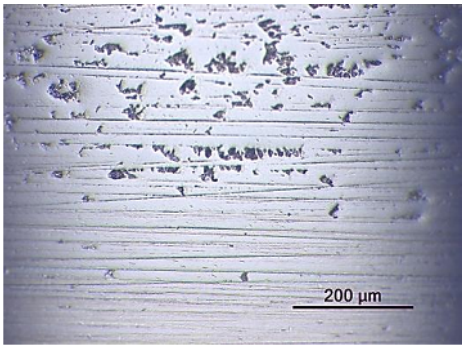
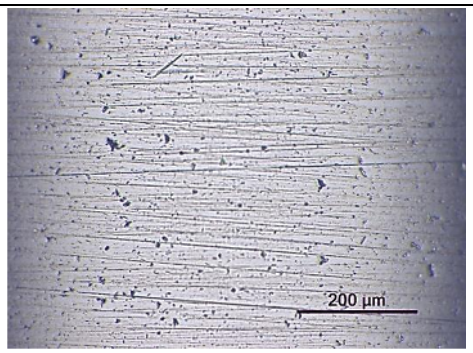
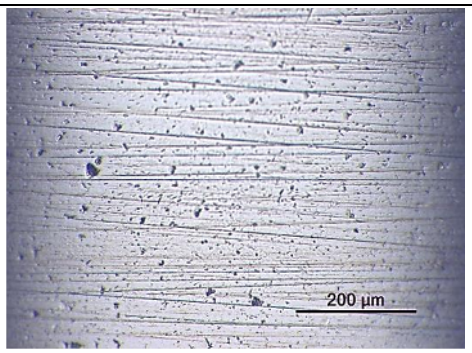
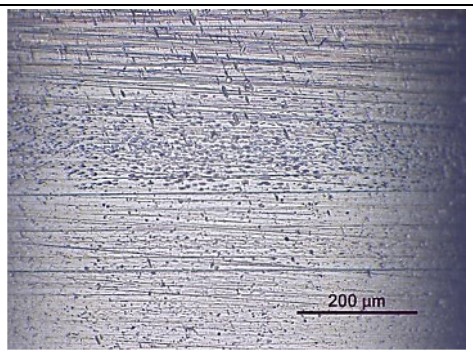
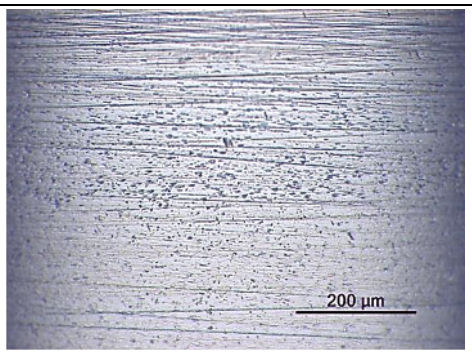
PAO-320	
Upper Raceway (1000 rpm with 10rollers - 50h+50h) - Blue Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	
Upper Raceway (1000 rpm with 10rollers - 50h+50h) - Green Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	

ESTER 320 - Upper Raceway - Red Zone (comparison)				
		Velocity profile 		**Specific film thickness** **Mass Loss** **Parameters for comparison**
1000 rpm with 10rollers - 50h+50h				
NEW		Sa=0,18 µm; Sq=0,23 µm; St=2,95 µm; Sp=0,92 µm; Sv=2,04 µm	/	/
10rollers - first 50h		Sa=0,09 µm; Sq=0,12 µm; St=2,03 µm; Sp=0,84 µm; Sv=1,18 µm T = 337,46 Nmm μ_{Kelley} = 0,064 μ_{CFT} = 0,0022	θ_{oil} = 80,7 θ_{cham} = 33,3 $\Delta\theta_{oil-c}$ = 47,4 θ_{lab} = 24,8 $\Delta\theta_{oil-l}$ = 55,9	λ = 1,364 31 mg $\frac{S_P}{S_{P0}}$ = 0,91 $\frac{S_v}{S_{v0}}$ = 0,58
10 rollers - second 50h		Sa=0,08 µm; Sq=0,11 µm; St=1,73 µm; Sp=0,66 µm; Sv=1,07µm T = 331,85 Nmm μ_{Kelley} = 0,063 μ_{CFT} = 0,0022	θ_{oil} = 77,4 θ_{cham} = 32,3 $\Delta\theta_{oil-c}$ = 45,1 θ_{lab} = 23,0 $\Delta\theta_{oil-l}$ = 54,4	λ = 1,484 2 mg $\frac{S_P}{S_{P0}}$ = 0,72 $\frac{S_v}{S_{v0}}$ = 0,52

ESTER-320	
Upper Raceway (1000 rpm with 10rollers - 50h+50h) - Blue Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	
Upper Raceway (1000 rpm with 10rollers - 50h+50h) - Green Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	

MIN-320	
Rolls (1000 rpm with 10rollers - 50h+50h) - Red Zone (comparison)	
	NEW
	
10rollers - first 50h	**10 rollers - second 50h**
	
Rolls (1000 rpm with 10rollers - 50h+50h) - Blue Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	
Rolls (1000 rpm with 10rollers - 50h+50h) - Green Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	

PAO-320	
Rolls (1000 rpm with 10rollers - 50h+50h) - Red Zone (comparison)	
	NEW
	
10rollers - first 50h	**10 rollers - second 50h**
	
Rolls (1000 rpm with 10rollers - 50h+50h) - Blue Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	
Rolls (1000 rpm with 10rollers - 50h+50h) - Green Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	

ESTER-320	
Rolls (1000 rpm with 10rollers - 50h+50h) - Red Zone (comparison)	
	NEW
	
10rollers - first 50h	**10 rollers - second 50h**
	
Rolls (1000 rpm with 10rollers - 50h+50h) - Blue Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	
Rolls (1000 rpm with 10rollers - 50h+50h) - Green Zone (comparison)	
10rollers - first 50h	**10 rollers - second 50h**
	

A.17. Analysis of Lubricants - Ferrometry and Analytical Ferrography - TRB

Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	03-04 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos Mineral 320 /
Nº de páginas: Data:	7 03/03/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante Mineral 320, resultantes de ensaios de rolamentos na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
Run-In	2	X	X
48H	48	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

	CLIENTE: ***INEGI***			ENSAIO: Rolamentos Axiais de Rolos			
	MORADA: Porto			Ref. ÓLEO: Mineral 320			
	DATA: 28/02/11						
IDENTIFICAÇÃO							
Amostra nº:	Run-In	48H					
Data amostra:	Fev-11	Fev-11					
Análise nº:	03/11	04/11					
Ciclos/Máquina:	-	-					
Ciclos/Óleo:	-	-					
FERROMETRIA							
d:	1	1					
DL:	45,8	58,7					
DS:	26,4	31,1					
CPUC:	72,2	89,8					
ISUC:	1,4E+03	2,5E+03					
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇAO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL -** Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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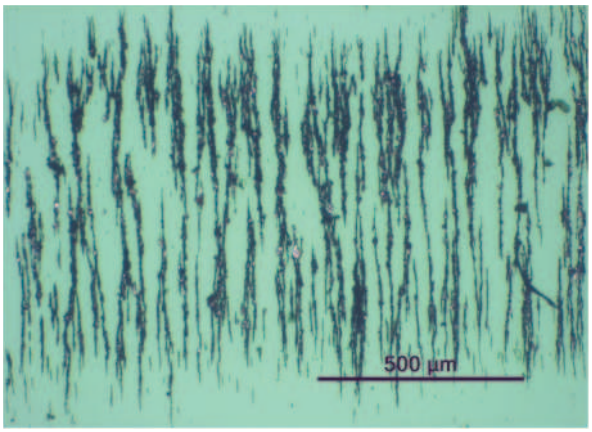
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Mineral 320 - Running In
DATA: 28/02/11	

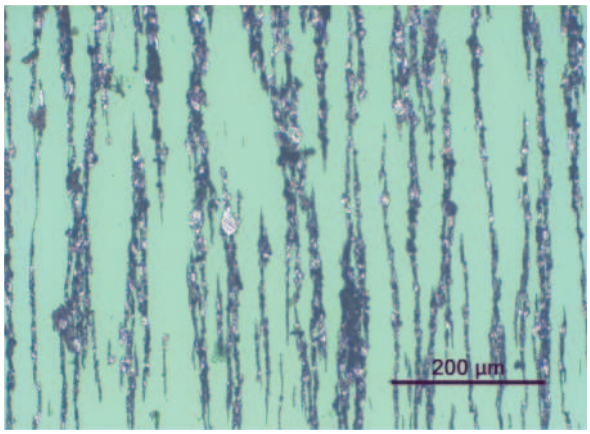
Fotografia 1



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

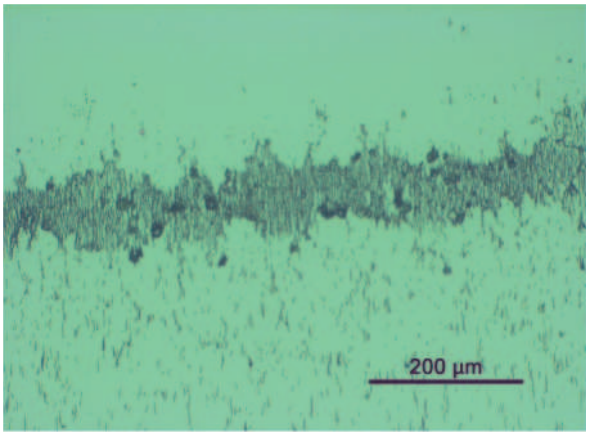
Fotografia 2



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões.

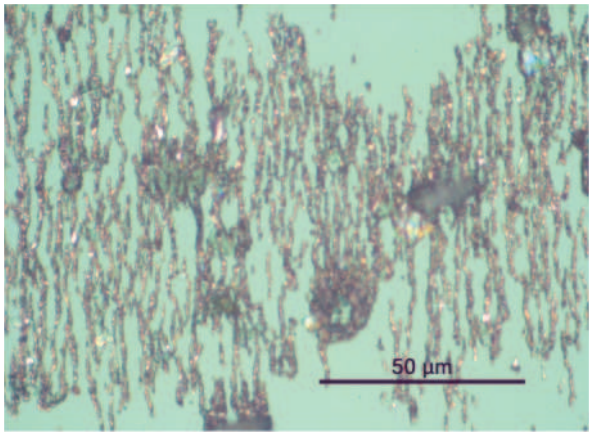
Fotografia 3



Ampliação: x 200 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Presença de algumas partículas ferrosas de muito pequenas dimensões (típicas de desgaste de corrosão).

Fotografia 4



Ampliação: x 1000 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Ampliação da Fotografia 3. Aspecto das partículas ferrosas de pequenas dimensões. Algumas dessas partículas encontram-se aglomeradas.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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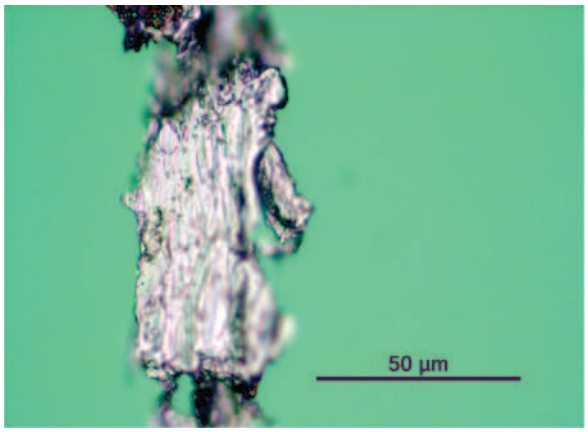
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Mineral 320 - Running In
DATA: 28/02/11	

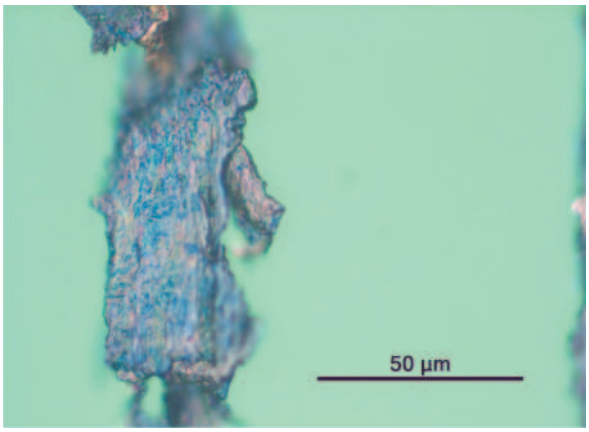
Fotografia 5



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Partícula ferrosa de grandes dimensões.

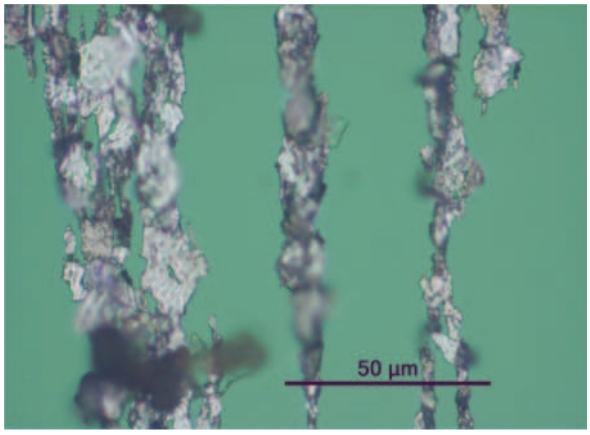
Fotografia 6



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto da partícula anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de uma partícula de aço de baixa liga.

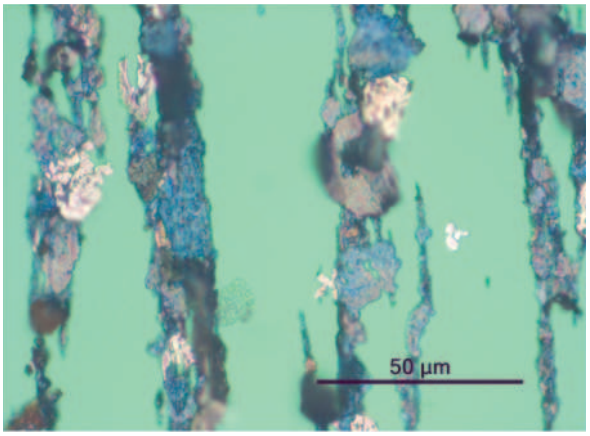
Fotografia 7



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Partículas ferrosas de médias dimensões e alguns óxidos térmicos.

Fotografia 8



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto de algumas partículas da Fotografia 1, após Tratamento Térmico. Note-se que a tonalidade de algumas das partículas não alterarou, significando que podem ser de aço de média ou alta liga (ou metal branco?).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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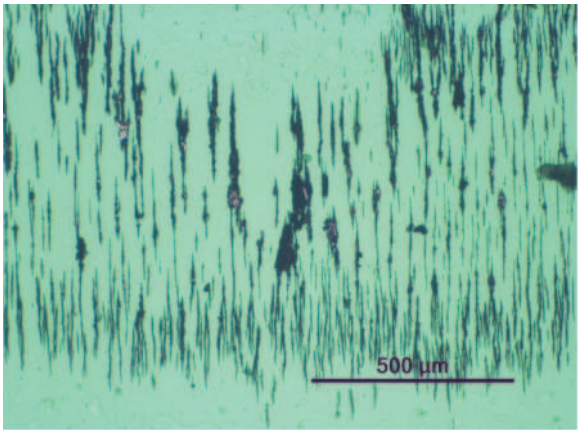
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Mineral 320 - 48H
DATA: 28/02/11	

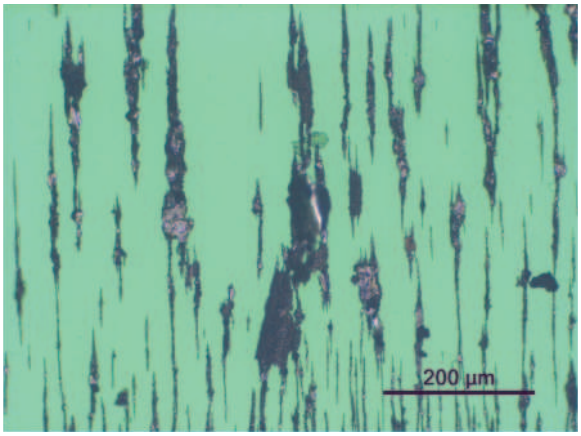
Fotografia 9



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

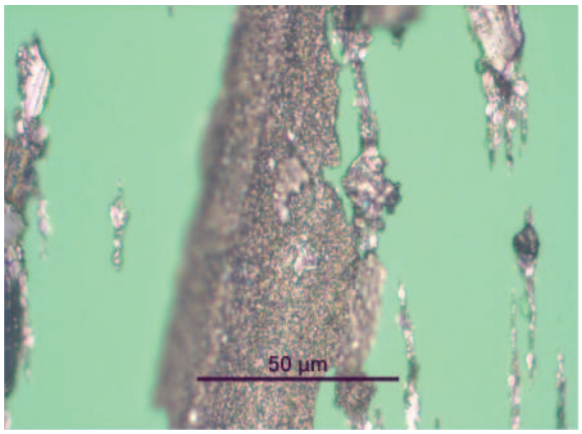
Fotografia 10



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Presença significativa de partículas ferrosas de grandes dimensões, algumas severamente oxidadas.

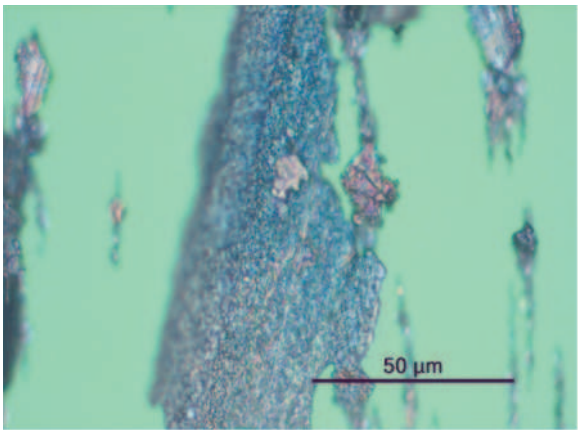
Fotografia 11



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Partícula ferrosa de desgaste, de grandes dimensões e oxidada.

Fotografia 12



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto da partícula anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de uma partícula de aço de baixa liga.

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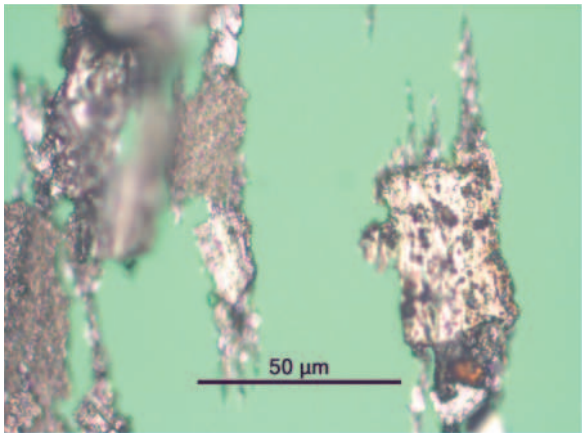
MORADA: Porto	Ref. ÓLEO: Mineral 320 - 48 H
DATA: 28/02/11	

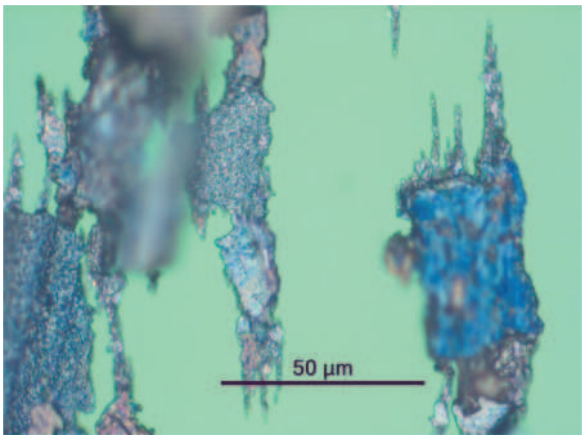
Fotografia 13



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Presença de partículas ferrosas de grandes dimensões, algumas oxidades.

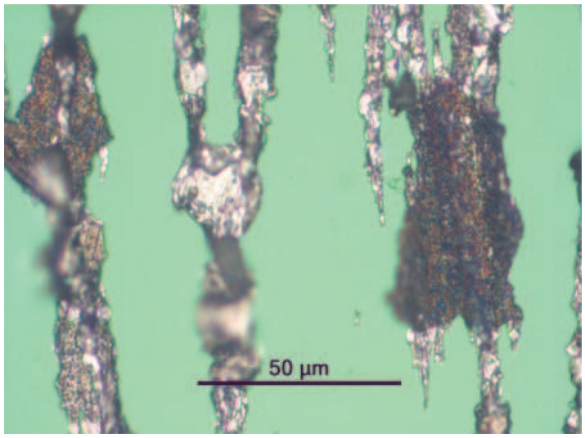
Fotografia 14



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto das partículas anteriores após Tratamento Térmico. A alteração de tonalidade para azul, indica tratarem-se de partículas de aço de baixa liga.

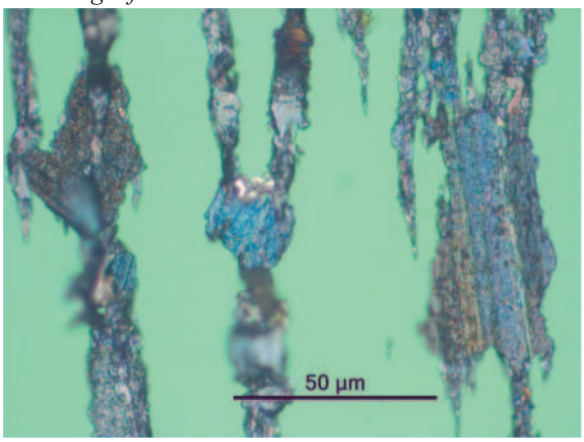
Fotografia 15



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações Ampliação da Fotografia 10. Presença de partículas ferrosas de grandes dimensões, algumas oxidades.

Fotografia 16



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto das partículas anteriores após Tratamento Térmico. A alteração de tonalidade para azul, indica tratarem-se de partículas de aço de baixa liga.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	05-06 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos PAO 320 /
Nº de páginas: Data:	7 03/03/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante PAO 320, resultantes de ensaios de rolamentos na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
Run-In	12	X	X
48H	48	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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CLIENTE: ***INEGI***
MORADA: Porto
DATA: 28/02/11

ENSAIO: Rolamentos Axiais de Rolos
Ref. ÓLEO: PAO 320

IDENTIFICAÇÃO							
Amostra nº:	Run-In	48H					
Data amostra:	Fev-11	Fev-11					
Análise nº:	05/11	06/11					
Ciclos/Máquina:	-	-					
Ciclos/Óleo:	-	-					
FERROMETRIA							
d:	1	0,1					
DL:	98,3	40,3					
DS:	39,7	18,5					
CPUC:	138,0	588,0					
ISUC:	8,1E+03	1,3E+05					
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL -** Índice de partículas grandes		Não existe
	DS - Indice de partículas pequenas	**I**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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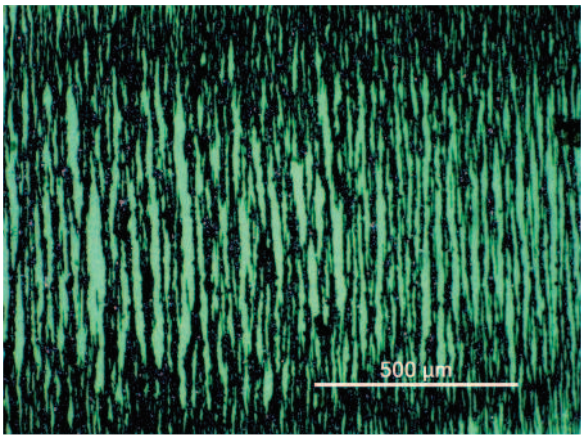
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: PAO 320 Running In
DATA: 28/02/11	

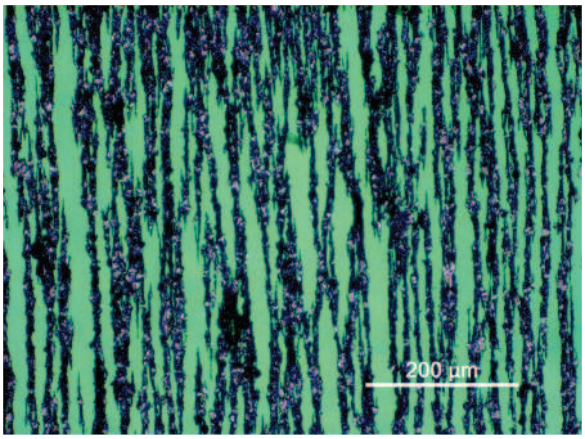
Fotografia 1



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

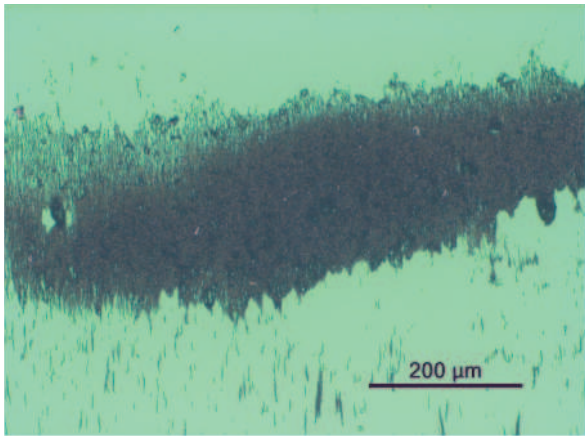
Fotografia 2



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões.

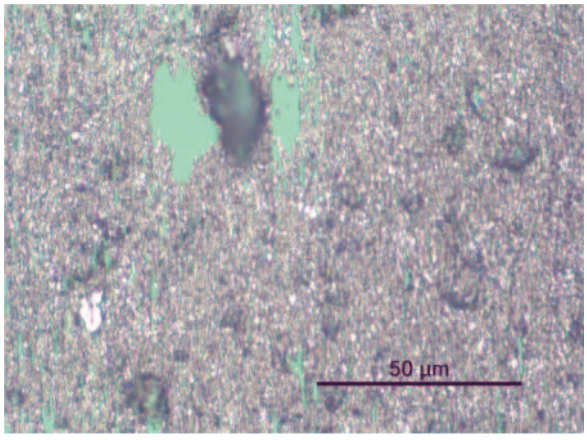
Fotografia 3



Ampliação: x 200 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Presença significativa de partículas ferrosas de muito pequenas dimensões (típicas de desgaste de corrosão).

Fotografia 4



Ampliação: x 1000 Diluição: 1
Localização: Saída Luz: Branca / Verde

Observações: Ampliação da Fotografia 3. Concentração excessiva de partículas ferrosas típicas de desgaste corrosivo.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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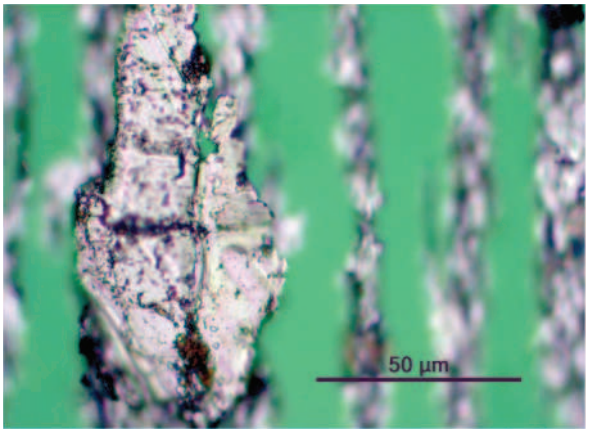
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: PAO 320 Running In
DATA: 28/02/11	

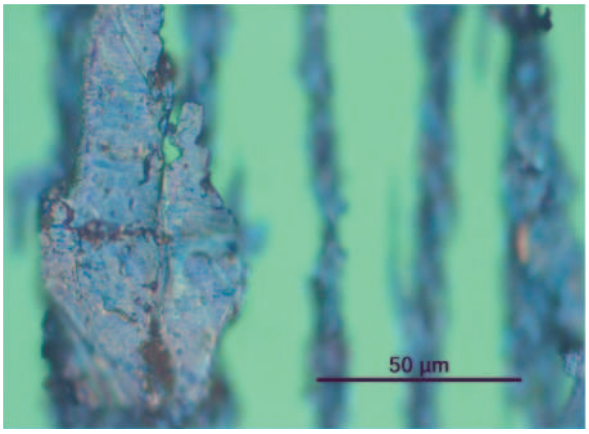
Fotografia 5



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de grande dimensão e outras de menores dimensões.

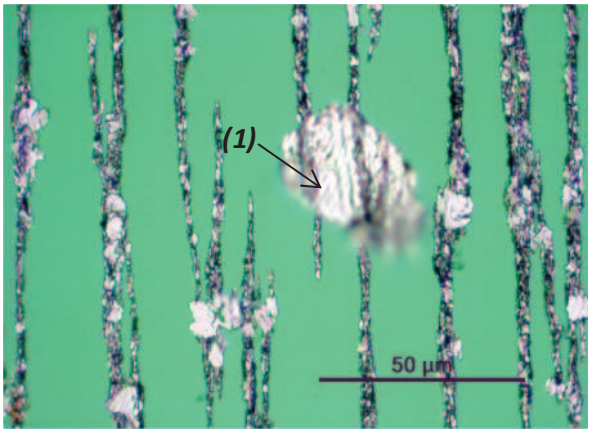
Fotografia 6



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto da partícula anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de uma partícula de aço de baixa liga.

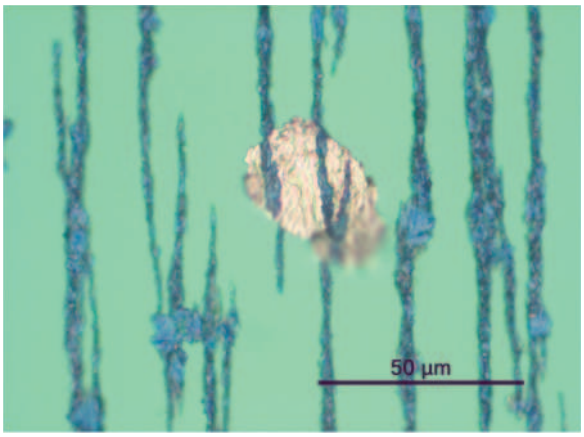
Fotografia 7



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Partículas ferrosas de desgaste de pequenas e médias dimensões. (1) - Partícula de desgaste, de grande dimensão, mas que se encontra não alinhada magnéticamente.

Fotografia 8



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto das partículas da Fotografia anterior, após Tratamento Térmico. Note-se que a tonalidade da partícula não magnética não alterarou, confirmando a sua natureza não ferrosa (metal branco).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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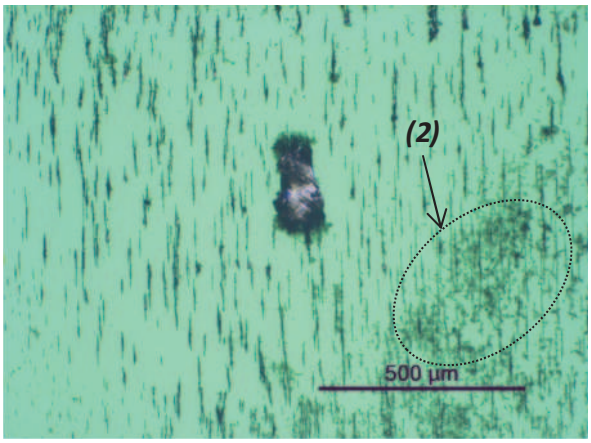
MORADA: Porto	Ref. ÓLEO: PAO 320 48H
DATA: 28/02/11	

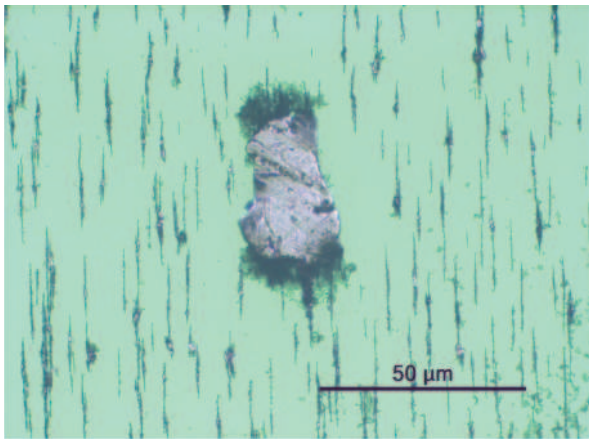
Fotografia 9



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de uma partícula ferrosa de desgaste de grandes dimensões e poucas de média e pequena dimensão. (2) - Presença significativa de polímeros de atrito.

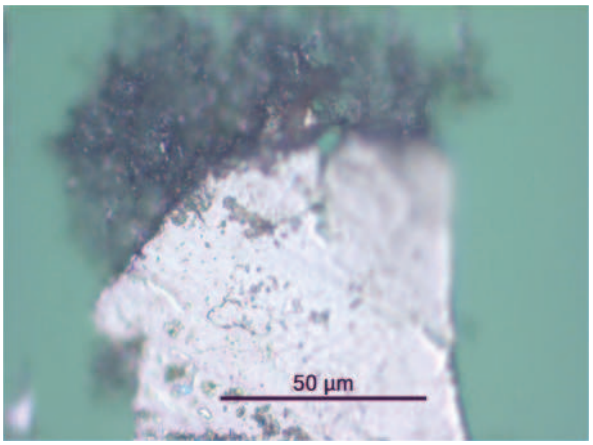
Fotografia 10



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Note-se a presença de poucas partículas de pequenas e médias dimensões.

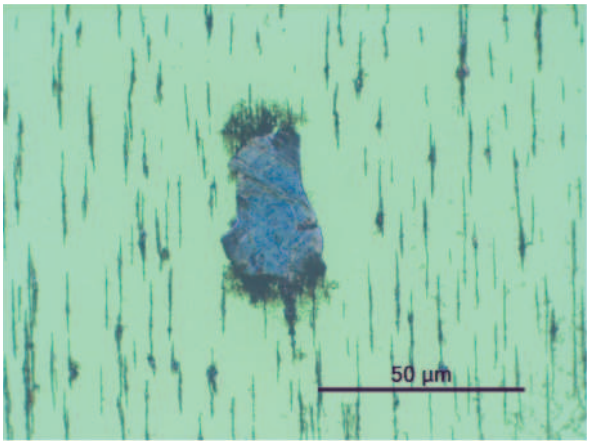
Fotografia 11



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Note-se a envolvencia da extremidade da partícula por polímeros de atrito.

Fotografia 12



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto da partícula anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de uma partícula de aço de baixa liga.

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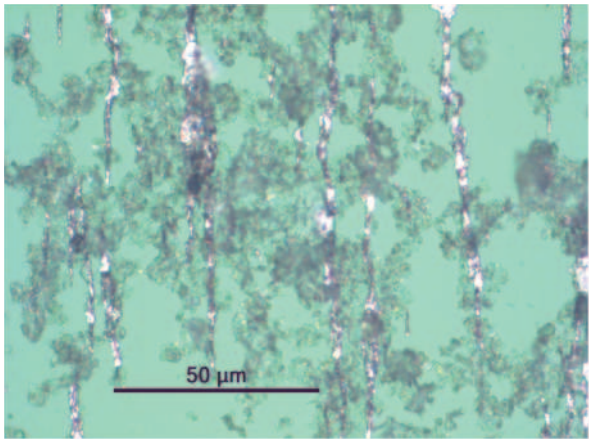
DATA: 28/02/11	

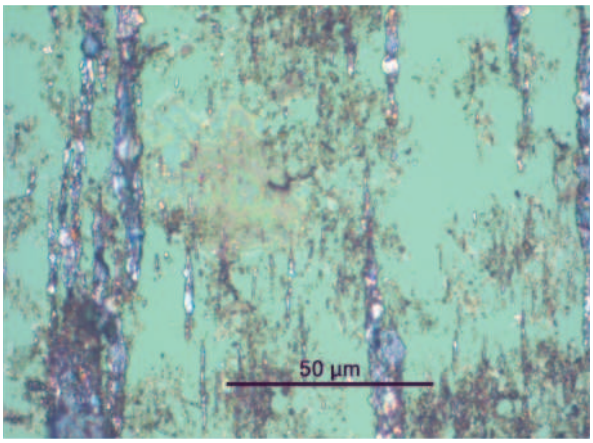
Fotografia 13



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas dimensões no seio de matrizes polimericas (polímeros de atrito).

Fotografia 14



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto das partículas e dos polímeros de atrito após Tratamento Térmico.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	07-09 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos Ester 320 /
Nº de páginas: Data:	7 09/03/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de duas amostras de óleo lubrificante Ester 320, resultantes de ensaios de rolamentos na Máquina de 4 Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
Run-In	2	X	X
48H	48	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***
MORADA: Porto
DATA: 09/03/11

ENSAIO: Rolamentos Axiais de Rolos
Ref. ÓLEO: Ester 320

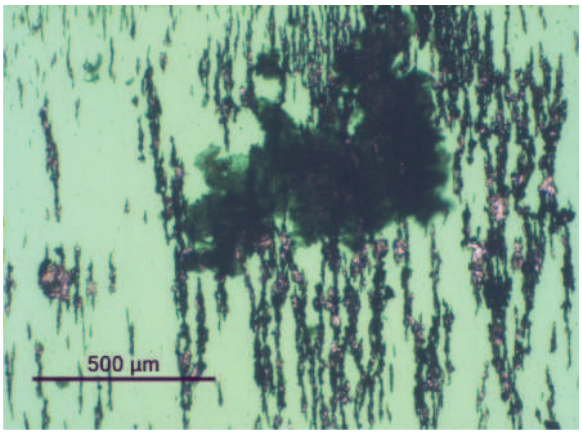
IDENTIFICAÇÃO							
Amostra nº:	Run-In	48H					
Data amostra:	Mar-11	Mar-11					
Análise nº:	07/11	09/11					
Ciclos/Máquina:	-	-					
Ciclos/Óleo:	-	-					
FERROMETRIA							
d:	1	1					
DL:	96,7	59,0					
DS:	39,9	21,4					
CPUC:	136,6	80,4					
ISUC:	7,8E+03	3,0E+03					
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA			
	DL - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**I**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 Running In
DATA: 09/03/11	

Fotografia 1

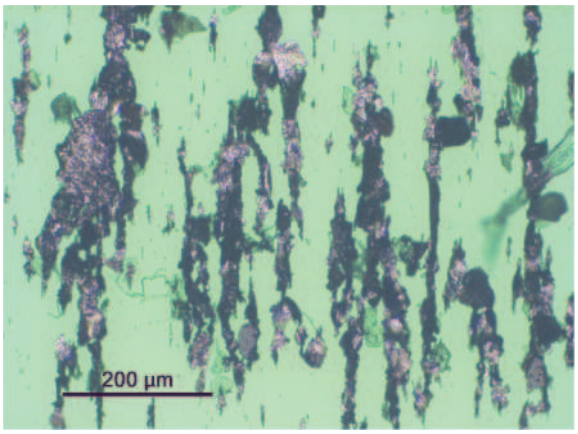


Ampliação: x 100 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões. Presença de um agomerado de grandes dimensões.

Fotografia 2

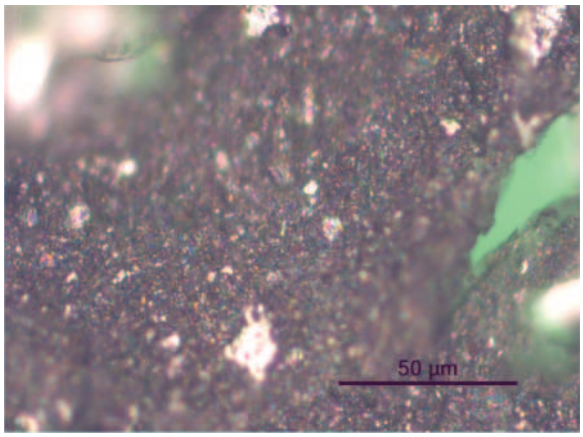


Ampliação: x 200 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões.

Fotografia 3

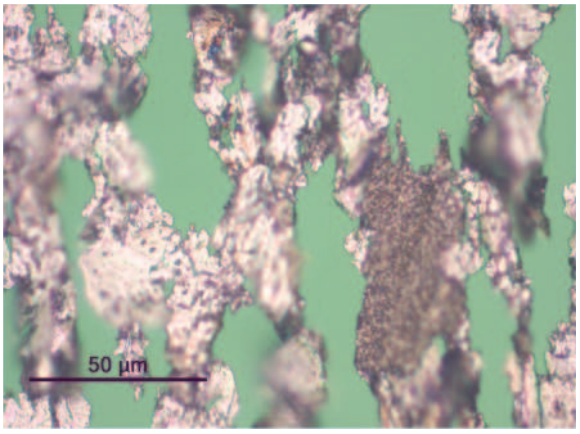


Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Particulas de pequenas dimensões embebidas numa matrix amorfa de tonalidade negra (gaiola do rolamento?).

Fotografia 4



Ampliação: x 1000 Diluição: 1

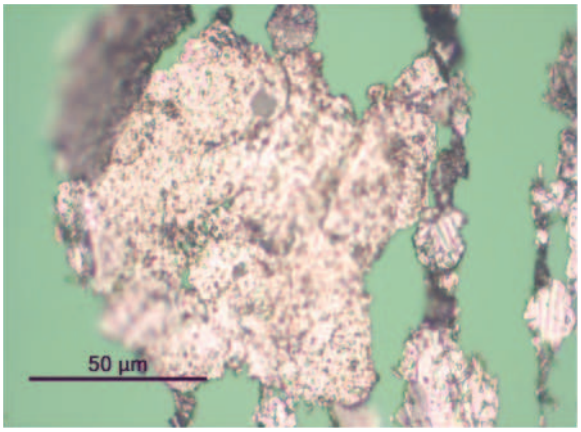
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partículas ferrosas de desgaste de grandes e médias dimensões.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 Running In
DATA: 09/03/11	

Fotografia 5

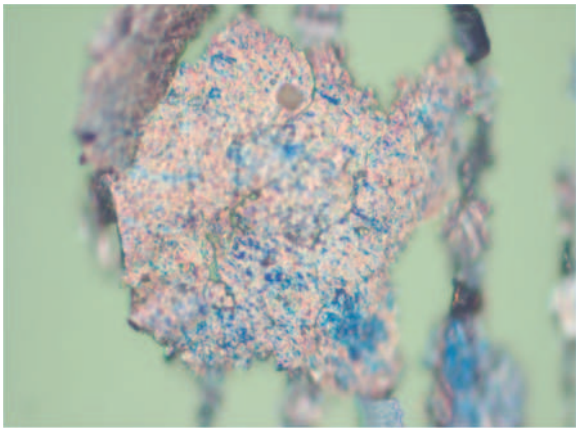


Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partícula ferrosa de grande dimensão e outras de menores dimensões.

Fotografia 6

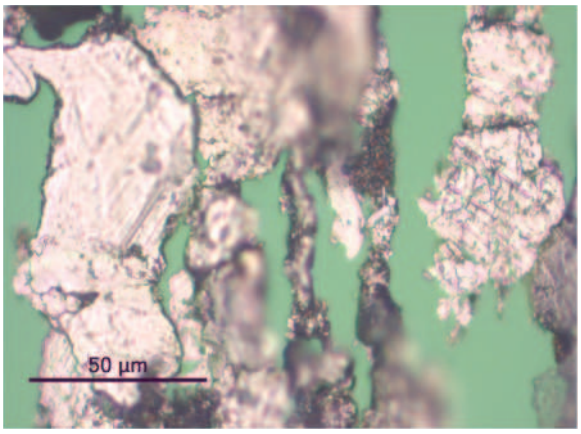


Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto da partícula anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de uma partícula de aço de baixa liga.

Fotografia 7

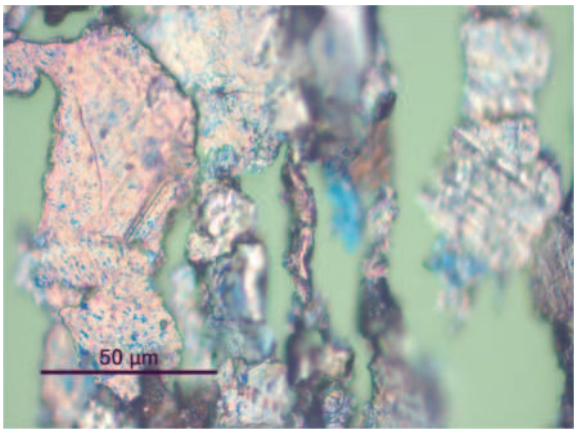


Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Partículas ferrosas de desgaste de grandes e médias dimensões.

Fotografia 8



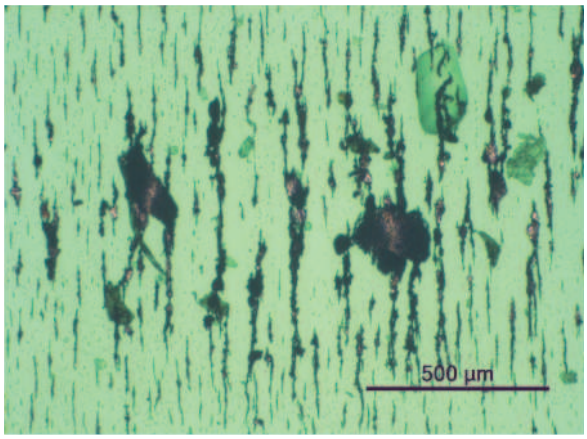
Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto das partículas da Fotografia anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de uma partícula de aço de baixa liga.

CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 48H
DATA: 09/03/11	

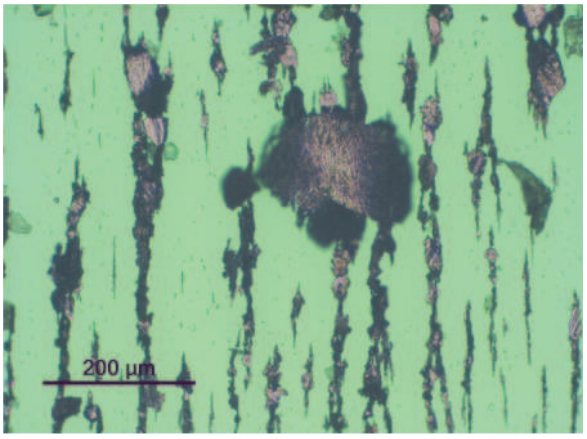
Fotografia 9



Ampliação: x 100 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

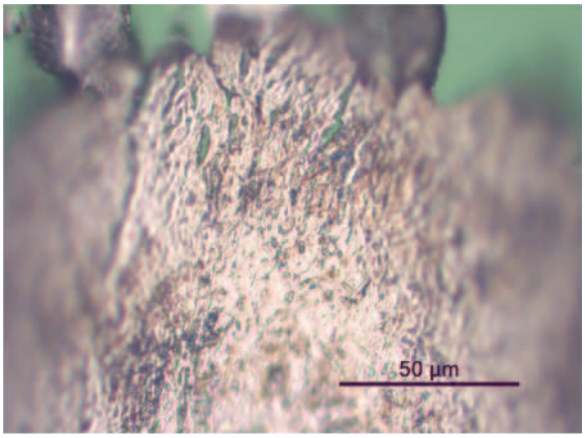
Fotografia 10



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 9. Presença de partículas de pequenas e grandes dimensões.

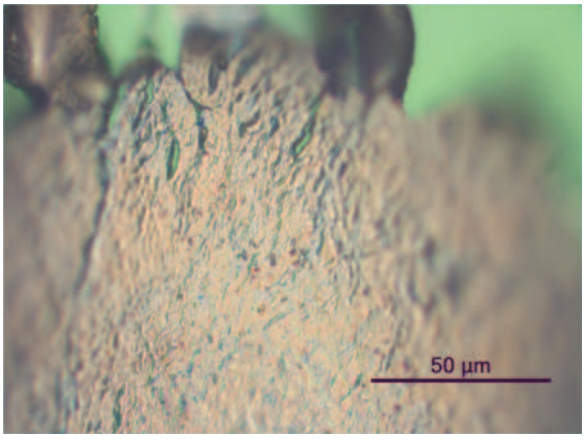
Fotografia 11



Ampliação: x 1000 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 10. Parte de uma das partículas de grandes dimensões.

Fotografia 12



Ampliação: x 200 Diluição: 1
Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto da partícula anterior após Tratamento Térmico. A alteração de tonalidade para azul não foi muito prenunciada (?).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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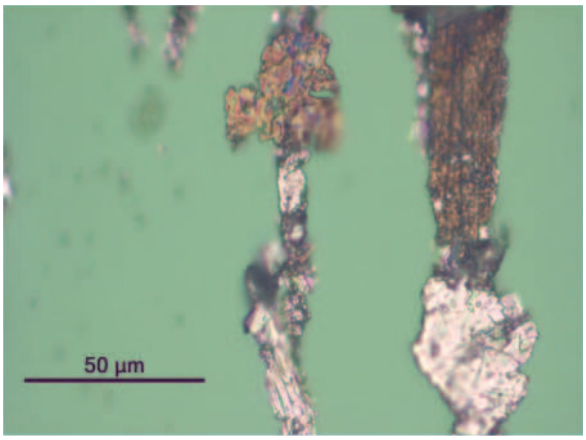
CLIENTE: ***INEGI***	ENSAIO: Rolamentos Axiais de Rolos
MORADA: Porto	Ref. ÓLEO: Ester 320 48H
DATA: 09/03/11	

Fotografia 13

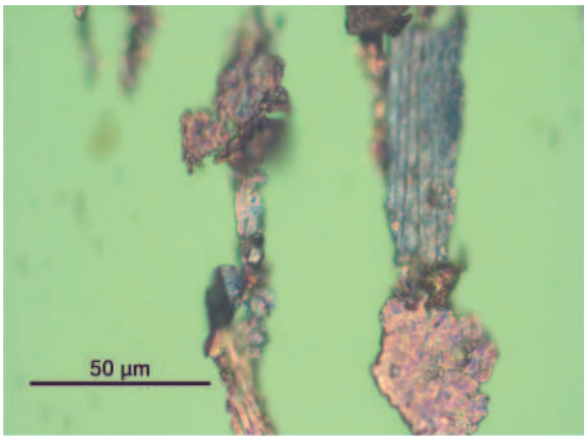


Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas dimensões no seio de matrizes polimericas (polímeros de atrito).

Fotografia 14

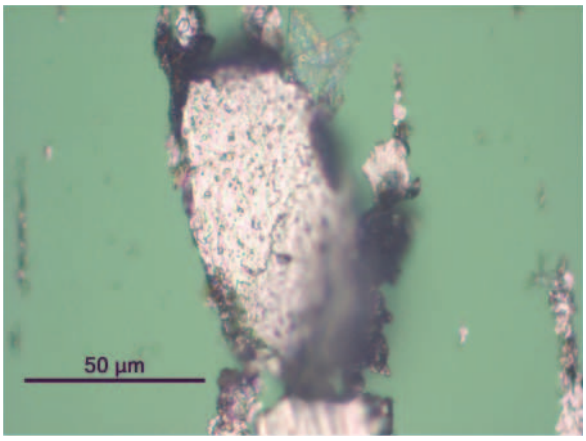


Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto das partículas da Fotografia anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de partículas de aço de baixa liga.

Fotografia 15

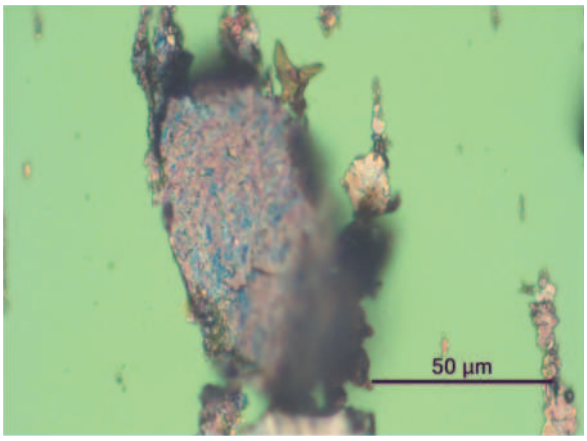


Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Partícula ferrosa de grande dimensão e de alguns óxidos.

Fotografia 16



Ampliação: x 1000 Diluição: 1

Localização: Núcleo Luz: Branca / Verde

Observações: Aspecto da partícula anterior após Tratamento Térmico. A alteração de tonalidade para azul, indica tratar-se de uma partícula de aço de baixa liga.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	52 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos (10R) Mineral 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de uma amostra de óleo lubrificante Mineral 320, resultantes de ensaios de Rolamentos Axiais de Rolos (10R) na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50	50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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CLIENTE: ***INEGI***
MORADA: Porto
DATA: 09/03/11

ENSAIO: Rol. Axiais de Rolos (10R)
Ref. ÓLEO: Mineral 320 50H

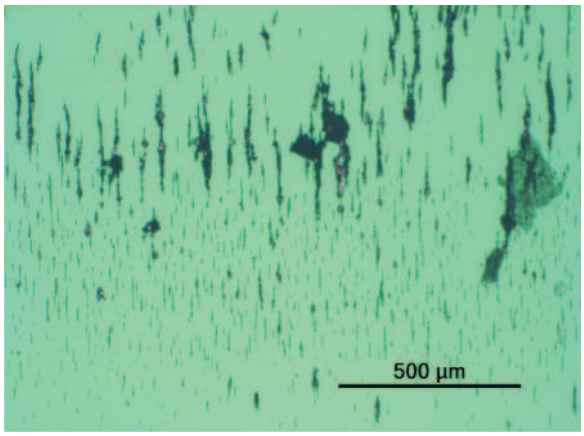
IDENTIFICAÇÃO							
Amostra nº:	50						
Data amostra:	Mai-11						
Análise nº:	52/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,1						
DL:	24,9						
DS:	5,1						
CPUC:	300,0						
ISUC:	5,9E+04						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Rolos (10R)
MORADA: Porto	Ref. ÓLEO: Mineral 320 50H
DATA: 09/06/11	

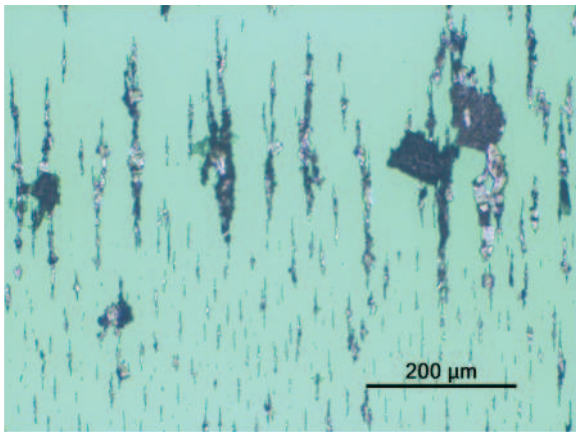
Fotografia 1



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

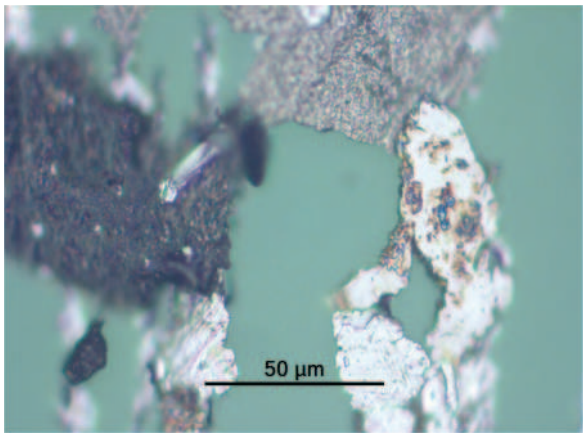
Fotografia 2



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1.
Presença de partículas ferrosas de pequenas e grandes dimensões.

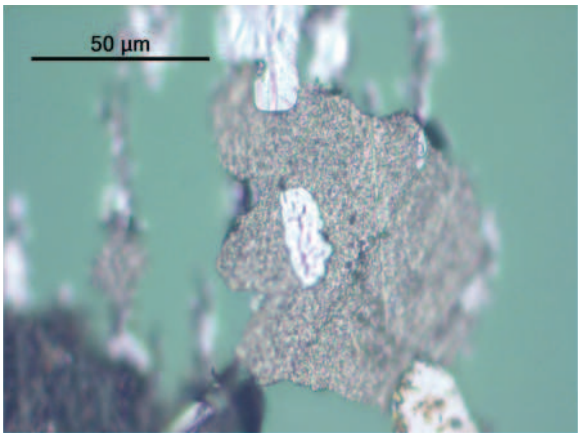
Fotografia 3



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1.
Particulas ferrosas de grandes dimensões típicas de desgaste de fadiga, algumas muito oxidadas.

Fotografia 4



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.
Particulas ferrosas de grandes dimensões típicas de desgaste de fadiga, algumas muito oxidadas.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	53 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos (10R) Mineral 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de uma amostra de óleo lubrificante PAO 320, resultantes de ensaios de Rolamentos Axiais de Rolos (10R) na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50	50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

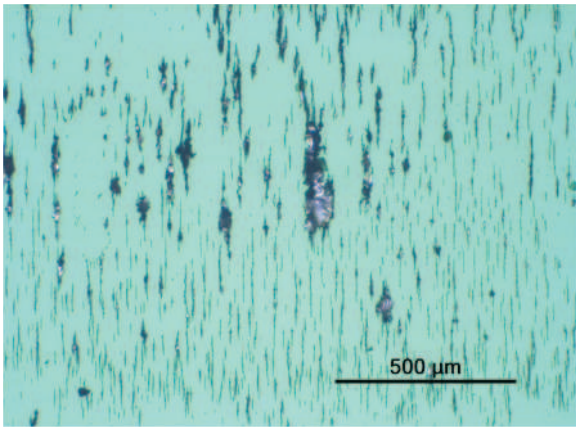
	CLIENTE: ***INEGI***		ENSAIO: Rol. Axiais de Rolos (10R)				
	MORADA: Porto		Ref. ÓLEO: PAO 320 50H				
	DATA: 09/06/11						
IDENTIFICAÇÃO							
Amostra nº:	50						
Data amostra:	Mai-11						
Análise nº:	53/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,1						
DL:	26,9						
DS:	7,9						
CPUC:	348,0						
ISUC:	6,6E+04						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Rolos (10R)
MORADA: Porto	Ref. ÓLEO: PAO 320 50H
DATA: 09/06/11	

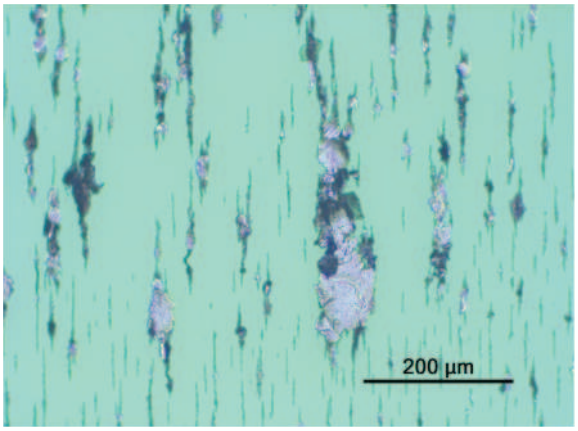
Fotografia 1



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

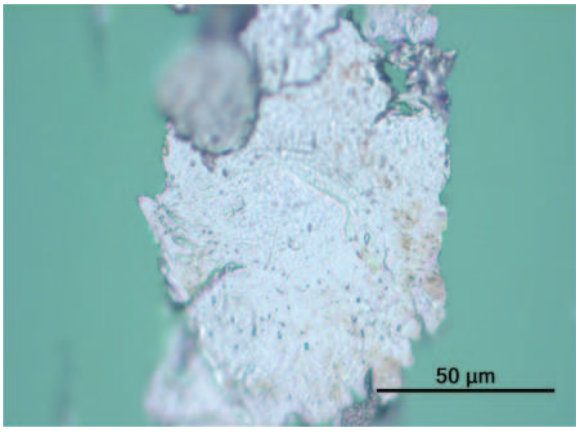
Fotografia 2



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1.
Presença de partículas ferrosas de pequenas e grandes dimensões.

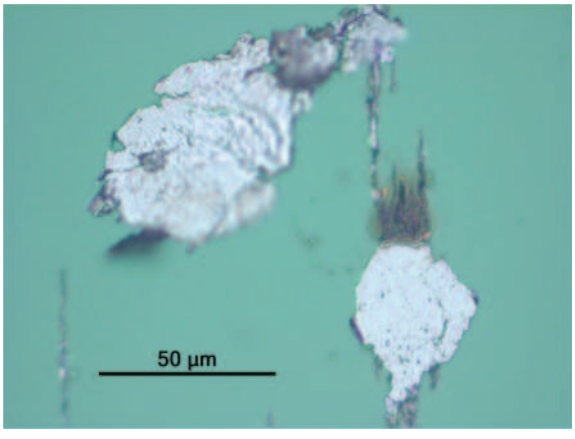
Fotografia 3



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1.
Particula ferrosa de grandes dimensões típica de desgaste de fadiga.

Fotografia 4



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.
Particulas ferrosas de grandes dimensões típicas de desgaste de fadiga.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	51 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos (10R) Ester 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de uma amostra de óleo lubrificante Ester 320, resultante de ensaios em Rolamentos Axiais de Rolos (10R) na Máquina de 4 Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50	50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

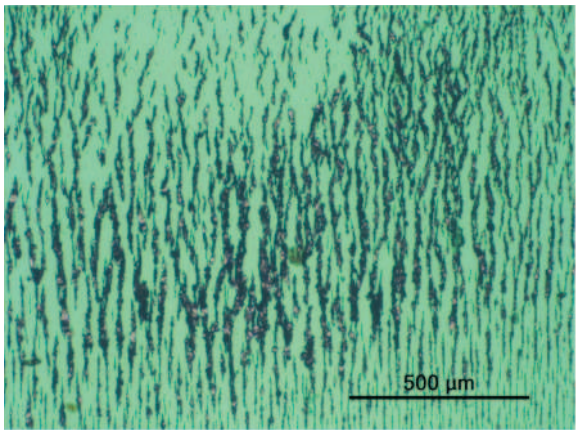
	CLIENTE: ***INEGI***			ENSAIO: Rol. Axiais de Rolos (10R)			
	MORADA: Porto			Ref. ÓLEO: Ester 320 50H			
	DATA: 09/03/11						
IDENTIFICAÇÃO							
Amostra nº:	50						
Data amostra:	Mai-11						
Análise nº:	51/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,1						
DL:	54,4						
DS:	10,6						
CPUC:	650,0						
ISUC:	2,8E+05						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Rolos (10R)
MORADA: Porto	Ref. ÓLEO: Ester 320 50H
DATA: 09/03/11	

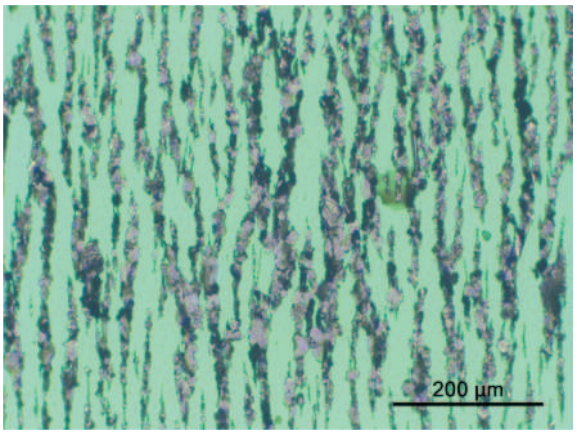
Fotografia 1



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

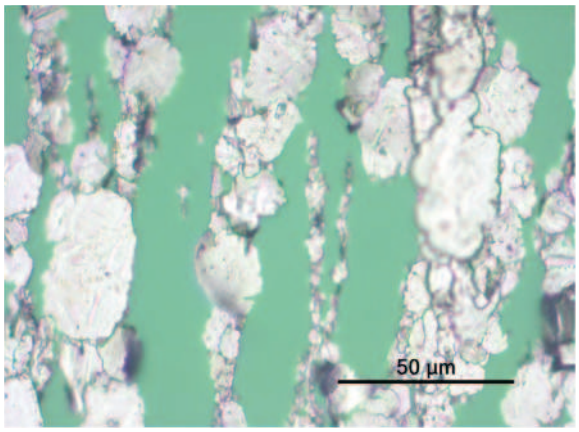
Fotografia 2



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1.
Presença de partículas ferrosas de pequenas e grandes dimensões.

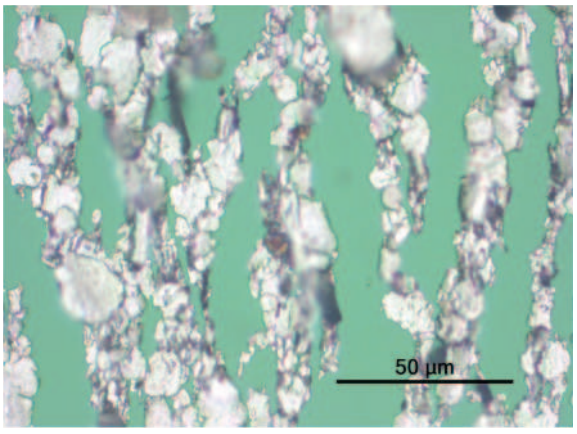
Fotografia 3



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1.
Particulas ferrosas de grandes dimensões típicas de desgaste de fadiga.

Fotografia 4



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2.
Particulas ferrosas de médias dimensões típicas de desgaste de fadiga.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	64 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos (10R) Mineral 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de uma amostra de óleo lubrificante Mineral 320, resultantes de ensaios de Rolamentos Axiais de Rolos (10R) na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50+50	50+50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

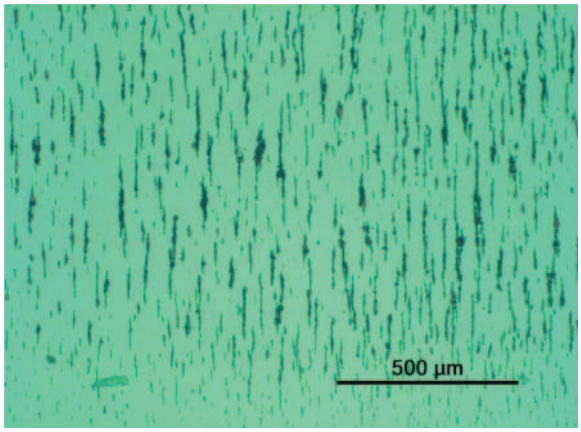
	CLIENTE: ***INEGI***			ENSAIO: Rol. Axiais de Rolos (10R)			
	MORADA: Porto			Ref. ÓLEO: Mineral 320 50+50H			
	DATA: 09/06/11						
IDENTIFICAÇÃO							
Amostra nº:	50+50						
Data amostra:	Mai-11						
Análise nº:	64/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,1						
DL:	12,8						
DS:	5,0						
CPUC:	178,0						
ISUC:	1,4E+04						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Índice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**I**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Rolos (10R)
MORADA: Porto	Ref. ÓLEO: Mineral 320 50+50H
DATA: 09/06/11	

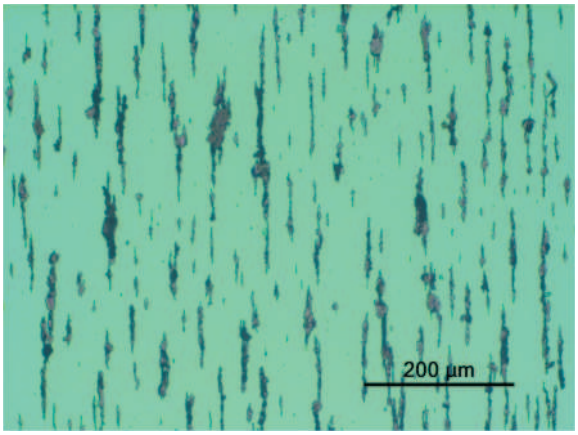
Fotografia 1



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

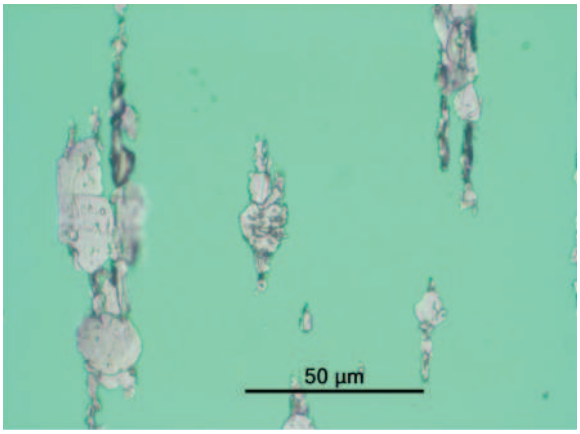
Fotografia 2



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões.

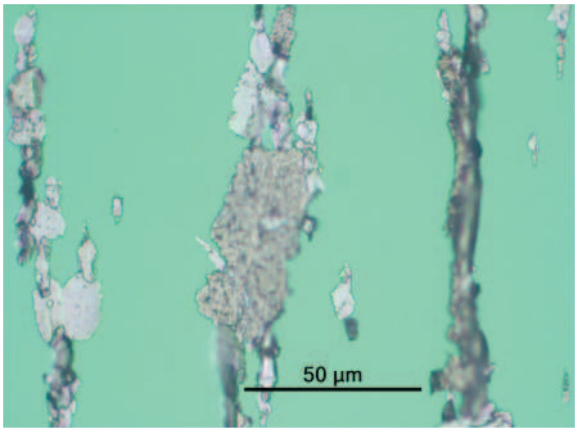
Fotografia 3



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Particulas ferrosas de médias dimensões típicas de desgaste de fadiga.

Fotografia 4



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Particulas ferrosas de grandes dimensões típicas de desgaste de fadiga, algumas muito oxidadas.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	66 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos (10R) Mineral 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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OBJECTIVO

Análise de uma amostra de óleo lubrificante PAO 320, resultantes de ensaios de Rolamentos Axiais de Rolos (10R) na Máquina de Quatro Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50+50	50+50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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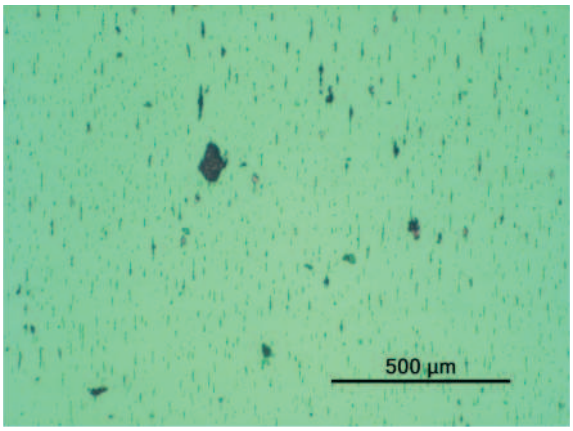
	CLIENTE: ***INEGI*** MORADA: Porto DATA: 09/06/11			ENSAIO: Rol. Axiais de Rolos (10R) Ref. ÓLEO: PAO 320 50+50H			
IDENTIFICAÇÃO							
Amostra nº:	50+50						
Data amostra:	Mai-11						
Análise nº:	66/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,1						
DL:	12,5						
DS:	3,6						
CPUC:	161,0						
ISUC:	1,4E+04						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Indice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Rolos (10R)
MORADA: Porto	Ref. ÓLEO: PAO 320 50+50H
DATA: 09/06/11	

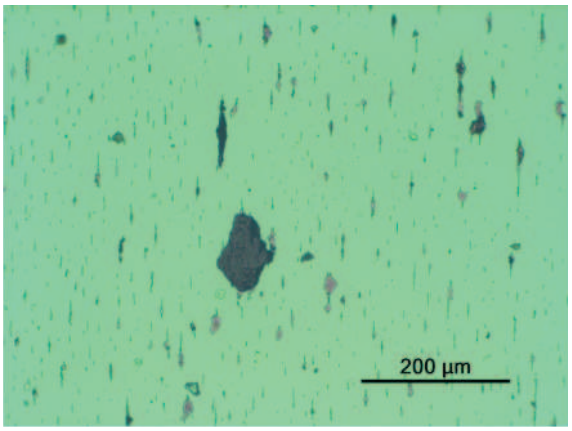
Fotografia 1



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e poucas de grandes dimensões.

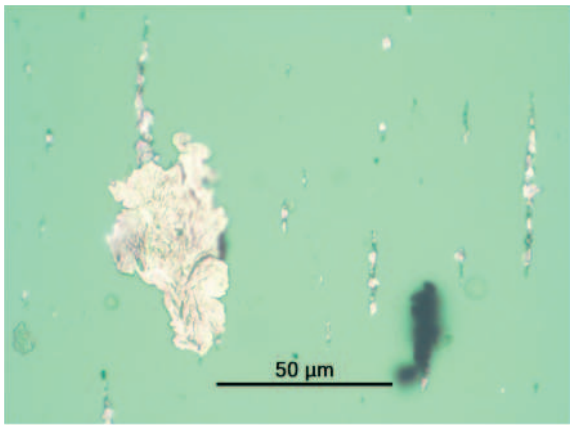
Fotografia 2



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e poucas grandes dimensões.

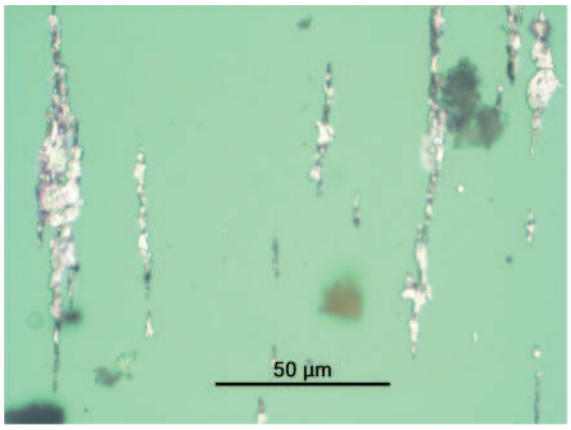
Fotografia 3



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Particula ferrosa de grandes dimensões típica de desgaste de fadiga.

Fotografia 4



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Particulas ferrosas de pequenas dimensões.

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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Relatório
de
Análise de Lubrificantes

Análise nº: Tipo de análise: Confidencialidade:	68 / 11 Ferrometria e Ferrografia Analítica 1
Cliente: Morada: Telefone / Fax:	INEGI - Cetrib Porto
Equipamento: Lubrificante: Dossier:	Ensaio de Rolamentos Axiais de Rolos (10R) Ester 320 /
Nº de páginas: Data:	4 09/06/11
Responsável: Rúbrica:	Beatriz Graça – Jorge Seabra

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
Este documento não pode ser reproduzido, total ou parcialmente, sem a autorização por escrito do INEGI.

OBJECTIVO

Análise de uma amostra de óleo lubrificante Ester 320, resultante de ensaios em Rolamentos Axiais de Rolos (10R) na Máquina de 4 Esferas para avaliação do desgaste presente.

As amostras analisadas foram as seguintes:

Amostra Nº	Horas	Análises efectuadas	
		Ferrometria	Ferrografia Analítica
50+50	50+50	X	X

RESULTADOS DAS ANÁLISES

Nas páginas seguintes são apresentados os resultados referentes às análises de Ferrometria (DR III) e Ferrografia Analítica (FM III).

Os resultados apresentados referem-se exclusivamente às amostras ensaiadas.
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	CLIENTE: ***INEGI***			ENSAIO: Rol. Axiais de Rolos (10R)			
	MORADA: Porto			Ref. ÓLEO: Ester 320 50+50H			
	DATA: 09/06/11						
IDENTIFICAÇÃO							
Amostra nº:	50+50						
Data amostra:	Mai-11						
Análise nº:	68/11						
Ciclos/Máquina:	-						
Ciclos/Óleo:	-						
FERROMETRIA							
d:	0,1						
DL:	24,1						
DS:	5,2						
CPUC:	293,0						
ISUC:	5,5E+04						
FERROGRAFIA:							
Desgaste normal							
Desgaste severo							
Desgaste abrasão							
Desgaste combinado							
Desgaste fadiga							
Esferas Metálicas							
Ligas não ferrosas							
Óxidos de ferro							
Minerais/Orgânicos							
OILVIEW:							
Índice OilLife:							
Índice Oxidação:							
Índice Contaminação:							
Índice Ferromagnético:							
Grandes Contaminantes:							
Constante Dieléctrica:							
FILTRAGEM							
(Nº Partículas/10 ml)							
5 - 15 µm							
15 - 25 µm							
25 - 50 µm							
50 - 100 µm							
> 100 µm							
VISCOSIDADE							
(cSt a 40° C):							
ACIDEZ (TAN)							
(mg KOH)							
P. INFLAMAÇÃO							
(° C)							
DIAGNÓSTICO:							

LEGENDA	**DL** - Índice de partículas grandes		Não existe
	DS - Índice de partículas pequenas	**f**	Fraco
	CPUC - Concentração de partículas de d	**M**	Médio
	ISUC - Índice de severidade de desgast	**F**	Forte

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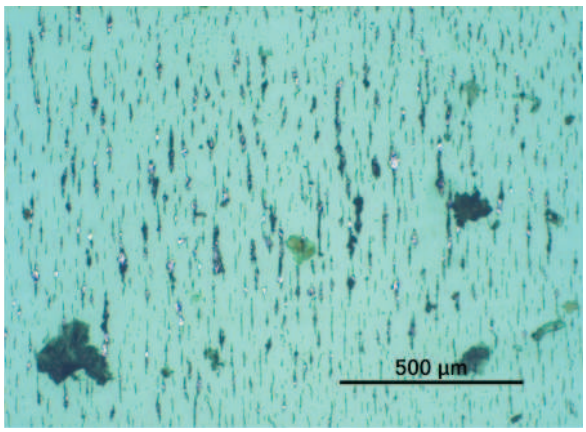
CLIENTE: ***INEGI***	ENSAIO: Rol. Axiais de Rolos (10R)
MORADA: Porto	Ref. ÓLEO: Ester 320 50+50H
DATA: 09/06/11	

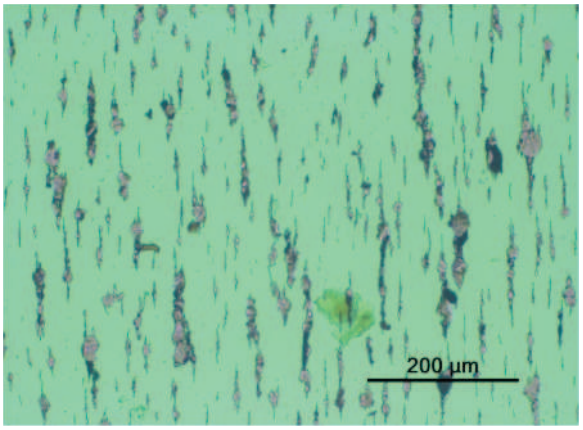
Fotografia 1



Ampliação: x 100 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Presença de partículas ferrosas de pequenas e grandes dimensões.

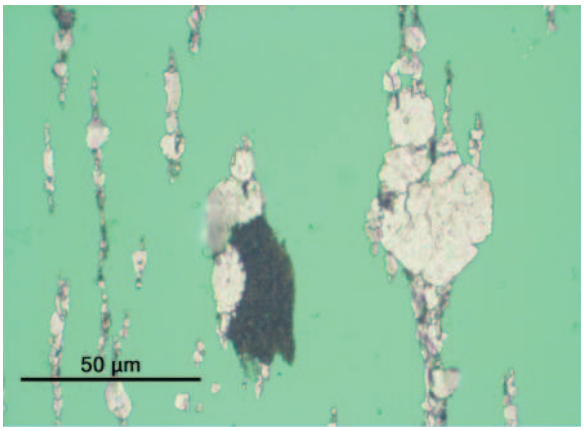
Fotografia 2



Ampliação: x 200 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Presença de partículas ferrosas de pequenas e grandes dimensões.

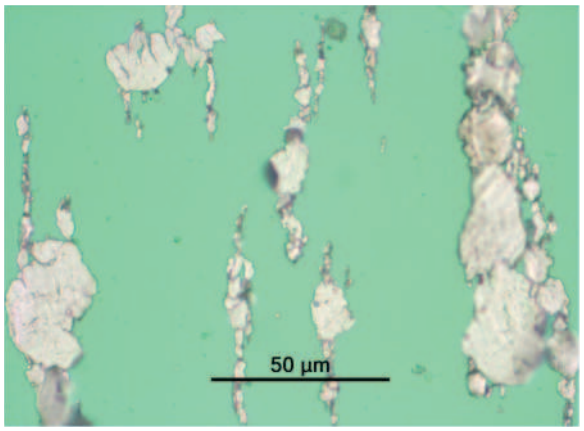
Fotografia 3



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 1. Particulas ferrosas de grandes dimensões típicas de desgaste de fadiga. Presença de alguns óxidos térmicos.

Fotografia 4



Ampliação: x 1000 Diluição: 0,1
Localização: Núcleo Luz: Branca / Verde

Observações: Ampliação da Fotografia 2. Particulas ferrosas de grandes dimensões típicas de desgaste de fadiga.

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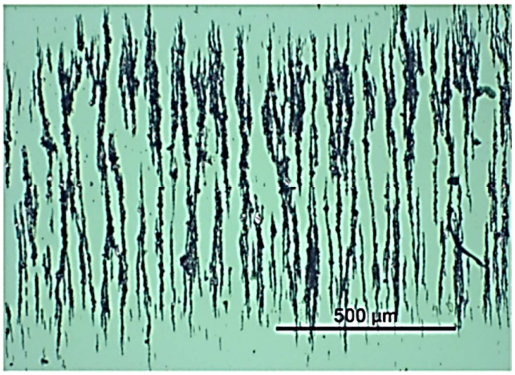
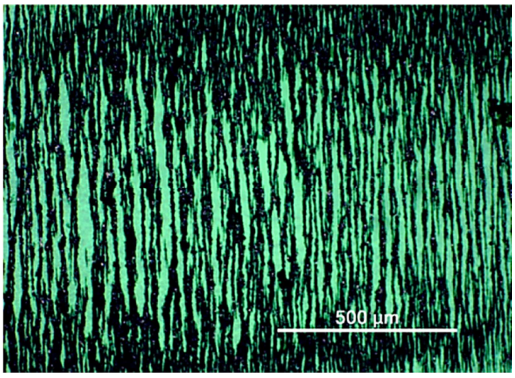
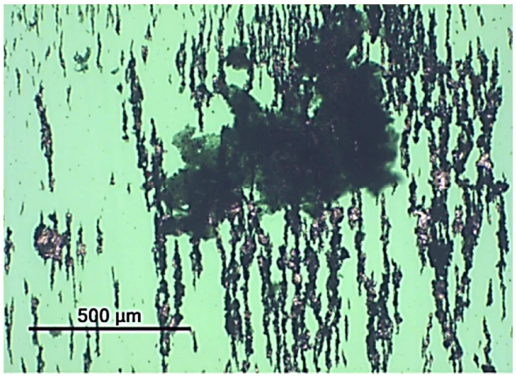
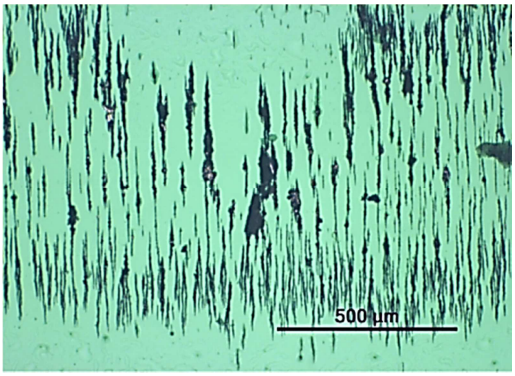
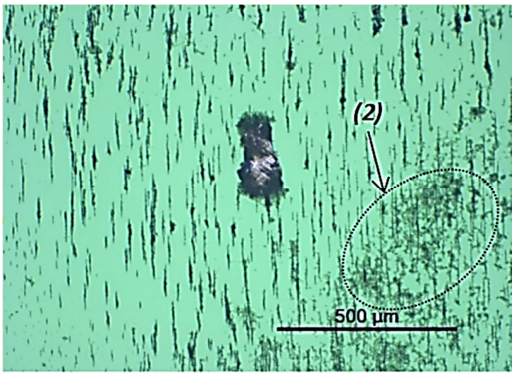
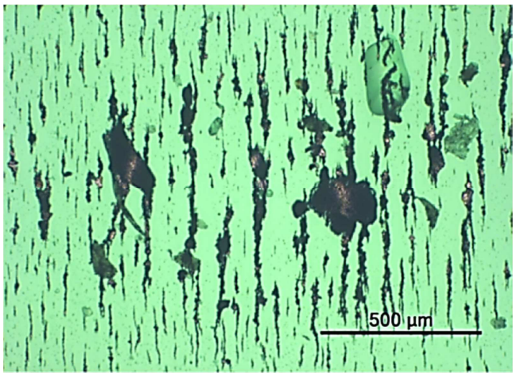
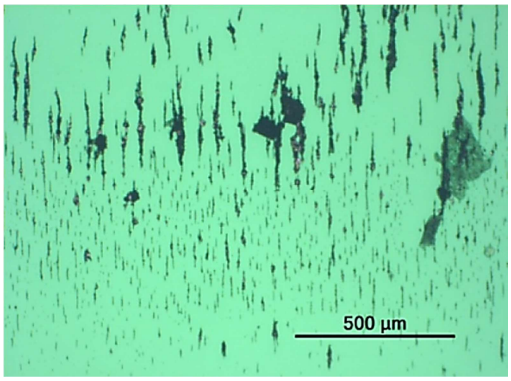
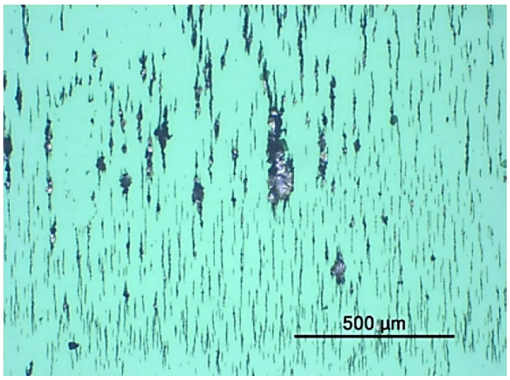
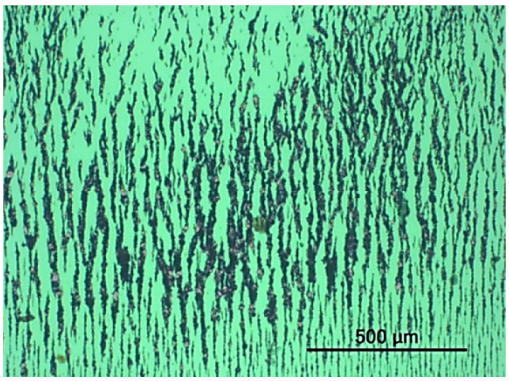
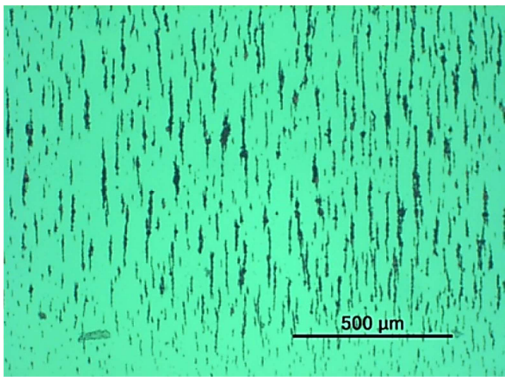
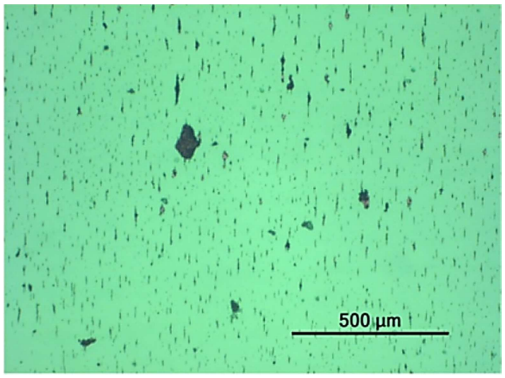
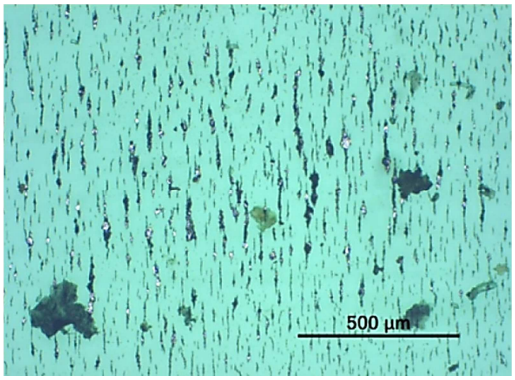
A.18. Ferrometry and Analytical Ferrography - TRB (20 rollers) - comparison

Analysis of Lubricants - Analytical Ferrography and Ferrometry		
	Thrust ball bearing (20 rollers)	**RUN-IN**
MIN - 320		d = 1 DL = 45,8 DS = 26,4 CPUC = 72,2 ISUC = 1,4E+03
PAO - 320		d = 1 DL = 98,3 DS = 39,7 CPUC = 138,0 ISUC = 8,1E+03
ESTER - 320		d = 1 DL = 96,7 Ds = 39,9 CPUC = 136,6 ISUC = 7,8E+03

Analysis of Lubricants - Analytical Ferrography and Ferrometry		
	Thrust ball bearing (20 rollers)	**Wear (48h)**
MIN - 320		d = 1 DL = 58,7 DS = 31,1 CPUC = 89,8 ISUC = 2,5E+03
PAO - 320		d = 0,1 DL = 40,3 DS = 18,5 CPUC = 588,0 ISUC = 1,3E+05 (2)- Presence of friction polymer
ESTER - 320		d = 1 DL = 59,0 DS = 21,4 CPUC = 80,4 ISUC = 3,0E+03

A.19. Ferrometry and Analytical Ferrography - TRB (10 rollers) - comparison

Analysis of Lubricants - Analytical Ferrography and Ferrometry		
	Thrust ball bearing 81107 TN	**Wear (10 rollers – first 50h)**
MIN - 320		d = 0,1 DL = 24,9 DS = 5,1 CPUC = 300,0 ISUC = 5,9E+04
PAO - 320		d = 0,1 DL = 26,9 DS = 7,9 CPUC = 348,0 ISUC = 6,6E+04
ESTER - 320		d = 0,1 DL = 54,4 Ds = 10,6 CPUC = 650,0 ISUC = 2,8E+05

Analysis of Lubricants - Analytical Ferrography and Ferrometry		
	Thrust ball bearing 81107 TN	**Wear (10 rollers – second 50h)**
MIN - 320		d = 0,1 DL = 12,8 DS = 5,0 CPUC = 178,0 ISUC = 1,4E+04
PAO - 320		d = 0,1 DL = 12,5 DS = 3,6 CPUC = 161,0 ISUC = 1,4E+04
ESTER - 320		d = 0,1 DL = 24,1 Ds = 5,2 CPUC = 293,0 ISUC = 5,5E+04