



Department of Mechanical Engineering

Tribology in Sheet Metal Forming

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Abstract

Current work is focused on the influence of friction in deep drawing process. Tribological tests were carried out using pin-on-disc machine and modified strip drawing tests, which were aimed to simulate behaviour and determine the coefficient of friction between sheet metal and tools during forming.

Experiments with various combinations of different tool, sheet materials and lubricants were performed to obtain friction coefficient variation with sliding velocity under different experimental conditions.

Different materials were tested for friction determination using pin-on-disc machine, in order to find the effect of lubricant properties and other variables on the friction coefficient of "Cold Rolled HSLA 380 and Cold Rolled HSLA 420" steel sheets in dry and lubricated conditions. Reciprocating sliding tests were performed, in order to obtain relevant information and prediction of the frictional behavior in these materials. Results were obtained in dry condition and twelve different combinations of lubricants.

Test results showed that values of friction coefficient varies over a wide range with different lubricating conditions and different sliding velocities. For some sliding velocities, the coefficient of friction is stable and low, while for others it is unstable and higher.

Friction measurements were also conducted using a modified tribotester based on strip sliding between tools. Four different tool surfaces were tested under similar contact conditions regarding contact area, normal pressure, sliding speed, lubricant and surface characteristics to calculate the friction coefficient between the tool surface and a high strength low alloy steel sheet HSLA 380.

Results of the experiments reveal that this novel tribotester is a very useful tool to evaluate and compare the friction between steel sheet and tool surfaces in alloyed steel for cold working applications. The outcomes have only small dispersion within the different test series, which indicates a stable process with good repeatability. The test method enables comparison of different surface finishes and treatments, lubricants and coatings in terms of friction and galling under conditions similar to those found in sheet metal forming processes. The four different types of surfaces considered for this study were grinded, polished, nitrided and quenched/tempered. The main difference among the tested tools in this work was the surface roughness, which was found to have a strong influence on friction.

Resumo

O presente trabalho está focado na influência do atrito nos processos de conformação plástica. Foram realizados ensaios em máquina pino-disco e num sistema desenvolvido para ensaio de deslizamento, com o objetivo de simular e determinar o coeficiente de atrito entre a chapa metálica e as ferramentas durante o processo de embutidura.

Foram realizados ensaios sob lubrificação com várias combinações de parâmetros para obter a variação do coeficiente de atrito com a velocidade de escorregamento sob diversas condições experimentais.

Foram ensaiados materiais diferentes para o estudo do atrito na máquina de pino-disco, para determinar o efeito das propriedades do lubrificante e de outras variáveis no coeficiente de atrito das chapas de aço laminadas a frio “*High Strength Low Alloy* - HSLA 380” e “HSLA 420” em condições a seco e sob lubrificação. Foram realizados ensaios de deslizamento alternativo para a obtenção de informação relevante e para a previsão do comportamento em atrito destes materiais e obtiveram-se resultados a seco e sob doze combinações diferentes de lubrificantes.

Os resultados dos ensaios mostraram que os valores do coeficiente de atrito dependem das condições experimentais utilizadas. O coeficiente de atrito varia numa gama larga com as diferentes condições de lubrificação e as diferentes velocidades de escorregamento. Para algumas velocidades de escorregamento o coeficiente de atrito é estável e baixo, enquanto para outras é instável e mais elevado.

Foram também efetuadas medições de atrito usando o sistema desenvolvido, tendo sido ensaiados quatro pares de ferramentas com preparações de superfície diferentes sob condições de contacto semelhantes no que diz respeito a área de contacto, pressão normal, velocidade de escorregamento, lubrificante e características superficiais para calcular o coeficiente de atrito entre a superfície da ferramenta e a banda em aço de alta resistência e baixa liga HSLA 380.

Os resultados dos ensaios revelaram que o novo sistema é uma ferramenta muito útil para determinar e comparar o atrito entre a superfície da ferramenta e a chapa de aço em situações de conformação a frio. Eles apresentam uma pequena dispersão experimental entre as diferentes séries o que indica que o processo é estável e com boa reprodutibilidade. O método de ensaio permite a comparação de diferentes acabamentos superficiais, tratamentos, lubrificantes e revestimentos em termos de atrito e desgaste em condições semelhantes às verificadas nos processos de conformação de chapa. A diferença principal entre as ferramentas ensaiadas neste trabalho está no acabamento superficial, que mostrou ter uma grande influência no atrito.

Keywords

Tribology

Friction

Roughness

Sheet metal forming

Lubricant

Steel sheet

Tool surface

Coefficient of friction

Normal force

Sliding speed

Contact pressure

Pin-on-disc

Strip drawing test

Sommerfeld Number

Stribeck curve

Surface texture measurement

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I will devote this work to the memories of my late mother, who always dreamed of seeing this day come true.

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Anvar Makhkamov



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Contents

1	Introduction	1
1.1	Motivation	2
1.2	Objectives	3
1.3	Thesis outline.....	4
2	Friction in sheet metal forming	5
2.1	Introduction	5
2.2	Friction	6
2.2.1	Parameters affecting friction force.....	8
2.2.2	The Stribeck curve in sheet metal forming.....	9
2.3	Roughness and Waviness	10
2.3.1	Surface texture measurement.....	11
2.3.2	Identifying and isolating surface characteristics.....	11
2.3.2.1	Roughness parameters.....	12
2.3.2.2	W_t – Total waviness height.....	14
2.3.2.3	T_{pa} / T_{pi} Material ratio	15
2.4	Tribology in sheet metal forming	15
2.4.1	Sheet metal forming in the automotive industry.....	16
2.4.2	Tribological systems	17
2.4.3	Tribological characteristics in the forming process	19
2.5	Lubrication influence in sheet metal forming.....	20
2.5.1	Lubricants for sheet metal forming.....	20
2.5.2	Preliminary lubrication	22
2.5.3	Lubricant friction	23
2.6	Conclusions	24
3	Tribological testing on modified pin-on-disc testing machine	25
3.1	Introduction	25
3.2	Methodology.....	26
3.3	Reciprocating tests and tested materials	27
3.4	Used lubricants for experimental tests	28
3.4.1	Oil properties measurement	30
3.4.1.1	Viscosity index.....	30

3.4.1.2	Density	30
3.5	Sheet materials.....	30
3.5.1	Mechanical properties and chemical composition.....	31
3.6	Pin-on-disc experimental conditions	32
3.7	Experimental results	33
3.7.1	Lubrication regime and the nature of friction	37
3.8	Friction determination and tribology testing in sheet metal forming under different loads	40
3.8.1	Experimental procedures	40
3.8.1.1	Influence of lubricant	41
3.8.1.2	Influence of speed	44
3.8.1.3	Influence of pressure	44
3.9	Conclusions	44
4	Determination of the friction coefficient in the flat strip drawing test	47
4.1	Introduction	47
4.2	Experimental setup	48
4.2.1	Tensile testing machine	48
4.2.2	The modified strip drawing tribotester	49
4.3	Assessment of tool surface roughness parameters	51
4.3.1	Tool materials	51
4.3.2	Tools with different surface finishes.....	52
4.3.3	Tool material properties.....	53
4.3.4	Tool and tool holder.....	54
4.3.4.1	Geometry of the tools	55
4.3.5	Hardness of tool materials	55
4.3.6	Bruker's NPFLEX 3D optical microscope	57
4.3.7	2D measuring method using contact device HOMMEL tester T500	60
4.4	Experimental conditions	62
4.5	Calculation of the coefficient of friction for the strip drawing tests	64
4.6	Friction coefficient versus Sommerfeld Number	70
4.6.1	Influence of viscosity	74
4.6.1.1	Viscosity pressure dependency	74
4.6.2	Influence of roughness.....	75

4.6.3	Influence of pressure	77
4.6.4	Influence of velocity	79
4.7	Discussion of results	81
4.7.1	Influence of lubricant	81
4.7.2	Influence of roughness	82
4.7.3	Analysing the Stribeck curve	82
4.8	Conclusions	84
5	Conclusions and future work	86
5.1	Concluding remarks	86
5.2	Future work	88
	References	89
	Annexes	94
A.	Lubrication regime and the nature of friction	94
A 1.	Comparing lubricant combinations	94
A 2.	Viscosity of Prelubes Fuchs Anticorit PI 3802-395 and Quaker Ferrocote S-6130 and their combination with other lubricants	96
A 3.	Pin-on-disk experimental test result with different loads and several lubricants	98
A 4.	Pin-on-disk experimental test result, by coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 420"	105
B.	Surface preparation of tool steels	107
B 1.	Basic tool design	107
B 1.1.	The surface parameters measured by Bruker's NPFLEX 3D optical microscope	114
B 2.	Contact measurement results by HOMMEL tester T500	123
C.	Strip drawing test results	129
C 1.	The coefficient of friction as a function of sliding speed and applied normal force	129
C 2.	Set of tools	133

List of figures

Figure 1.1 Influencing factors to the forming properties of sheet metals, adapted from [6].....	3
Figure 2.1 Schematic illustration of the deep-drawing process, adapted from [6].....	5
Figure 2.2 Coulomb friction model, adapted from [26]	7
Figure 2.3 Stribeck curve diagram, adapted from [29].....	9
Figure 2.4 The principle of measuring average roughness R_a , adapted from [43]	13
Figure 2.5 R_z maximum height of profile, R_{zmax} maximum height of profile [50].....	14
Figure 2.6 Waviness height [50].....	14
Figure 2.7 Comparison of the parameters T_{pi} and T_{pa} for different profiles [50]	15
Figure 2.8 Schematic representation of conversion metallic sheet into components [56]	16
Figure 2.9 Tribological system, adapted from [67]	18
Figure 2.10 Experimental rig for strip pulling test, adapted from [68]	19
Figure 3.1 Modified pin-on-disc machine (Plint TE 67/R)	26
Figure 3.2 Test samples of the steel sheet are stacked on the plate.....	27
Figure 3.3 Preparation of combined lubricants for viscosity measurement	29
Figure 3.4 Samples of the steel sheet HSLA 380	30
Figure 3.5 Dry test - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"	33
Figure 3.6 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"	34
Figure 3.7 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"	35
Figure 3.8 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"	35
Figure 3.9 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"	35
Figure 3.10 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"	36
Figure 3.11 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"	36
Figure 3.12 Sommerfeld number and average coefficient of friction, for Prelube Fuchs Anticorit PL 3802-39S and various combination with different lubricants.....	39
Figure 3.13 Sommerfeld number and average coefficient of friction, for Prelube Quaker Ferrocote S-6130 and various combination with different lubricants	39

Figure 3.14 Friction coefficient against Sommerfeld number for Base lubricant Prelube A ...	42
Figure 3.15 Friction coefficient against Sommerfeld number for Base lubricant Prelube B ...	43
Figure 4.1 Schematic illustration set of the modified strip drawing tribotester	47
Figure 4.2 Tensile testing machine and modified strip drawing tribotester	49
Figure 4.3 Tool plates set of the modified strip drawing tribotester (L – means Left side of the tool plates, when looking at the front side; R - means Right side of the tool plates)	50
Figure 4.4 Set of tools and sheet metal layout	51
Figure 4.5 Tool couples with different surface finishes (L-Left plate; R-Right Plate)	52
Figure 4.6 View of the tool and tool holder	54
Figure 4.7 Strip drawing test tool dimensions	55
Figure 4.8 Vickers hardness test method, adapted from [89]	56
Figure 4.9 Bruker's NPFLEX 3D optical microscope; its large nominal working volume handles small or large sample coupons and multi-sample trays	57
Figure 4.10. Measured surface area 5x5 mm ² , tool surface Grinded along the Sliding direction	57
Figure 4.11 3D analysis of a surface of a profile of Grinded “L” tool	58
Figure 4.12 3D analysis of a surface of a profile of Grinded “R” tool	59
Figure 4.13 Method of measurement of tool surface with traditional HOMMEL TESTER T500	60
Figure 4.14 Dimensions of test samples of the steel sheet HSLA 380	63
Figure 4.15 Tested steel sheets	63
Figure 4.16 Selected tools with different surface finish or treatment after friction tests (L-Left plate; R-Right Plate)	64
Figure 4.17 The coefficient of friction as a function of displacement at constant sliding speed and applied normal force	66
Figure 4.18 Coefficient of friction as a function of normal pressure for Grinded surface	67
Figure 4.19 Coefficient of friction as a function of normal pressure for Polished surface	68
Figure 4.20 Coefficient of friction as a function of normal pressure for Nitrided surface	69
Figure 4.21 Coefficient of friction as a function of normal pressure for Quenched/tempered	70
Figure 4.22 Sommerfeld's Number - lines for different tool surface conditions	72
Figure 4.23 Friction coefficient versus Sommerfeld number for the Polished surface	72
Figure 4.24 Friction coefficient versus Sommerfeld number for the Grinded surface	73
Figure 4.25 Friction coefficient versus Sommerfeld number for the Nitrided surface	73
Figure 4.26 Friction coefficient versus Sommerfeld number for different surface texture	74

Figure 4.27 Variation of average coefficient of friction with modified Sommerfeld number for various types of surface textures under lubricated conditions.....	76
Figure 4.28 Friction coefficient versus Sommerfeld number with the variation of pressure ...	78
Figure 4.29 Friction coefficient versus Sommerfeld with the variation of sliding speed	80
Figure 4.30 Schematic of Stribeck curve to compare experimental tests Strip tension test and Pin-on-disc	83

List of Table

Table 2.1 Classification system for form deviations according to DIN 4760 [47]	12
Table 2.2 Different types of lubricants for metal forming process [72].....	21
Table 3.1 Typical chemical composition of AISI D2 Steel [82]	27
Table 3.2 Prelube lubricants and ten different combinations with Press oils.....	28
Table 3.3 Ladle analysis chemical composition of steel sheets HSLA 380 and HSLA 420....	31
Table 3.4 Mechanical properties of steel sheets HSLA 380 and HSLA 420	31
Table 3.5 Surface roughness parameters of the tested steel sheet material before tests.....	32
Table 3.6 Friction test sliding velocities.....	33
Table 3.7 Average coefficient of friction results of different combined lubricants and varying sliding velocity	37
Table 3.8 Sommerfeld number and coefficient of friction, for Prelube Fuchs Anticorit PL 3802-39S and various combination with different lubricants.....	38
Table 3.9 Sommerfeld number and coefficient of friction, for Prelube Quaker Ferrocode S-6130 and various combination with different lubricants	38
Table 3.10 Prelube lubricants and four different combinations with Press oils	40
Table 3.11 Average coefficient of friction results of different combined lubricants and varying sliding velocity, under different loads	41
Table 4.1 Chemical composition, (average %) [85], [86]	53
Table 4.2 Hardness of selected tool materials	56
Table 4.3 Surface roughness parameters of the tested tools before tests	59
Table 4.4 Surface roughness parameters of the tested tools after tests	60
Table 4.5 Grinded “L” surface parameters - Before tests.....	61
Table 4.6 Grinded “L” surface parameters - After tests	61

Table 4.7 Grinded “R” surface parameters - Before tests	61
Table 4.8 Grinded “R” surface parameters - After tests.....	62
Table 4.9 The specifications for strip drawing test	62
Table 4.10 Properties of lubricant	63
Table 4.11 Experimental results	66
Table 4.12 Output parameters of Grinded surface experimental tests	67
Table 4.13 Output parameters of Polished surface experimental tests.....	68
Table 4.14 Output parameters of Nitrided surface experimental tests	69
Table 4.15 Output parameters of Quenched/tempered surface experimental tests	70
Table 4.16 Parameters for Sommerfeld number calculation	71
Table 4.17. Value of the roughness Rz.....	76

List of Symbols

Symbols	Units	Designation
A	mm^2	Area
C_p	N/mm^2	apparent contact pressure
$C_F, (P)$	N	contact force
$F, (F_T)$	kN	friction force, (tangential force)
F_N	kN	normal force
F_p	kN	pulling force
$F_p \sigma$	-	pulling standard deviation
I_n	-	evaluated over the measured length
L_w	-	single measured length
N	kN	normal load
R_a	μm	roughness average
$R_{max}, (Rt)$	μm	maximum peak-to-valley height within one cut-off
R_{pm}	μm	roughness parameters of surface
R_y	μm	roughness parameter
$R_{z(DIN)}$	μm	maximum roughness profile height
S	m	Sommerfeld number
S^*	m^{-1}	modified Sommerfeld number
S_a	μm	average roughness, (3D)
S_{ku}	-	surface kurtosis
S_p	μm	highest peak of the surface
S_q	μm	root mean square roughness parameter
S_{sk}	-	surface skewness
S_v	μm	maximum pit depth
S_z	μm	10-point peak valley surface roughness
T_{pi}	-	micro-material ratio
T_{pa}	-	macro-material ratio
W_t	μm	total waviness height
Z_i	μm	maximum peak-to-valley height
l	$l = 10 \text{ mm}$	track length
p	MPa	pressure
rpm	-	rotation per minute
t	second	time required for one cycle in seconds
α	-	viscosity pressure coefficient
η	mPa.s	dynamic viscosity
η_0	mPa.s	is the dynamic viscosity at 1 bar
η_p	mPa.s	the dynamic viscosity at a pressure p
λ_c	-	low-pass filtering with the cut-off wavelength
λ_f	-	high-pass filtering with the cut-off wavelength
μ	-	coefficient of friction
ν	Pa.s	absolute viscosity
u	mm/s	sliding speed

1 Introduction

This thesis is related with the tribological behaviour of materials involved in sheet metal forming processes. The fundamental mechanisms controlling the forming properties of sheet metals depend on a complex combination of factors such as steel sheet, tool material and lubricant, besides tribological conditions, press parameters and other variables. It is a typical tribological problem, where the interaction mechanisms between two surfaces in relative motion must be identified. To solve the tribological problem a basic understanding of the tribological conditions prevailing during sheet metal forming is important. Tribological knowledge is a specific tool for sheet metal forming operations [1], but also for the development of new surface engineering concepts able to reduce problems such as high coefficient of friction and lubrication conditions, which are also demanded.

Tribology takes all theoretical and practical results from friction, wear and lubrication [2] with much more new senses and contents based on the development of science and technology. Tribology cannot be looked simply as involving only friction, wear, lubrication or any other related technique. Several studies, e.g. Bharat Bhushan et al. [1] and Peter Blau [3] have provided further evidence of this complexity. This area of knowledge has been studied in many different practical applications, independently from very different points of view over a long period of time. However, its unifying concepts have been defined more recently and therefore tribology can be viewed as an old topic and also a very young discipline.

Tribology found its roots in problems faced in drive systems. Since then much emphasis has been put on problems like the reduction of friction in technological processes, for example sheet metal forming. Furthermore, mixed lubrication has been faintly studied. If a system is lubricated, it is preferably designed in such a way that hydrodynamic lubrication occurs, thereby decreasing friction. Theo Mang [4] gives some examples of this phenomenon, although only a few of the studies on mixed lubrication have been carried out by performing actual friction experiments. Friction knowledge is very important because it affects many aspects of manufacturing processes, such as the required force, the die wear and in some cases the process feasibility.

In conventional sheet forming processes, such as stamping or drawing, significant contact phenomena take place between workpiece and die surfaces. Especially, sliding motion and normal loads generate friction which influences some aspects of processes such as material flow, tools wear and life and total force needed to complete the process [5].

Deep drawing is among the most dominant processes in modern industry and steel is the most widely used material in the world, due to its strength, versatility and low cost. Steel is therefore one of the basic ingredients in the development of automotive industry and the whole society. On the other hand, sheet metal forming processes, e.g. deep drawing, usually involves large plastic deformation.

Tribological tests were carried out using pin-on-disc machine and modified strip drawing tests, which were aimed to simulate behaviour and determine the coefficient of friction between sheet metal and tools during forming.

Experiments with various combinations using lubricants were tested to obtain friction coefficient variation with sliding velocity under different experimental conditions. Different materials were tested for friction determination using the pin-on-disc machine, to find the effect of lubricant properties and other process variables on the coefficient of friction between sheet metals and tools. In this study, the friction experiments were conducted using mixed lubricants. Furthermore, a method has been developed for the friction tests with pressure dependent variable, when steel sheets slide against cold work steel tools with different profile surfaces.

1.1 Motivation

The study of the frictional characteristics of selected steel sheets is a demanding topic from automotive industry and its motivation comes from a cooperation with an industrial partner producing automotive parts. The research was focused on determination and comparison of friction coefficients obtained by two types of tribological tests: a pin-on-disc test and a strip drawing test.

The traditional approach to friction is Coulomb's friction law, which is simple and used commonly, but very often with limitations to fully model the experimental behavior. Therefore, different alternatives had been investigated considering different parameters or variables like, e.g., applied pressure, lubricant viscosity, sliding speed, surface roughness and material properties.

In this way, the methodology of current thesis included: study and definition of tribology tests for sheet metal forming, design and implementation. Thus, experimental research under current topic had the following directions:

- to understand apparent contact pressure conditions during sheet metal forming;
- to assess the influence of lubricants in sheet metal drawing operations;
- to analyse friction behaviour by performing actual friction experiments for steel sheets with cold work steel tools and different surface finishes.

Therefore, experimental research has included classical tests, where each influencing parameter could be isolated and controlled. Additionally, the connection to modelling has been searched in order to allow and test transferability of the results from the laboratory to the different industrial metal forming operations.

This study has evaluated surface properties of tool materials for metal forming operations by comparing different tribological test methods. It was proved that load scanning is a very simple and suitable method to evaluate surface properties of tool materials. This method was successfully applied to study the effect of the surface treatment and the roughness of tool material as well as the behaviour of different lubricants.

The assessment of friction during sheet metal forming operations is a very complex task, and the selected laboratory test presents a fundamental importance to gather usable friction data.

Results of the experiments reveal that a developed tribotester is a very useful tool to evaluate and compare the friction between steel sheet and tool steel for cold working applications. The outcomes have only small dispersion within the different test series which indicates a stable process with good repeatability. The test method enables comparison of different surface finishes and treatments, lubricants and coatings in terms of friction and galling under sheet metal forming process conditions. Valid frictional data is also very important as an input parameter for simulation models to achieve reliable results.

The main difference between the tested tools in this work was the surface roughness, which has a strong influence on friction. The four different types of surfaces were obtained by different heat treatments or thermochemical treatment and different mechanical surface finishes.

1.2 Objectives

The objectives of this research included the determination of tribological behaviour of tool surfaces and the study of two grades of deep drawing steel sheets that are commonly used in automotive industry. Parameters such as applied normal force, contact area, lubricant, temperature, surface texture and sliding velocity are fully controllable. Figure 1.1 presents influencing factors to the forming properties of sheet metals.

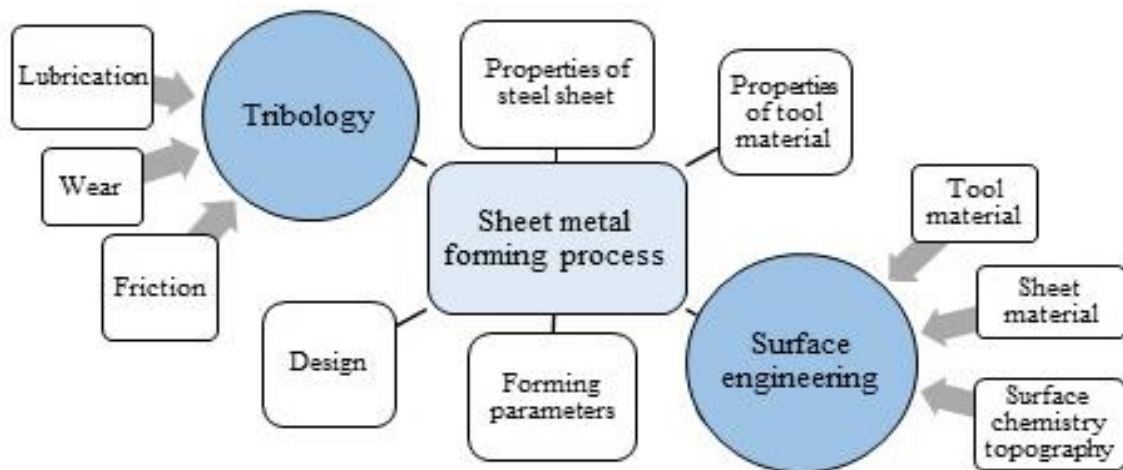


Figure 1.1 Influencing factors to the forming properties of sheet metals, adapted from [6]

Tribological tests were carried out by using pin-on-disc machine and modified strip drawing test, which were aimed to determine the coefficient of friction behaviour between sheet metal and tools during forming. The main variables under analysis were:

- value of the friction coefficient;
- specimen orientation;
- normal load;

- friction measurement with orientation to the rolling direction of the sheet;
- surface roughness of tools;
- lubricant conditions.

Moreover, the estimation of changes in the surface roughness of tools and steel sheets was also performed.

1.3 Thesis outline

This thesis consists of five main chapters and three annexes:

Chapter 2, entitled “Friction in sheet metal forming”, presents a literature review on different sources of importance the tribology - friction, wear and lubrication - in sheet metal forming, also giving a general understanding of the Stribeck curve. The different classes of surface irregularity are presented and also the difference between waviness and roughness concepts and measurement methods. Tribological characteristics and methods of lubricant selection for forming process are addressed.

Chapter 3, entitled “Tribological testing on modified pin-on-disc testing machine”, presents the coefficient of friction measurements, carried out on a pin-on-disc machine lubricated with Prelube oils and their combinations with different Press oils. The coefficient of friction is discussed and the experimental results are compared. The friction behaviour of the oils was measured in a wide range of operating conditions. Test procedures and analyses are also presented. The materials that have been chosen for this work are presented and also their properties and characteristics. A set of two Prelube oils (Fuchs Anticorit PI 3802-395 and Quaker Ferrocode S-6130) and its combination with five Press oils have been selected for the study and characterized. Two cold rolled high strength low alloy steels HSLA 380 and HSLA 420 have been elected, so, their mechanical properties and chemical compositions are also presented.

Chapter 4, entitled “Determination of the friction coefficient in the flat strip drawing test”, presents an overview of testing procedures and experimental results. The drawing experiments and friction coefficient determination have been performed by the modified strip drawing tribotester. The effects of contact pressure and sliding velocity under lubrication were estimated based on a long steel sheet drawn between two tools. The discussion and analysis of the friction test results were represented based on Sommerfeld number. The surface roughness measurements were carried out using the two available instruments: Bruker’s NPFLEX 3D optical microscope and contact measuring device HOMMEL tester T500. Surface texture measurements, taken before and after test are discussed and compared. The hardness of the tool materials was also measured and discussed.

Chapter 5, entitled “Conclusions”, presents the final conclusions of the thesis and suggests possible future work.

2 Friction in sheet metal forming

2.1 Introduction

In sheet metal forming industry, friction and lubrication are influenced by many factors such as material properties, temperature, surface finish, contact pressure, sliding velocity and lubricant characteristics [7]. The current literature on this subject argues that sheet metal forming friction and friction related aspects are major concerns as they have a big influence on productivity and product quality [8]. In sheet metal forming a blank of sheet material is deformed plastically and formed to a final shape, as seen in Figure 2.1. The process is based on sheet deformation caused by the relative movement between tools and a sheet metal, an interaction that generates friction forces. In sheet metal forming process, to produce top quality products, it is important to understand and to be able to control the frictional conditions as the frictional forces influence the formability of the sheet by affecting the strain distribution in various regions of the tool. By controlling the tribological conditions in the process, it is possible to reduce defects or problems, like crack formation, shrinkage, surface deflections (e.g. wrinkles) and severe tool wear.

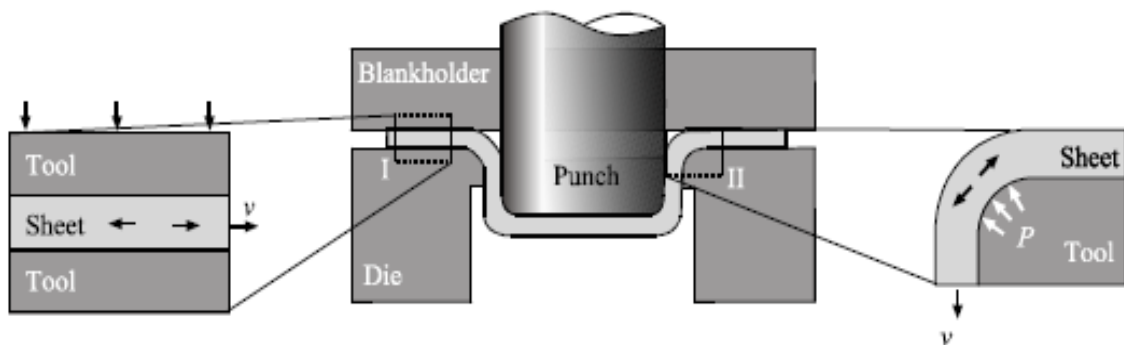


Figure 2.1 Schematic illustration of the deep-drawing process, adapted from [6]

Figure 2.1 schematically presents the main variables related to friction in a drawing process. P represents contact pressure and v the sliding speed in region I, where sheet is allowed to slide between the blank holder and die; in region II, the highest wear rate of the tool and the sheet is expected, due to a bending and unbending deformation.

The studies of Trzepieciński et al. [9a] have provided further evidence that the forming process is influenced not only by the surface topography, but also by several parameters such as lubricant, surface chemistry, contact pressure, and sliding speed. Furthermore, previous study also examines the work of Choi et al. [9b] reporting the significance of friction in the deep drawing process and its relation with increasing inequality of deformation and loading force value and worsening the quality of the drawn piece surface. Therefore, clarification of friction is essential for modelling and analysing sheet metal forming processes. Nevertheless, in sheet

stamping, friction cannot be considered as a static parameter due to the varying process conditions during the forming operation. It can be argued that friction fluctuates widely in the forming tool depending on the actual forming conditions.

Considering that much work has been devoted to developing various tribotesters, both commercial and non-commercial, the literature by Bay et al. [10] explores the ways in which several kinds of friction tests have been developed, in order to determine the coefficient of friction in different regions of formed draw piece. The results from laboratory friction tests and their analysis are very significant for reducing time and costs in the testing phase, before parts production. The friction data should be both accurate and comprehensive. Using several friction tests setups to cover the actual working area, takes time and increases the source of errors due to the vague correlation between different setups.

Ceretti et al. [11] discusses the different ways in which there are several standard methods for friction measurement, in order to investigate and to determine the friction value, taking into account tests, such as ring test [12], strip test [13] and pin-on-disc [14]. For the last decades many authors have proposed new methods to evaluate friction, like twist compression test, pin-on-disc, block on ring, pin on V-block and other variants [11], [15]. These methods are often poorly correlated to true friction or wear conditions. They consider different parameters such as contact area, applied load and geometry. These test devices are often not comparable to manufacturing processes like sheet metal forming, so their estimates of the friction coefficient may be misleading. A few tribological test apparatus have been developed to specifically imitate the load conditions in different sheet forming processes. Several methods have been proposed such as bending under tension [16], [17], strip drawing [18], drawbead simulation test [19], strip reduction test [20] and they are often used to estimate the friction and wear behaviour between surfaces.

Nevertheless, these methods have some drawbacks. Many of them can only take a few parameters into consideration, like a fixed or limited tool size, instead of real contact situations such as a line or point contact. In addition, they rely on a static test procedure with fixed parameters like load and speed to calculate friction.

2.2 Friction

Coefficient of friction is defined as the ratio between the friction force and the normal load [17]. Authors like William Ruff [21], Kenneth Ludema [22], Niklas Axen et al. [23] and Peter Blau [24] argue that when the forming tool surface is sliding against the workpiece under a given load there will be a friction force between them, opposite to the sliding direction. This phenomenon is called friction, and the ratio between the two forces is called coefficient of friction:

$$\mu = \frac{F_T}{F_N} \quad (2.1)$$

where, μ the coefficient of friction; F_N normal force; F_T tangential force (friction force) [24].

The most common form of friction law is known variously as the "Amontons-Coulomb Law" referring to work done by the two scientists in 1699 and 1785, respectively [25], [26]. According to them:

- “the force of friction is directly proportional to the applied load” - Amontons first law;
- “the force of friction is independent of the apparent area of contact” - Amontons second law;
- “kinetic friction is independent of the sliding velocity” - Coulomb's law of friction.

Several studies [25], [27] were dedicated on the identification of the effect of speed to the coefficient of friction. Coulomb drew attention to the existence of such a relationship, but according to Coulomb's law of friction the friction force is independent of the sliding velocity [28]. In a first approximation, the coefficient of friction μ only depends on the nature of the two surfaces and it does not depend on the normal force F_N , the size of the apparent contact area or the relative speed at which the surfaces are gliding [29]. Very often the coefficient of friction μ is assumed as constant, with the basic idea that it is a constant with respect to contact pressure or stress for a given situation [26]. This case highlights the importance the coefficient of friction μ , as the value which describes the ratio of the force of friction between two bodies and the force pressing them together. Coefficient of friction ranges from near zero to greater than one.

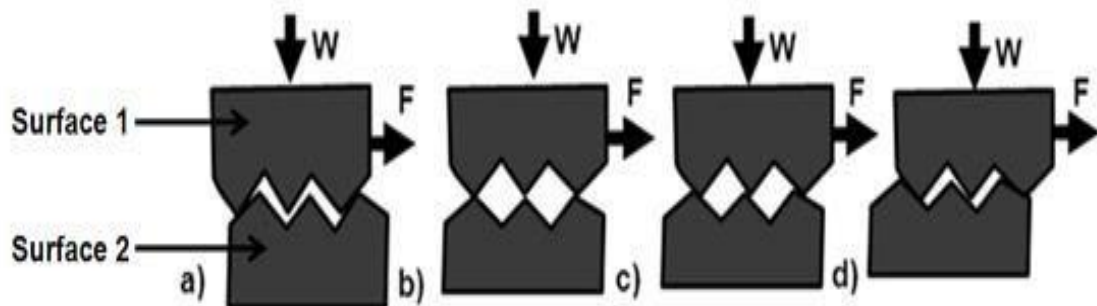


Figure 2.2 Coulomb friction model, adapted from [26]

Figure 2.2 shows the model for Coulomb friction in a contact between rough surfaces, where W is weight and F is the pulling force. In this approximation, the friction coefficient does not depend on the normal load, the size of the apparent contact area or the sliding speed. However, there are cases where the coefficient of friction cannot be considered as a constant and they include the following situations [29]:

- when normal forces are very high, μ decreases at very high levels of F_N , and the maximum shear stress at the surface is limited by the material strength, therefore the tangential force F_T is limited as well;
- at high levels of friction forces, the surface may get damaged by what is called scoring or galling; this increases friction;

- when the microscopic space between the two contacting surfaces is filled with lubricant, a pressure can be generated in the lubricant by hydrodynamic effects, which carries some part of the normal force, F_N , and this effect decreases friction.

2.2.1 Parameters affecting friction force

Different researchers have studied the role of parameters that can affect friction force, in which this variable is measured under conditions close to those observed in forming operations [30], [31], [32]. Main parameters to be considered are:

- contact pressure: the friction force increases as the contact pressure or normal force increases;
- sliding speed: the dynamic friction force is smaller than the static friction force;
- materials: the elastic and plastic properties of the materials in contact will certainly affect how difficult it is to slide two materials across one another; at low true contact pressure, the asperities are more likely to interact elastically; also, the materials may have different fracture characteristics that lead to changes in the surface topology and debris generation on the friction surface;
- surface roughness: the shape and density of asperities may have a major effect on friction, whether lubricated or dry; however, even the measurement of surface roughness is difficult and its quantification is not standard, except for a few simple parameters;
- lubrication and debris: the presence of other materials at the contact surfaces is important; the properties of the lubricant (rheology, compressibility, temperature sensitivity, and so on) must be considered; the distribution of lubricant depends intimately on surface conditions, pressure, and sliding speed, and knowledge of these depends on the forming operation analysis;
- temperature: the local temperature at contact points and in lubricants will depend on thermal conductivity and plastic work dissipation;
- concurrent deformation: this effect is particularly relevant for metal forming because the workpiece is usually deforming plastically while the friction forces are operating; the deformation changes the surface roughness, eliminates most elastic effects in the contact and opens the new surface by the action of dislocation slip.

With these variables influencing friction, it is necessary to make measurements under conditions as close as possible to the real ones (defined as similitude) in the forming operations. Also, for purposes of simulation, it is necessary to adopt simple laws allowing measurement of a limited number of coefficients. These two principles, **similitude** and **simplicity** are often contrary, but they guide the design of most applied friction tests [22].

2.2.2 The Stribeck curve in sheet metal forming

According to the Stribeck curve the friction between two surfaces in contact varies with velocity, applied load and type of lubricant. However, in a sheet stamping operation, the friction cannot be considered as a static parameter due to the varying process conditions during the forming operation [33], [34]. In reality, friction fluctuates widely in the forming tool depending on the actual forming conditions. In the literature on this subject [29] there is a study which was published in 1902 by a German researcher named Stribeck. He proposes that friction effects can be conveniently highlighted by plotting the so called Stribeck curves.

The Stribeck curve illustrates schematically the onset of various types of lubrication mechanisms. Coefficient of friction, μ , is plotted as a function of the Sommerfeld number, S , defined as the product of dynamic viscosity of the lubricant, η , by the sliding speed, v , divided by apparent pressure, P [28], [29], as presented in equation 2.2.

$$S = \frac{\eta \cdot v}{P} \quad (2.2)$$

Conventionally, S is plotted on a logarithmic scale and in the obtained Stribeck plots, one may see three distinct regions, as shown in Figure 2.3.

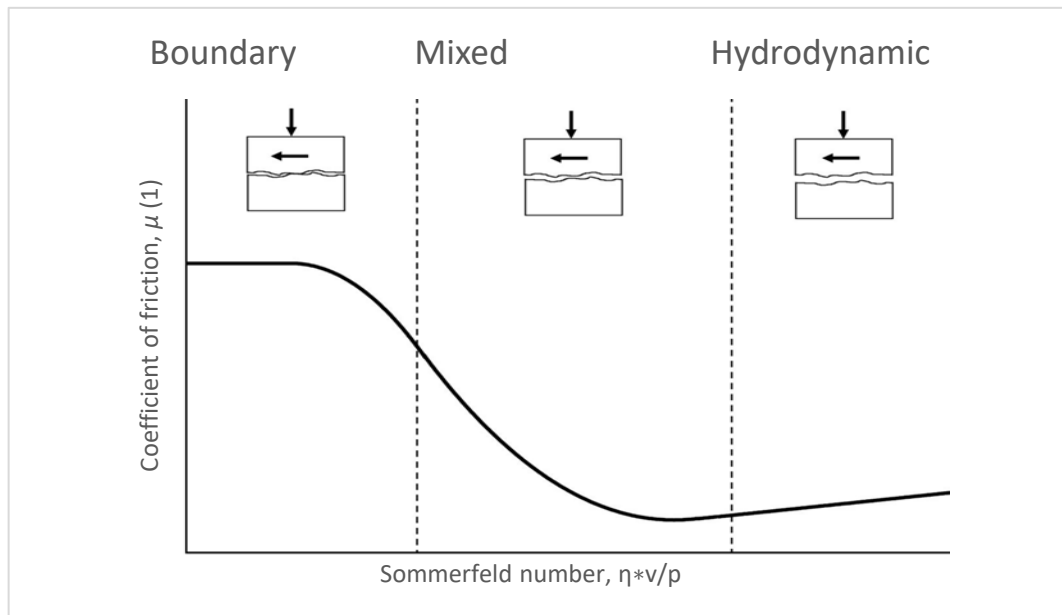


Figure 2.3 Stribeck curve diagram, adapted from [29]

As seen in Figure 2.3, three regimes of lubrication can be observed: boundary lubrication, mixed lubrication and hydrodynamic lubrication. They can be defined as:

- boundary lubrication, where the full load is carried by the asperities of the contacting surfaces;

- mixed lubrication, where the load is partially carried by the asperities and partially by the lubricant;
- hydrodynamic lubrication, where the full load is carried by the lubricant.

At boundary lubrication, any pressure build-up in the lubricant is neglected, and there is no clear frontier separating this regime to the mixed lubrication. There is, however, a basic difference between mixed and hydrodynamic lubrication: at hydrodynamic lubrication, the two surfaces are completely separated from each other by the lubricant, while at mixed lubrication there is physical contact between the surfaces which can be checked for example by electric measurements [4], [35].

Boundary lubrication is lubrication by a liquid under conditions where the solid surfaces are so close together that appreciable contact between opposing asperities is actually occurring. The friction and wear in boundary lubrication are determined predominantly by interaction between the solid surfaces. The bulk flow properties of the liquid play little or no part in the friction and wear behaviour.

Some published papers by Figueiredo et al. [17] and Mortier et al. [36], highlight the importance of Stribeck curve in sheet metal forming. Especially important for metal forming is to know the transition conditions from boundary to mixed and to hydrodynamic lubrication regimes. In this case, the micro-peaks of the metal surface experience boundary lubrication conditions and the micro valleys of the metal surface become filled with lubricant [37]. Hydrodynamic lubrication is experienced in a few sheet metal forming processes, such as high speed sheet roll forming operations, where large velocities at the material tool interface create hydrodynamic conditions [38]. However, in a sheet stamping process, there are several other parameters, like type of material, hardness, texture, surface morphology, roughness, all of them influencing friction [39]. This is a significant obstacle not only in the actual stamping operation but also during simulations of the forming process. It is usually difficult to unambiguously establish which type of sliding mode is occurring, but an empirical criterion, based on the Stribeck curve is often used as an indicator.

2.3 Roughness and Waviness

Surface texture, repetitive deviation from the nominal surface, includes roughness (nano and micro-roughness), waviness and lay. Several studies e.g. Chunju Wang et. al. [40], have provided further evidence of this topic. The roughness on sheet metal is normally applied by a rolling process and different types of roughness are named according to the way in which the rolls are roughened (textured) [14]. Every part's surface is made up of texture and roughness which varies due to manufacturing techniques and the part structure itself.

Surface roughness is a measure of the texture of that surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are great, the surface is rough, if they are small, the surface is smooth. Roughness is typically considered to be the high frequency, short-wavelength component of a measured surface profile [41].

Waviness includes all irregularities whose spacing is greater than the roughness sampling length and less than the waviness sampling length [42]. Lay is the principal direction of the predominant surface pattern, ordinarily determined by the production method [43].

2.3.1 Surface texture measurement

The primary metrological features of a surface area include: size, position, form (or contour), waviness and roughness.

Relying on human senses to determine surface texture is subjective and suffers the following problems [44], [45]:

- reliant on experience and expertise;
- dependant on what the inspector wants to see;
- inconsistent and inaccurate;
- difficult to record and communicate;
- inadmissible as evidence in future disputes.

Measuring surface texture with analytical instruments is a quantitative process. Various instruments are available for the roughness measurement. The measurement technique can be divided into two broad categories [43]:

- a contact type in which during measurement a component of the measurement instrument actually contacts the surface to be measured;
- a noncontact type.

A contact type instrument may damage surfaces when used with a sharp stylus tip, particularly soft surfaces. For these measurements, the normal loads must be low enough so that the contact stresses do not exceed the hardness of the surface to be measured.

2.3.2 Identifying and isolating surface characteristics

Every surface is composed of different classes of surface irregularity. The difference between the waviness and roughness classes are based on the surface profile, wavelength or peak-to-peak spacing.

The form error in the part is caused by misalignment of the workpiece axis to the cutting tool guide-way. The waviness in the part is a result of the guide-ways not being straight as well as machine tool vibration. But, the roughness is a direct result of the selected tool feeds, speeds, and cutting tool geometry.

Surface profile characteristics can be classified into six categories as shown in Table 2.1. Shape, waviness and roughness (periodic and random) are the main concerns in general manufacturing. These are designated as the first, second, third and fourth orders of profile form deviations [46].

Table 2.1 Classification system for form deviations according to DIN 4760 [47]

Form deviation (shown exaggerated as profile section)	Examples	Causes
Class 1: Shape deviations 	Deviation from straightness, flatness, roundness, etc.	Faults in machine tool guideways, deflection of machine or workpiece, incorrect clamping of workpiece, hardening distortion, wear
Class 2: Waviness 	Undulation (see DIN 4761)	Eccentric clamping, deviations in the geometry or running of a cutter, vibration of the machine tool or tool chatter
Class 3: Roughness 	Grooves (see DIN 4761)	Form of tool cutting edge, feed or infeed of tool
Class 4: Roughness 	Score marks, flaking, protuberances (see DIN 4761)	Chip formation process (segmental chip, continuous chip, built-up edge), deformation of material during blasting, bud formation during electrolytic treatment
Class 5: Roughness	Crystalline structure	Crystallization process, modification of surface through chemical action (e.g. acid treatment), corrosion processes
Class 6: Note: No longer capable of straightforward representation in pictorial form	Lattice structure of material	
The class 1 to 4 form deviations above are usually superimposed on the actual surface. Example: 		

Surfaces defects are composed of surface roughness, bumps and hills and a criterion to differentiate between these different characteristics can be defined. The point at which roughness becomes waviness (the cut-off point) is arbitrary, and related to the manufacturing process and the function of the surface. No absolute definition exists of what constitutes roughness and when roughness becomes waviness.

Products which have identical designations but come from different batches or different suppliers may have noticeably different roughness characteristics [42].

2.3.2.1 Roughness parameters

2.3.2.1.1 R_a (CLA, AA) – Average Roughness

The roughness of a surface has most commonly been measured by the instrument in which a stylus travels across the surface, the movement of the stylus is amplified and the signal recorded [48], [49]. The result is generally expressed as R_a or average roughness which is the arithmetic mean of the deviations (absolute values) of the profile about the centerline, Figure 2.4.

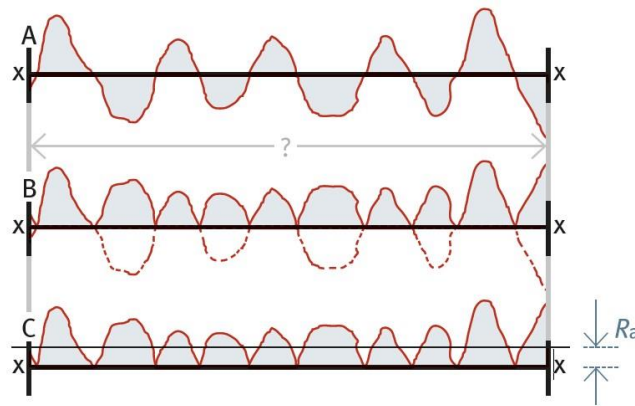


Figure 2.4 The principle of measuring average roughness R_a , adapted from [43]

R_a was known as the CLA – Center Line Average in England, or AA – Arithmetic Average in the U.S.A. R_a can be expressed in microinches (μ inch) or micrometres (μ m) [50].

Its widespread results from the ease of calculation using simple analogy devices. Therefore, R_a is the average distance from the profile to the mean line over the length of assessment, and is determined by the following formula:

$$R_a = \frac{1}{l_m} \int_0^{l_m} |y(x)| dx \quad (2.3)$$

The parameter R_a is primarily used to monitor a production process where gradual changes in the surface finish due to cutting tool wear can occur. R_a can be measured with most inexpensive surface roughness analysers. Defects in the surface do not influence the measured results greatly. Therefore, an instrument measuring R_a will have a higher measuring repeatability than an instrument measuring a parameter sensitive to individual peaks and valleys such as $R_{z(DIN)}$ [41], [46].

2.3.2.1.2 $R_{z(DIN)}$ (R_{tm}) – Mean peak-to-valley height, R_{max} (R_{ymax} , R_{ma}) – Maximum peak-to-valley height

To determine the parameters $R_{z(DIN)}$ and R_{max} , the filtered roughness profile is divided into 5 equal lengths (nominally equal to the cut-off length). The maximum peak-to-valley height (Z_i) is determined within each cut-off length as shown in Figure 2.5 $R_{z(DIN)}$ is the average of the 5 peak-to-valley heights, while R_{max} is the maximum peak-to-valley height within one cut-off. $R_{z(DIN)}$ is determined by the following formula [50]:

$$R_{z(DIN)} = \frac{1}{5} \sum_{i=1}^5 Z_i \quad (2.4)$$

R_z is generally more sensitive to changes in surface finish than R_a . $R_{z(DIN)}$ is a useful tool for monitoring a production process. R_{max} is an indication of the maximum defect height (peak or valley) within the assessed profile and is useful for surfaces where a single defect is not permissible [51].

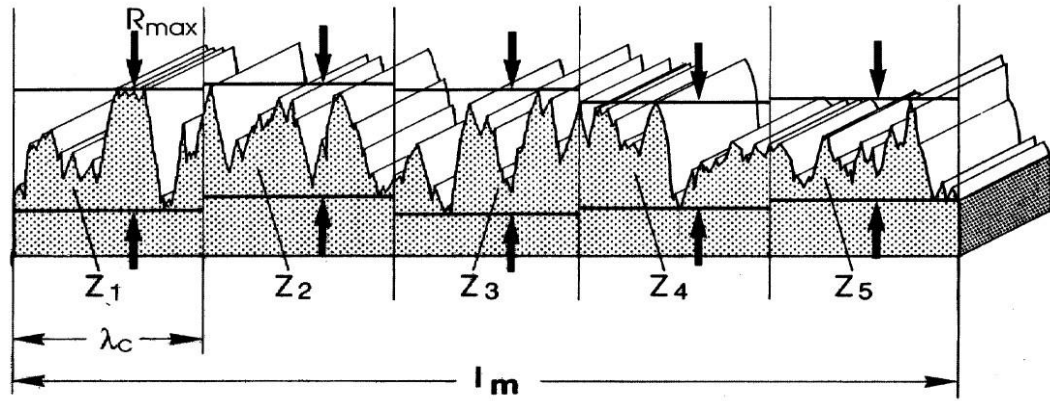


Figure 2.5 R_z maximum height of profile, R_{zmax} maximum height of profile [50]

The parameters $R_{z(DIN)}$ and R_{max} used together are valuable tools in monitoring the variation of surface finish in a production process. Similar values of $R_{z(DIN)}$ and R_{max} indicate a consistent surface finish while a significant difference indicates a surface defect, in an otherwise consistent surface.

2.3.2.2 W_t – Total waviness height

The parameter W_t is analogous to the roughness parameter R_y or R_t [50], but applied to the waviness profile. As shown in Figure 2.6, it is the maximum peak to valley height of the levelled and filtered waviness profile.

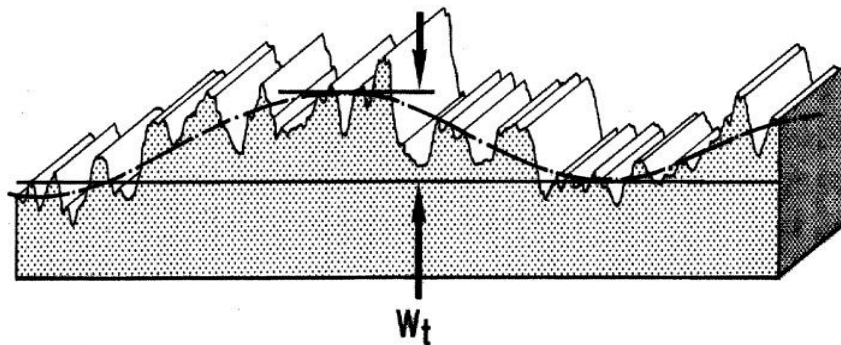


Figure 2.6 Waviness height [50]

W_t is used to monitor a production process where waviness, not roughness alone, is a critical production variable [49]. The waviness of the sealing surface of a cylinder head produced on a

vertical mill largely depends on the alignment of the cutting tips in the milling head. Both roughness and waviness must be controlled if thin and less compliant gaskets are used. The waviness profile results from low-pass filtering the primary profile with the cut-off wavelength λ_c and high-pass filtering with the cut-off wavelength λ_f . The parameters are identified by W and evaluated over the measured length I_n which is composed of several sampling lengths L_w [43], [52]. The single measured length L_w corresponds to the cut-off wavelength λ_f of the high-pass filter.

2.3.2.3 T_{pa} / T_{pi} Material ratio

The quality of an engineering surface is often determined by how it interacts with another surface. The two surfaces are normally separated by a lubricating fluid. Any peak greater than the fluid film thickness will contact the opposing surface causing wear, heat build-up, and friction. The material ratio is used to predict the character of a surface [43].

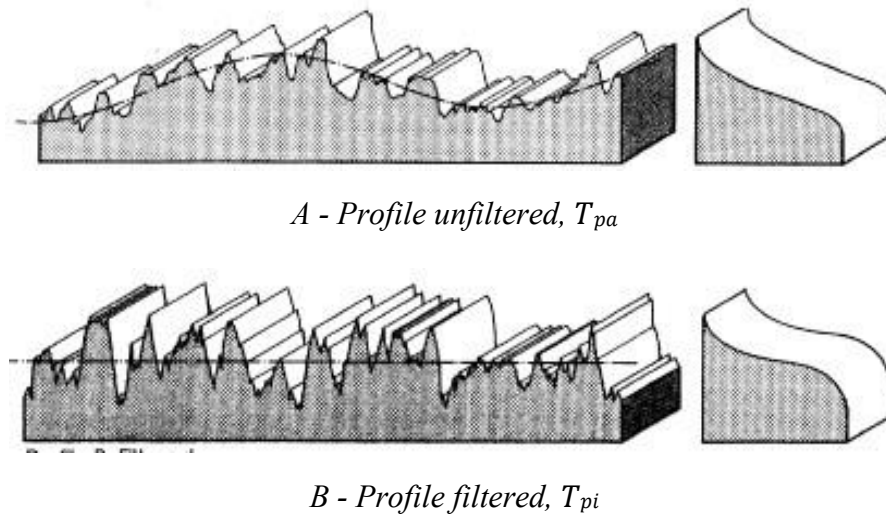


Figure 2.7 Comparison of the parameters T_{pi} and T_{pa} for different profiles [50]

As shown in Figure 2.7, the parameters T_{pi} and T_{pa} are the material ratios at selected depths through the surface profile [50]. T_{pi} is the micro-material ratio, or the material ratio of the filtered roughness profile. T_{pa} is the macro-material ratio, or the material ratio of the unfiltered (total) profile. Unless otherwise stated, the material ratio of the filtered profile, T_{pi} is used. The effects of waviness are not included in the measured results because T_{pi} is measured by the filtered roughness profile.

2.4 Tribology in sheet metal forming

In this section deformation processes of sheet metal and tribology of sheet metal forming are discussed. The performance of sheet metal forming processes depends on the characteristics of the type of forming process the sheet metal, the tool material, the tribological conditions at the

tool/steel sheet interface, the amount of plastic deformation used and the finished product requirements [28], [53]. During this process, the blank sheet is likely to develop defects if the process parameters are not selected properly. Therefore, it is important to optimize the process parameters to avoid defects in the parts and to minimize production cost. Optimization of the process parameters such as die radius, blank holder force, lubricant, can be accomplished based on their degree of importance on the sheet metal forming characteristics [54], [55]. The high formability of steel sheet metal gives great opportunity to form products to a wide range of shapes.

The objective of this subsection was to investigate previous scientific works and to determine the influence of process parameters on characteristics of the formed parts. Some most common types of experiments will briefly be described, while the focus will be concentrated upon the tribological mechanisms which may appear in the interface between the tool and the steel sheet.

2.4.1 Sheet metal forming in the automotive industry

In sheet metal forming a flat steel sheet material is deformed plastically and formed to a final shape. In the case of complicated product shapes sometimes several processes are necessary to obtain the final shape [4]. A scheme of processing the sheet metal into parts of the car body is shown in Figure 2.8.

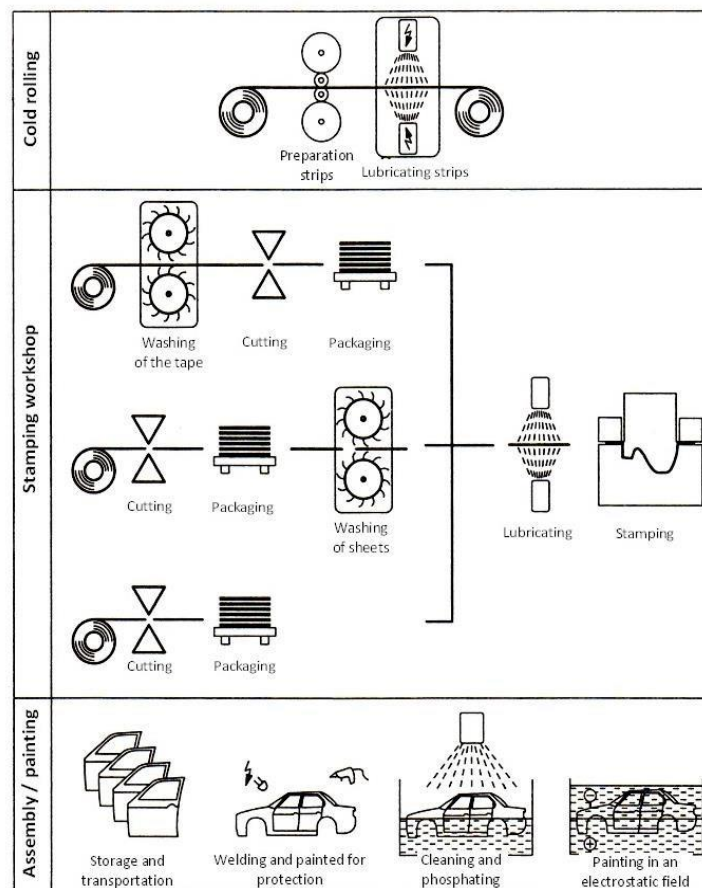


Figure 2.8 Schematic representation of conversion metallic sheet into components [56]

The works of Ghassemieh [57], Henning et al. [58], Ajay et al. [59] show that the stamping process of car body parts is one of the most relevant production processes in sheet metal forming. Also, the anticorrosive oil used for rolling mills, has a role in the forming of sheet metal and it is sufficient for common drawing operations. Therefore, at each stage where a new lubricant is required for the operation it is needed to observe the compatibility of lubricants, in order to ensure the reliability of production at the lowest cost.

The existing literature emphasizes [56], [57] that the materials used in automotive industry need to fulfil several criteria before being approved. Some of the criteria are the results of regulation and legislation with environmental and safety concerns, others are the requirements of the customers. In many occasions, different factors are conflicting and therefore a successful design would only be possible through an optimised and balanced solution. In sheet metal forming the control of the friction level has a significant role since it influences the stress and strain distribution in the sheet. It should be neither too high nor too low to obtain a final part with desirable quality.

2.4.2 Tribological systems

Where there is contact with relative motion, there is tribology. Tribo-systems play sometimes very critical roles in machines working sometimes under extreme severe conditions. Tribology is the branch of engineering that deals with the interaction of surfaces in relative motion: their design, friction, wear and lubrication. Most researchers working in this area e.g. Michael [60] and You-Bai [61] agree that tribology is known as the science and technology of interacting surfaces in relative motion. It includes the study of the complex elements in friction and wear processes, existing links between them and the properties of these elements. Bhushan [62] have pointed out that interacting elements form a single system, which is under external consideration and perception. Srblav et al., [63] shows that, in the sheet metal forming processes, tribological factors have the same influence as other forming system factors (material ductility, strain rate, tools, machine, etc.). They have pointed out that in the analysis of processes involving tribological systems, it is necessary to define clearly its boundaries.

Several studies e.g. Bhushan [64], Kenneth et al. [65], show that analogously it cannot be attributed to a single element of the tribological system, characteristics of wear resistance (rate of wear, intensity of wear), since they depend on the properties of all elements of the tribosystem.

In many manufacturing processes, friction is necessary to control the process. The research by Emmens [29] indicates that, in deep drawing, friction in the blank holder is needed to control the movement in the tool. When the friction in the blank holder is not sufficient, additional restraining elements like draw beads are placed in the tool. The aim of tribology in manufacturing processes is therefore not to minimize friction, but to control friction.

Given that the failure of most components are surface initiated, tribological performance of materials, coatings and lubricants must be considered an important factor for the design of system components.

While reviewing the following examples, one can conclude that variation of a single parameter at a time in a friction experiment may not be the best option. In the literature on this subject Peter Blau [66] highlights the importance of raising the normal force; the wear rate may increase, in turn altering the surface roughness and introducing debris particles into the interface. When studying the effects of sliding speed over a wide range, the temperature in the interface can vary as well. Peter Blau [66] argues that isolating the effects of only one variable on tribological transitions is a challenge in light of such synergistic factors.

The behaviour of a tribological system is determined by the combined action of all operation parameters and system configuration, as seen in Figure 2.9. The operational parameters are load, velocity, temperature, type of motion, time and materials flow. Every friction contact can be reduced to four components of the tribological system [34]:

- base body
- counter face body
- lubrication layer
- working medium

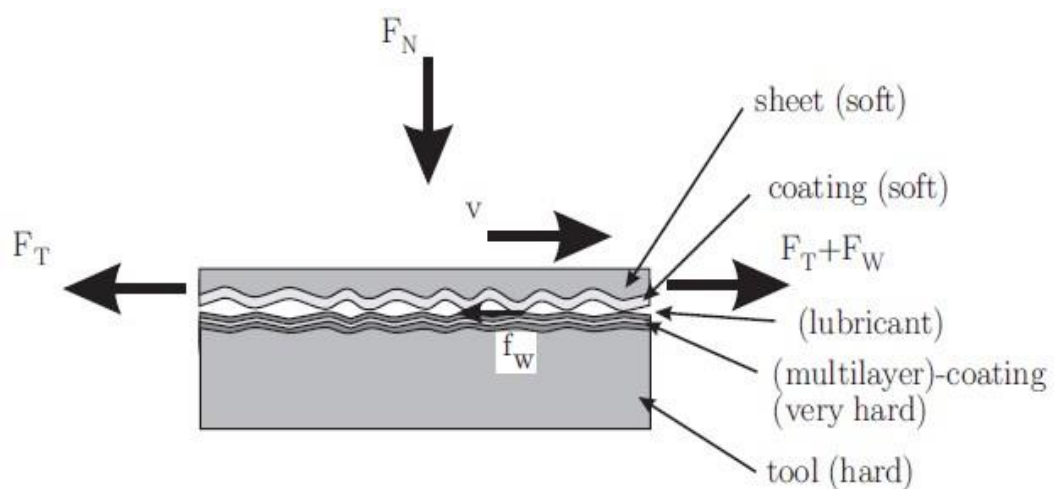


Figure 2.9 Tribological system, adapted from [67]

In Figure 2.9, F_T represents the tangential force; F_N the normal force; F_W the work force and v the sliding speed.

In this system, tribological behaviours are governed by the operational parameters and each element properties including the lubricant and the environment.

The use of lubricant as intermediate media is one of the possible ways of separating the main and counter surfaces, increasing load capacity and reducing wear. In the environment, more often air is present, but also any accidental splashes of water or eventual presence of the

chemicals. Solvents or varnishes, as well as a vacuum or any radiation load, also must be considered as elements of the "environment" and should be included under this unit. In such cases, the resistance of lubricant under ambient conditions is often needed to be tested.

2.4.3 Tribological characteristics in the forming process

To evaluate the lubricant which is used in forming operations of deep drawing, the most common methods are the strip tests, which are carried out with or without deflection. These methods simulate the conditions arising under the blank-holder and during forming with dies. Evaluation of such data allows lubricants to be developed which are ideal for metal forming operations. An example for a strip testing equipment is shown in Figure 2.10 adapted from [68]. The test stand used by the Institute for Production and Forming Technology of the University of Darmstadt, Germany, enables tribological systems to be examined with large tool dimensions, variable drawing speeds and very high normal contact pressures [4]. In a typical strip test, sheet metal slides between two flat dies. The required pulling force is used with the measured normal force for determination of friction coefficient. Essential characteristics are also the dimensions of the material, the tools, the speed and the maximum forming force [60]. The consensus seems to be that aside from the coefficient of friction, an important criterion for tribosystem assessments is the uniformity of the periods of application of force. Ideally, the metal must be pulled uniformly in order to avoid any intermittent movement. The minimum clamping force that avoids motion is a measure of the ability of the lubricant under pressure to separate the sheet metal from the tool. By assessing these indicators, it is possible to develop lubricants that are ideal for forming processes.

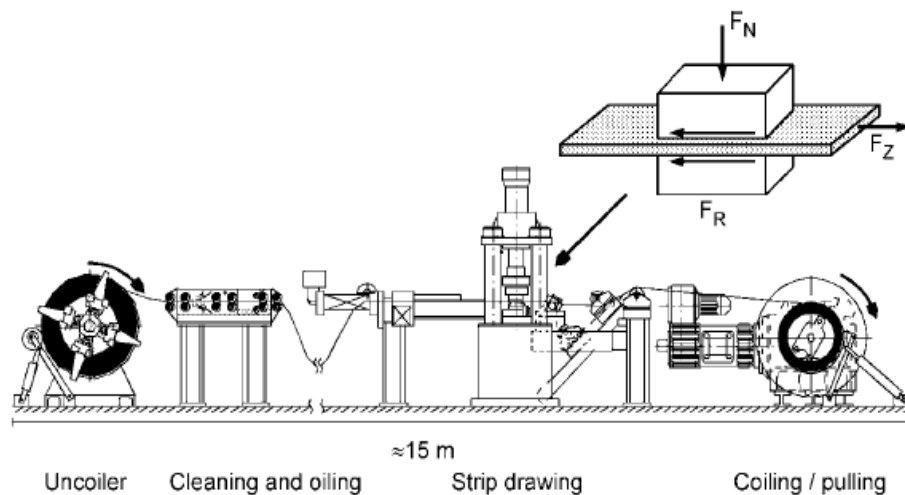


Figure 2.10 Experimental rig for strip pulling test, adapted from [68]

Also, to evaluate a tribological system (consisting of the tools, plate and lubricant) it has been proven [4], [68] that it is very useful to represent the determined coefficients of friction in function of the contact normal stress and sliding speed graphically. It can mark the occurrence of any stick-slip effects on the graph, which is also a very important information.

2.5 Lubrication influence in sheet metal forming

A number of previous studies [12], [15], [17] showed that the coefficient of friction for an unlubricated forming operation is rarely lower than 0.5. In sheet metal forming such high values would often lead to intolerable high friction forces leading to fracture and frictional energy losses. In sheet metal forming industry, therefore, lubricants are used to reduce and control the frictional force between surfaces [4], [69]. Reduction in friction happens due to a decrease in adhesion element of friction compared to abrasion component of friction.

In lubricated sliding contacts and generally on curved surfaces, tapering on the input clearance involves the liquid lubricant [70], which under some conditions (load, speed, elastic characteristics and geometry of surfaces) is forced to enter into the contact gap, thus supporting the applied load.

If it exists an excess of oil (more than the necessary amount for the formation of the boundary film) this excess restores the wear boundary film. This process of friction under boundary lubrication flows steadily. In his study, Rudi Haar [71] argued that increase of oil in the gap between the mating parts leads to a mixed regime of friction.

2.5.1 Lubricants for sheet metal forming

Quality requirements and gained knowledge about the occurring processes in the working area, demand for lubricants in forming processes. The choice of lubricant and its application depends on various conditions and should be considered from three different perspectives [4]:

- the state of lubrication and the preform for forming and its practical application;
- behaviour during the forming process;
- anti-corrosion protection and the ability to remove lubricant after forming.

In selecting lubricants for sheet metal forming process, the following factors should be considered [7]:

- methods of lubricant application;
- types of additives;
- viscosity/desired film thickness;
- corrosion control;
- cleanliness and removal methods;
- compatibility with prelubricants and preapplied oils;
- post-metal forming operations (e.g., welding and adhesive joining);
- environmental safety and recycling.

Nowadays great importance attaches to economic, environmental, sanitary and toxicological requirements.

Using the pre-lubrication in rolling mills to reduce the number of lubrication points required for stamping operations is an important topic. The economic benefit by using pre-lubrication is

achieved not only by saving lubricants. The real benefit, using pre-lubrication and not using special oils in each step of the entire process chain, will be a significant decrease in the cost of the process and therefore it is important in the optimization of all the manufacturing steps.

Appropriate oils for pre-lubrication allow to obtain greater economic benefits. This is especially effective when using multipurpose lubricants that are fully compatible and can be used for various purposes. Today, pre-lubrication systems are modular, so you can use oils with different viscosities.

Table 2.2 shows different types of lubricants for the forming process and the most suitable areas of application.

In the case of deep drawing process lubricant can be applied to the metal sheet manually, by rotating roller, by dip, by spray or lubricated with grease.

Table 2.2 Different types of lubricants for metal forming process [72]

Lubricant	Main application	Note
Base (without additives) lubricant		
Lubricant for milling	Stamping, extrusion, forming. Deep drawing. Punching and Calibration	The flashpoint 40 – 65 °C
Lubricant containing polar additives	Punching thin plates and circular blanks. Embossing, stamping, forming, pressing. Production of car bodies, deep drawing	Apply low viscosity oils, some mineral oils without additives, biodegradable, compatible with the previously used lubricant
Lubricant containing anti-scuffing additives (without chlorine)	Deep pressing, pressing. Exact blank operations. Deep drawing and thinning of the sheet material when stretched	Lubricants may cause corrosion spots on copper.
Lubricants for forming, not containing solid components	Complex forming	Low and high carbon steel
Lubricants for forming, containing solid components or anti-scuffing additives	Deep drawing	Basically, like pasty lubricants
Lubricants, water miscible		
Lubricants	The emulsions or solutions for forming. Using hydraulic fluids for hydraulic forming	Synthetic, semi synthetic or the corresponding compositions lubricant
Lubricants for forming, not containing solid lubricant components	Deep drawing	Sometimes like pasty lubricants
Lubricants for forming, containing solid lubricant components	Most difficult forming and deep drawing	Often like pasty lubricants

Cleaning fluids and emulsions which are used for cleaning large parts of automobile bodies before forming, should be compatible with the oils for milling and pre-lubrication that were already applied to the sheet metal and ideally, they should have the same chemical nature [73].

The most convenient method of application is spraying, since as with manual application, it is possible to apply the lubricant to the desired location. In principle, oils, emulsion and lubricants for forming processes can be applied by spraying. Requirements in spraying can be specifically set for lubricants to ensure compliance with norms of industrial shops.

The choice of lubricant is mainly determined by the complexity of the forming process. The lubricant should improve sliding when processing the workpiece by reducing friction and simultaneously to ensure the formation of an effective separation layer between the workpiece and the tool. Because the hydrodynamic friction regime in the forming process appears only in rare cases, the lubricant must contain additives which provide an effective separating layer during the entire process. Previous studies of Erdemir [74] have demonstrated, that additives may be either polar compounds or compounds which can change the metal surface in the result of chemical reactions. For instance, separation effect can be achieved by entering fine solids into the lubricant, as a solid lubricant component or as an inert filler.

2.5.2 Preliminary lubrication

The idea of the combination of anti-corrosion properties of the protective oil as a lubricating oil to be used in forming operations has led to the development of preliminary lubrication.

Preliminary lubricant in the final stage of rolling process, acts as a lubricant for the further processing of the forming component. A necessary condition for the protective oil, and for preliminary lubrication is their absolute compatibility with all the processes of every processing of the part, from unwinding the coil to the finished car body parts. Using the preliminary lubrication in rolling mills significantly reduces the number of operations for lubrication in the press shop [30]. If the principle of compatibility is observed throughout the production line, preliminary grease can be limited without use of any additional lubrication operations. Thus, the modern system of preliminary lubrication can be modular, if suitable lubricants even with different viscosities fit into the overall concept of technology.

By using the specifications of many oils for rolling mills a common standard of the Association of German Automotive Manufacturers (VDA) has been developed [75], which describes all the characteristic requirements applicable to multifunctional lubricants and their most important properties of all test methods. The results, except lubricity, have to be compared with the protective oil Anticorit RP 4107S, which has been chosen as the reference standard. Accordingly, the requirements of the VDA lubricating oil used for the preliminary lubrication should be thixotropic to reduce leakage and being suitable for application by spray in an electrostatic field. Moreover, this oil must protect the metal from corrosion as efficiently as the standard one. When mixed with a standard oil sediment formation can occur and other chemical reactions. The oil used for preliminary lubrication must be compatible with the paint, applied by cataphoretic and adhesives which are used at the assembly line. Also, this oil should be easily removed with industrial detergents in preliminary preparation for phosphatizing or painting in an electrostatic field.

2.5.3 Lubricant friction

The friction mechanism at boundary lubrication can be represented in different forms. Under lower loading, producing only elastic behaviour in the body, plastic deformation can occur in some contact areas. The boundary layer is a monolayer film of lubricant, consisting of a single layer of lubricant molecules physically attached to the surface [76]. On the contact area it can occur mutual interaction of surfaces without disturbing the integrity of the lubricating film. The resistance to movement comes from the shear resistance of the boundary layer and the "gouge" resistance of interpenetrated surface asperities.

In addition, the contact area can be subjected to significant plastic deformation and rupture of the boundary layer can occur, thus developing higher surface temperatures and allowing direct metal to metal contact and causing additional resistance to movement.

Due to the mobility of the lubricant molecules on the friction surface, adsorption proceeds at a high rate allowing that lubricating film properties will have "self-healing" of some local damages. This property of the lubricant film plays an important role in preventing a possible avalanche setting process.

The viscosity of the oil is not playing a major role on the boundary lubrication process [77] and therefore oils with the same viscosity but different compositions have a different lubricating effect. For example, adding in boundary layer a lubricant aqueous solution of surfactants increases the thickness of the boundary layer and reduces wear (up to two times).

The lubricating action, besides of the factor of adsorption, depends on the chemical interaction with metal and the lubricant. Fatty acids, entering into the reaction with the metal surface form a soap (metallic salts of fatty acids) having as a consequence a higher cohesion with metal surface and allowing to withstand higher loadings without significant boundary layer destruction with deformation [64].

The disadvantage of a boundary film relates to its low thermal fastness. Sometimes to promote an artificial increase in the chemical activity, additives (called dopants) are introduced in the special oil, containing organic compounds like sulphur, phosphorous, chlorine or combinations of these. Under conditions of high temperatures on micro contacts the active part dopants, decompose and interacts with metal surface, forming a film of iron sulphide, phosphate or iron phosphate, iron chloride or oxidized chloride. Formed films prevent metal to metal contact, reducing the resistance to friction and impeding further local increase in temperature. This film has a weak shear resistance and therefore friction force is kept at lower values.

Chlorinated hydrocarbons films are formed on the steel surface, at buildable temperature up to 400 °C. Above this temperature occurs melting or decomposition, but the lubricating ability persists up to 800 °C [38].

From the aforesaid follows that the boundary film must have high resistance to bursting, providing a sufficient load carrying capacity in conjugation with a low shear resistance, thus allowing to obtain a minimum friction loss.

Lubrication of metal sliding units can be carried out using selective transfer [78]. In this case, the frictional force can be reduced several times and the wear eliminated. Here, there are other acting forces and principles: electrostatic forces, retaining the film in the gap, hiding surface microroughness, which recessed in the film. The lubricant transports the metal into the zone of friction where physical and chemical processes take place at the contact surface leading to the formation of a new metal film [68].

2.6 Conclusions

In this chapter, it was briefly described friction in sheet metal forming processes. The performance of sheet metal forming processes depends on the characteristics of the forming process, the tool material, the tribological conditions at the tool/sheet interface, the amount of plastic deformation and finished product requirements. The objective of this chapter was to investigate other scientific works and to determine the influence of process parameters on characteristics of the formed part.

The high formability of sheet metal gives great opportunities to form products to a wide range of shapes. The focus was concentrated upon the tribological mechanisms which may appear in the interface between the tool and the steel sheet.

Ra values are commonly used to describe surfaces, the limits of this indicator should not be forgotten. Products having identical designations but coming from different batches or different suppliers may have noticeably different roughness characteristics. In architectural and other applications, where surface appearance is important, roughness values must be carefully controlled. Eventually they might be insufficient to characterise the surface.

The friction coefficient for an unlubricated forming operation is rarely lower than 0.5. In sheet metal forming such high values would often lead to intolerable high friction forces, leading to fracture and frictional energy losses. In industry, therefore, lubricants are used to reduce and control the frictional force between surfaces.

It is well known for ages that oils and lubricants decrease the friction between sliding surfaces, by filling the surface cavities and reducing solid bodies interaction. The action of liquid oils is known as lubrication. Reduction in friction happens due to a decrease in adhesion component of friction. Every relatively moving component in an assembly usually requires lubrication.

A necessary condition for the protective oil used for preliminary lubrication is its absolute compatibility with every operation in the processing chain, from unwinding the coil to the finished car body parts. Using the preliminary lubrication in rolling mills significantly reduces the number of operations for lubrication in the press shop.

The oil used for preliminary lubrication must be compatible with paints and with adhesives that might be applied in the assembly line. It should be easily removed by industrial detergents to allow further processing.

3 Tribological testing on modified pin-on-disc testing machine

3.1 Introduction

Sheet metal forming processes were the main motivation for this study on tribology testing and friction determination. Under these processes the desired shape is achieved through plastic deformation and sliding occurs between sheet metal and tools (punch, blank holder and die) [79].

It is known that press oils and base lubricants decrease the friction between sliding surfaces, by filling the surface cavities and making the surfaces flatter [7]. Therefore, tribology knowledge is essential to understand the importance of friction during the interaction of sheet and tool and dissimilar contacts can be distinguished [11]. The different conditions for each contact may lead to diverse frictional behaviour, which in turn may lead to unacceptable variations in the process or even in rejection of the final product [4], [63]. All sheet metal forming processes have in common that they are mostly performed with the aid of presses which drive the tools to deform the initially flat sheet material into a product. The sliding of a plastically deforming sheet against the tools makes both tribological and mechanical knowledge a fundamental need for optimum processing [80], [15]. Friction between the sheet and the punch/die/blank holder is thus an important factor in sheet metal forming.

Interacting with the lubricant itself, the properties of the tool materials and the surface morphology play significant role with regard to friction and wear as well as workpiece quality.

The success of sheet metal forming depends mainly on three groups of influencing variables [4]:

- the metallurgical properties of the metal and its surface;
- the mechanical forming process and the corresponding machine and tools;
- the type and quantity of lubricant applied, its consistency and its performance features.

The most significant variable in all metal forming processes is the formability of the material. The degree of difficulty determined by this variable is essential for lubricant selection. It is expected that a lubricant will facilitate the sliding of the workpiece in the tool by reducing friction and, at the same time will provide an effective separation layer between the workpiece and the tool. Since the lubricant must contain additives which ensure an effective separation layer during the entire forming process, these additives can change the surface of the metal by chemical reaction. In this way, metal contact between the metal surfaces is avoided. A similar separation effect can be achieved by adding finely distributed solid substances in the lubricant which works as an inert filler or solid matter lubricant.

The drawing tools used for manufacturing high batch productions frequently consist of low wear hard metal materials while less resistant to wear tool materials can be used for small batch productions.

The past years have seen steady increases in the use of high-strength steels (HSS), many versions of which are referred to as high-strength low-alloy (HSLA) steels.

Today's most commonly used materials for vehicles continue to be, mainly, different types of steel. They offer a wide variety of material characteristics such as thermal, chemical or mechanical resistance, ease of manufacture and durability. The development process on steel has continuously created new materials for applications within the automotive industry with improved characteristics. These high strength grades are increasingly used in the high-volume production for parts, which are assembled by special manufacturing techniques [58].

Steel is the most widely used material in the world, due to its versatility and competitive costs. Steel is therefore one of the basic ingredients in the development of industry and the whole society. Carbon steel sheet is used in the automotive appliance and building industries. New applications of high strength steels in automotive and other sheet metal forming industries have been increased to the forming capability of steels.

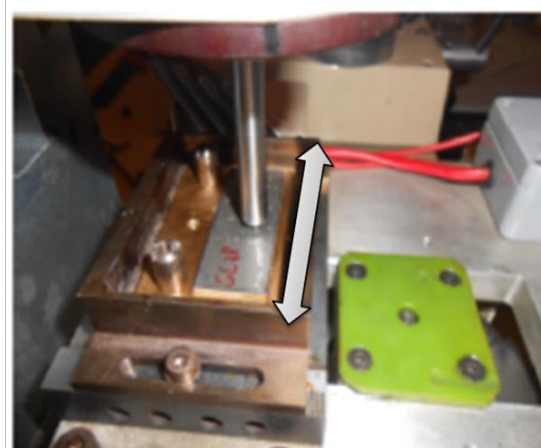
In sheet metal manufacturing, high requirements are placed on the surface finish. Not only for aesthetic reasons but also in order to obtain a surface topography, that is optimal in a forming process. Besides a corrosion attack, the surface may also be affected by mechanical degradation.

3.2 Methodology

Under current research work, a methodology has been followed, which included the study and definition of tribological tests, its design and the possibility of implementation. These tests were performed as presented in Figure 3.1 with modification of pin-on-disc machine, to find the effect of metal properties and other variables on the coefficient of friction.



a) General view of the reciprocating attachment



b) Close up view of test specimens

Figure 3.1 Modified pin-on-disc machine (Plint TE 67/R)

Large amounts of test equipment for the evaluation of friction properties, often referred to as tribometers, have been designed over the years for a variety of purposes [81]. In this section, only a small number of model tests are presented and these tests merit attention either because of being frequently used, or for representing interesting recent developments in the field of tribotesting.

3.3 Reciprocating tests and tested materials

The materials used in experimental tests included steel alloys those known as high-strength low-alloy cold rolled “HSLA 380” and “HSLA 420” steels which provide increased strength-to-weight ratios over conventional low-carbon steels. For these materials tribology tests were performed with different lubricants.

Lubricants were applied with different combinations. First the sample is cleaned with ether alcohol and after the lubricant is applied with a brush. Lubricants defined as Base lubricants Prelube A and Prelube B were combined with other five different lubricants and as a result there were 12 different combined lubricants.

The sheet was cut to give rectangular samples of 50x20 mm². The major length of samples was aligned with rolling direction so that friction tests could be performed along such direction. To minimize irregularities during testing, the samples were carefully deburred and visually inspected to remove test pieces with errors like scratches or imprints of any kind. The initial roughness of the samples measured in the sliding direction was $R_a = 1.45 \pm 0.20 \mu\text{m}$. The rectangular sheet metal samples, were bonded to brass supports as shown in Figure 3.2.



Figure 3.2 Test samples of the steel sheet are stacked on the plate

A pin-on-disc machine with reciprocating attachment has been used for the tests, using a sphere ball (tool material mounted on pin). The material of the ball used for the friction test is “AISI D2 Steel”. D2 steel is an air hardening, high-carbon, high-chromium tool steel, which chemical composition is presented in Table 3.1.

Table 3.1 Typical chemical composition of AISI D2 Steel [82]

C	Si	Cr	Mo	V
1.50%	0.30%	12.00%	0.80%	0.90%

3.4 Used lubricants for experimental tests

The continuous process improvements and the increased knowledge in metal forming working area have also increased the demands on the lubricants characteristics required for sheet metal forming. The selection of lubricants and their use depend upon various properties and are, in principle, to be viewed from three different perspectives [4]:

- state of lubricant and workpiece before forming and practicable application;
- behaviour during forming;
- corrosion protection and removability of the lubricant after forming.

For the lubricated parts, the coefficient of friction depends on contact pressure, sliding velocity and lubricant properties. On the other hand, an adhesive friction state exists in most of the dry friction regions. Therefore, the coefficient of friction of dry surfaces is usually assumed to depend on the mechanical properties of the steel sheet, such as shear strength and plastic flow stress.

Therefore, the sliding condition in an actual stamping process is estimated to be placed between the unlubricated condition and fully lubricated condition in friction test, as we will discuss later in Chapter 4. Additional tribology tests were performed to define frictional characteristics of steel sheet materials with lubrication conditions using the two base Prelube lubricants, now mixed with other five different press oils. For these materials, tribology tests were performed with different lubricants, as shown in Table 3.2.

The idea to combine the corrosion protection properties of a corrosion preventive oil with the lubricity of a drawing oil led to the development of Prelubes. Applied at the finishing lines of the steel mills, they serve as the forming lubricant in the press shops. Adding press oils is only justified if difficult stamping problem has to be overcome.

Table 3.2 Prelube lubricants and ten different combinations with Press oils

Lubricant	Short names	Viscosity [mPa.s]	Density [g/cm ³]
Prelube Fuchs Anticorit PI 3802-395	Base lubricant Prelube A	40 °C 45	24.2 °C 0.900
Fuchs + EMB 1150	Prelube A + Press oil 1	40 °C 58	23.9 °C 0.900
Fuchs + UBO 377.19	Prelube A + Press oil 2	-	-
Fuchs + Renoform EMP 1310 P	Prelube A + Press oil 3	40 °C 85	23.8 °C 0.904
Fuchs + Hakuform 70/2	Prelube A + Press oil 4	40 °C 90	24.2 °C 0.965
Fuchs + Hakuform 20/38	Prelube A + Press oil 5	40 °C 52	23.7 °C 0.897
Prelube Quaker Ferrocote S-6130	Base lubricant Prelube B	38 °C 28	23.3 °C 0.892
Quaker + EMB 1150	Prelube B + Press oil 1	38 °C 46	23.7 °C 0.894
Quaker + UBO 377.19	Prelube B + Press oil 2	-	-
Quaker + Renoform EMP 1310 P	Prelube B + Press oil 3	38 °C 69	24.1 °C 0.900
Quaker + Hakuform 70/2	Prelube B + Press oil 4	38 °C 45	23.9 °C 0.928
Quaker + Hakuform 20/38	Prelube B + Press oil 5	38 °C 37	24 °C 0.897

The use of prelubes in steel mills reduces dramatically the number of spot lubricants for additional press shop oiling. But their benefits can only be achieved if the compatibility principle is applied throughout the manufacturing chain. Therefore, modern prelubes systems are modular, even different viscosities can be part of the same concept. This results in a far-reaching multi-functionality for all applications.



Figure 3.3 Preparation of combined lubricants for viscosity measurement

Figure 3.3 shows the preparation of different lubricant combinations prior to viscosity measurement. The influence of temperature and pressure on viscosity can be given by means of a VPT (viscosity, pressure, temperature) diagram [39]. The so-called Burns equation for pressure and temperature dependence on the viscosity clearly shows that straight oils have decreasing viscosity η at higher temperatures:

$$\eta = \eta_0 e^{\alpha p - \beta \Delta \theta} \quad (3.1)$$

In equation 3.1, η_0 is the reference viscosity determined at the reference temperature, $\Delta \theta$ gives the temperature difference, p is the pressure, while α and β give the pressure and temperature dependency coefficients, respectively.

The straightforward temperature dependence on viscosity is only valid if there are no chemically active compounds in the lubricant. Heating accelerates chemical reactions between these additives and the sliding surfaces, causing the lubricant to adhere [39]. Eventually it is possible that friction first rises, reaches a maximum and then decreases by this effect. On the other hand, reactivity in the boundary lubrication regime is improved when the temperature increases. However, when the temperature is high, boundary layers can break down, resulting in loss of lubrication functionality, first in decreasing friction and then by increasing friction.

3.4.1 Oil properties measurement

In current work, the tested lubricants were submitted to density and viscosity measurement to confirm the data provided by the manufacturers.

3.4.1.1 Viscosity index

Of these liquid lubricants, it is especially important to understand the concept of viscosity. Viscosity is expressed as either absolute viscosity or kinematic viscosity. Sometimes the term dynamic viscosity is used in place of absolute viscosity. The absolute viscosity is the ratio of the shear stress causing a flow to the resultant velocity gradient.

The viscosity index represents the need to specify how the various classes of oils react to temperature variation. The most used method was proposed by Dan and Davis in 1929 [4]. These authors classified all known oils, at that time, in distinct categories according to the value of its kinematic viscosity (SUS) at 98.8 °C. Annex A presents the measured viscosity variation with temperature of Prelubes Fuchs Anticorit PI 3802-395 and Quaker Ferrocote S-6130 and their combination with other lubricants.

3.4.1.2 Density

Density (kg/m^3) is the ratio between the mass and the volume of a body [83]. Usually its variation with the temperature is not relevant, however the variation with the pressure might be important as the lubricant film thickness is highly influenced by the contact pressure.

3.5 Sheet materials

Steel alloys known as high-strength low-alloy steels (HSLA) provide increased strength-to-weight ratios over conventional low-carbon steels. Experimental work under this thesis has been performed using the sheet steel materials HSLA 380 and HSLA 420. This sheet metal grade, Figure 3.4 is used in the manufacture of cars, trains, aircraft, farm equipment, machine components and other products [57].



Figure 3.4 Samples of the steel sheet HSLA 380

This group of steels is strengthened primarily by micro-alloying elements, contributing to fine carbide precipitation and grain-size refinement, resulting in high strength with low alloy content. This enhances weldability and choice of coatings since these steels exhibit neither weld zone softening nor grain coarsening. The HSLA range of products is available in hot and cold rolled grades. The various grades are identified by their yield strength.

3.5.1 Mechanical properties and chemical composition

HSLA steels with improved formability were developed primarily for the automotive industry to replace low-carbon steel parts with thinner cross section for reduced weight without sacrificing strength and dent resistance. HSLA steels are available in all standard wrought forms — sheet, strip, plate, structural shapes, bar-size shapes and special shapes.

The “low-alloy” means that the strengthening mechanism used in these steels is grain refinement and precipitation due to addition of small amounts of alloy elements such as titanium, vanadium and niobium. Vanadium and niobium additions promote grain refinement, which leads to an increase of the material’s strength, especially the yield strength.

Titanium has a great affinity with carbon and nitrogen, leading to the formation of carbides, nitrides, carbonitrides that precipitate in the ferrite matrix, thus contributing with some precipitation hardening that adds to the grain refinement effect.

HSLA chemical composition and mechanical properties in the transverse direction are shown in Table 3.3 and Table 3.4, respectively [84].

Table 3.3 Ladle analysis chemical composition of steel sheets HSLA 380 and HSLA 420

Components	HSLA 380	HSLA 420
C max (wt., %)	0.12	0.14
Si max (wt., %)	0.5	0.5
Mn max (wt., %)	1.8	1.8
P max (wt., %)	0.030	0.030
S max (wt., %)	0.025	0.025
Al max (wt., %)	0.015	0.015
Ti max (wt., %)	0.15	0.15
Nb max (wt., %)	0.09	0.09

Table 3.4 Mechanical properties of steel sheets HSLA 380 and HSLA 420

Variables	HSLA 380	HSLA 420
Steel number	1.0550	1.0558
0.2 % proof strength Rp0.2 TD (MPa)	380-480	420-520
Tensile strength TD (MPa)	440-580	470-800
Elongation A80 min TD (%)	≥ 19%	≥ 17%
Availability from Inapal Production	Yes – 1,20 + 1,50 mm thickness	Yes – 1,20 + 1,50 mm thickness

TD - Transverse Direction

Table 3.5 Surface roughness parameters of the tested steel sheet material before tests

Surface condition	Steel sheet surface roughness parameters						
	Sa	Sku	Sp	Sq	Ssk	Sv	Sz
	μm		μm	μm		μm	μm
Steel sheet HSLA 380	1.23	0.003	19.02	1.52	0.000	-11.60	30.62
Steel sheet HSLA 420	1.28	0.003	24.67	1.57	0.000	-9.76	34.42

Cold rolled HSLA 380 and HSLA 420 are ruled by EN 10268 standard, where they are designated as HC380LA and HC420LA, respectively. The number (380 or 420) refers to the minimum yield strength in transverse direction.

In Table 3.5 it is presented some surface roughness measurement parameters of a sheet sample. These surface roughness parameters were measured using a Bruker's NPFLEX 3D optical microscope.

3.6 Pin-on-disc experimental conditions

The stroke length used in all tests was 10 mm, and the frequency was defined from 30 min⁻¹ to 78 min⁻¹. The contact pressure between blank and tool was settled in the range of 6 to 9 MPa.

For the friction test with constant load, the following setup is used:

- load = 24.5 N;
- diameter of contact area = 0.6 to 0.7 mm;
- ball diameter is 6 mm;
- area = 0.28 to 0.38 mm²;
- pressure = 9 to 6.5 MPa.

The contact area between the sphere ball (mounted on pin) and the sample is circular. During the experiments, this circular contact was kept almost constant by changing periodically those spheres and therefore the contact area for all the tests was considered the same. The coefficient of friction between the sphere ball and the surface of sheet metal is calculated according to Coulomb's friction law, $\mu = F/N$, where F is the friction force and N is the normal applied load [62], [9a]. The value of F - friction force is measured by load cell attached to the pin-on-disc machine.

For the friction sliding test different sliding velocities were achieved by varying the cycles (rpm) of the pin-on-disc machine.

The equations used for the calculations of sliding velocity are as follows.

$$t = \frac{y}{x} \quad (3.2)$$

$$v = \frac{2 \cdot l}{t} \quad (3.3)$$

where, v is sliding velocity, t is time required for one cycle in seconds, x is number of cycles per minute (rpm), $y = 60$ seconds, l is track length ($l = 10$ mm). The distance covered in one revolution is twice the track length as the tool is in reciprocating motion.

Table 3.6 Friction test sliding velocities

Frequency [rpm]	Time for one cycle [sec.]	Average linear velocity [mm/s]
30	2	10
42	1.43	14
54	1.11	18
66	0.90	22
78	0.77	26

Table 3.6 shows the relation between velocity (rpm) and the corresponding average linear velocity, by using Eq. (3.2) and (3.3). For the friction tests on pin-on-disc machine the lowest velocity used was 30 rpm. Using lower velocity than 30 rpm is avoided as the machine would give non-smooth motion.

3.7 Experimental results

In this work, it is found that the initial lubrication condition is enough to reduce the friction from 0.40 - 0.78 in dry conditions, as seen in Figure 3.5 to values under 0.12, Figure 3.6.

Figure 3.5 shows dry coefficient of friction obtained with varying sliding velocity in reciprocating motion. Each test corresponds only to 40 seconds. Between 40 and 80 seconds the test stopped and therefore during this period the friction line must be ignored. The same is valid for the periods 120-160; 200-240; and 280-320 s.

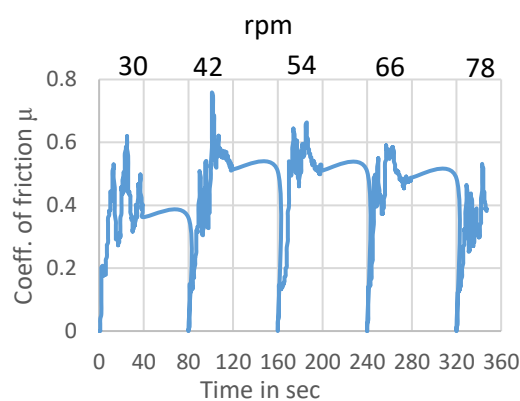
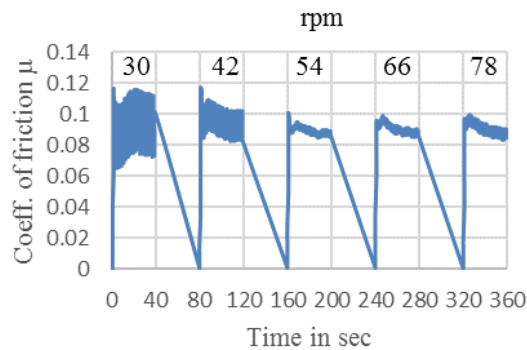


Figure 3.5 Dry test - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"

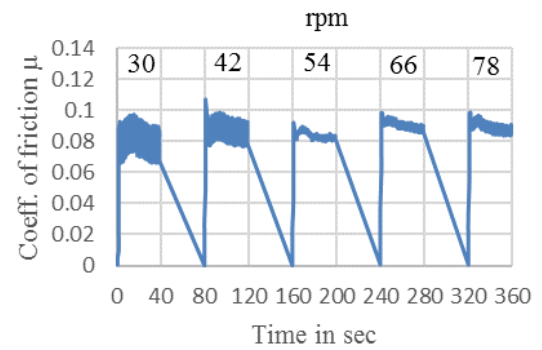
An adhesive friction state exists in most of the dry friction regions. Therefore, the coefficient of friction of dry surfaces is assumed to depend on the mechanical properties of the steel sheet,

such as shear strength and plastic flow stress, and it is usually defined as a constant value for simulation or calculation proposes.

Similar tests were carried out using different lubricated condition and the results with Base lubricants Prelube A and Prelube B, are presented in Figure 3.6 (a) and (b) respectively. The sliding velocity corresponding to the lowest friction is **18 mm/s** (54 rpm) for both the Base lubricants Prelube A and Prelube B.



(a) Base lubricant Prelube A



(b) Base lubricant Prelube B

Figure 3.6 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"

At the sliding velocity corresponding to 54 rpm the smallest value coefficient of friction was obtained and the values are more stable, but at the beginning the coefficient of friction was higher but reducing with time. To summarize, all specified graphs show that the stable values of coefficient of friction are obtained with the sliding velocities 18 mm/s, 22 mm/s and 26 mm/s.

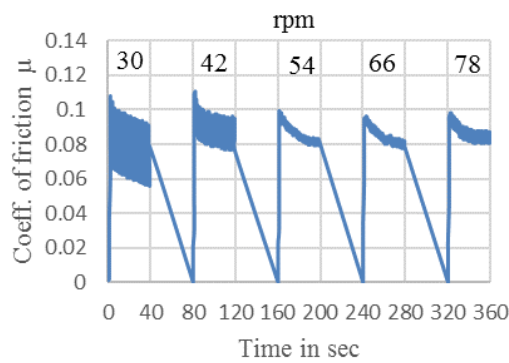
The higher values for coefficient of friction are obtained for sliding velocities 10 mm/s and 14 mm/s. These lower velocities also give higher instability for coefficient of friction.

For the lubricated parts the coefficient of friction depends on contact pressure, sliding velocity and lubricant properties.

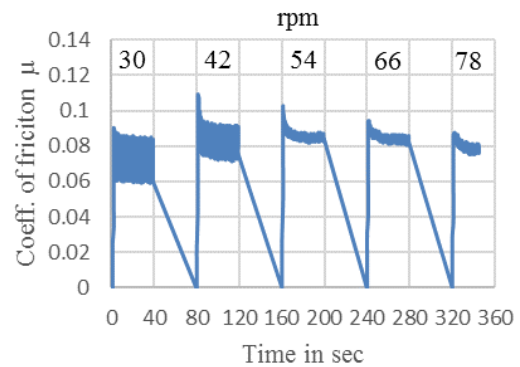
Based on these results, the sliding condition in an actual stamping process is estimated to be placed between the unlubricated condition and the lubricated condition in friction test. Additional tribology tests were performed with lubrication conditions using the two base Prelube lubricants, now mixed with other five different press oils and the corresponding results are presented in Figure 3.7 to Figure 3.11.

The lower coefficient of friction values are obtained for sliding velocities corresponding to **18 mm/s** (54 rpm - Figure 3.9 (a), Figure 3.10 (a) and Figure 3.10 (b)), **22 mm/s** (66 rpm - Figure 3.9 (b) and Figure 3.10 (b)) and **26 mm/s** (78 rpm - Figure 3.10 (b)).

Also, it is seen in Figure 3.7 and Figure 3.9 that at beginning of sliding the coefficient of friction is higher and it gradually decreases with time.

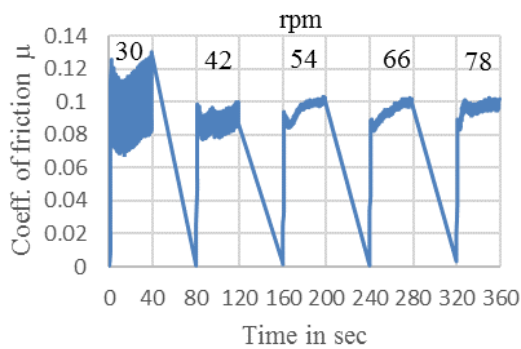


(a) Prelube A + Press oil 1

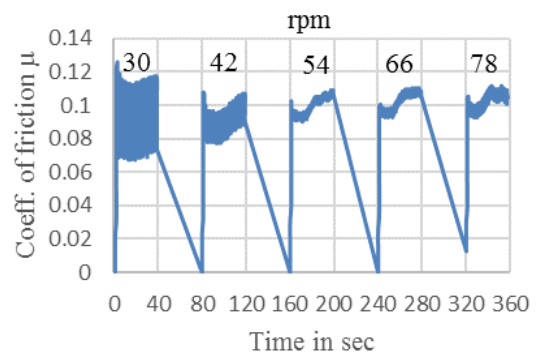


(b) Prelube B + Press oil 1

Figure 3.7 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"

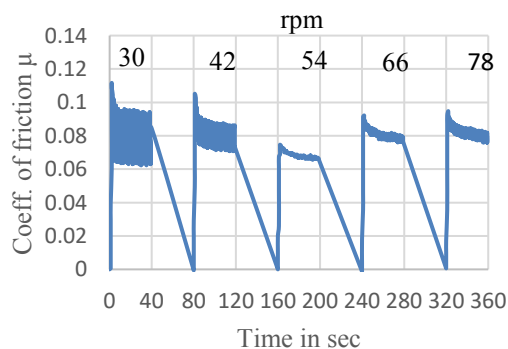


(a) Prelube A + Press oil 2

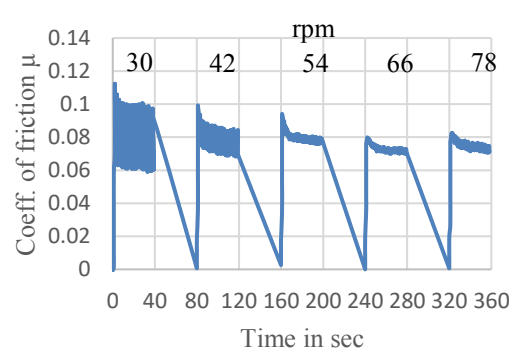


(b) Prelube B + Press oil 2

Figure 3.8 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"

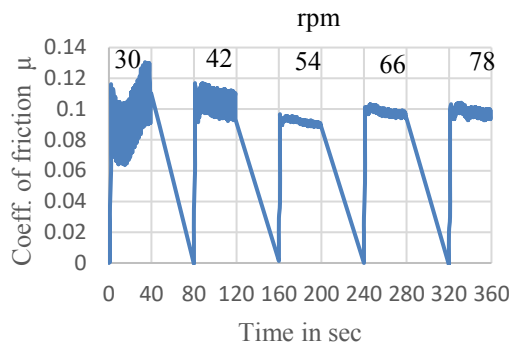


(a) Prelube A + Press oil 3

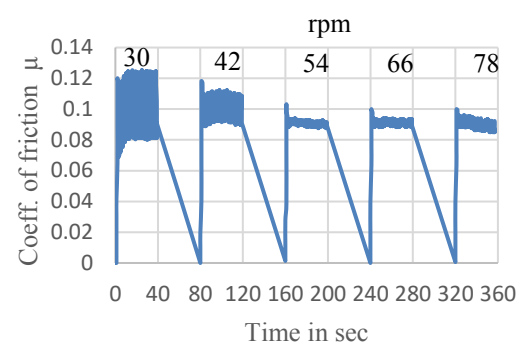


(b) Prelube B + Press oil 3

Figure 3.9 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"

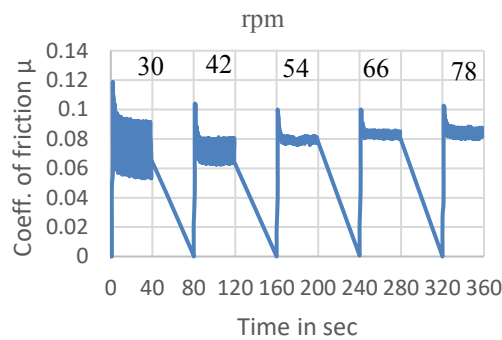


(a) Prelube A + Press oil 4

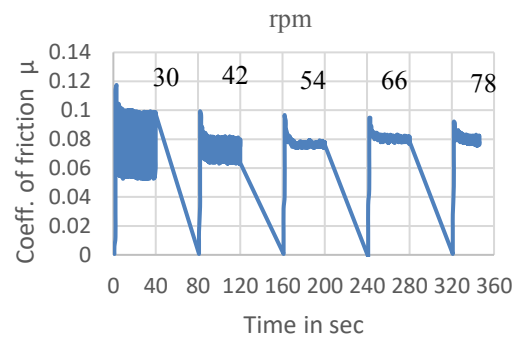


(b) Prelube B + Press oil 4

Figure 3.10 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"



(a) Prelube A + Press oil 5



(b) Prelube B + Press oil 5

Figure 3.11 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 380"

Results presented in Figures 3.7 to 3.11 show that similar instability pattern is observed for the lower sliding velocities **10 mm/s** (30 rpm) and **14 mm/s** (42 rpm). More stability in all graphs is observed for the higher sliding velocities **18 mm/s** (54 rpm), **22 mm/s** (66 rpm) and **26 mm/s** (78 rpm). Only when Base lubricant Prelube A + Press oil 2 and Base lubricant Prelube B + Press oil 2 are used a different behaviour is observed, as seen in Figure 3.8. It is clear from these test results that the Press oil 2 is having a negative effect on friction behaviour. It increases the coefficient of friction with time as it can be clearly seen in Figure 3.8. Press oil 2 is a vanishing oil (designed to evaporate very quickly) and loses lubrication capacity within the test duration.

The calculated average values of friction coefficients from previous graphs are presented in Table 3.7.

Table 3.7 Average coefficient of friction results of different combined lubricants and varying sliding velocity

Lubricants	Normal load, [N]	Average linear velocity				
		10 mm/s	14 mm/s	18 mm/s	22 mm/s	26 mm/s
Dry	24.5	0.38	0.50	0.55	0.49	0.41
Base lubricant Prelube A	24.5	0.092	0.095	0.089	0.090	0.091
Prelube A + Press oil 1	24.5	0.079	0.089	0.086	0.084	0.087
Prelube A + Press oil 2	24.5	0.095	0.088	0.096	0.094	0.096
Prelube A + Press oil 3	24.5	0.080	0.081	0.068	0.081	0.082
Prelube A + Press oil 4	24.5	0.095	0.104	0.092	0.098	0.098
Prelube A + Press oil 5	24.5	0.075	0.073	0.080	0.084	0.085
Base lubricant Prelube B	24.5	0.081	0.092	0.083	0.093	0.092
Prelube B + Press oil 1	24.5	0.071	0.083	0.084	0.083	0.081
Prelube B + Press oil 2	24.5	0.096	0.093	0.101	0.102	0.103
Prelube B + Press oil 3	24.5	0.081	0.077	0.079	0.073	0.075
Prelube B + Press oil 4	24.5	0.103	0.10	0.090	0.091	0.090
Prelube B + Press oil 5	24.5	0.078	0.074	0.079	0.081	0.080

3.7.1 Lubrication regime and the nature of friction

In current subsection, the basic idea of the Stribeck curve is being considered. Stribeck plots have three distinct regions: boundary lubrication, mixed lubrication and hydrodynamic lubrication, already seen in Chapter 2, Figure 2.3. Generally, it has been recognised that most deep drawing operations are performed in boundary lubrication and mixed lubrication distinct regions. As seen, the friction coefficient in the boundary lubrication regime is independent of the Sommerfeld number, while a dependence can be observed in the mixed lubrication regime. Important aspects of lubricants are formed by the reactivity of the lubricant, which determines whether the lubricant can form a monolayer in the case of boundary lubrication. With hydrodynamic lubrication, the most important factor is viscosity. The boundary lubrication part is based on the properties of the lubricant to form a chemical or physical bond with the workpiece and tool material. When a lubricant does not have this characteristic, circumstances which fulfil the requirements for hydrodynamic lubrication will immediately lead to asperity peaks breaking through the lubricant film, leading to metallic contact. This will lead at least to an increased friction coefficient, which might be followed by product failure or even tooling breakdown.

A lubricant is characterised only by the viscosity to the Sommerfeld number, which is a property that mainly influences the hydrodynamic lubrication of the frictional conditions.

A large amount of the frictional conditions is related to contributions that are made by specific material properties. Important properties of material combinations are the physical and chemical interactions.

Besides the type of the lubricant and the applied amount of lubricant, the resulting film thickness also play an important role. In deep drawing, however, film thickness depends on the amount of lubricant supplied on the sheet at the start of pressing. When the actual deep drawing

subsequently starts, oil partly becomes trapped between the sheet and die, and thus will supply lubrication when drawing the sheet between tools.

The uniformity of the friction coefficient during various production batches in the press shop is also of major importance. The quest, is to select combinations of parameters that lead to a friction coefficient which is as much stable as possible.

Experimental tests on the pin-on-disc machine are used to investigate the coefficient of friction between ball and steel sample surface, under variation of lubrication, load and sliding speed.

In metal forming practice, it is common to apply lubrication which specifically aims at reducing friction and wear. Figure 3.12 and Figure 3.13 relates the Sommerfeld number with the coefficient of friction, for base lubricant Prelubes A and B, as well as their various combination with four Press oils. Comparison of lubrication combinations is presented in Annex A.

For the calculation of Sommerfeld number input parameters were used from experimental tests. In the formula (2.2), the Sommerfeld number S is defined as a function of dynamic viscosity of the lubricant η (see Table 3.2), average linear velocities v (as illustrated in Table 3.6) with force P (is equal to the 24.5 N). Average coefficient of friction with different combined lubricants are given in the Table 3.7. Conventionally S is plotted on a logarithmic scale in the Stribeck plots. Results of friction coefficient against Sommerfeld number are presented in Table 3.8 and Table 3.9. These results will be discussed in Chapter 4.

Table 3.8 Sommerfeld number and coefficient of friction, for Prelube Fuchs Anticorit PL 3802-39S and various combination with different lubricants

Base lubricant Prelube A			Prelube A + Press oil 1		Prelube A + Press oil 3		Prelube A + Press oil 4		Prelube A + Press oil 5	
Speed [mm/s]	Sommerfeld number	μ	Sommerfeld number	μ	Sommerfeld number	μ	Sommerfeld number	μ	Sommerfeld number	μ
10	1.84E-05	0.092	2.37E-05	0.079	3.47E-05	0.080	3.67E-05	0.095	2.12E-05	0.075
14	2.57E-05	0.095	3.31E-05	0.089	4.86E-05	0.081	5.14E-05	0.104	2.97E-05	0.073
18	3.31E-05	0.089	4.26E-05	0.086	6.24E-05	0.068	6.61E-05	0.092	3.82E-05	0.080
22	4.04E-05	0.090	5.21E-05	0.084	7.63E-05	0.081	8.08E-05	0.098	4.67E-05	0.084
26	4.78E-05	0.091	6.16E-05	0.087	9.02E-05	0.082	9.55E-05	0.098	5.52E-05	0.085

Table 3.9 Sommerfeld number and coefficient of friction, for Prelube Quaker Ferrocoate S-6130 and various combination with different lubricants

Base lubricant Prelube B			Prelube B + Press oil 1		Prelube B + Press oil 3		Prelube B + Press oil 4		Prelube B + Press oil 5	
Speed [mm/s]	Sommerfeld number	μ	Sommerfeld number	μ	Sommerfeld number	μ	Sommerfeld number	μ	Sommerfeld number	μ
10	1.14E-05	0.081	1.88E-05	0.071	2.82E-05	0.081	1.84E-05	0.103	1.51E-05	0.078
14	1.60E-05	0.092	2.63E-05	0.083	3.94E-05	0.077	2.57E-05	0.100	2.11E-05	0.074
18	2.06E-05	0.083	3.38E-05	0.084	5.07E-05	0.079	3.31E-05	0.090	2.72E-05	0.079
22	2.51E-05	0.093	4.13E-05	0.083	6.20E-05	0.073	4.04E-05	0.091	3.32E-05	0.081
26	2.97E-05	0.092	4.88E-05	0.081	7.32E-05	0.075	4.78E-05	0.090	3.93E-05	0.080

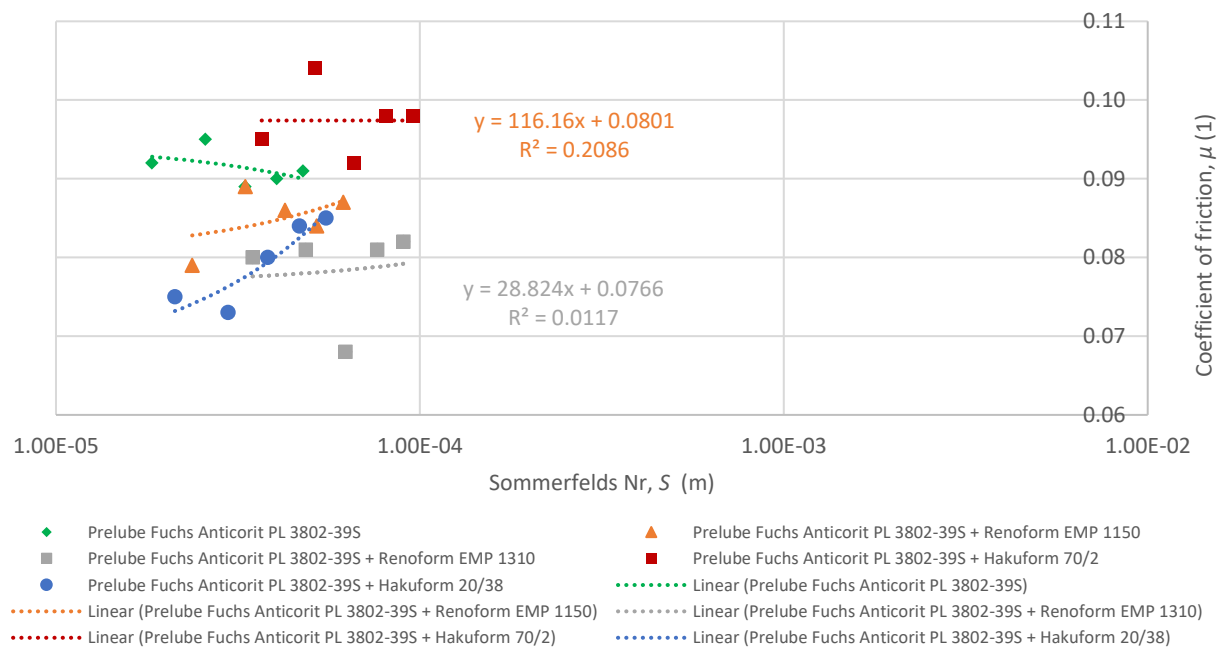


Figure 3.12 Sommerfeld number and average coefficient of friction, for Prelube Fuchs Anticorit PL 3802-39S and various combination with different lubricants

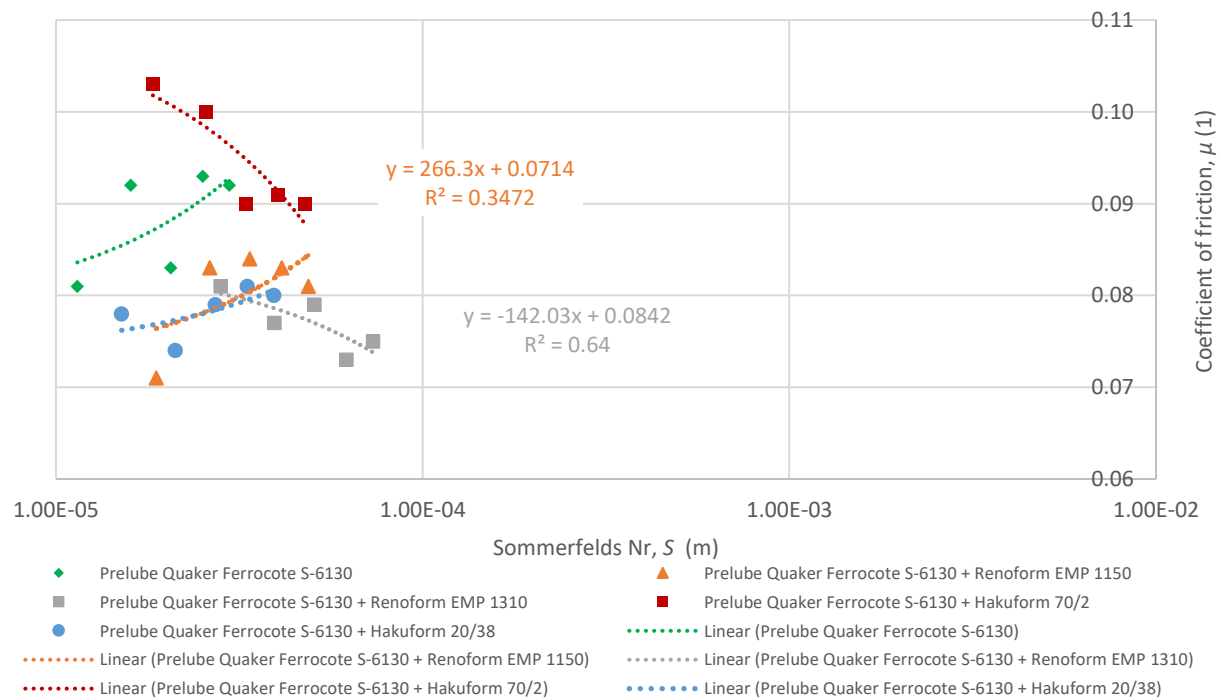


Figure 3.13 Sommerfeld number and average coefficient of friction, for Prelube Quaker Ferrocote S-6130 and various combination with different lubricants

3.8 Friction determination and tribology testing in sheet metal forming under different loads

In this subsection, the friction tests under different loads used at Sommerfeld number and the limitations of the pin-on-disc machine are discussed. Comparison of the tests reveal an influence of the different load on lubricated friction with various combined lubricants and sliding speeds.

To overcome challenges and improve forming efficiency, it is fundamental to understand how tribological loading works in surface contact. Friction is important in sheet metal forming, because for industrial production it can be a main reason for variability, success or failure.

As it will be apparent from the discussions in Chapter 4, the relative importance of each variable on test results depends on the materials, the test configuration and the applied conditions. Developed standards and recommended practices help engineers and scientists systematise the measurement of friction related data. Standards typically identify which variables should be controlled and which can vary, how data are to be collected and how they are reported. However, simply because a certain variable is not explicitly mentioned in a standard does not mean that it cannot affect friction under another set of circumstances.

3.8.1 Experimental procedures

Three different normal loads, from 15 N to 35 N with an increment step of 10 N, were individually chosen to apply on the pin-on-disc tester, so that different pressures were achieved in the interface between the tool and workpiece. Table 3.10 shows combinations of used lubricants.

Table 3.10 Prelube lubricants and four different combinations with Press oils

Lubricant	Used lubricant combinations
Prelube Fuchs Anticorit PI 3802-395	Base lubricant Prelube A
Fuchs + Renoform EMP 1310 P	Prelube A + Press oil 3
Fuchs + Hakuform 20/38	Prelube A + Press oil 5
Prelube Quaker Ferrocote S-6130	Base lubricant Prelube B
Quaker + Renoform EMP 1310 P	Prelube B + Press oil 3
Quaker + Hakuform 20/38	Prelube B + Press oil 5

For the calculation of Sommerfeld number the input parameters from experimental tests are used in the equation (3.5), with different forces P : 15 N, 25 N and 35 N. Average coefficient of friction is given in Table 3.11. Results of friction coefficient against Sommerfeld number for Base lubricant Prelubes A and B are presented in Figure 3.14 to Figure 3.15. Each lubricant is characterised in three separate charts, giving the same results; the first in general and the other two grouped by constant speed and by constant pressure. Annex A3 gives the results, which illustrated all the data and figures for combined lubricants.

Table 3.11 Average coefficient of friction results of different combined lubricants and varying sliding velocity, under different loads

Lubricants	Normal load, [N]	Average linear velocity				
		10 mm/s	14 mm/s	18 mm/s	22 mm/s	26 mm/s
Base lubricant Prelube A	15	0.083	0.050	0.051	0.051	0.053
	25	0.081	0.080	0.083	0.079	0.091
	35	0.119	0.155	0.160	0.154	0.105
Prelube A + Press oil 3	15	0.045	0.044	0.042	0.042	0.043
	25	0.080	0.081	0.068	0.081	0.082
	35	0.111	0.115	0.145	0.145	0.144
Prelube A + Press oil 5	15	0.035	0.032	0.038	0.049	0.037
	25	0.075	0.073	0.080	0.084	0.085
	35	0.115	0.159	0.201	0.105	0.106
Base lubricant Prelube B	15	0.065	0.084	0.040	0.041	0.038
	25	0.081	0.092	0.083	0.093	0.092
	35	0.115	0.130	0.125	0.145	0.111
Prelube B + Press oil 3	15	0.036	0.039	0.034	0.038	0.052
	25	0.081	0.077	0.079	0.073	0.075
	35	0.114	0.112	0.105	0.121	0.109
Prelube B + Press oil 5	15	0.036	0.030	0.034	0.029	0.037
	25	0.078	0.074	0.079	0.081	0.080
	35	0.117	0.101	0.112	0.113	0.114

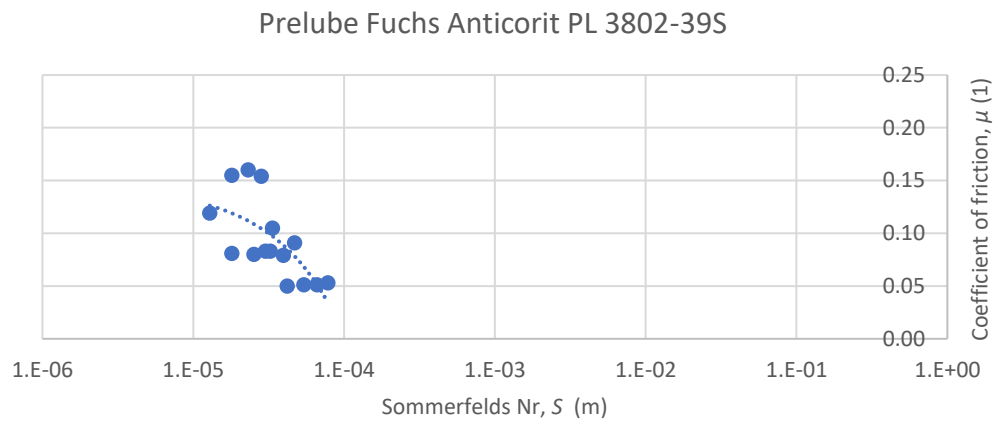
3.8.1.1 Influence of lubricant

The friction affects at boundary lubrication as well as at mixed lubrication, each one in a different way.

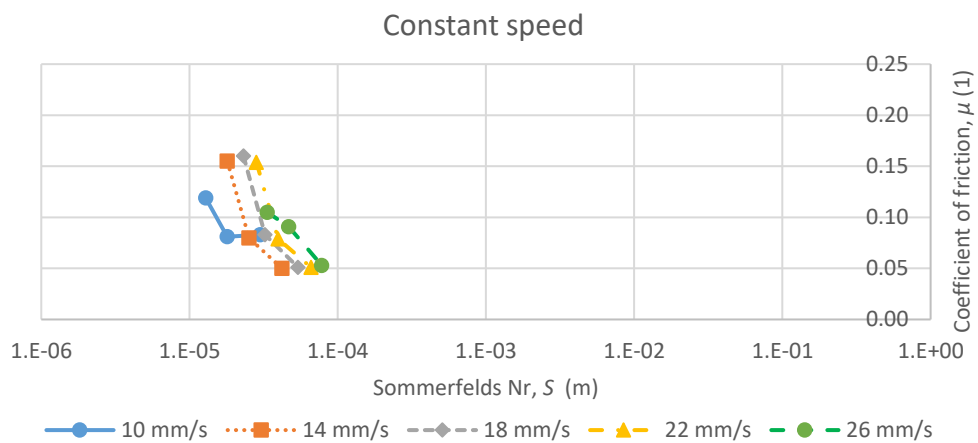
At mixed lubrication, pressure is generated in the lubricant by hydrodynamic effects and this pressure strongly affects friction. Generation of pressure is related to the viscosity of the lubricant and it is taken into account in the definition of the Sommerfeld number. Without exception, it has been found that different lubricants always give results which merge into a single Stribeck curve within normal scatter (all lubricants used in the experiments show Newtonian behaviour).

The friction force at boundary lubrication is the product of the total contact area and the mean shear stress on those contacts. The latter is strongly affected by the lubricant properties and an influence of lubricant is clear in the results presented in Table 3.11. For pin-on-disc machine tests this effect has been noticed where the different combined lubricants give dissimilar results in identical testing conditions. This may be caused by diverse chemical reactions between the lubricants and the metal surface.

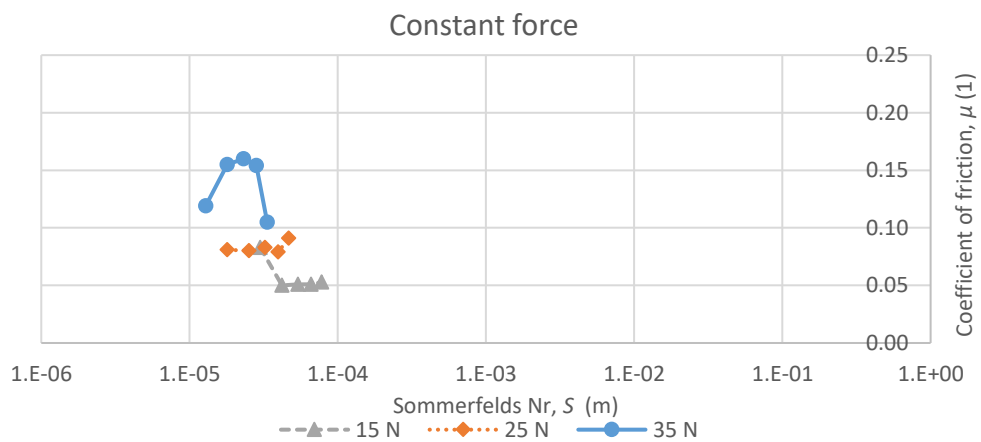
At the onset of mixed lubrication, both types of Prelubes give different friction values. For all lubricants, reducing the speed causes, in general, a friction increase. A mechanism for this effect has been proposed by Felder (as stated in Emmens [29]), who states that at contact spots microhydrodynamic effects may occur, which induce a reduced form of mixed lubrication and hence an influence of speed. The effect of an additive in this proposed mechanism is not clear.



a) *Base lubricant Prelube A*

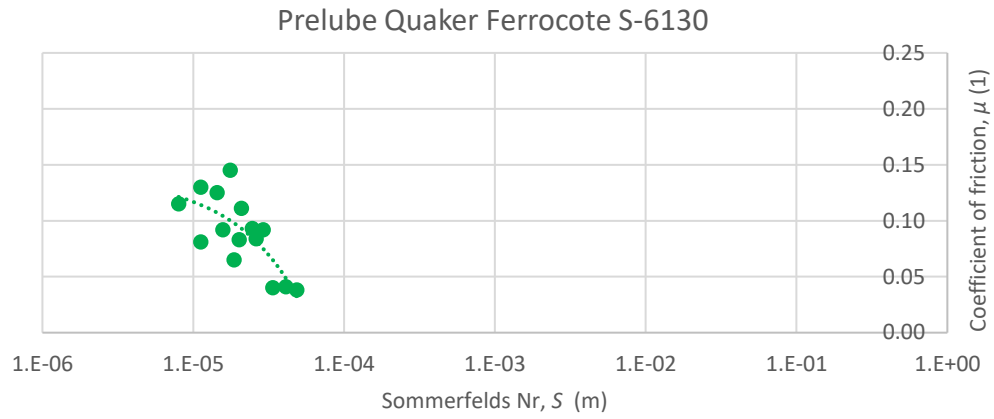


b) *"Constant Speed curves" for Base lubricant Prelube A*

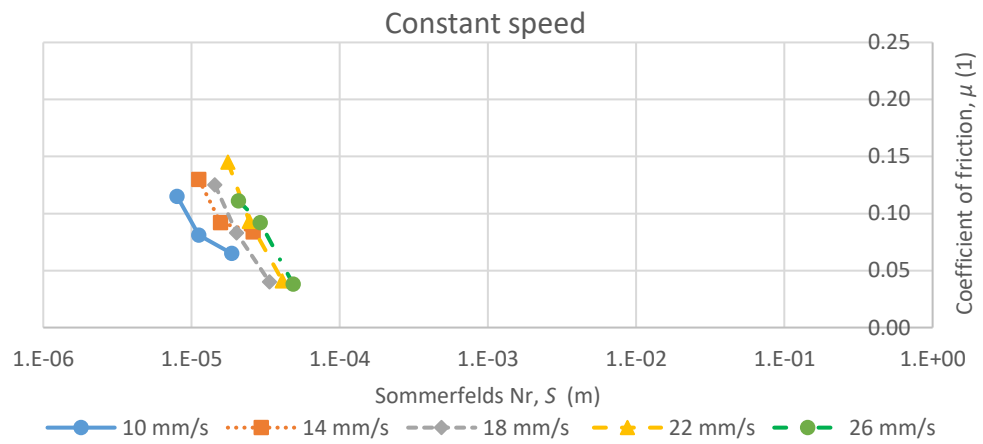


c) *"Isobaric curves" for Base lubricant Prelube A*

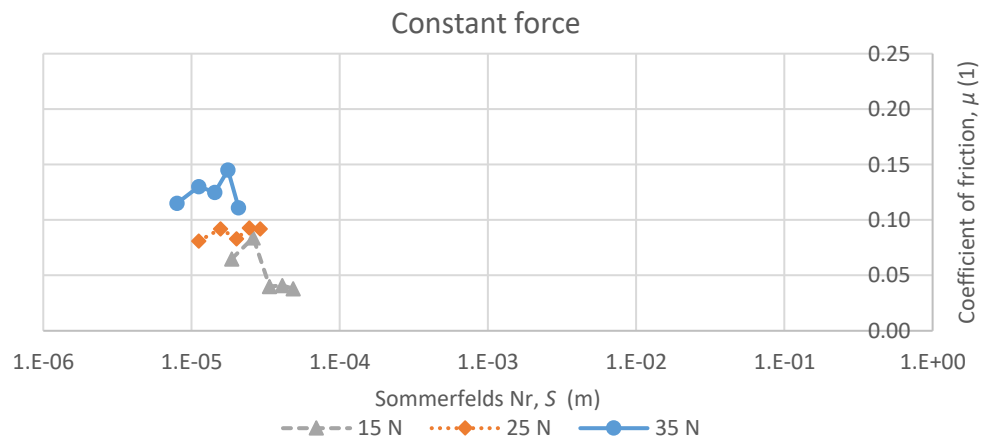
Figure 3.14 Friction coefficient against Sommerfeld number for Base lubricant Prelube A



a) *Base lubricant Prelube B*



b) *"Constant Speed curves" for Base lubricant Prelube B*



c) *"Isobaric curves" for Base lubricant Prelube B*

Figure 3.15 Friction coefficient against Sommerfeld number for Base lubricant Prelube B

3.8.1.2 Influence of speed

The (sliding) velocity is one of the components of the Sommerfeld number, and thus one of the determining factors in creating a certain lubrication regime. The sliding velocity in deep drawing is largely based on the punch velocity.

Furthermore, metal forming is an irreversible process and part of the energy transforms to heat. If a deep drawing process is now performed at higher speed, it means that the same amount of heat is generated in a shorter time.

As seen in Figures 3.14 and 3.15, when speed is increasing, the constant speed curves are shifting to the right (Sommerfeld number is increasing), but there is no much change on the friction coefficient values, since the curves are kept at the same level.

3.8.1.3 Influence of pressure

The position of the Stribeck curve, more precisely the position of the transition points depends on the pressure. This has been checked for our experiments by plotting in the different values of constant pressure at the midpoint of mixed lubrication against pressure as done in Figure 3.14 and Figure 3.15 (more results are presented in Annex A). This figure shows that the Stribeck curve shifts slightly to the left with increasing pressure.

In general, at real work process, the contact pressure can only be influenced by controlling the blank holder force, but the largest share of the contact pressure distribution is determined by the geometry of the process and the material behaviour of the sheet material.

As seen in Figure 3.14 and 3.15, in constant pressure curves, when curve value is higher, friction coefficient also increases. Since higher pressure corresponds to lower Sommerfeld number, one may expect that experimental results are located in the transition region of the Stribeck curve, where such behaviour has major effects, thus impacting on the analysed relation between pressure and friction coefficient.

3.9 Conclusions

Tribological tests were carried out using pin-on-disc machine which aimed to determine the coefficient of friction and behaviour between sheet metal and tools during forming. The research has considered the frictional characterization of reciprocating sliding tests, to find the effect of lubricant and other variables on the coefficient of friction of the cold rolled HSLA 380 and cold rolled HSLA 420 steel sheets with different lubrication conditions.

It is highlighted that:

1. this chapter gives a comprehensive account of the materials, that have been chosen for this work presenting their properties and characteristics that are relevant for the study; lubrication involves not only the selection and formulation of lubricants but also the design of contact geometry;

a set of two Prelube oils and its combination with five Press oils have been selected for the study and characterized;

two high strength low alloy steels HSLA 380 and HSLA 420 have been elected because they provide increased strength to weight ratios over conventional low carbon steels for only a modest price premium. As HSLA alloys are stronger, they can be used in thinner sections, making them particularly attractive for transportation equipment components where weight reduction is important;

2. it was found that Prelube A + Press oil 3 lubricant gives the lowest value of friction coefficient and a constant behaviour with time. It is also found that the optimum sliding velocity is 18 mm/s, of the 54 rpm. For the combination, Prelube B + Press oil 3 lubricant the lowest values coefficient of friction corresponds to 22 mm/s, i.e. 66 rpm; when the Press oil 2 is combined with Base lubricant Prelubes A and B an adverse effect is obtained, on the coefficient of friction and friction behaviour; press oil 2 is a vanishing oil which evaporates very quickly and leaves residuals on the surfaces; hence, this combination of the lubrication may not be very useful for the sheet metal drawing operations;
3. reciprocating sliding tests were performed, to find the effect of lubricant properties and other variables on the coefficient of friction of the steel sheets cold rolled HSLA 380 and HSLA 420 under different loads; the coefficient of friction varies over a wide range of different lubricating conditions and different sliding velocities. In the range of tested velocities, the influence of speed does not show to have a great effect on friction coefficient values; on the other side, pressure shows a sensible effect on friction coefficient defined as higher pressure will give higher friction.

Also, experiments were characterised by the Sommerfeld number, where main input parameters influence the frictional behaviour. These include the normal force, velocity and acceleration characteristics, direction of motion relative to surface features, surface cleanliness, roughness and lubricant properties.

4 Determination of the friction coefficient in the flat strip drawing test

4.1 Introduction

Tribology is the science and technology for friction, lubrication and wear. Tribology plays a key role in metal forming processes through the relative motion and interaction between the applied sheet material, the lubrication and the tooling. Tribology may determine the quality of metal formed products and may influence the stability and efficiency of the production process.

A modified strip drawing tribotester has been used to generate the movement between the tool and sheet. The uniqueness with this device compared to existing tribotesters used within sheet forming applications is the ability to fully control the applied normal force and drawing velocity during experimentation to simulate true tribological conditions more accurately. This option makes it possible to combine very accurate control of the relative movement between the sheet and the tool with consistent load and pulling force measurement.

The test method enables comparison of different surface finishes and treatments, lubricants and coatings in terms of friction and galling under settings similar to sheet metal forming process conditions. Valid frictional data is also very important [8], [9a] as an input parameter for simulation models to achieve reliable results.

The basic functioning of the tribotester is illustrated in Figure 4.1. The linear motion of the tensile testing machine moving table is hydraulically driven. The specification for the linear motion in terms of velocity, distance, force and load is primarily based on estimates from sheet forming processes.

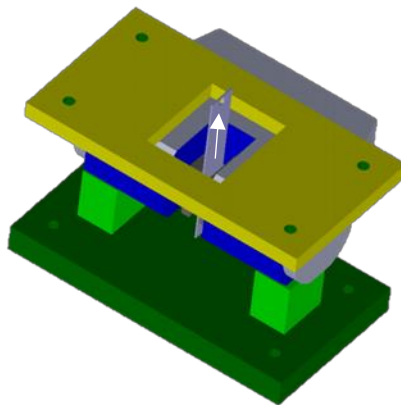


Figure 4.1 Schematic illustration set of the modified strip drawing tribotester

The actuator generating the movement between the tool and sheet, as well as the controllable normal load are the main characteristics of this device and other tribotesters based on parallel strip drawing. This option makes it possible to combine very accurate control of the relative movement between the sheet and the tool with interesting dynamic properties.

4.2 Experimental setup

Four types of surface textures were produced on tool plates. The surfaces were produced on the steel plates with roughness obtained by grinding. For this type of surface texture, care was taken so that the grinding marks were unidirectional in nature and parallel to sliding direction.

Preliminary experiments were used with similar tool plates having two different types of grinding surfaces: one of them with grinding parallel to the sliding direction and another type with grinding perpendicular to sliding direction. Results with perpendicular grinding have been negative, therefore the experiments with this type of surface finish did not continue in next phase.

Before each experiment, the tool surface and steel sheet samples were thoroughly cleaned with ether alcohol and then the lubricant was applied with a brush. The steel sheet sample was fixed vertically at the grip of the tensile testing machine.

Then steel sheet sample was tested under four different loads at the sliding speeds of 60, 150 and 240 mm/min. Sliding track length for each test was around 150 mm. The average coefficient of friction values were calculated for a sliding track of 100 to 120 mm and loads were defined for 10.4, 16.25, 32.5 and 48.75 kN. Therefore, the effect of normal load and speed on the coefficient of friction could be studied.

Experiments were conducted under lubricated conditions on each sheet sample using just one combination of load and sliding speed. Before the tests, the lubricant (Renoform EMP 172) was applied on both surfaces of the steel plate. The viscosity of lubricant oil was found to be 68 mPa.s at 40 °C.

The profiles and surface roughness parameters of the tool materials and steel sheet samples were measured in the direction of the sliding and perpendicular to the sliding direction using two-instruments: Bruker's NPFLEX 3D optical microscope and contact measuring device HOMMEL tester T500.

It was reported that the coefficient of friction depends on sliding direction. For this reason, 2D roughness parameters, along the sliding direction, were considered in this study. The coefficient of friction values obtained in the experiments were correlated with roughness parameters of the tool surface.

4.2.1 Tensile testing machine

Figure 4.2 presents the modified strip drawing tribotesters under this work and the corresponding experimental tensile testing machine. Depending on the test, the influence of the contact normal stress, sliding speed, temperature, stretching status, tensile status, surface texture, tool and workpiece materials, coating, lubricant type and amount of lubricant can be specifically examined.

To evaluate a tribological system (consisting of the tool, plate and lubricant) it is important to represent the determined friction coefficient dependent on the contact normal stress and sliding speed graphically and to mark the occurrence or any stick-slip effects on the graph. In doing so, a comparison of the tribosystems based on differing criteria (maximum attainable contact normal stress, progress and level of the friction coefficients) is possible.



Figure 4.2 Tensile testing machine and modified strip drawing tribotester

4.2.2 The modified strip drawing tribotester

The basic functioning of the modified strip drawing tribotester is illustrated in Figure 4.3. These tests enable faster and more accurate measurement of friction coefficient for metal forming with enriched functionalities.

Strip drawing tests, which considers contact pressure, sliding velocity and sliding length were developed to improve the accuracy of predictions of the coefficient of friction of steel sheets. The effects of contact pressure and sliding velocity under lubrication were estimated based on a friction test in which steel sheet was drawn between two tools.

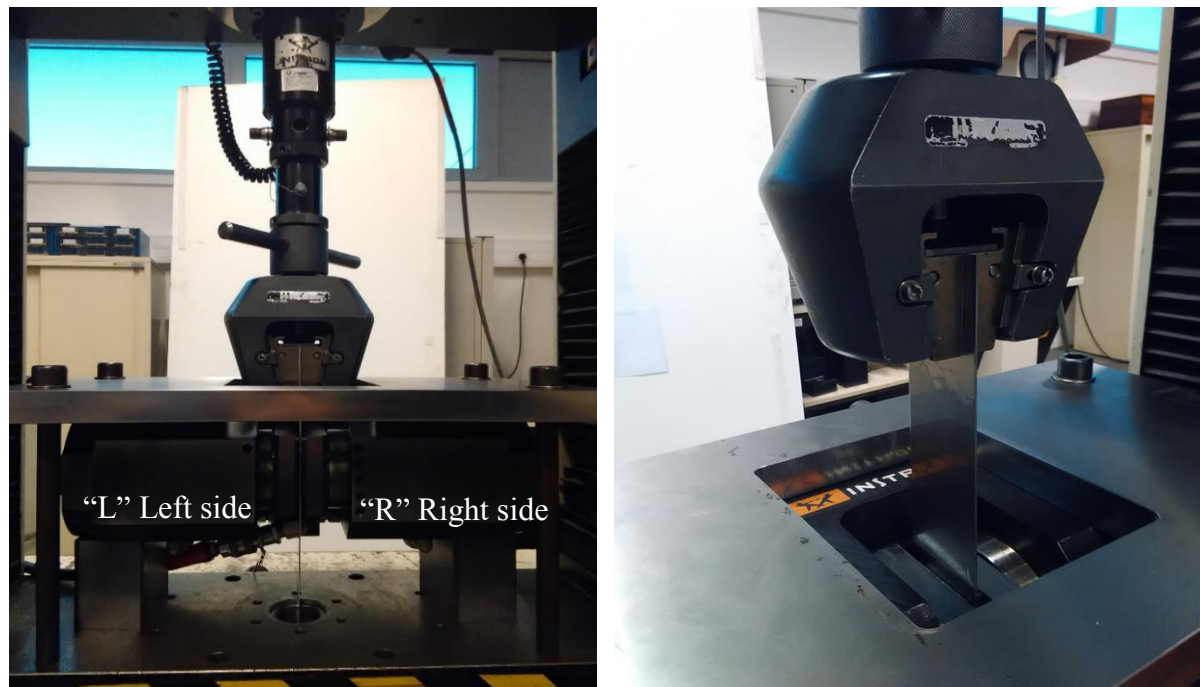


Figure 4.3 Tool plates set of the modified strip drawing tribotester (L – means Left side of the tool plates, when looking at the front side; R - means Right side of the tool plates)

Four different tool surfaces have been selected for strip drawing tests. To study the effect of the roughness peaks on coefficient of friction, grinded and polished surfaces have been tested. Also, to detect the result of different material properties, grinded surfaces has been nitrided and quenched/tempered.

The conditions for the strip drawing tests were similar for all different experimental tools. Previous experimental tests on HSLA 380 steel have been carried out using the pin-on-disc machine, with the reciprocating attachment. Much lower loads and different counterpart material has been used in such tests. Consequently, a direct comparison is not possible, because of different conditions used, which have been already presented in Chapter 3.

Therefore, some additional tests with steel sheet and tools with different surface finishes have been carried out on the modified strip drawing tribotester, using as much as possible the same experimental conditions. Figure 4.4 illustrates the basic function and details of the modified tribotester. The tensile testing machine, already mentioned in previous section, was used to provide force and displacement control for the modified strip drawing tribotester.

This tribology-system consists of:

- sheet (material properties, coating/treatment and surface finish);
- tooling (material type, coating/treatment and surface finish);
- lubrication (type of lubricant, liquid, amount and distribution);
- process (pressure, velocity and stroke length).

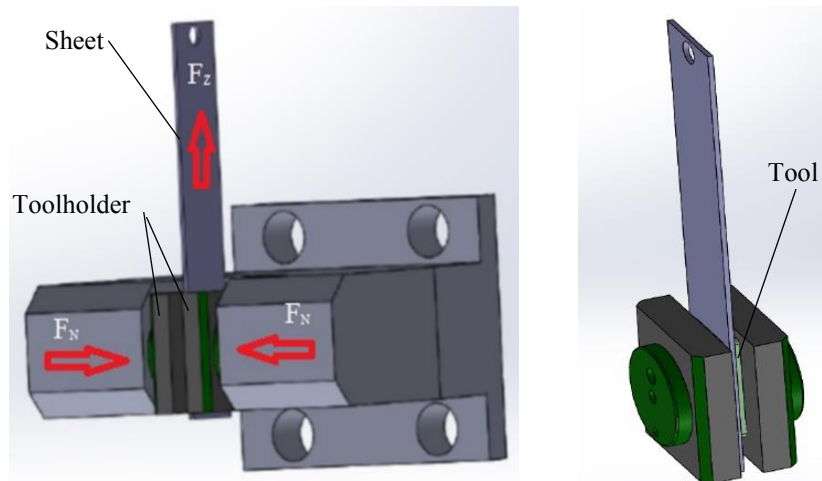


Figure 4.4 Set of tools and sheet metal layout

The current industrial standard is to use a constant (Coulomb) coefficient of friction for calculation proposes. To achieve more realistic simulation results with increased reliability, it is crucial to accurately account for tribology effects in metal forming.

4.3 Assessment of tool surface roughness parameters

The measurement of surface roughness parameters was carried out using the two instruments: a Bruker's NPFLEX 3D optical microscope and a contact measuring device HOMMEL tester T500.

Surfaces with similar or even identical average surface roughness values (R_a) might have vastly different surface topographies. In order to better quantify and differentiate these types of surfaces, industries have begun to develop three-dimensional (3D) methodologies.

The benefit to measure surfaces is both the possibility to study them in the micro and nanoscale and a way to quantitatively evaluate them. But, there is a huge amount of available 2D and 3D parameters (abbreviated R and S parameters, respectively).

2D parameters, usually obtained by a mechanical profiler, can be used to quantify the surface quality in a limited extent. The most frequently used in practical work with forms is the R_a value describing the average height of the measured surface. However, it is a rather limited description of the surface form of smaller defects and certain textures will be “averaged out” and undetected as already seen in Chapter 2.

4.3.1 Tool materials

A typical request for tools used in cold work applications is a high hardness. The reason is that the work materials to be formed are already often hard and high strength materials. Therefore, higher tool hardness is necessary to prevent plastic deformation or heavy tool wear. A negative

consequence of high hardness level is that the tool material becomes more brittle. Tool steel for cold work applications needs high wear resistance, sufficient compressible strength toughness and ductility [14]. The following tool material characteristics are important:

- high wear resistance to increase tool life and to reduce the need of production stoppages for tool maintenance;
- sufficient compressible strength to avoid plastic deformation of the active tool surfaces;
- sufficient toughness and ductility to avoid premature tool breakage and chipping.

High wear resistance is not just a question of hardness. Typically, tool steel grades for cold work applications also contain hard carbides, giving an extra contribution to the wear resistance. These carbides are chemical compounds of carbon and carbide forming elements such as chromium, vanadium, molybdenum or tungsten. Generally, the more frequent, larger and harder the carbides are, the better wear resistance is achieved in the tool.

4.3.2 Tools with different surface finishes

Four tool couples with different surface topographies are incorporated in this work as considered in Figure 4.5. The materials are commercial tool steels developed to satisfy different applications within the sheet forming industry. There are no general applicable standards for the materials. Grinded and Polished corresponds to K 340, also Nitrided and Quenched/tempered corresponds to C 265, as seen in Table 4.2.



a) Grinded “L” and “R”



b) Polished “L” and “R”



c) Nitrided “L” and “R”



d) Quenched/tempered “L” and “R”

Figure 4.5 Tool couples with different surface finishes (L-Left plate; R-Right Plate)

The difficulty with cold work applications in general, especially when blanking hard work materials, is to minimize crack initiating defects [14]. This must be done while maintaining wear resistance which demands high hardness and hard particles in the steel matrix.

Crack initiating defects such as notches are not necessarily due to carbides. Large slag inclusions, defects in the tool surface or sharp corners in combination with high hardness may also act as sites for crack initiation at fatigue loading. For this reason, the cleanliness of the metallurgical process and the surface finish of the tool or the tool design will strongly influence tool performance [85].

4.3.3 Tool material properties

The 12% chromium tool steels remain the most commonly used materials for cold working tools worldwide. It is a tool steel with very good resistance to abrasive wear, but limited with respect to resistance to fracture. Being the basis of cold work applications, there are numerous advantages in its use, such as heat treatment knowledge and manufacturing parameters. For a tool used in series of medium duration it is a correct choice, where the main failure mechanism is abrasive wear, with low risk of fragmentation or cracking.

The tool materials used in all experiments under this work are K 340 and C 265 steels [85], [86]. The materials are commonly used in cold working tools, such as blanking and stamping tools in the sheet metal forming industry, due to its high resistance to wear and chipping. The chemical composition of the tool materials can be seen in Table 4.1.

Table 4.1 Chemical composition, (average %) [85], [86]

Tool materials		C	Si	Mn	P	S	Cr	Mo	V	Other
K 340 (X110CrMoV8-2) EN		1.10	0.90	0.40		0.90	8.30	2.10	0.50	+Nb, +Al
C 265 (X160CrMoV12-1) EN	Min	1.45	0.10	0.20			11.0	0.70	0.70	
	Max	1.60	0.60	0.60	0.030	0.030	13.0	1.00	1.00	

Cold work tool steels are employed to the manufacturing of tools for applications involving surface temperatures of not more than 200 °C. In this temperature range, they must feature the following properties in order to guarantee tool resistance to the high stresses arising from the numerous machining and shaping procedures [86]:

- superior hardness;
- high wear resistance;
- good toughness;
- excellent compressive and impact strength;
- high dimensional stability in heat treatment;
- sufficient machinability.

A well-balanced alloy content ensures that optimum properties are achieved for individual applications.

4.3.4 Tool and tool holder

Tool dimensions for flat drawing test were defined according to VDA 230-213 standard [87], thus prescribing also the holder features and its adjustment to existing machine and system requirements.

To further reduce effects like scratching and galling initiation, which can be originated from sharp edges during testing, the edge between the active surface and the corner radius were carefully chamfered. Figure 4.6 shows used tool and holder of the tool.

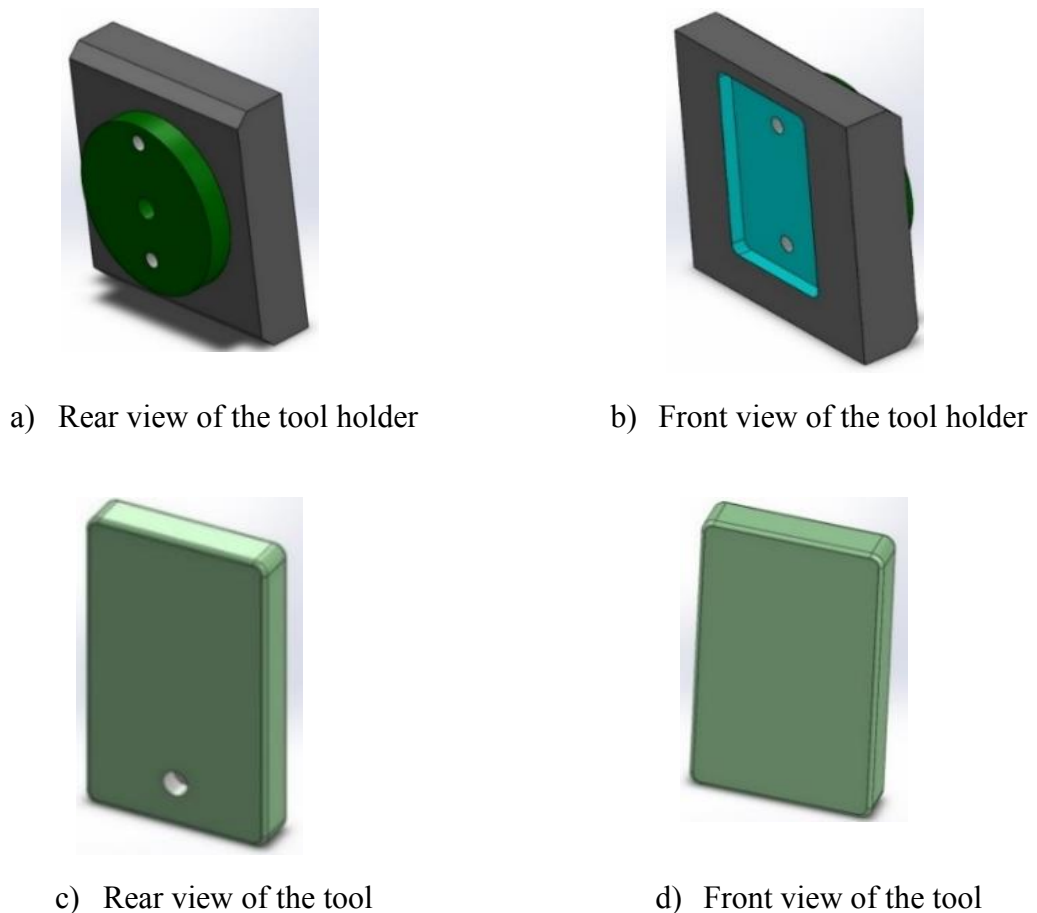


Figure 4.6 View of the tool and tool holder

Tools made from high alloy steel which have been quenched and tempered are particularly sensitive during grinding operations. Extra care is demanded here. Under unfavourable grinding conditions the tool steel can be affected as follows [88]:

- surface hardness is reduced (temper burn) and this will adversely affect wear resistance;
- hardening of the ground surface may take place and result in the formation of grinding cracks and problems with tool breakage and chipping;
- severe stresses are introduced into the tool and these can enhance the risk of failure.

4.3.4.1 Geometry of the tools

Tools were produced with an active area of 42.80 x 69.90 mm², as shown in Figure 4.7. A radius of 3 mm was initially created at the edges to prevent and reduce boundary effects from the edges of the tool during experiments.

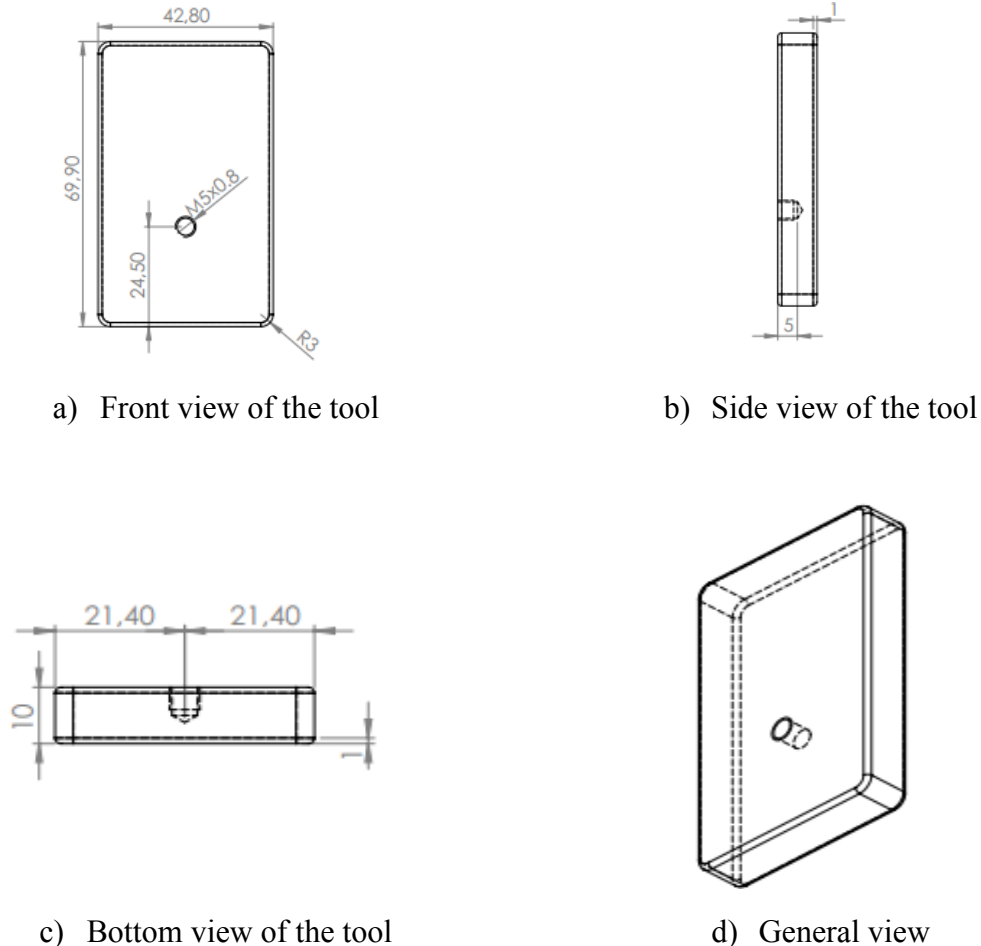


Figure 4.7 Strip drawing test tool dimensions

It was decided to use a small amount of lubricant in the experiments. Preliminary experiments were performed to explore the running in behaviour of the tools and the overall stability of the process. An even imprint from the tool has indicated that an aligned movement was obtained as well as a satisfactory control on boundary effects.

4.3.5 Hardness of tool materials

Hardness is a characteristic of a material, not a fundamental physical property. It is defined as the resistance to indentation, and it is usually determined by measuring the permanent depth of the indentation. When using a fixed force (load) and a given indenter, the smaller the indentation, the harder the material. Indentation hardness value is obtained by measuring its dimensions.

The tool must have sufficient hardness to prevent plastic deformation. Therefore, the need for higher hardness in the tool steel becomes obvious.

The used hardness level depends on the sheet thickness and the part geometry. It will normally be in the range 56-63 HRC. Table 4.2 presents Rockwell and Vickers hardness measurement results for experiment tool materials (Grinded, Polished, Nitrided, Quenched/tempered).

Table 4.2 Hardness of selected tool materials

Tool materials	Surface condition	Recommended Hardness Levels HRC	Measured HRC	HV [390 N]
K 340 (X110CrMoV8-2) EN	Grinded "L"	52-63	61	724
	Grinded "R"	52-63	61	724
	Polished "L"	52-63	63	772
	Polished "R"	52-63	63	772
C 265 (X160CrMoV12-1) EN	Nitrided "L"	58-60	29	297
	Nitrided "R"	58-60	29	297
	Quenched/tempered "L"	58-60	60	702
	Quenched/tempered "R"	58-60	60	702

L- Left plate; R-Right plate

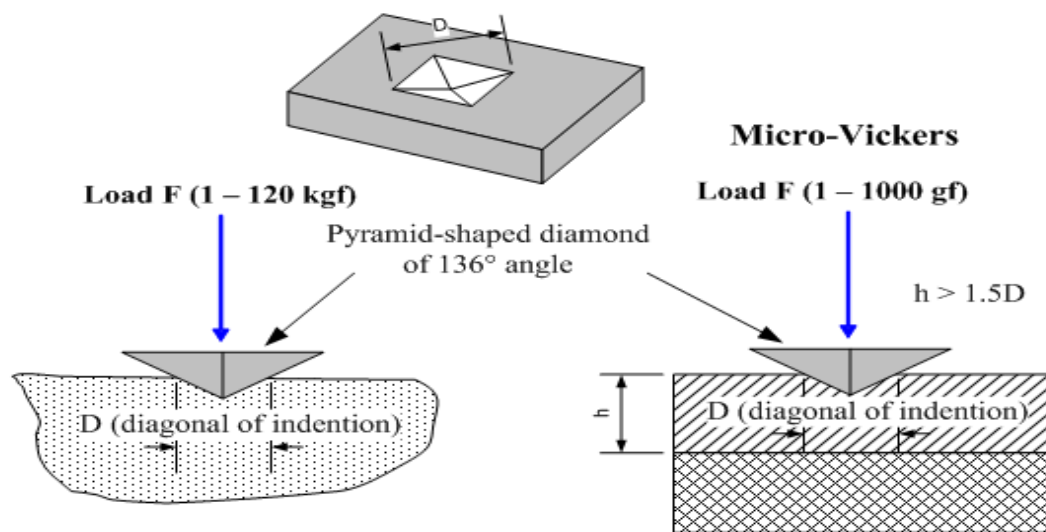


Figure 4.8 Vickers hardness test method, adapted from [89]

where, the load varying from 1 kgf to 120 kgf, is usually applied for 30 seconds. The micro-hardness methods are mostly used to test metallic materials, although almost any other material can be tested.

In Figure 4.8 it is illustrated Vickers hardness test method. The Vickers hardness test method, also referred to as a micro-hardness test method, is mostly used for small parts, thin sections, or case depth work. The Vickers method is based on an optical measurement system. It is very useful for testing on a wide type of materials as long as test samples are carefully prepared. A square base pyramid shaped diamond is used for testing in the Vickers scale.

4.3.6 Bruker's NPFLEX 3D optical microscope

Bruker's 3D optical microscopes have targeted automation and analysis capabilities that can save the time. Figure 4.9 shows the Bruker's NPFLEX 3D optical microscope, general view and close up, used in current work.

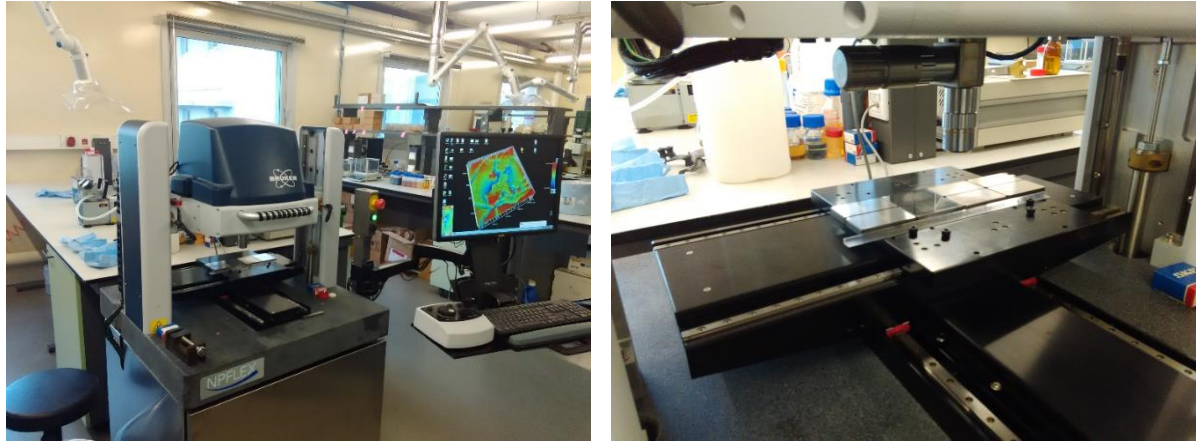


Figure 4.9 Bruker's NPFLEX 3D optical microscope; its large nominal working volume handles small or large sample coupons and multi-sample trays

Bruker 3D optical microscopes provide accurate, adequate measurements of surface roughness. Optical profiling measures surface roughness and shape using the interference of light, resolving surface anomalies from millimeter-scale step heights through nanometer-scale roughness. The 3D analysis allows the estimation of hundreds of parameters to completely describe surface roughness.

Acquiring image and characterising sample surfaces on the micrometer and nanometer scale is key to attaining a functional understanding of a wide range of materials. In fields, such as optics, image acquisition is also critical to the production process. Figure 4.10 presents the sampling area for measuring 3D surface texture of a tool plate.



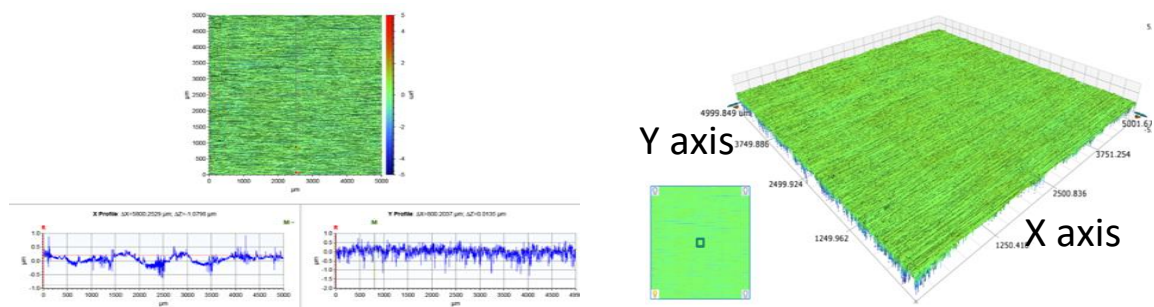
Figure 4.10. Measured surface area 5x5 mm², tool surface Grinded along the Sliding direction

The use of 3D instrumentation with higher resolution provides more accurate surface measurements of forms with complex geometries which in turn means that quantitative surface

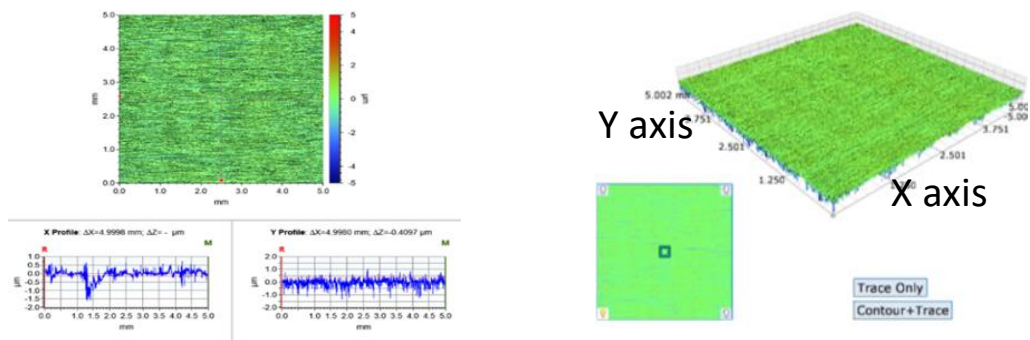
quality controls can be performed. The values of these measured parameters are presented in Table 4.3 and Table 4.4 and the complete parameters are illustrated in Annex B. Considered parameters are roughness average S_a , the surface kurtosis S_{ku} , the highest peak of the surface S_p , the root mean square roughness parameter S_q , the surface skewness S_{sk} , the maximum peak depth S_v and the 10-point peak to valley surface roughness S_z . The results of surface roughness measurements clearly show that the used steel sheets have narrow range of S_a parameter value. It seems that this allows determination of the effect of mechanical properties of the sheets on the value of friction coefficient.

Tool surfaces measurement had been conducted before and after friction tests. After friction tests in grinded surfaces, a quality of the previous condition is much better than other surfaces finishes. The effects for Grinded surfaces are presented in more detail in Figure 4.11 and Figure 4.12, and complete data for other different surfaces is presented in Annex B.

In sheet metal forming the analysis of conditions of tool surface is a challenging issue. However, a number of techniques is available to handle the challenges with a special focus on lowering costs and improving reliability. With large sample area, analysis cap and automatic data acquisition capabilities, 3D optical microscopes have good solutions.

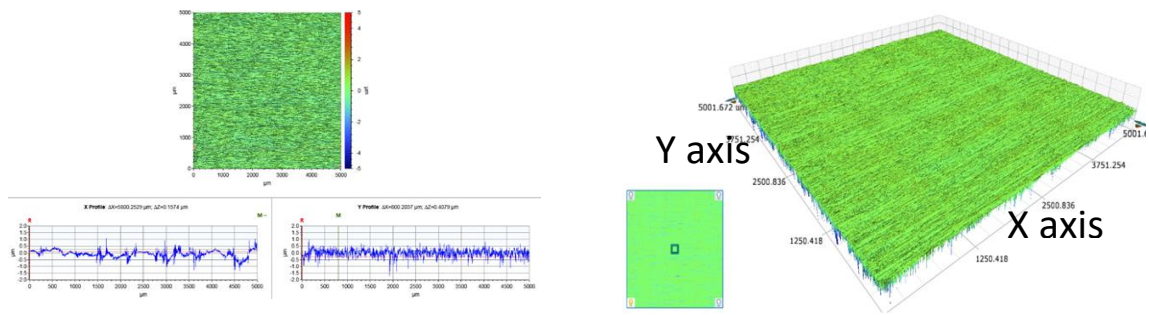


a) Before tests, X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = -1.0798 \mu\text{m}$
Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = 0.0135 \mu\text{m}$



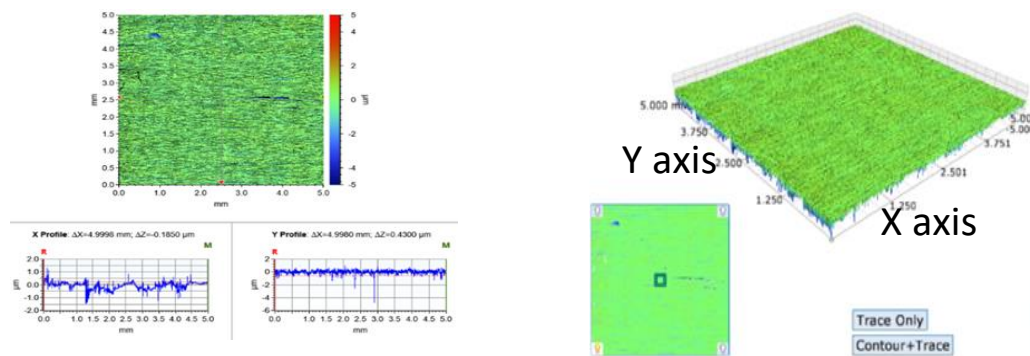
b) After tests, X Profile: $\Delta X = 4.9998 \mu\text{m}$; $\Delta Z = - \mu\text{m}$
Y Profile: $\Delta X = 4.9980 \mu\text{m}$; $\Delta Z = -0.4097 \mu\text{m}$

Figure 4.11 3D analysis of a surface of a profile of Grinded "L" tool



a) Before tests, X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = 0.1574 \mu\text{m}$

Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = 0.4079 \mu\text{m}$



b) After tests, X Profile: $\Delta X = 4.9998 \mu\text{m}$; $\Delta Z = -0.1850 \mu\text{m}$

Y Profile: $\Delta X = 4.9980 \mu\text{m}$; $\Delta Z = 0.4300 \mu\text{m}$

Figure 4.12 3D analysis of a surface of a profile of Grinded "R" tool

Table 4.3 Surface roughness parameters of the tested tools before tests

Surface condition	Tool surface roughness parameters						
	Sa μm	Sku	Sp μm	Sq μm	Ssk	Sv μm	Sz μm
Grinded "L"	0.18	0.008	5.62	0.25	-0.001	-3.14	8.76
Grinded "R"	0.19	0.007	9.20	0.26	-0.001	-3.17	12.37
Polished "L"	0.04	0.053	3.12	0.06	-0.004	-2.22	5.33
Polished "R"	0.06	0.057	8.81	0.11	-0.005	-2.64	11.45
Nitrided "L"	0.76	0.005	16.28	0.97	0.000	-9.09	25.37
Nitrided "R"	0.80	0.003	8.83	1.01	0.000	-8.26	17.09
Quenched/tempered "L"	0.17	0.009	5.37	0.24	-0.001	-4.24	9.61
Quenched/tempered "R"	0.20	0.009	2.22	0.28	-0.001	-9.91	12.13

L- Left plate; R-Right plate

Table 4.4 Surface roughness parameters of the tested tools after tests

Surface condition	Tool surface roughness parameters						
	Sa	Sku	Sp	Sq	Ssk	Sv	Sz
	μm		μm	μm		μm	μm
Grinded "L"	0.19	0.006	7.36	0.25	-0.0007	-2.84	10.20
Grinded "R"	0.21	0.035	14.82	0.31	-0.0031	-6.36	21.18
Polished "L"	0.04	0.435	11.18	0.07	-0.0087	-6.34	17.52
Polished "R"	0.06	9.563	27.45	0.13	0.0461	-8.71	36.16
Nitrided "L"	0.70	0.005	35.15	0.89	-0.0004	-11.98	47.13
Nitrided "R"	0.71	0.004	35.39	0.90	-0.0003	-12.87	48.26
Quenched/tempered "L"	0.18	0.012	14.67	0.24	-0.0013	-3.82	18.48
Quenched/tempered "R"	0.20	0.011	20.09	0.28	-0.0012	-3.51	23.60

L- Left plate; R-Right plate

4.3.7 2D measuring method using contact device HOMMEL tester T500

The contact roughness measuring device corresponds to a simple measurement and to a standard in the class of mobile roughness measuring instruments. With just two keys and one thumb wheel, the HOMMEL TESTER T500 is easy to handle in production. The instrument calculates all common parameters and monitors the tolerance limits set for them. The measurement results can be saved in the instrument and can be evaluated by the Windows software TURBO DATAWIN.

Measuring surface roughness and quality surfaces are traditionally estimated by the naked eye and measured by mechanical profilers for surface roughness, commonly described with the Ra , Rz , $Rmax$ or Rt values. Typical output parameters are the Ra (arithmetic mean value of a profile), the Rz (mean peak to valley height) and the $Rmax$ (or Rt , the maximum peak to valley height). The values of these measured parameters are given in Annex B.



Figure 4.13 Method of measurement of tool surface with traditional HOMMEL TESTER T500

In 2D measuring method two different direction, were used as seen in Figure 4.13: **first** position is measured **along** to sliding direction of friction test; **second** position is measured **perpendicular** to sliding direction. From Table 4.5 to Table 4.8 measured results are presented for Grinded “L” and Grinded “R” surfaces Before and After tests. The values of these measured parameters for the other tested surfaces are illustrated in Annex B.

Table 4.5 Grinded “L” surface parameters - Before tests

Grinded “L”	Measurement <u>along</u> to sliding direction			Measuring <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.69	0.48	0.07	1.90	1.34	0.14
2	1.01	0.64	0.09	1.44	1.21	0.13
3	0.82	0.65	0.10	1.71	1.32	0.12
Average	0.84	0.59	0.09	1.68	1.29	0.13
Measured by optical microscope	1.61	1.20	0.09	2.23	1.86	0.18

Table 4.6 Grinded “L” surface parameters - After tests

Grinded “L”	Measurement <u>along</u> to sliding direction			Measuring <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.94	0.70	0.10	1.62	1.16	0.12
2	0.92	0.72	0.10	1.60	1.14	0.12
3	0.60	0.52	0.08	1.54	1.28	0.14
Average	0.82	0.65	0.09	1.59	1.19	0.13
Measured by optical microscope	1.63	1.25	0.10	2.17	1.83	0.18

Table 4.7 Grinded “R” surface parameters - Before tests

Grinded “R”	Measurement <u>along</u> to sliding direction			Measuring <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.75	0.66	0.11	1.63	1.28	0.14
2	0.57	0.50	0.09	1.30	1.19	0.13
3	1.12	0.81	0.12	1.60	1.15	0.13
Average	0.81	0.66	0.11	1.51	1.21	0.13
Measured by optical microscope	1.66	1.28	0.11	2.39	1.92	0.18

Table 4.8 Grinded “R” surface parameters - After tests

Grinded “R”	Measurement <u>along</u> to sliding direction			Measuring <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.76	0.68	0.10	1.70	1.30	0.14
2	1.12	0.78	0.10	1.76	1.38	0.14
3	0.74	0.56	0.08	1.14	1.00	0.12
Average	0.87	0.67	0.09	1.53	1.23	0.13
Measured by optical microscope	1.83	1.35	0.12	3.24	2.16	0.20

4.4 Experimental conditions

The range of applied loads and velocities used for these experiments was mainly based on real process conditions in sheet stamping and limited by machine operability. In the present measurements, the applied normal load varies from 10 to 49 kN, but the normal pressure can easily be altered by using different force. The range for the initial experiments varied from 4 MPa to 18 MPa for the normal pressure and from 60 mm/min to 240 mm/min for speed. The tests were performed using tool surfaces of 2746 mm² in order to cover the test area (4 to 18 MPa in pressure) without changing tool size.

Table 4.9 The specifications for strip drawing test

Test material properties	
Test material:	Cold Rolled HC380LA
Test material thickness:	1.5 mm
Tool materials:	K 340 (X110CrMoV8-2) EN; C 265 (X160CrMoV12-1) EN
Surfaces:	Grinded, Polished, Nitrided and Quenched/tempered
Tools active area:	2746 mm ²
Lubricant:	Renoform EMP 172 (viscosity 68 mm ² /s)
Normal loads:	$F_N \approx 10.4, 16.25, 32.5$ and 48.75 [kN]
Sliding speeds:	60, 150 and 240 [mm/min]
Sliding length:	120 - 130 [mm]

The sliding length in each experiment was defined between 120 mm and 130 mm depending on the situation. High-load tests required shorter distances to stabilize the pulling force compared to the low-load tests. Table 4.9 brought together the values and test conditions used in the strip drawing tests.

The Renoform EMP 172 (viscosity 68 mm²/s) lubricant was used during the experiments. It is commonly used in the metal forming industry as a press oil. Table 4.10 summarizes the properties for this lubricant.

Table 4.10 Properties of lubricant

Renoform EMP 172	
Density:	25°C 0.90 g/cm ³
Viscosity:	40°C 68 cSt

The samples for the strip tests were cut in rolling direction so that the larger dimension, 300 mm corresponds to the sliding direction. Each strip was deburred and carefully visually inspected for surface defects. Samples with any kind of imprints, scratches, or other defects were removed to minimize errors during testing. The samples were cut in pieces of 300 x 55 mm. Figure 4.14 illustrates the sample dimensions. Mechanical properties and chemical composition of the sheet metal are referred in Chapter 3.

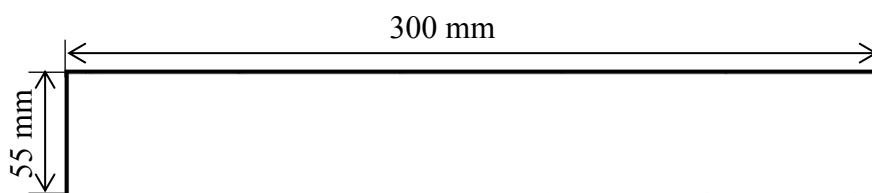


Figure 4.14 Dimensions of test samples of the steel sheet HSLA 380

Each steel sheet was thoroughly cleaned with ethanol before applying the lubricant. The oil was applied with a cloth, in order to get uniform distribution and film thickness.

Figure 4.15 shows a successfully drawn set, with some of the sheet strips displaying the imprints of the active area of the tool $40.5 \times 67.8 \text{ mm}^2$ plus the sliding path ($\sim 120 \text{ mm}$). Sheet preparation such as deburring and removing irregularities in the form of indents of any kind appeared to be very important to obtain valid results.



Figure 4.15 Tested steel sheets

Figure 4.16 illustrates four pairs of tools with different surface finish or treatment after experimental tests. The tested tool materials were steels K 340 (EN X110CrMoV8-2) and C 265 (EN X160CrMoV12-1) with different types of surface roughness. The tool surface condition can be divided into four groups: Grinded and Polished in K 340 tool material and Nitrided and Quenched/tempered in C 265 tool steel.

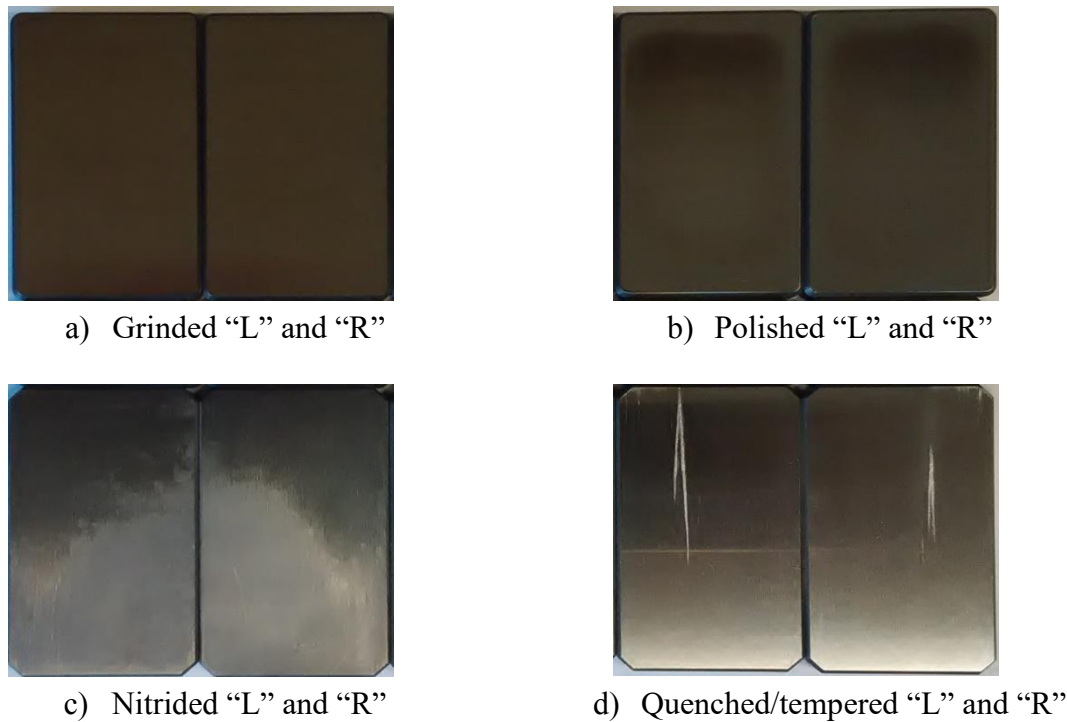


Figure 4.16 Selected tools with different surface finish or treatment after friction tests (L-Left plate; R-Right Plate)

For all tests, the force-displacements curves have been recorded and the average coefficient of friction has been determined from the data. It has been observed that in many cases the friction varied significantly during one test. In those cases, a calculated mean coefficient of friction can be unreliable. Therefore, it has been decided to exclude all tests where the friction varied more than a certain value over the length of the strip (different variation limits have been tested). Unfortunately, this applied to nearly all observations with the quenched/tempered condition.

4.5 Calculation of the coefficient of friction for the strip drawing tests

The friction force was acquired and the friction coefficient was calculated for constant speed and constant normal force. Each test was performed with lubricants. The corresponding plates involved four different surface conditions (grinded, polished, nitrided and quenched/tempered) and three different sliding speeds. Also, four different normal force values were applied. Therefore, twelve tests were performed for each tool plates set. But, for quenched/tempered tools only four tests have been completed because the surfaces of tools started to lose their quality from the beginning of tests.

The tribosystem consists of the tool couples pressed at the required load F_N against the test sheet in between, Figure 4.4. The operating parameters defined for the modified tribotester were as follows: normal load $F_N \approx 10.4, 16.25, 32.5$ and 48.75 , kN; sliding speed $v = 60, 150$ and 240 , mm/min; steel sheet HSLA 380 Cold Rolled; tool contact area $A = 40.5 \times 67.8 = 2746$, mm²; lubricant Renoform EMP 172 (viscosity 68 mm²/s).

During the tests, the friction force and the sliding distance were measured and a computer program was used to register and display the values of the friction force as a function of time or displacement.

The coefficient of friction is defined as the ratio of force of friction to the normal force, as seen in Eq. (4.1). If the externally applied force F_N is equal to the force of sliding friction F_p , then the object slides at the constant speed and the coefficient of friction involved is called the coefficient of sliding friction, μ . The value of friction coefficient was determined based on the values of both normal force F_N and pulling force F_p from the formula (4.1). Eq. (4.2) corresponds to the calculation of standard deviation for coefficient of friction. Eq. (4.3) illustrate formula to obtain the apparent contact pressure C_p . The results of the experimental tests are presented in Table 4.11.

$$\mu = \frac{F_p}{2F_N} \quad (4.1)$$

$$\sigma = \frac{F_p \sigma}{2F_N} \quad (4.2)$$

$$C_p = \frac{F_N}{A} \quad (4.3)$$

where, μ – coefficient of friction; F_p – pulling force, kN; F_N – normal force, kN; σ – standard deviation; $F_p \sigma$ – pulling standard deviation; C_p – apparent contact pressure, N/mm²; A – area.

Data acquisition was started manually and stopped automatically when the pre set displacement was attained. The friction coefficient for the tests using constant speed was calculated by taking the mean value of the filtered friction function at 70–90% of the travel distance. Experiments were repeated to check the distribution between deterministic experiments for different speed and applied forces. Twelve tests were performed for grinded surface. The test conditions are shown in Table 4.9.

The contact area between the tools and the sample is rectangular. Sheet has contact on both sides. The coefficient of friction between the tools and the surface of sheet metal is calculated according to Coulomb's friction law, as referred in Eq. (4.4). The value of F_p , pulling force, is measured by a load cell attached to the modified machine, connecting the tested strip to the moving table. Following example presents calculation coefficient of friction for grinded surface tools under normal force 10.4 kN and sliding speed 60 mm/min.

Similar tests were carried out using different loads and sliding speeds. The results for all tests are presented in Table 4.11 and Figure 4.17 displays a single friction curve, presented as an example.

$$\mu = \frac{F_p}{2F_N} = \frac{2.98}{20.8} = 0.143 \quad (4.4)$$

where, $F_p \approx 2.98$ kN; $F_N \approx 10.4$ kN; $\mu \approx 0.143$

Table 4.11 Experimental results

Surface condition	Sliding speed, [mm/min]	Coefficient of friction			
		10.4 kN	16.25 kN	32.5 kN	48.75 kN
Grinded	60	0.143 ±0.002	0.108 ±0.002	0.099 ±0.001	0.107 ±0.002
	150	0.108 ±0.003	0.122 ±0.001	0.092 ±0.001	0.097 ±0.002
	240	0.104 ±0.002	0.104 ±0.003	0.088 ±0.002	0.098 ±0.0006
Polished	60	0.084 ±0.002	0.081 ±0.0008	0.069 ±0.001	0.073 ±0.001
	150	0.085 ±0.002	0.082 ±0.002	0.070 ±0.001	0.079 ±0.0009
	240	0.099 ±0.0004	0.084 ±0.0006	0.074 ±0.0008	0.078 ±0.001
Nitrided	60	0.136 ±0.009	0.125 ±0.008	0.107 ±0.004	0.106 ±0.004
	150	0.141 ±0.003	0.138 ±0.003	0.111 ±0.003	0.118 ±0.001
	240	0.164 ±0.003	0.145 ±0.002	0.124 ±0.004	0.118 ±0.003
Quenched/tempered	60	0.119 ±0.004	0.216 ±0.014	0.119 ±0.003	0.182 ±0.04
	150	-	-	-	-
	240	-	-	-	-

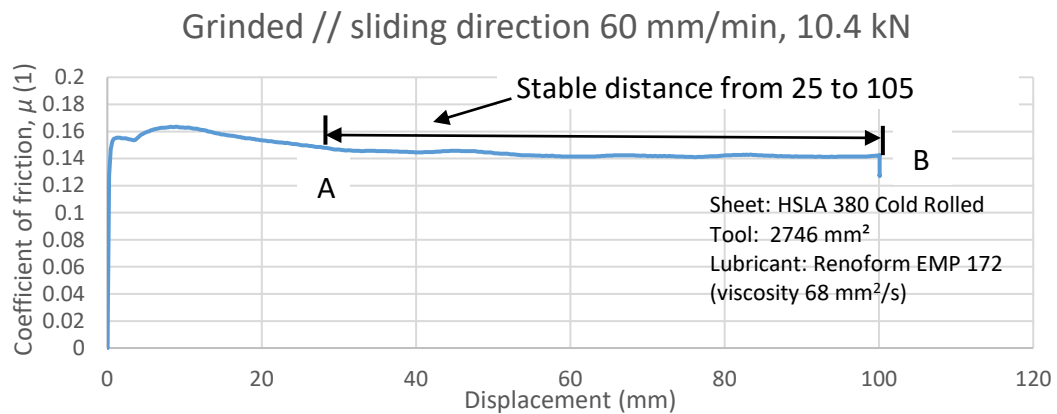


Figure 4.17 The coefficient of friction as a function of displacement at constant sliding speed and applied normal force

Averages for F_p and μ were calculated using the values taken from stable distance 25 to 105 mm, to avoid the initial fluctuation. Other individual test results for Grinded surface are presented in Table 4.12.

The variability and instability of the measured pulling force seems to increase with decreased applied load, generating deviations in the calculated friction values. Figure 4.18 shows results from the calculated mean friction values as a function of apparent contact pressure for each individual experimental tests.

Experiments were also performed to evaluate how friction correlates with sliding speed. Three different sliding speeds were performed for each load case. Table 4.12 shows the results of friction coefficient, as a function of speed, under different applied normal pressures, for all experimental tests using the grinded surface tools.

$$C_p = \frac{F_N}{A} = \frac{10400}{2746} = 3.8 \quad (4.5)$$

where, $F_N \approx 10.4, 16.25, 32.5$ and 48.75 , kN; $A = 40.5 \times 67.8 = 2746 \text{ mm}^2$; $C_p = 3.8, 5.9, 11.8$, and 17.8 , N/mm².

Similar tests were carried out using different load and sliding speed the results are presented in Table 4.12 and Figure 4.18 respectively.

Table 4.12 Output parameters of Grinded surface experimental tests

Grinded // sliding direction 10.4 kN					
Stable distance, from A to B, [mm]	Average of Pulling Force Fp.av, [kN]	Average coefficient of friction, μ	Standard deviation, St.dev.	Apparent contact pressure Cp, [N/mm ²]	Sliding speed, [mm/min]
25-105	2.98	0.143	± 0.002	3.8	60
20-120	2.24	0.108	± 0.003	3.8	150
20-120	2.16	0.104	± 0.002	3.8	240
Grinded // sliding direction 16.25 kN					
10-105	3.52	0.108	± 0.002	5.9	60
10-120	3.97	0.122	± 0.001	5.9	150
20-120	3.37	0.104	± 0.003	5.9	240
Grinded // sliding direction 32.5 kN					
10-105	6.42	0.099	± 0.001	11.8	60
10-110	5.97	0.092	± 0.001	11.8	150
10-110	5.69	0.088	± 0.002	11.8	240
Grinded // sliding direction 48.75 kN					
10-105	10.42	0.107	± 0.002	17.8	60
10-110	9.44	0.097	± 0.002	17.8	150
10-120	9.54	0.098	± 0.0006	17.8	240

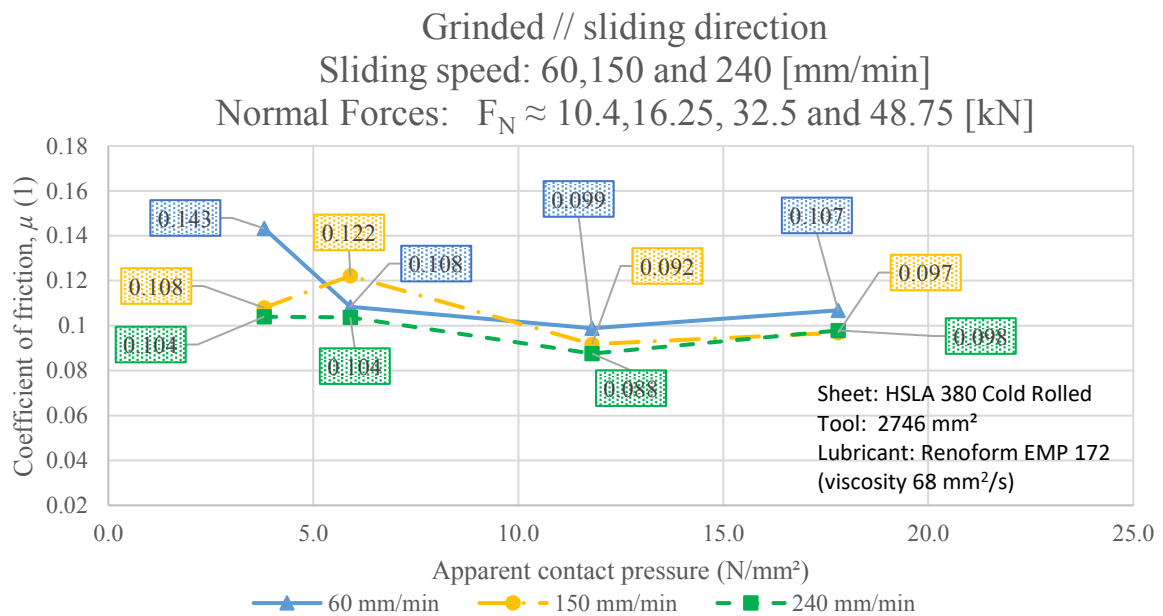


Figure 4.18 Coefficient of friction as a function of normal pressure for Grinded surface

Also, similar tests were carried out using different load and sliding speed for another tool sets (Polished, Nitrided and Quenched/tempered), the results for all tests are presented in Table 4.13 to Table 4.15 and Figure 4.19 to Figure 4.21. In Annex C1, it is given the coefficient of friction as a function of displacement at constant sliding speed and applied normal force.

Table 4.13 Output parameters of Polished surface experimental tests

Polished surface 10.4 kN					
Stable distance, from A to B, [mm]	Average of Pulling Force Fp.av, [kN]	Average coefficient of friction, μ	Standard deviation, St.dev.	Apparent contact pressure Cp, [N/mm ²]	Sliding speed, [mm/min]
10-120	1.74	0.084	± 0.002	3.8	60
10-130	1.77	0.085	± 0.002	3.8	150
10-120	2.06	0.099	± 0.0004	3.8	240
Polished surface 16.25 kN					
10-120	2.64	0.081	± 0.0008	5.9	60
10-120	2.67	0.082	± 0.002	5.9	150
10-120	2.72	0.084	± 0.0006	5.9	240
Polished surface 32.5 kN					
10-110	4.50	0.069	± 0.001	11.8	60
10-120	4.58	0.070	± 0.001	11.8	150
10-120	4.78	0.074	± 0.0008	11.8	240
Polished surface 48.75 kN					
10-120	7.16	0.073	± 0.001	17.8	60
10-120	7.70	0.079	± 0.0009	17.8	150
10-120	7.58	0.078	± 0.001	17.8	240

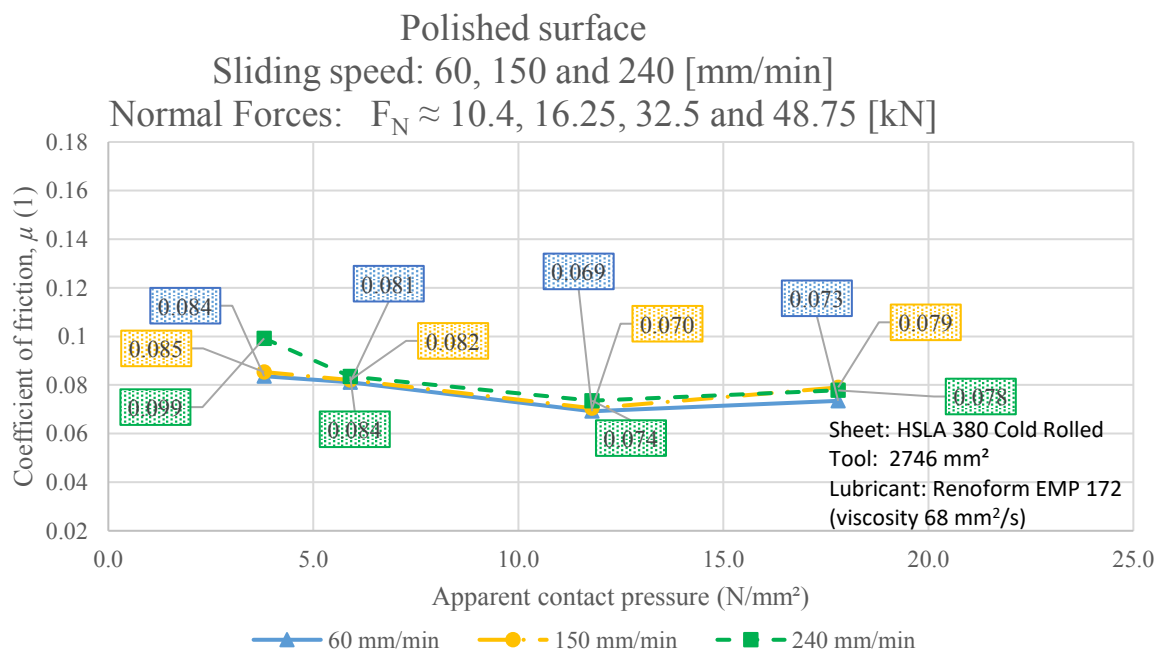


Figure 4.19 Coefficient of friction as a function of normal pressure for Polished surface

Table 4.14 Output parameters of Nitrided surface experimental tests

Nitrided surface 10.4 kN					
Stable distance, from A to B, [mm]	Average of Pulling Force Fp.av, [kN]	Average coefficient of friction, μ	Standard deviation, St.dev.	Apparent contact pressure Cp, [N/mm ²]	Sliding speed, [mm/min]
10-110	2.83	0.136	± 0.009	3.8	60
20-120	2.93	0.141	± 0.003	3.8	150
20-120	3.41	0.164	± 0.003	3.8	240
Nitrided surface 16.25 kN					
10-110	4.06	0.125	± 0.008	5.9	60
20-120	4.49	0.138	± 0.003	5.9	150
20-120	4.72	0.145	± 0.002	5.9	240
Nitrided surface 32.5 kN					
20-120	6.93	0.107	± 0.004	11.8	60
20-120	7.19	0.111	± 0.003	11.8	150
20-120	8.06	0.124	± 0.004	11.8	240
Nitrided surface 48.75 kN					
20-120	10.35	0.106	± 0.004	17.8	60
20-120	11.52	0.118	± 0.001	17.8	150
20-120	11.52	0.118	± 0.003	17.8	240

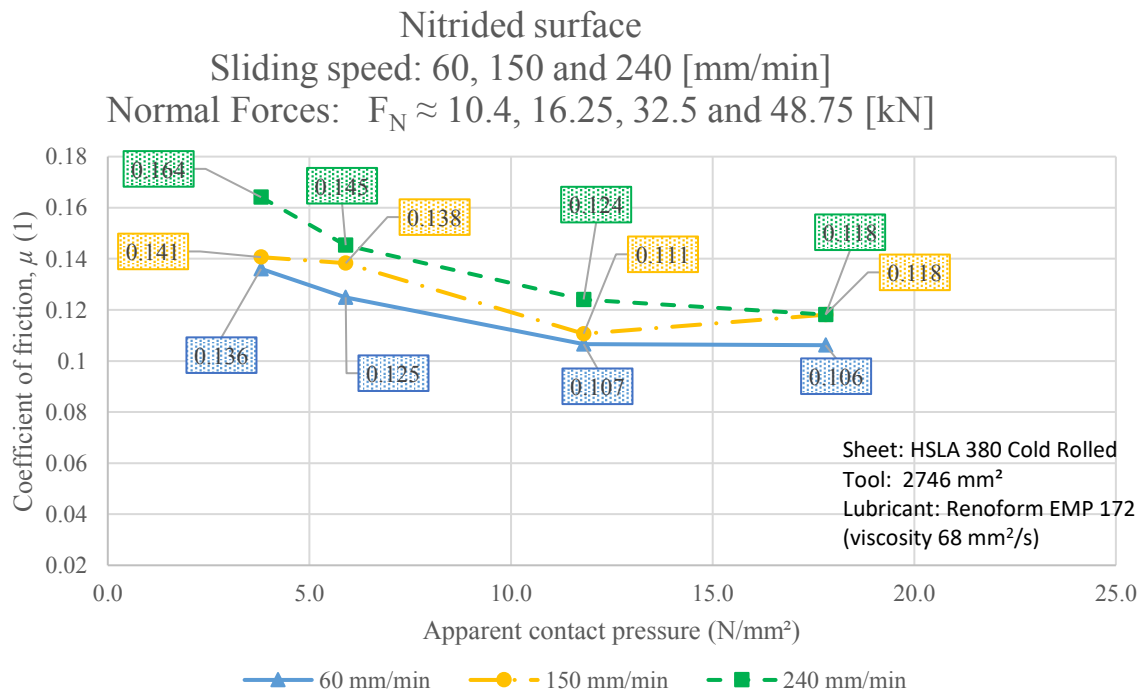


Figure 4.20 Coefficient of friction as a function of normal pressure for Nitrided surface

Table 4.15 Output parameters of Quenched/tempered surface experimental tests

Quenched/tempered surface 10.4 kN					
Stable distance, from A to B, [mm]	Average of Pulling Force Fp.av, [kN]	Average coefficient of friction, μ	Standard deviation, St.dev.	Apparent contact pressure Cp, [N/mm ²]	Sliding speed, [mm/min]
10 to 60	2.48	0.119	± 0.004	3.8	60
Quenched/tempered surface 16.25 kN					
30-110	7.02	0.216	± 0.014	5.9	60
Quenched/tempered surface 32.5 kN					
30-110	7.74	0.119	± 0.003	11.8	60
Quenched/tempered surface 48.75 kN					
10-105	17.75	0.182	± 0.04	17.8	60

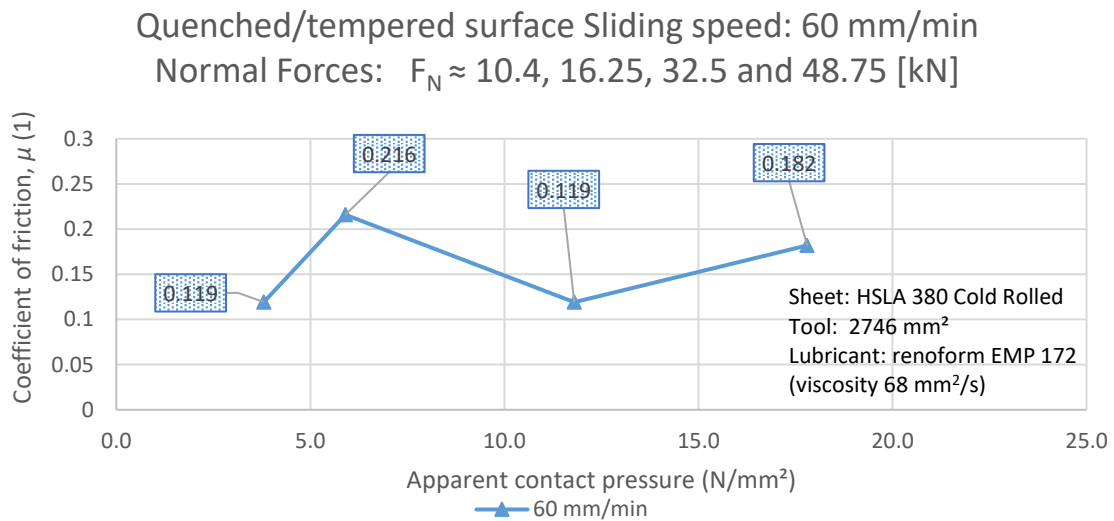


Figure 4.21 Coefficient of friction as a function of normal pressure for Quenched/tempered

4.6 Friction coefficient versus Sommerfeld Number

In this section, the friction test results are plotted against Sommerfeld number to discuss the results of strip drawing tests.

The frictional aspects of sheet metal forming can be studied in two ways, one by doing actual forming tests and the other by doing application-oriented friction experiments on small material samples. Most of the friction tests which apply to studies of sheet metal forming is related with friction tests on flat samples (flat strip tests).

Friction tests have been restricted to experiments with flat contacts, notably with flat strips. This method has the advantage that all process parameters can be adjusted independently.

The available expressions were compared and used to predict experimental results trying to draw an overview about the main advantages and disadvantages of each method. A load sharing

function to predict the coefficient of friction was developed based on a modified Sommerfeld's parameter. A coefficient of friction equation is then proposed, trying to improve the existing methods, including the influence of the oil pressure-viscosity parameter, roughness, pressure and sliding speed on the coefficient of friction.

The strip drawing test allows for evaluation of the friction over a range of relative velocities and/or loads. In a Stribeck curve the key parameter, against which the coefficient of friction is plotted, is called the Sommerfeld number. The Sommerfeld number is the dimensionless number obtained from the velocity (m/s), times the absolute viscosity (Pa·s = N·s/m²), divided by a load of apparent contact pressure (N/mm²).

Table 4.16 Parameters for Sommerfeld number calculation

Conditions	Value	Unit
Lubricant's dynamic viscosity:	68	cSt = mm ² /s
Lubricant's density:	913	kg/m ³
Lubricant's absolute viscosity:	0.0621	Pa.s
Tool Area:	2746	mm ²
Contact Pressure 1:	3.8	N/mm ²
Contact Pressure 2:	5.9	N/mm ²
Contact Pressure 3:	11.8	N/mm ²
Contact Pressure 4:	17.8	N/mm ²
Contact Force 1:	10434.42	N
Contact Force 2:	16200.81	N
Contact Force 3:	32401.62	N
Contact Force 4:	48877.02	N
Speed 1:	1.00E-03	m/s
Speed 2:	2.50E-03	m/s
Speed 3:	4.00E-03	m/s

The formula (4.6) correspond to the calculation of Sommerfeld number for coefficient of friction. Eq. (4.7) illustrates the formula to obtain the lubricants absolute viscosity, ν . The values of the parameters for Sommerfeld number calculation are given in Table 4.16. Figure 4.22 presents the coefficient of friction versus Sommerfeld's surface conditions. Same results are presented individually for each surface conditions, Figure 4.23 to Figure 4.25 and all together in Figure 4.26 using extended Sommerfeld number axis from 1.E-09 to 1.00E-02.

$$S = \frac{\nu * v}{C_p} \quad (4.6)$$

where, ν - absolute viscosity, Pa.s; v - sliding speed, m/s; C_p – contact pressure, N./mm².

The formula to determine the lubricant's absolute viscosity is:

$$\nu = \eta * 0.000001 * density = 68 * 0.000001 * 913 = 0.0621 \text{ Pa.s} \quad (4.7)$$

where, η is dynamic viscosity of the lubricant.

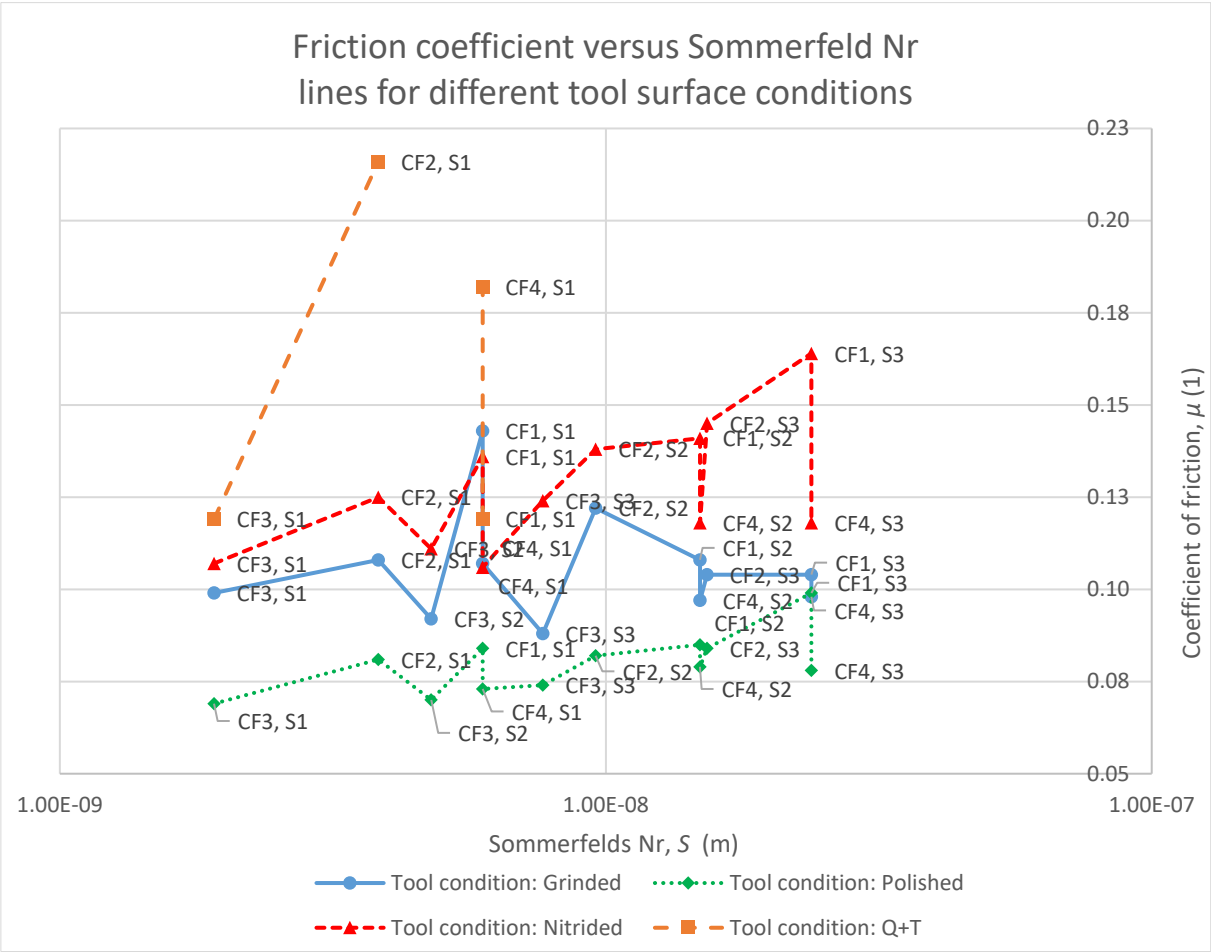


Figure 4.22 Sommerfeld's Number - lines for different tool surface conditions

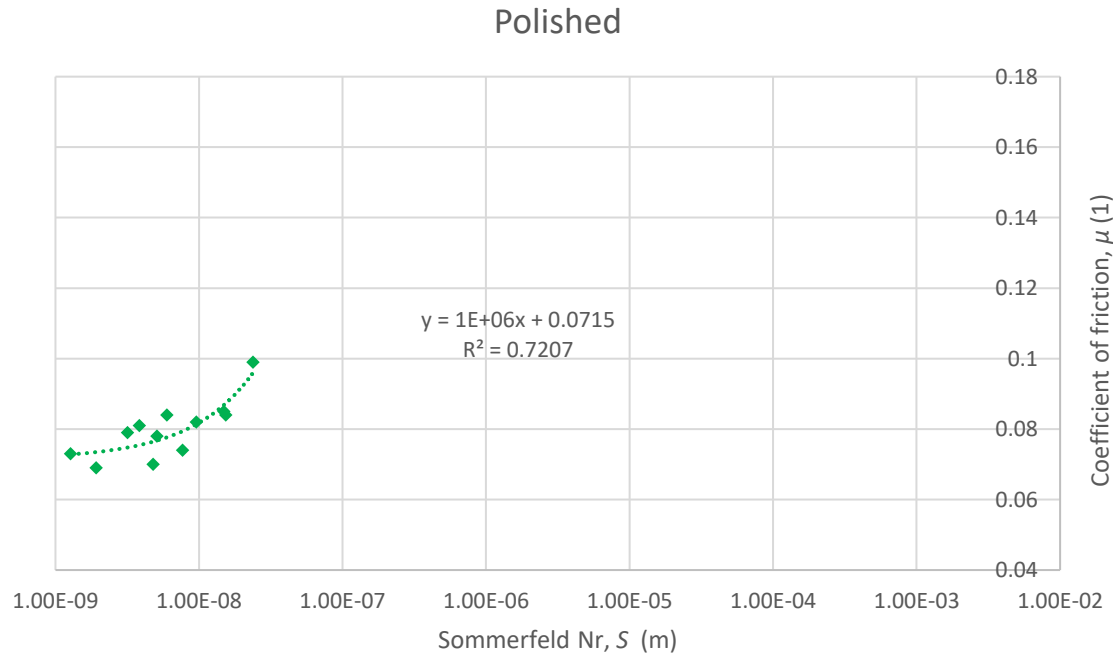


Figure 4.23 Friction coefficient versus Sommerfeld number for the Polished surface

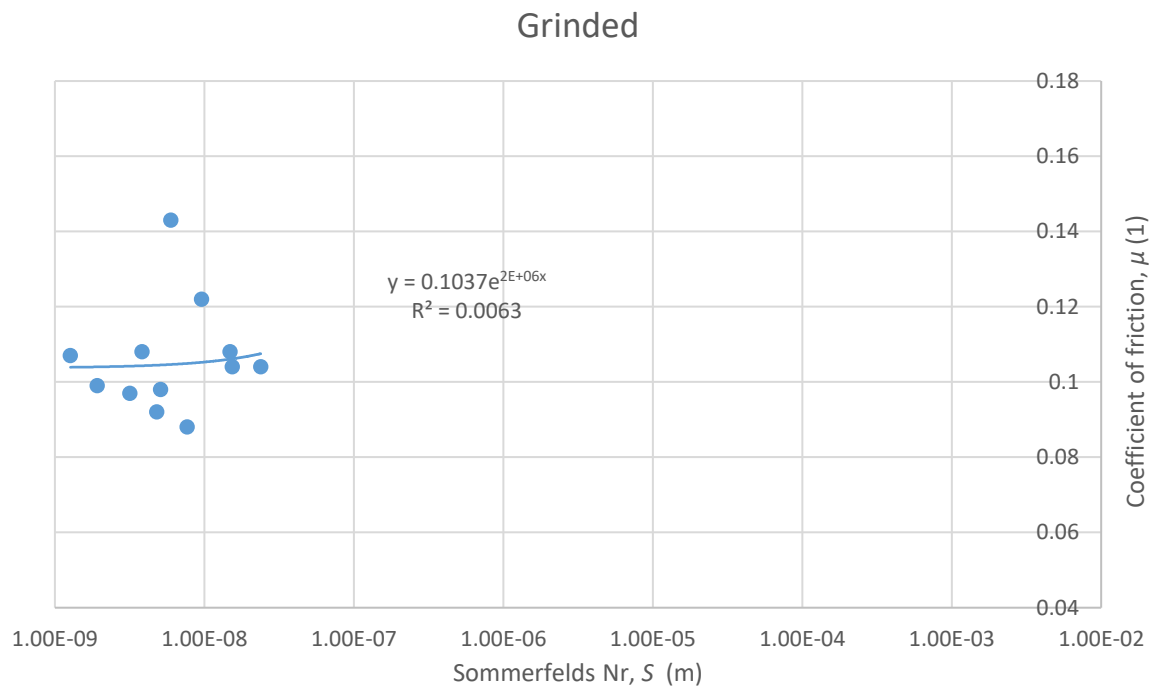


Figure 4.24 Friction coefficient versus Sommerfeld number for the Grinded surface

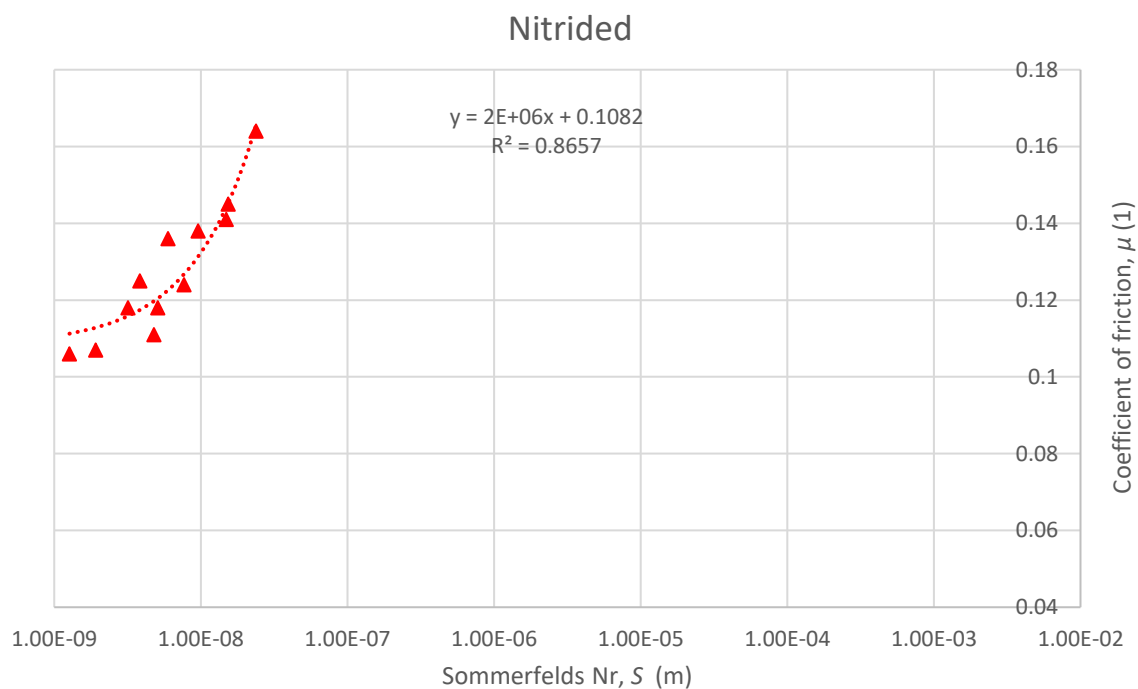


Figure 4.25 Friction coefficient versus Sommerfeld number for the Nitrided surface

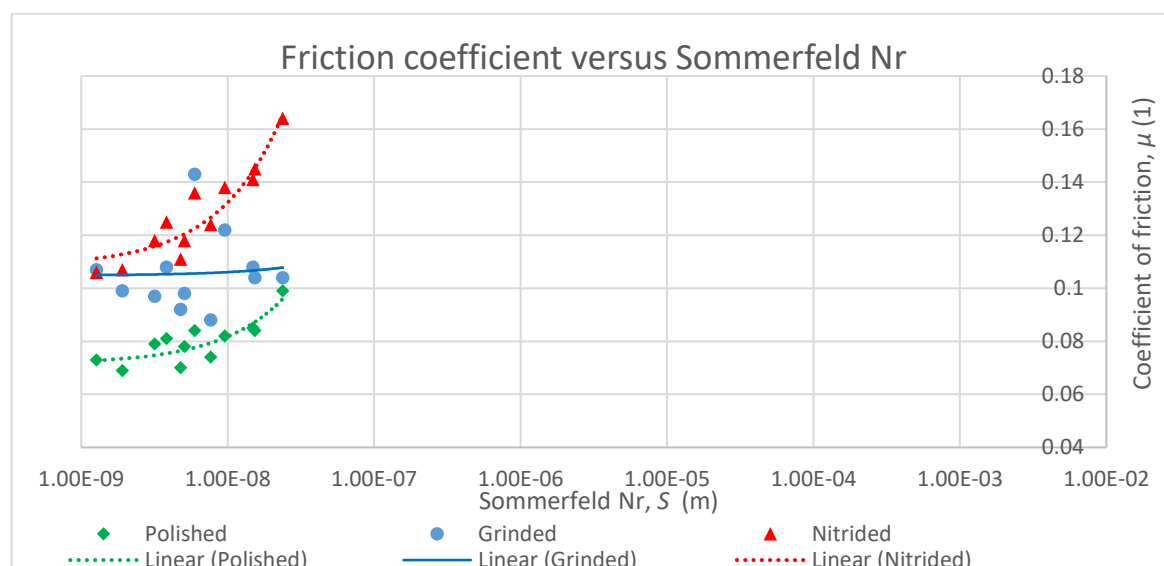


Figure 4.26 Friction coefficient versus Sommerfeld number for different surface texture

The simplest method to obtain a Stribeck curve, is to keep two variables fixed for example, load and viscosity and to vary the third one (e.g., velocity) over a suitable range, so that the contact interface goes from the region of asperity contact, boundary lubrication to mixed lubrication and then to hydrodynamic lubrication. This is most easily done in a unidirectional manner, using the movement between the sheet and tool and the controllable normal load as in parallel strip drawing test.

4.6.1 Influence of viscosity

In the right-hand branch of the Stribeck graph Figure 2.3, friction is decreased in the mixed lubrication part. If a packet of fluid layers is sheared, the individual fluid layers are displaced in the direction of the shearing force. The upper layers move more rapidly than the lower layers because molecular forces act to resist movement between the layers. These forces create resistance to shearing and this resistance is given by the term dynamic viscosity and the difference in velocity between two given fluid layers, related to their linear displacement, is referred to as shear rate. This velocity gradient is proportional to the shear stress. The proportionality constant is called dynamic viscosity with unit Pa·s.

The relationship between dynamic viscosity and specific gravity is referred to as kinematic viscosity. The use of kinematic viscosity dominates in the lubricants industry even though dynamic viscosity is a much more important parameter in lubrication technology.

4.6.1.1 Viscosity pressure dependency

In the Sommerfeld number, a lubricant is characterised by the viscosity only, which is a property that mainly influences the hydrodynamic lubrication of the frictional conditions. The mixed lubrication part is, to a large extent, based on the properties of the lubricant to form a chemical or physical bond with the steel sheet and tool surfaces. When a lubricant does not

have this characteristic, circumstances which would fulfil the requirements for hydrodynamic lubrication will immediately lead to asperity peaks breaking through the lubricant film, provoking metallic contact. This will at least produce an increased friction coefficient, which might be followed by product failure or even tooling breakdown.

The significance of viscosity–pressure dependency (ν_p behavior) was, and still is underestimated for numerous lubrication applications. ν_p behavior has become a part of the calculation of elastohydrodynamic lubricant films. The exponential dependence of viscosity on pressure means that viscosity increases very rapidly with pressure. ν_p behavior can be described by Eq. 4.8 [4]:

$$\eta_p = \eta_1 * e^{\alpha(p-p_1)} \quad (4.8)$$

where η_p is the dynamic viscosity at a pressure p , η_1 is the dynamic viscosity at pressure p_1 and α is the viscosity pressure coefficient.

4.6.2 Influence of roughness

The surface texture is considered to be the local deviations of a surface from its ideal shape. It is one of the most important factors that influence the coefficient of friction during sliding. Many attempts by several authors have been made to study the influence of surface textures on coefficient of friction during sliding [29], [39].

In present work tool specimens were prepared to various degrees of roughness by grinding, polishing, nitriding and quenched/tempered. The results showed that the behaviour of surfaces and thus friction during sliding depends on the degree of roughness.

The roughness parameter, which describes the surface texture, can eventually be correlated with friction coefficient. Several well-known roughness parameters were used to quantify surface texture. The surface roughness parameter R_a is the most generally used to describe a surface.

A considerable amount of work also has been done to study the influence of various roughness parameters on the coefficient of friction. Menezes et al. [41] studied the influence of surface roughness on normal sliding lubrication and reported that the R_{max} and R_t were the most significant surface roughness parameters with regard to influence on lubrication.

However, it was noticed that like friction, the correlation coefficient between the coefficient of friction and roughness parameters, was system dependent. Thus, keeping this view in mind, this Sommerfeld number presents the results of an experimental study aimed at understanding the frictional response of sliding against various surface textures. In addition, attempts have been made to identify the surface roughness parameters that strongly correlate with the coefficient of friction during sliding, parameters of R_z presented in Table 4.17.

It was observed that the coefficient of friction varies with surface texture. Here, the range of surface roughness varies for different textured surfaces. Thus, it is important to characterize the surface texture by means of surface roughness parameters. As previously described, roughness parameters of all surfaces involved in this study were measured. Now we will try to correlate

them with the coefficient of friction. The roughness parameter changes during surface preparation, due to texture and hence affects the coefficient of friction. The surface roughness parameters R_z and R_{pm} were taken into consideration.

Table 4.17. Value of the roughness R_z

Conditions	Rz value	Unit
Polished	0.32	μm
Grinded	1.24	μm
Nitrided	3.39	μm
Quenched/tempered	1.35	μm

$$S^* = \frac{S}{R_{pm}^2} \quad (4.9)$$

Eq. (4.9) defines the modified Sommerfeld number S^* in function of Sommerfeld number S and R_{pm}^2 .

The influence of surface roughness on friction is illustrated in Figure 4.27, where modified Sommerfeld parameters with different roughness conditions (grinded, polished and nitrided) are compared. Clearly, the consideration of roughness causes the Stribeck curves to shift to the right without changing the shape or the height of the curves very much, as seen when comparing with Figure 4.26.

Within each material, small variations of the friction of coefficient are observed, with an exception for the nitrided surface, where growing evolution is clear. The fact that the difference between the materials can be fully ascribed to the difference in roughness implies that the difference in hardness of the materials has little impact. However, the results here have been obtained with materials harder than normal, while for the rougher material has a slightly higher friction coefficient at boundary lubrication than the smoother material.

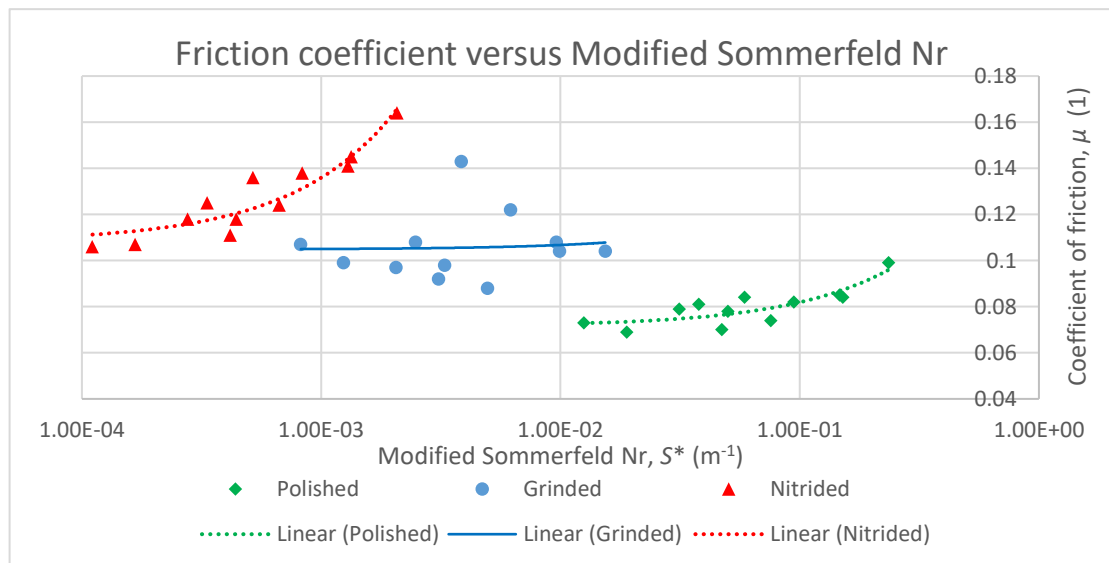


Figure 4.27 Variation of average coefficient of friction with modified Sommerfeld number for various types of surface textures under lubricated conditions

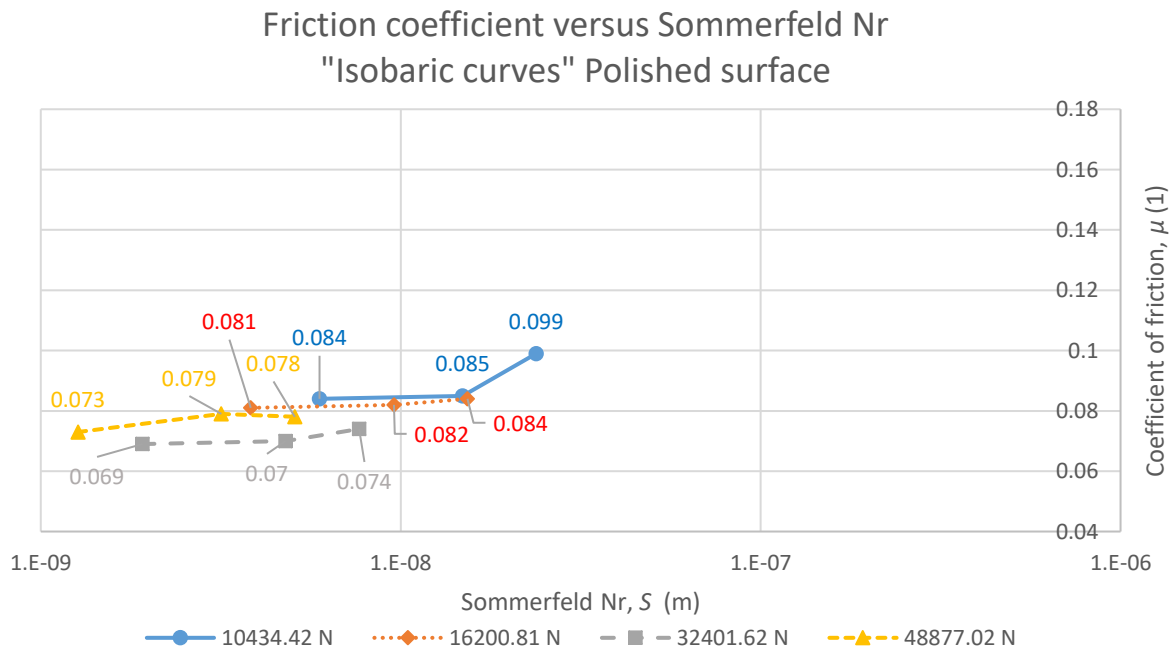
4.6.3 Influence of pressure

Tribology phenomena are very dependent on applied load, mechanical properties of contact materials and surface topographies. When load or viscosity values higher than the reference values are applied, the frictional resistance increases and the reference speed should be adjusted.

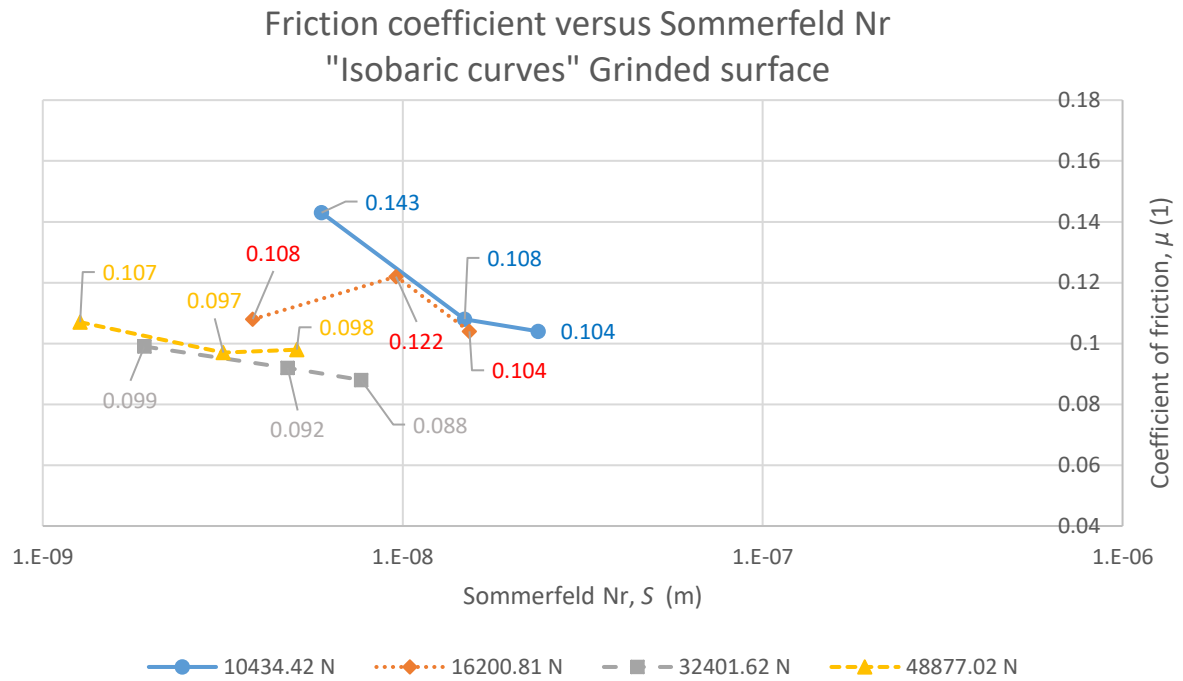
It has been observed that the position of the Stribeck curve (or more precisely the position of the transition points) depends on the pressure. This has been checked for our experiments by plotting the values of friction coefficient against Sommerfeld number at the isobaric curves as presented in Figure 4.28. This figure shows that the isobaric curve shifts slightly to the left (lower values of S) with increasing pressure. For most materials, the friction at mixed lubrication decreases with increasing pressure.

The isobaric curves do not form nice 'parallel' lines. Notably, Polished surface exhibits an overall lower slope the other materials. In general, the height of the curves is much influenced by the surface roughness. As expected, the value of the friction coefficient is lower for polished surface due to reduced roughness.

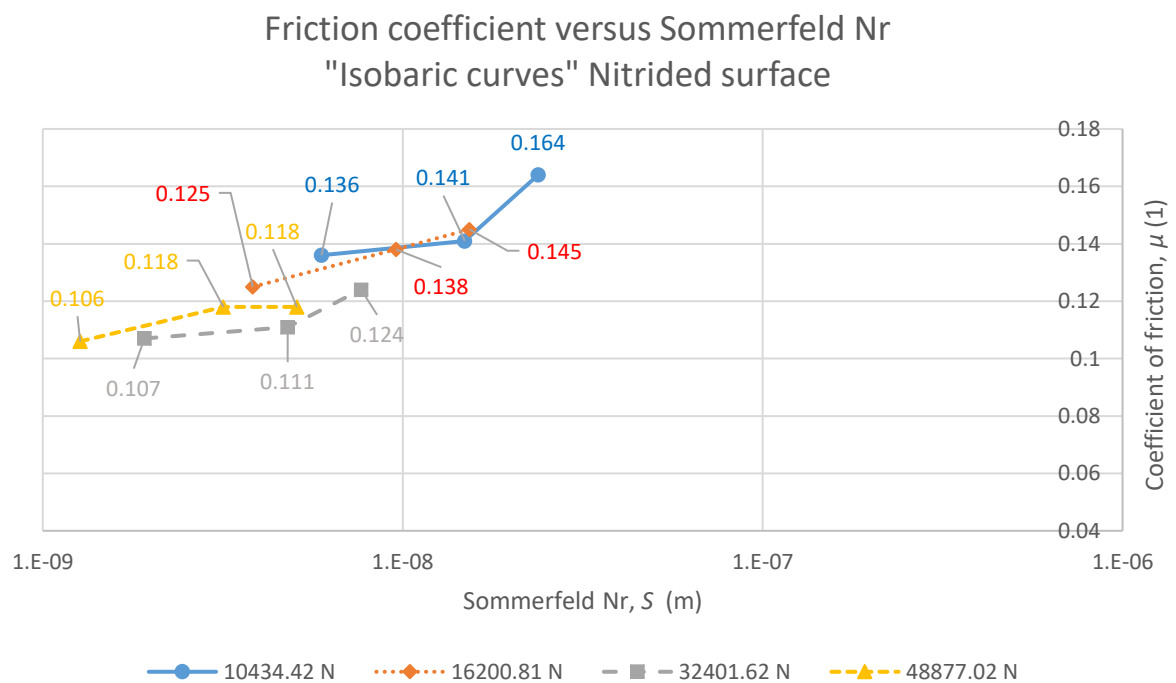
Owing to the varying width of the mixed region, the values of the transition points also show larger scatter. Figure 4.28 presents the position of the isobaric curves as characterised by the different speeds with constant pressure. This parameter shows little scatter. The isobaric curves shift slightly to the left with increasing pressure, by the definition of Sommerfeld number. Evidently, when there are only a limited number of data points in the mixed lubrication part, the width of the mixed lubrication seems to be more sensitive to scatter in the results than the midpoint.



a) "Isobaric curves" for the Polished surface



b) "Isobaric curves" for the Grinded surface



c) "Isobaric curves" for the Nitrided surface

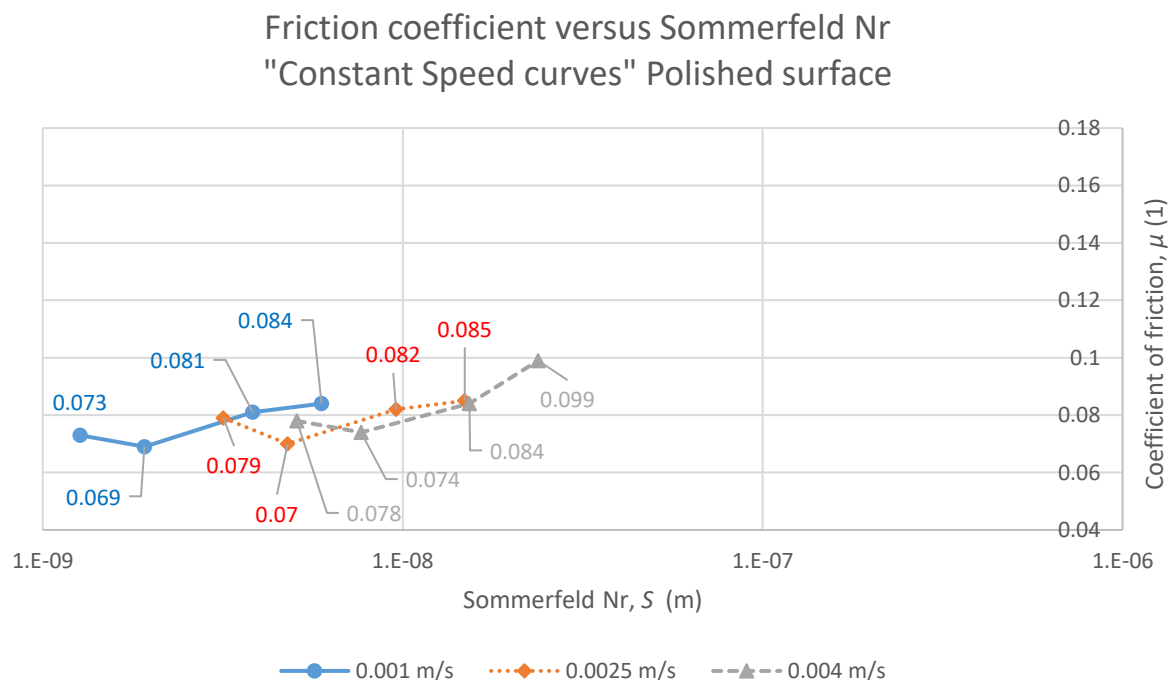
Figure 4.28 Friction coefficient versus Sommerfeld number with the variation of pressure

4.6.4 Influence of velocity

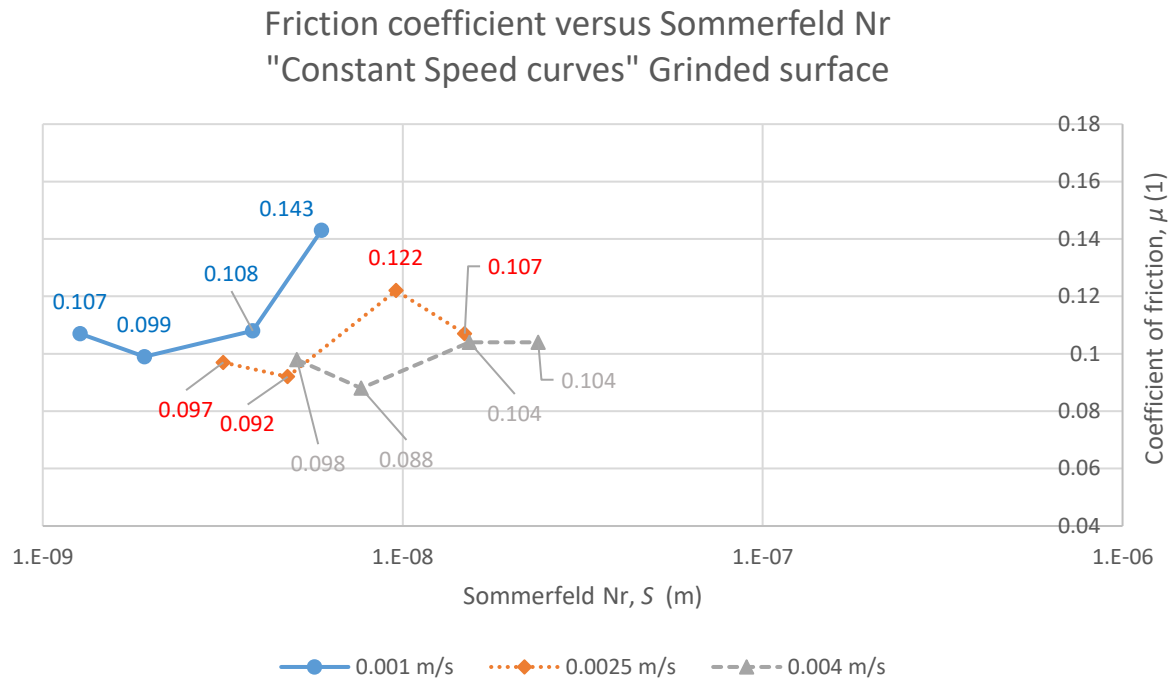
Table 4.11 presents the average values of the friction coefficient of the steel sheet sliding against tool surface at four different normal loads and three different sliding speeds.

The friction force is a function of velocity and time of contact. For most materials when the velocity increases, friction decreases and when duration of contact increases, friction increases. The dependence of friction on velocity may be explained using Figure 4.29. When velocity increases, momentum transfer in the normal direction increases, producing an upward force on the upper surface. This results in an increased separation between the two surfaces which will decrease the real area of contact. Contributing to the increased separation is the fact that at higher speeds, the time during which opposite asperities compress each other is reduced, thus increasing the level on which the top surfaces moves.

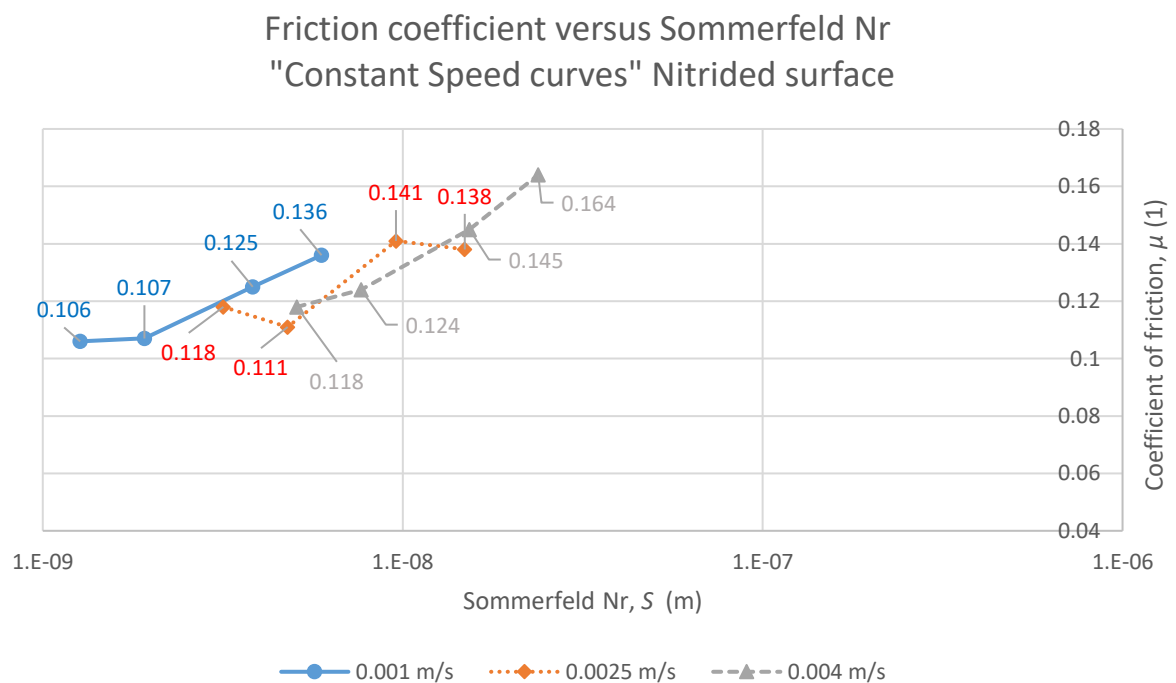
In the case of materials with surface films which are either deliberately applied or produced by reaction with environment, the coefficient of friction may not remain constant as a function of load. In many metal pairs in the high-load regime, the coefficient of friction decreases with load. It was observed that the coefficient of friction may be very low for very smooth surfaces. In spite of these investigations the effects of sliding speed and normal load are yet to be clearly understood. Therefore, in this study an attempt is made to investigate the effect of sliding speed and normal load on friction. It is expected that the applications of these results will contribute to the different concerned mechanical processes.



a) "Constant Speed curves" for the Polished surface



b) "Constant Speed curves" for the Grinded surface



c) "Constant Speed curves" for the Nitrided surface

Figure 4.29 Friction coefficient versus Sommerfeld with the variation of sliding speed

4.7 Discussion of results

This chapter deals with the measurement of friction with flat contacts. The demands on the testing equipment are severe, notably in regard to the flatness of the slider. An ideal experiment should give results which do not depend on the way of testing. This has been noticed by other researchers, but the nature of the effects is not always well known. In general, larger sliders give lower friction, but the precise influence of length and width of the slider may be different. A whole series of friction tests must be performed using one and the same slider. But, on the other end, after the slider has been used once its surface has been modified and it is no more identical to its initial condition.

In the tests at different sliding speed, the influence of the mixed lubrication has been found. The higher pressure gave lower friction coefficient. To understand the phenomena in detail the exact conditions must be known and these cannot be derived from simple considerations.

Another effect that has been encountered is that the friction at boundary condition may react strongly to minor changes in the surface texture. This indicates that friction experiments should be carried out in a comparative way, meaning that the tribological properties of a material can only be measured by comparing it with a ‘standard’ material in the same test. Furthermore, experiments should be carried in such a way that global changes in conditions do not influence the principal results. As a consequence, one should be careful to draw conclusions from the absolute value of the friction coefficient at mixed lubrication.

4.7.1 Influence of lubricant

The lubricant affects friction at boundary lubrication as well as friction at mixed lubrication, but in a different way. At mixed lubrication, pressure is generated in the lubricant by hydrodynamic effects and this pressure strongly affects friction. This generation of pressure is related to the viscosity of the lubricant and this is taken into account in the definition of the Sommerfeld parameter. In mixed lubrication regime, friction is strongly affected by the lubricant properties and an influence of lubricant has been found for the different surface textures.

For pin-on-disc machine tests this effect has been noticed in our experiments, where the different combined lubricants have been used. This may be caused by different (chemical) reactions between the lubricants and the metal surface. At the very contact spots, micro hydrodynamic effects may occur, which induce a reduced form of mixed lubrication and hence an influence of speed. The effect of an additive in this proposed mechanism is not clear.

All the strip drawing tests have been carried out using lubricant Renoform EMP 172. So, no conclusions on the effect of lubricant can be drawn from these tests.

In practice, extrusion oils are assessed firstly by the surface roughness of the workpieces, but more frequently by observing the service life of the tools. To be considered, especially when determining the service life, what matters is the lubricant ability to spread on the tool surface.

4.7.2 Influence of roughness

Surface texture and thus roughness parameters influence coefficient of friction during sliding. In the present investigation, four kinds of surface textures with varying roughness were attained on the tool surfaces.

The influence of roughness has already been mentioned above. The surface textures of the tools were characterized in terms of roughness parameter using Bruker's NPFLEX 3D optical microscope and contact measuring device HOMMEL tester T500. Then the tools made of various materials, such as K 340 (EN X110CrMoV8-2) and C 265 (EN X160CrMoV12-1) were pressed against the prepared steel sheets using strip drawing tester under lubricated conditions. During sliding, friction usually attained an almost constant value in most of the tests, as described before. It was observed that the surface roughness parameter, namely, S_z , for different textured surfaces was comparable to one another although they were prepared by different machining techniques. It was also observed that for a given kind of surface texture the coefficient of friction was changing with R_z . However, the coefficient of friction changes considerably with surface textures for similar S_z values, for all the materials investigated. Thus, attempts were made to study other surface roughness parameters of the tools and correlate them with coefficient of friction.

An influence of the type of surface roughness has been found for all tool surfaces. The Stribeck curves are steeper for Nitrided surfaces than for Polished surfaces and the influence of pressure is also different. The conclusion is that the coefficient of friction would be higher for higher surface texture (Nitrided, $R_z=3.4\text{ }\mu\text{m}$) and lower for a lower surface texture (Polished, $R_z=0.32\text{ }\mu\text{m}$).

4.7.3 Analysing the Stribeck curve

In many cases it is necessary to compare experimental results obtained in very different conditions. The use of Stribeck approach may be helpful in this context, as presented in Figure 4.30.

The friction under lubricated conditions can vary between boundary, mixed and hydrodynamic lubrication as graphically illustrated by use of Stribeck curve, Figure 2.3. This can be done by representing the coefficient of friction against Sommerfeld number providing that the three lubrication regimes are covered by the experimental results. The latter procedure, however, is only meaningful if the shape of the curve is constant. As it will be shown by the results, this is not always the case. In the description of the results of the friction tests the expression "the position of the Stribeck curve" is sometimes used as a numerical parameter. In that case, any numerical value establishing the position of the curve, like the transition points, can be used.

The term Stribeck curve is used to describe a plot showing the frictional characteristics of a liquid lubricant over conditions usually spanning the Boundary, Mixed and Hydrodynamic regimes, as presented in Chapter 2. Each regime is defined by the ratio of the film thickness to

the surface roughness. Such curves are often used to evaluate the effect of changes to the lubricant's viscosity or the effect of surface roughness. The primary requirement for generating a Stribeck curve is a fluid that can be drawn into a converging gap, thus creating a pressure increase to support the load and sliding speed.

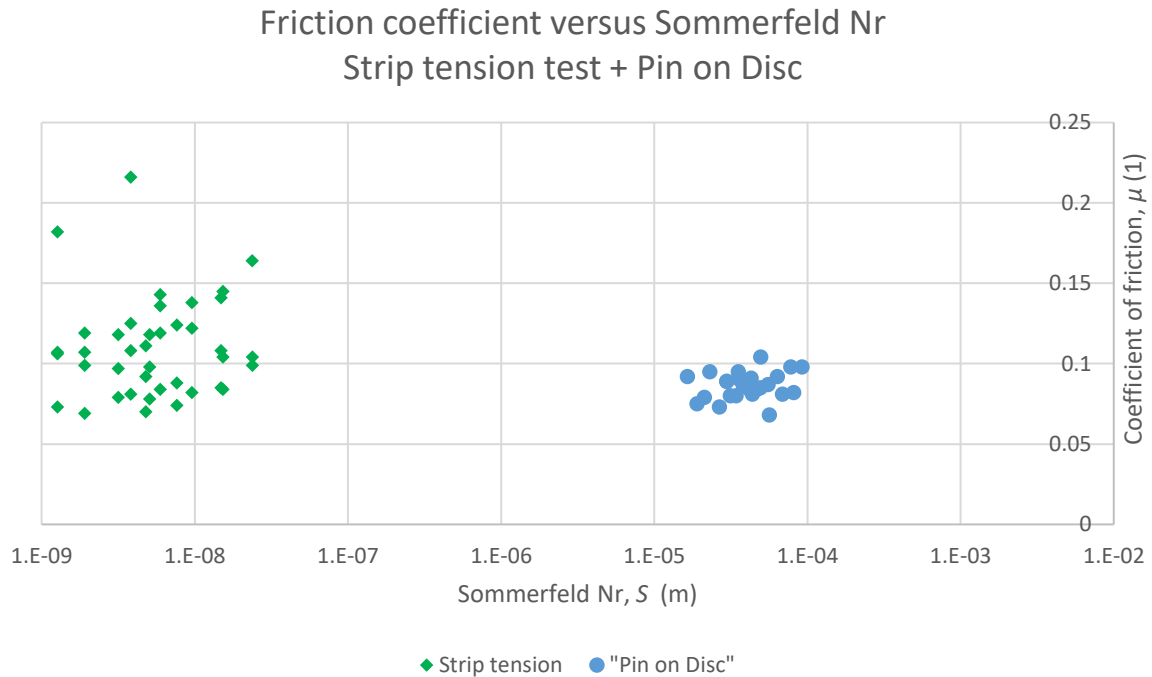


Figure 4.30 Schematic of Stribeck curve to compare experimental tests Strip tension test and Pin-on-disc

Recently, however, there has been considerable interest in evaluating lubricant frictional characteristics using a reciprocating test mode. A particular type of such test rigs are sometimes referred to as a high-frequency reciprocating rig. An example of how a reciprocating test mode might be used is the modified pin-on-disc tests.

The challenge for developing a Stribeck curve in the reciprocating mode is to develop enough velocity, over a long enough stroke length before reversal, in order to build up the pressure and film thickness required to reach the hydrodynamic lubrication regime.

The stroke length used was 10 mm, the load 24.5 N for all pin-on-disc tests and the frequency was defined from 30 min^{-1} to 78 min^{-1} . Lubricants defined as Base lubricants Prelube A and Prelube B were combined with other five different lubricants, which created 12 different combined lubricants. Tests were conducted at room temperature. Figure 4.30 presents, in the right side of the graph, the friction results of these twelve different lubricants and compare them with strip draw test results, in the left.

While there is currently no published standard test method for generating a Stribeck curve, either in reciprocating or unidirectional motion, a number of other lubricant performance-related tests can be conducted with the same reciprocating motion for the lower sample.

While classical Stribeck curve generation is done using a unidirectional test, it has been a challenge to obtain similar evaluations of lubricants and surface treatments using a reciprocating motion test. Modified strip drawing tribotester is equipped with low speed linear and adjustable stroke lengths, as well as the measurement capabilities and companion software data reduction algorithms, to perform such characterization. Stribeck curves can be produced in a reciprocating test, which has direct applicability to lubricant development and evaluation for sheet metal forming systems and other important engineering systems.

4.8 Conclusions

Friction measurements were conducted using a modified developed tribotester based on flat strip drawing. Four different tool surfaces were tested under similar contact conditions regarding contact area (2746 mm²), normal force, sliding speed, lubricant and surface characteristics to calculate the friction coefficient between the tool surfaces and steel sheet HSLA 380. The applied normal load was defined from 10 to 49 kN and the sliding speed from 60 mm/min to 240 mm/min.

Results of the experiments reveal that the modified strip drawing tribotester is a very useful tool to friction determination.

From test results, it was found that:

1. due to stability, generally 80–90% of the sliding length was used for average friction determination; however, for quenched/tempered surfaces, only 25–30% of the sliding length was possible to be used, due to more unstable sliding conditions;
2. the test method enables comparison of different tool surface finishes and lubricants in terms of friction under true sheet metal forming process conditions; valid frictional data is also very important as an input parameter for simulation models to achieve reliable results;

the main difference between the tested tools in this work was the surface conditions; the results showed that the behaviour of surfaces and thus friction during sliding depends on the degree of roughness; thus, keeping this view in mind, the modified Sommerfeld number was used to present the results of the experimental study aimed at understanding the frictional response of sliding against various surface textures;

3. lubrication allows to minimize the effect of the directionality of tool surface topography on the friction behaviour by decreasing the range of friction coefficient value variation along the friction track length;
4. the surface roughness was measured before and after tests by Bruker's 3D optical microscopes and contact measuring device HOMMEL TESTER T500. Measurements of

the surface topography show that change in friction is associated with a change in contact ratio between the tool and metal sheet. For the calculation of modified Sommerfeld numbers it was chosen, as roughness parameter, the R_z value measured by using NPFLEX 3D optical microscope;

friction coefficients are higher for Nitrided surfaces and all results have corresponding values higher than 0.1; while for Polished surfaces, its results show values lower than 0.1; therefore, it can be concluded that the coefficient of friction is higher for higher surface texture (Nitrided, $R_z=3.4 \mu\text{m}$) and lower for lower surface texture (Polished, $R_z=0.32 \mu\text{m}$);

Grinded surfaces, ($R_z=1.24 \mu\text{m}$) show that for loads up to 16.25 kN, μ is higher than 0.1, while for forces equal or higher than 32.5 kN, μ is lower than 0.1; the single exception is that for 48.75 kN load and sliding speed 60 mm/min the coefficient of friction is 0.107.

The ability to control the applied normal load and speed as a function of time creates great opportunities to improve tribotesting by reducing the number of tests.

5 Conclusions and future work

5.1 Concluding remarks

This work had its focus on the influence of friction under conditions applied to deep drawing processes, by considering different tool materials and finishes, as well as different sheet steels and lubricants. Also, different tribological tests were carried out, which included the pin-on-disc machine and a developed modified strip drawing test, both aimed to simulate behaviour and to investigate the friction between sheet metal and tools during forming.

The work was divided into several chapters, as defined in general introduction, from which some main conclusions can be summarized.

Chapter two introduced friction in sheet metal forming processes and described investigations and scientific works on the influence of process parameters on characteristics of the formed parts. Some of the highlights from this part are:

- the high formability of sheet metal gives great opportunities to form products to a wide range of shapes;
- products having identical designations but coming from different batches or different suppliers may have noticeably different roughness characteristics; Ra values are commonly used to describe surfaces, but the limits of this indicator should not be forgotten;
- in sheet metal forming high values of friction coefficient would often lead to intolerable high friction forces, leading to fracture and frictional energy losses, therefore lubricants are used to reduce and control the frictional force between surfaces;
- oils and lubricants decrease the friction between sliding surfaces, by filling the surface cavities and reducing solid bodies interaction; reduction in friction happens due to a decrease in adhesion component of friction;
- a necessary condition for the protective oil used for preliminary lubrication is its absolute compatibility with every operation in the processing chain, from unwinding the coil to the finished car body parts; using the preliminary lubrication in rolling mills significantly reduces the number of operations for lubrication in the press shop;
- the oil used for preliminary lubrication must be compatible with paints and with adhesives that might be applied in the assembly line, besides the need that it should be easily removed by industrial detergents to allow further processing.

The third chapter deals with tribological tests carried out using pin-on-disc machine and determination of coefficient of friction and behaviour between sheet metal and tools during forming. It was considered frictional characterization of reciprocating sliding tests and the effect of lubricant and other variables on the coefficient of friction of the cold rolled HSLA 380 and cold rolled HSLA 420 steel sheets with a set of two Prelube oils and its combination with five Press oils.

The principal conclusions drawn from this part are:

- Prelube A + Press oil 3 lubricant gives the lowest value of friction coefficient and a constant behaviour with time; also the optimum sliding velocity is 18 mm/s (54 rpm);
- Prelube B + Press oil 3 lubricant, the lowest values coefficient of friction corresponds to 22 mm/s (66 rpm);
- Press oil 2 combined with Base lubricant Prelubes A and B give an adverse effect, on the coefficient of friction and friction behaviour; press oil 2 is a vanishing oil which evaporates very quickly and leaves residuals on the surfaces; hence, this combination of the lubrication may not be very useful for the sheet metal drawing operations;
- reciprocating sliding tests were performed, to find the effect of lubricant properties and other variables on the coefficient of friction of the steel sheets cold rolled "HSLA 380" under different loads; the coefficient of friction varies over a wide range of different lubricating conditions and different sliding velocities; in the range of tested velocities the influence of speed doesn't show to have a great effect on friction coefficient values; on the other side, pressure shows a sensible effect on friction coefficient and higher pressure will give higher friction;
- experiments were characterised by the Sommerfeld number, where main input parameters influence the frictional behaviour; these include the normal force, velocity and acceleration characteristics, direction of motion relative to surface features, surface cleanliness, roughness and lubricant properties.

Chapter four was related with friction measurements using a modified developed tribotester based on flat strip drawing. Four different tool surfaces were tested under similar contact conditions regarding contact area, normal force, sliding speed, lubricant and surface characteristics applied to steel sheet HSLA 380.

Results of the experiments reveal that:

- due to stability, generally 80–90% of the sliding length shall be used for average friction determination; however, for quenched/tempered surfaces, only 25–30% of the sliding length is possible to be used, due to more unstable sliding conditions;
- the test method enables comparison of different tool surface finishes and lubricants in terms of friction under true sheet metal forming process conditions;
- the results show that the behaviour of surfaces and thus friction during sliding depends on the degree of roughness; having this in mind, the modified Sommerfeld number can be used to present the results of the experimental study aimed at understanding the frictional response of sliding against various surface textures;
- lubrication allows minimization of tool surface topography directionality effect on the friction behaviour, by decreasing the range of friction coefficient value variation along the friction track length;
- measurements of the surface topography show that change in friction is associated with a change in contact ratio between the tool and metal sheet; for the calculation of

modified Sommerfeld numbers, it is proposed as roughness parameter, the R_z value measured by using NPFLEX 3D optical microscope;

- friction coefficients are higher for Nitrided surfaces and all results have corresponding values higher than 0.1; while for Polished surfaces, its results show values lower than 0.1; therefore, it can be concluded that the coefficient of friction is higher for higher surface texture (Nitrided, $R_z=3.4 \mu\text{m}$) and lower for lower surface texture (Polished, $R_z=0.32 \mu\text{m}$);
- grinded surfaces, ($R_z=1.24 \mu\text{m}$) show that for loads up to 16.25 kN, μ is higher than 0.1, while for forces equal or higher than 32.5 kN, μ is lower than 0.1; the single exception is that for 48.75 kN load and sliding speed 60 mm/min the coefficient of friction is 0.107.

5.2 Future work

This dissertation has provided an insight into friction determination and analysis as well as corresponding experimental testing in sheet metal forming area. From current work it was understood that further research could be undertaken in the following directions:

- selection and upgrading of experiments to a higher range of sliding velocities and applied loads, in order to get higher range of Sommerfeld values to complete the current Stribeck analysis;
- development of new equipment following previous requirements, which should be simple and adapted to higher velocities and different load configurations;
- performing additional experiments on material and lubricant characterization in order to obtain new Stribeck curves, using for instance advanced tool steels such as “Caldie” and “Sleipner” steels;
- taking experimental results and frictional behaviour into consideration and proposing a friction model that would give alternatives to the usual constant coefficient of friction, thus being possible having a more realistic and accurate model using updated and extended friction or lubrication data.

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Annexes

A. Lubrication regime and the nature of friction

Experimental tests on the pin-on-disk machine are used to investigate the coefficient of friction between ball and steel sample surface, under variation of lubrication, load and sliding speed. Figures identifies the Sommerfeld number with the coefficient of friction, for base Prelube lubricants, as well as their various combination with four Press oils. Comparing lubrication combinations are presented in Figures A1 to A5.

A 1. Comparing lubricant combinations

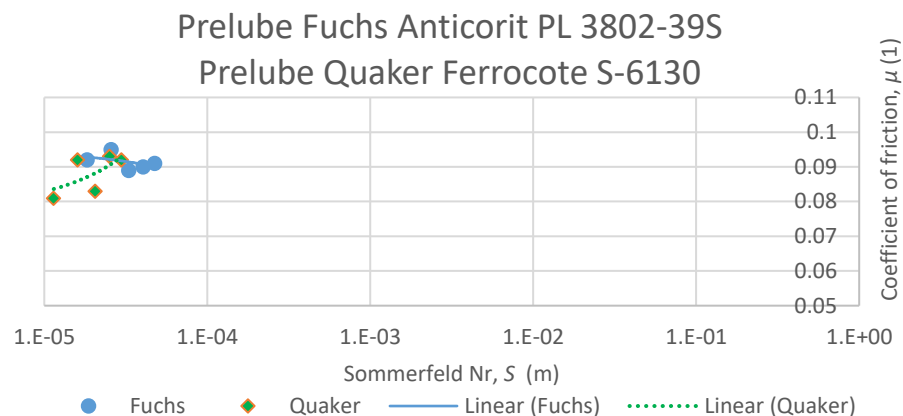


Figure A1 Comparing Sommerfeld number and average coefficient of friction of Prelube Fuchs Anticorit PL 3802-39S and Prelube Quaker Ferrocote S-6130

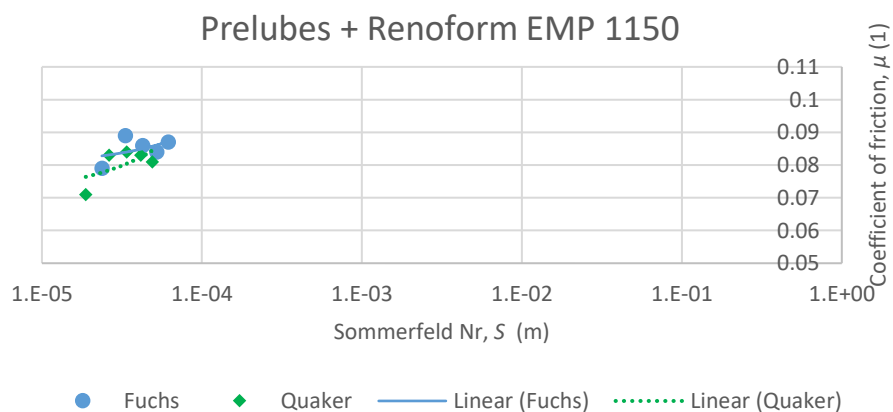


Figure A2 Comparing Sommerfeld number and average coefficient of friction, for combination Prelubes Fuchs and Prelube Quaker with Press oil Renoform EMP 1150

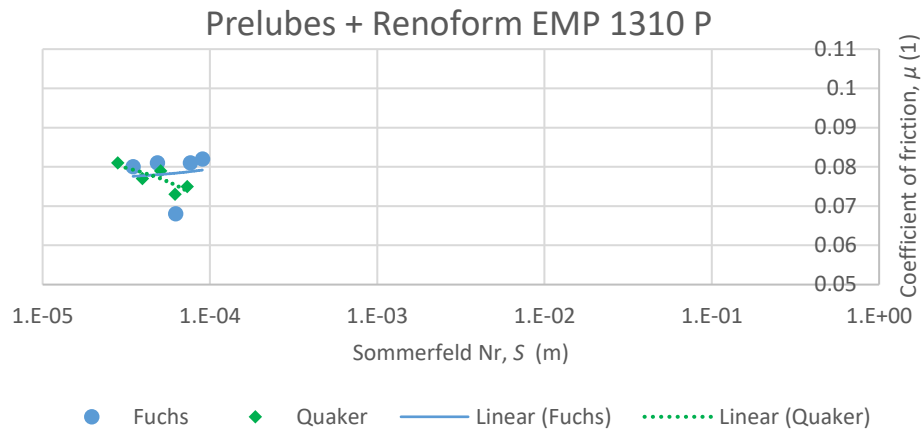


Figure A3 Comparing Sommerfeld number and average coefficient of friction, for combination Prelubes Fuchs and Prelube Quaker with Press oil Renoform EMP 1310 P

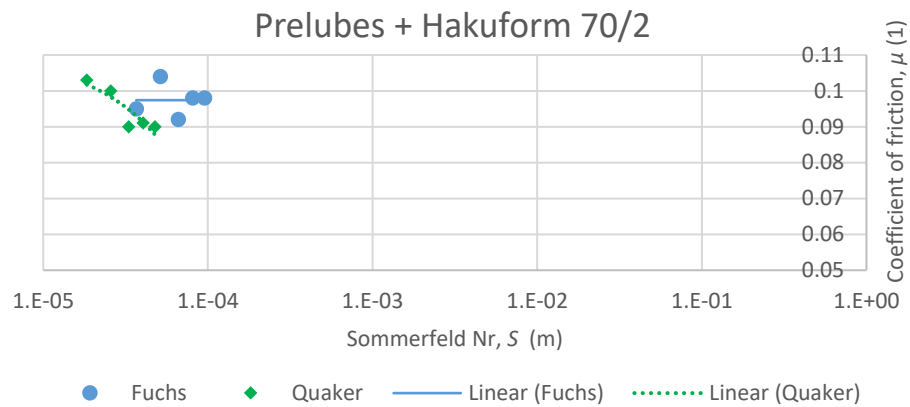


Figure A4 Comparing Sommerfeld number and average coefficient of friction, for combination Prelubes Fuchs and Prelube Quaker with Press oil Hakuform 70/2

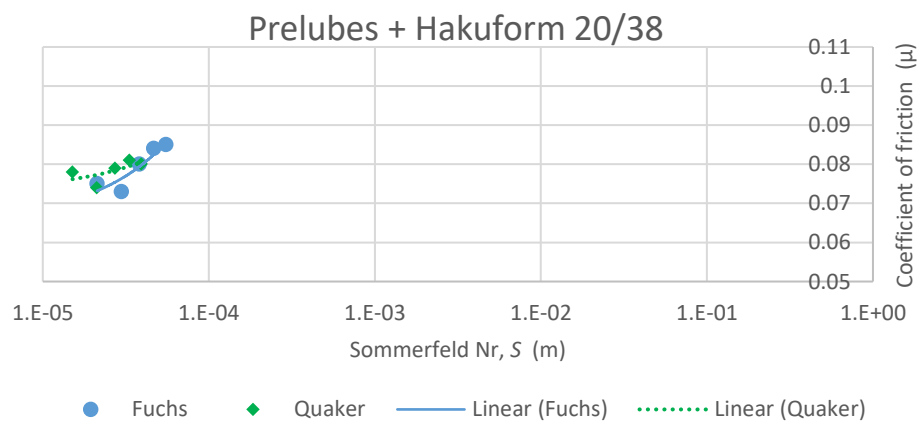


Figure A5 Comparing Sommerfeld number and average coefficient of friction, for combination Prelubes Fuchs and Prelube Quaker with Press oil Hakuform 20/38

A 2. Viscosity of Prelubes Fuchs Anticorit PI 3802-395 and Quaker Ferrocode S-6130 and their combination with other lubricants

Figure A6, is presented the measure viscosity variation with temperature of Prelube Fuchs Anticorit PI 3802-395 and four other different lubricant combinations: 1 - Prelube Fuchs Anticorit PI 3802-395, 2 - Fuchs + EMB 1150, 3 - Fuchs + Renoform EMP 1310 P, 4 - Fuchs + Hakuform 70/2, 5 - Fuchs + Hakuform 20/38. Table 3.2 shows the values of viscosity at 40°C.

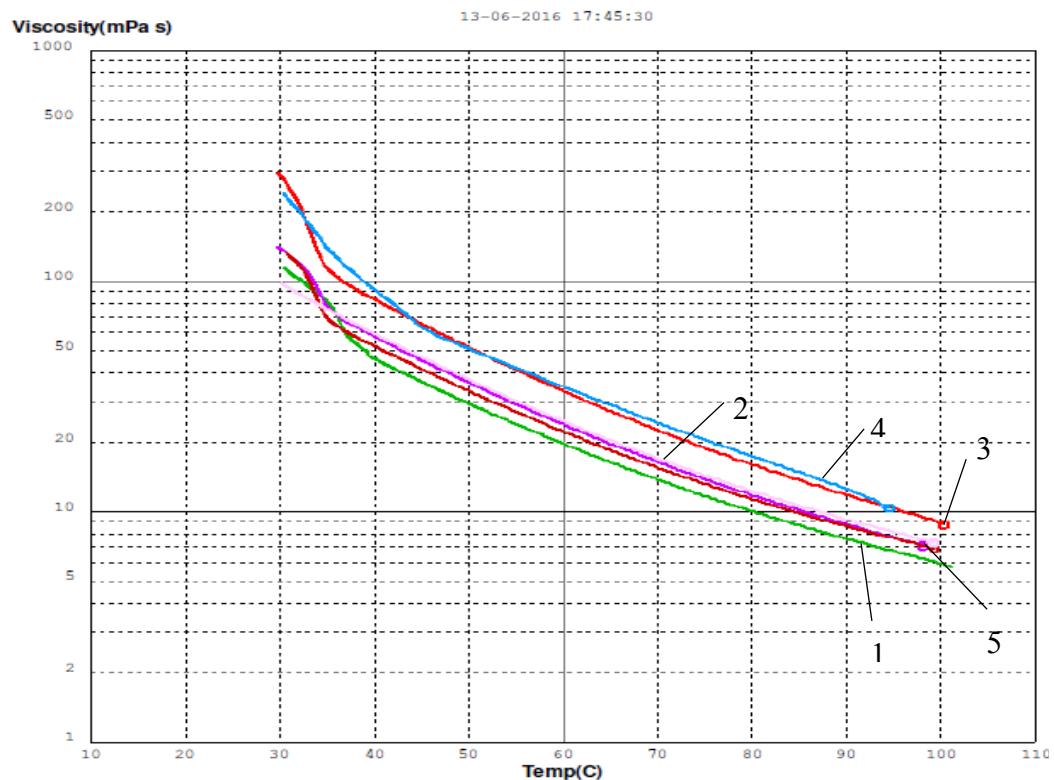


Figure A6 Viscosity parameters of Prelube Fuchs Anticorit PI 3802-395, with other combined lubricants

Figure A7, is presented the measure viscosity variation with temperature of Prelube Quaker Ferrocote S-6130 and four other different lubricant combinations: 1 - Prelube Quaker Ferrocote S-6130, 2 - Quaker + EMB 1150, 3 - Quaker + Renoform EMP 1310 P, 4 - Quaker + Hakuform 70/2, 5 - Quaker + Hakuform 20/38. Table 3.2 shows the values of viscosity at 40 °C.

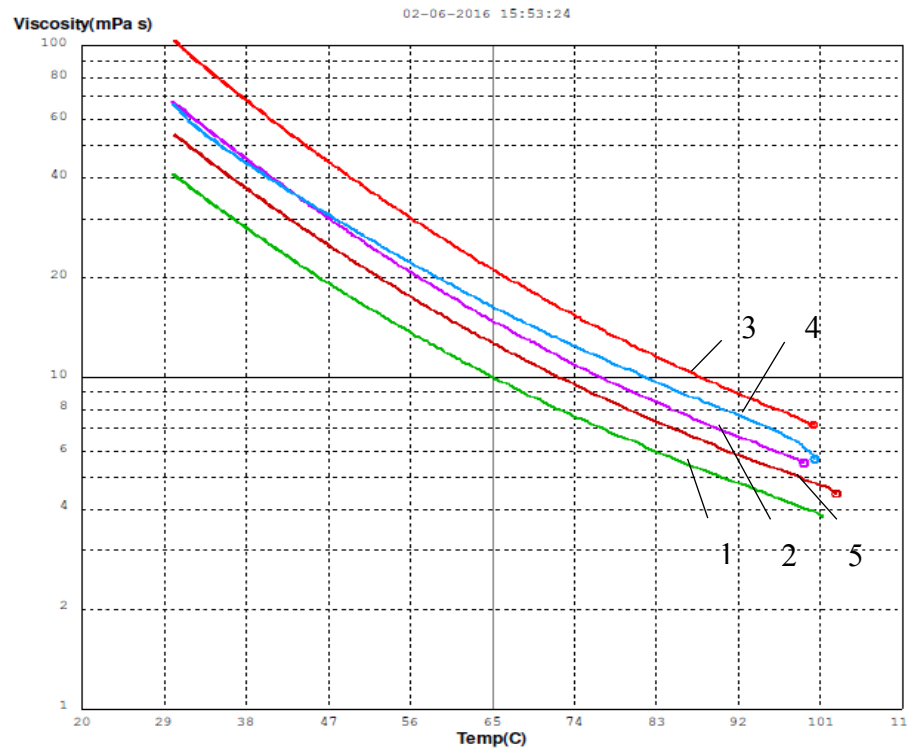


Figure A.7 Viscosity parameters of Prelube Quaker Ferrocote S-6130, with other combined lubricants

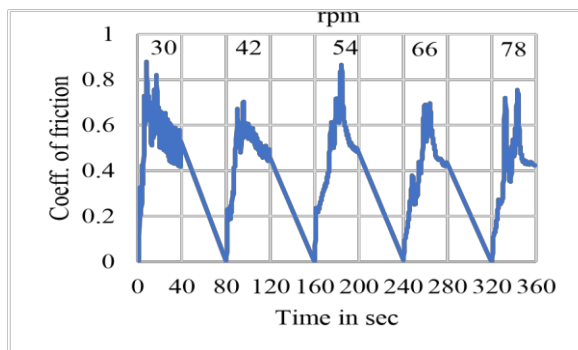
A 3. Pin-on-disk experimental test result with different loads and several lubricants

Reciprocating sliding tests were performed, to find the effect of lubricant properties and other variables on the coefficient of friction of the steel sheets "Cold Rolled HSLA 380" under different testing conditions. Three different normal loads, from 15 N to 35 N with an increment step of 10 N, were individually chosen to apply on the pin-on-disk tester, so that different pressures were achieved in the interface between the tool and sheet metal. The results of all tests carried out using dry and lubricated conditions, are presented in Figures A8 to A17.

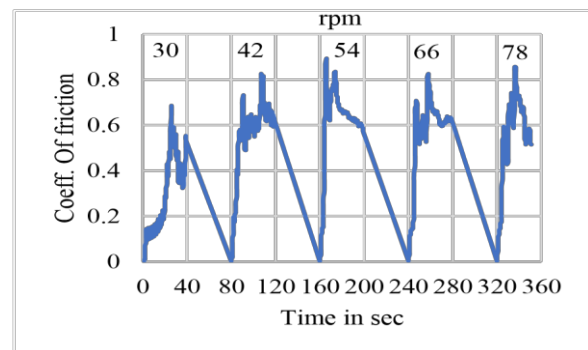
The graphs show the evolution with time of the coefficient of friction under three different loads, on dry and several lubricating conditions. Each graph illustrates the coefficient of friction measured on 5 different sliding velocities (30 rpm, 42 rpm, 54 rpm, 66 rpm and 78 rpm). The duration time of each test 40 seconds.

The coefficient of friction varies over a wide range depending on lubricating conditions and sliding velocity. It was observed that for higher sliding velocities the coefficient of friction is usually stable and lower, while for low sliding velocities it is unstable and higher.

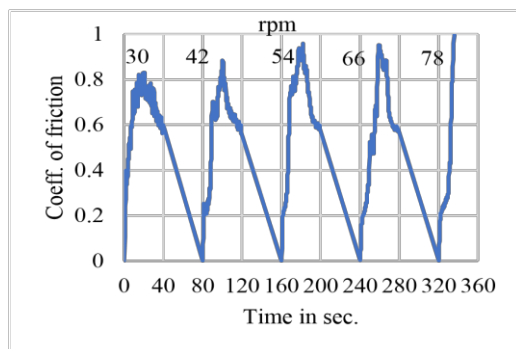
These results can be used as rough estimations of the friction coefficient under similar sliding conditions (load, velocity and lubricant) in an actual stamping process. When tribology tests were performed with dry conditions, higher values of coefficient of friction were obtained for all sliding velocities and applied loads, as expected.



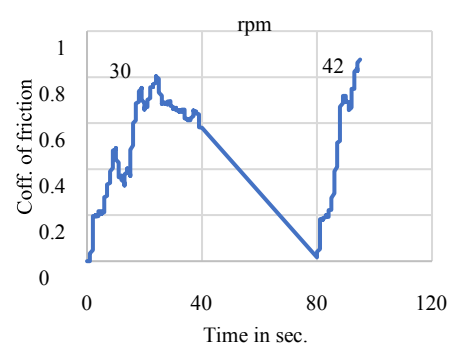
(a) Dry test – 15 N



(b) Dry test – 25 N

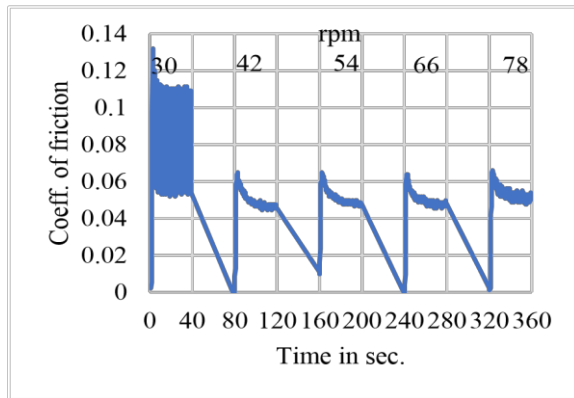


(c) Dry test – 30 N

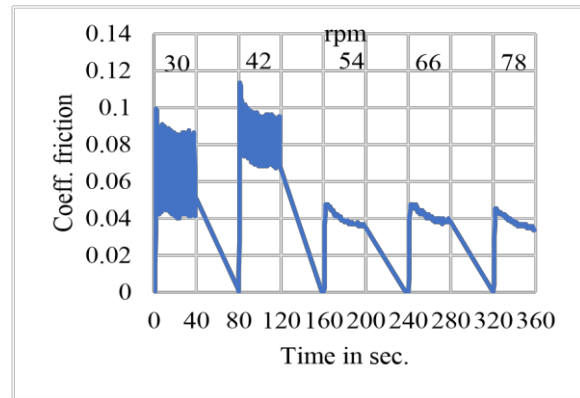


(d) Dry test – 35 N

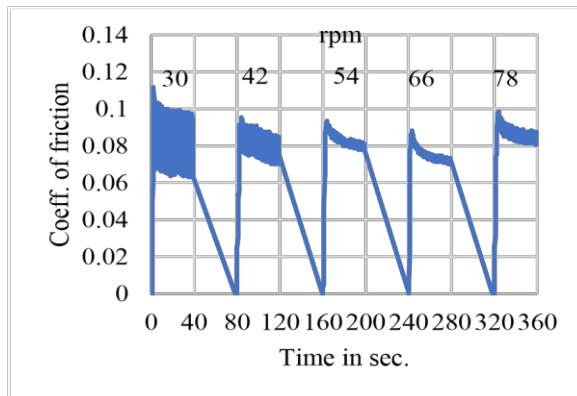
Figure A8 Dry test - the friction coefficient curves under different loads



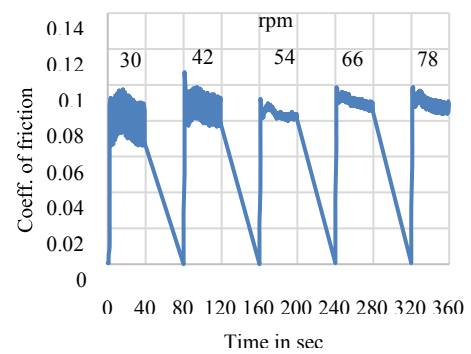
(a) Base lubricant Prelube A, 15 N



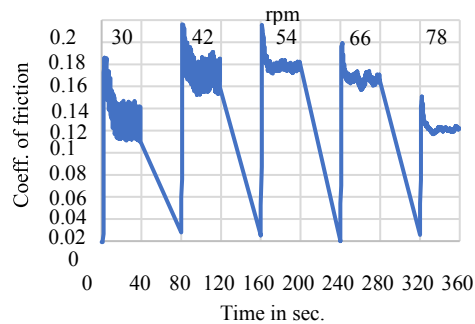
(b) Base lubricant Prelube B, 15 N

Figure A9 Friction coefficient curves with different lubricants under 15 N

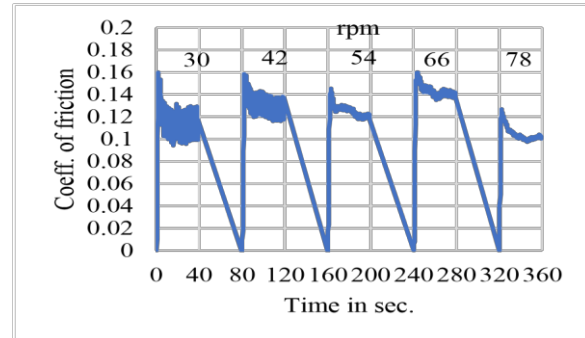
(a) Base lubricant Prelube A, 25 N



(b) Base lubricant Prelube B, 25 N

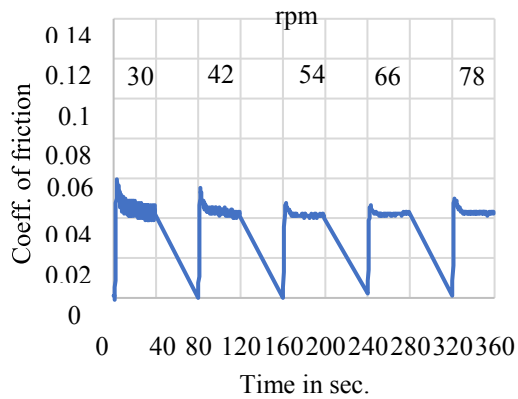
Figure A10 Friction coefficient curves with different lubricants under 25 N

(a) Base lubricant Prelube A, 35 N

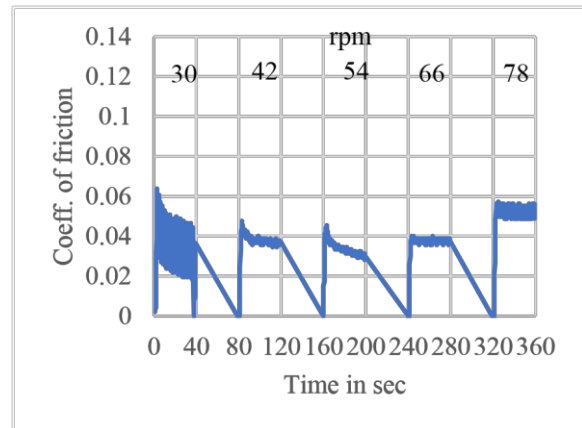


(b) Base lubricant Prelube B, 35 N

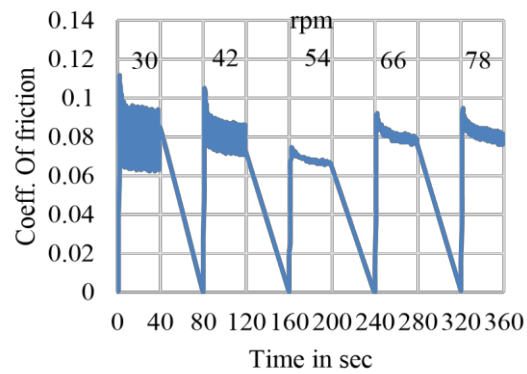
Figure A11 Friction coefficient curves with different lubricants under 35 N



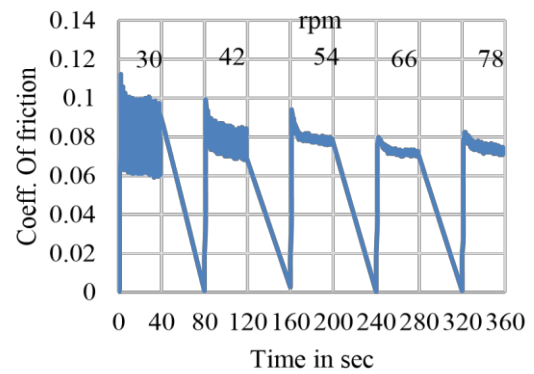
(a) Prelube A + Press oil 3, 15 N



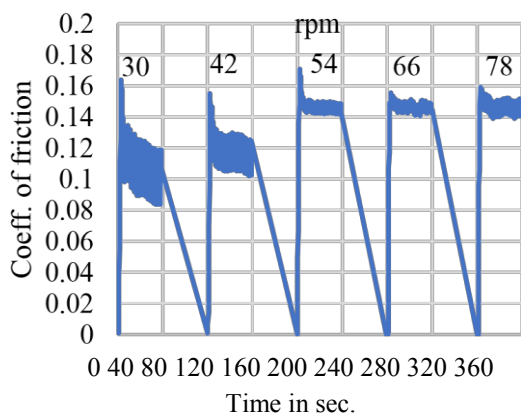
(b) Prelube B + Press oil 3, 15 N

Figure A12 Friction coefficient curves with different lubricants under 15 N

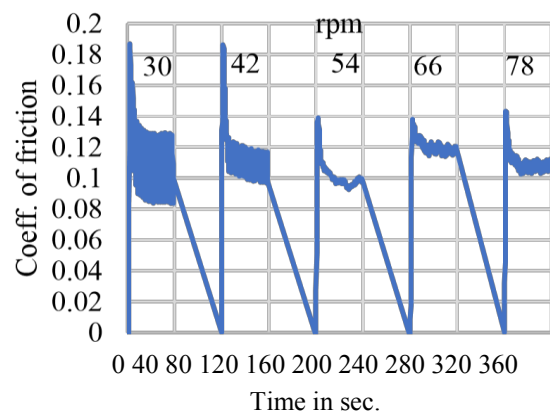
(a) Prelube A + Press oil 3, 25 N



(b) Prelube B + Press oil 3, 25 N

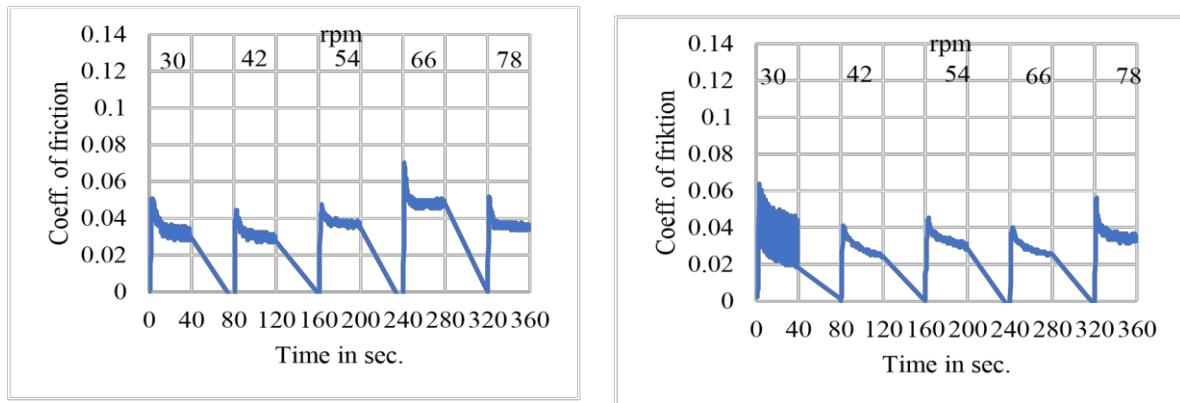
Figure A13 Friction coefficient curves with different lubricants under 25 N

(a) Prelube A + Press oil 3, 35 N



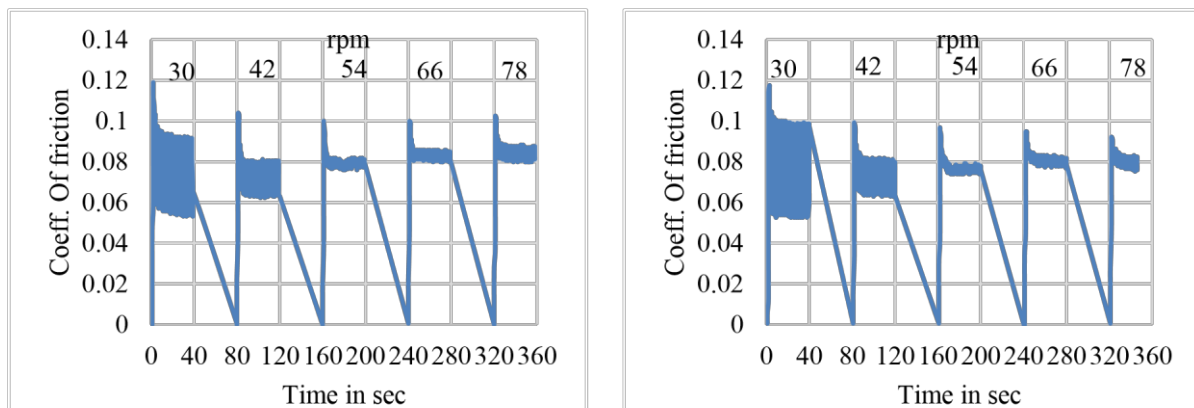
(b) Prelube B + Press oil 3, 35 N

Figure A14 Friction coefficient curves with different lubricants under 35 N



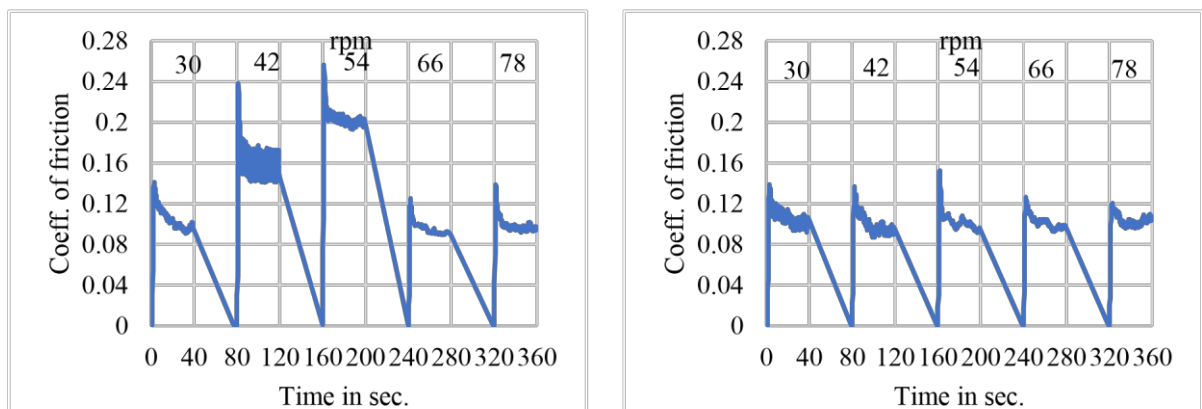
(a) Prelube A + Press oil 5, 15 N

(b) Prelube B + Press oil 5, 15 N

Figure A15 Friction coefficient curves with different lubricants under 15 N

(a) Prelube A + Press oil 5, 25 N

(b) Prelube B + Press oil 5, 25 N

Figure A16 Friction coefficient curves with different lubricants under 25 N

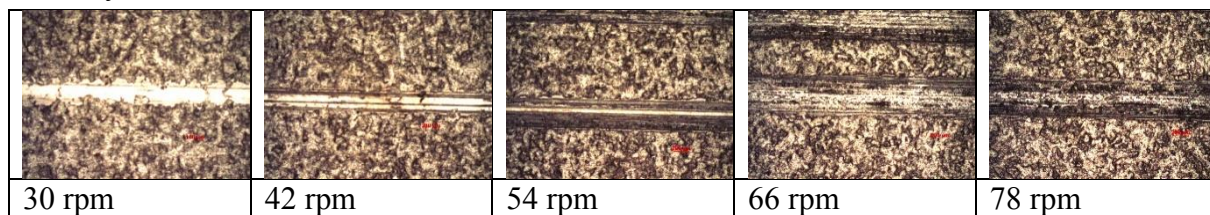
(a) Prelube A + Press oil 5, 35 N

(b) Prelube B + Press oil 5, 35 N

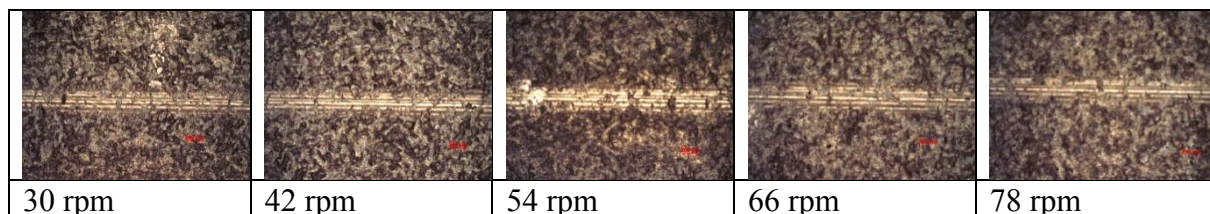
Figure A17 Friction coefficient curves with different lubricants under 35 N

The pictures presented in Figures A18 to A20 show optical photos of part of the wear tracks (approximately 2 mm long) in the central region of each wear sample.

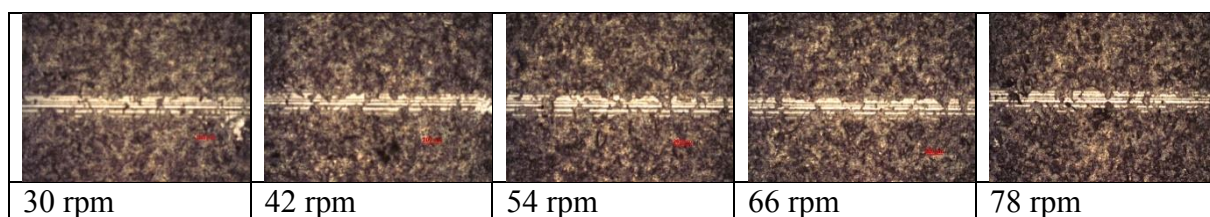
15N Dry



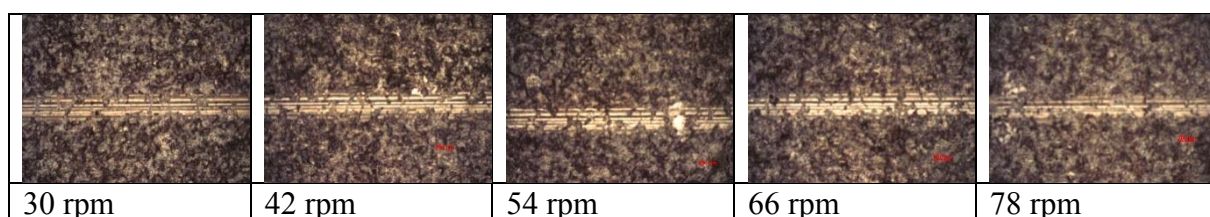
15N Fuchs



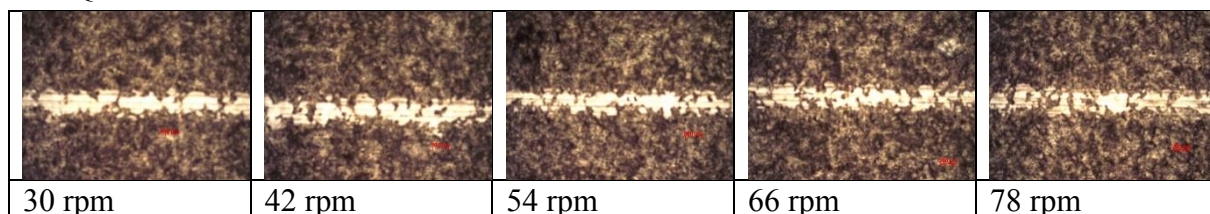
15N Fuchs + Hakuform 20/38



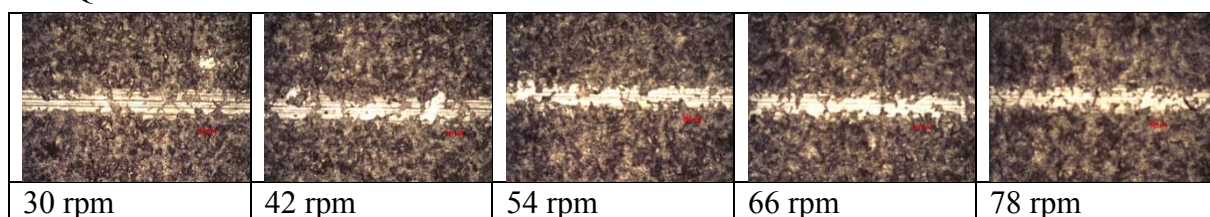
15N Fuchs + Renoform EMP 1310 P



15N Quaker



15N Quaker + Hakuform 20/38



15N Quaker + Renoform EMP 1310 P

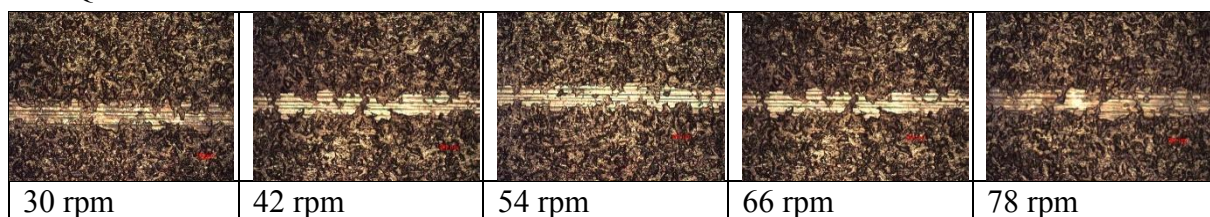
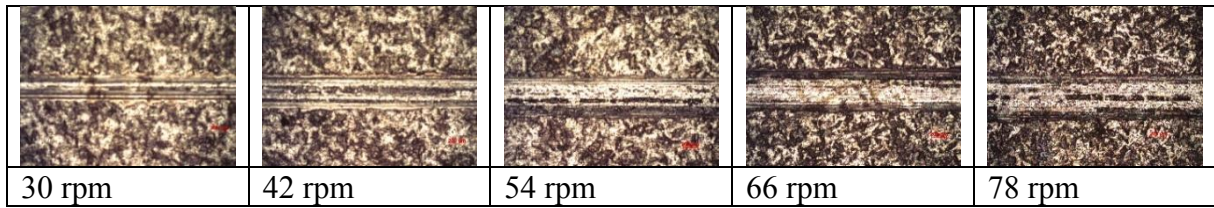
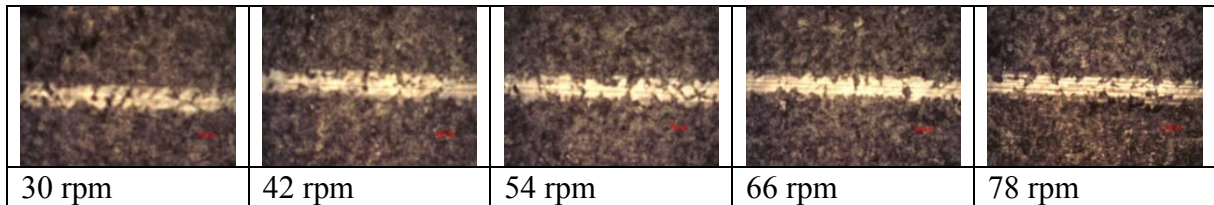


Figure A18 Pictures differences track length on sheet metal under 15 N

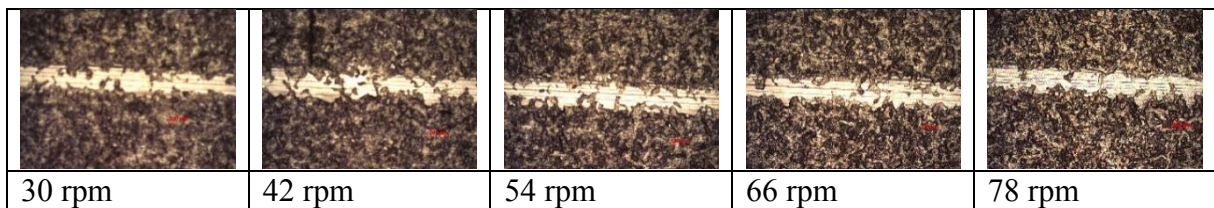
25N Dry



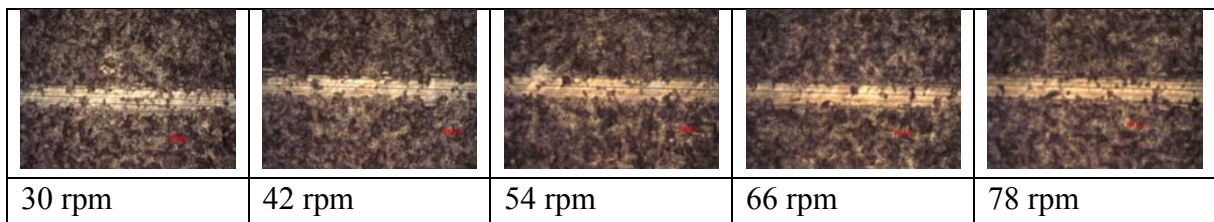
25N Fuchs



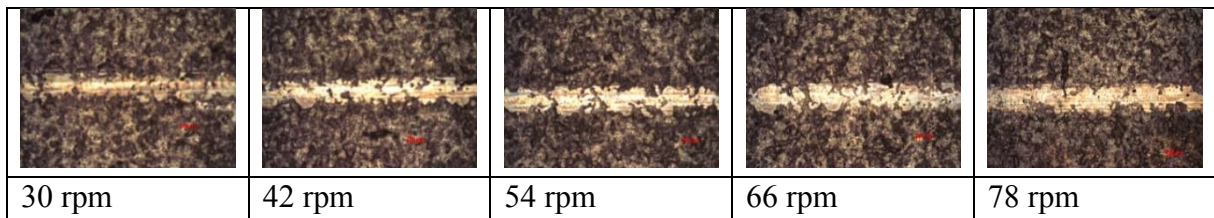
25N Fuchs + Hakuform 20/38



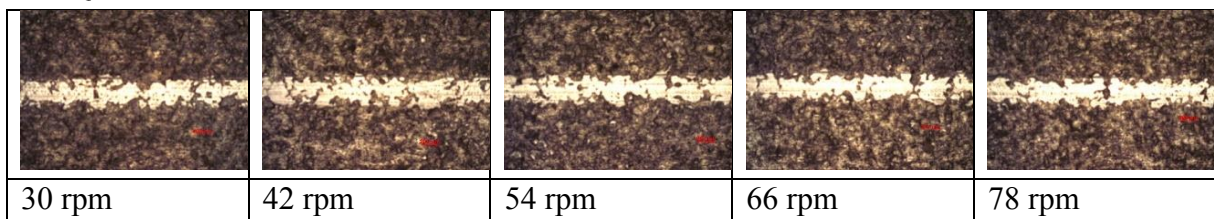
25N Fuchs + Renoform EMP 1310 P



25N Quaker



25N Quaker + Hakuform 20/38



25N Quaker + Renoform EMP 1310 P

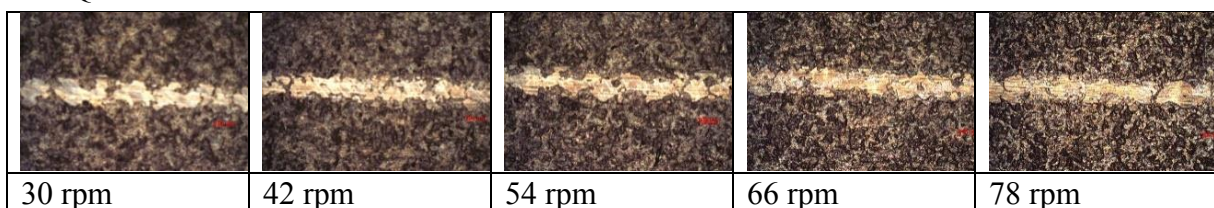
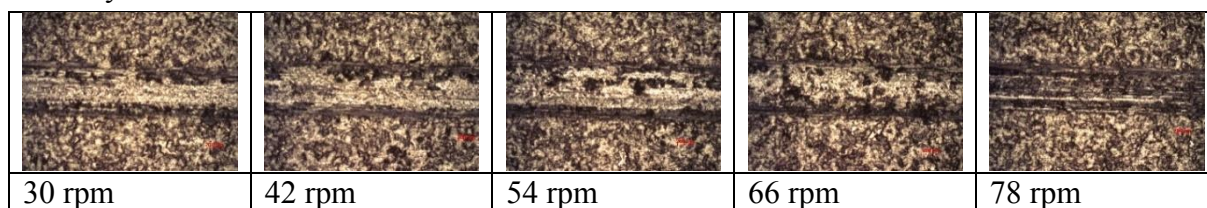
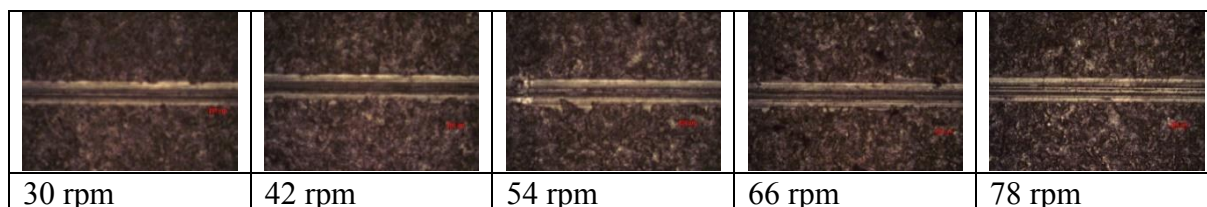


Figure A19 Pictures differences track length on sheet metal under 25 N

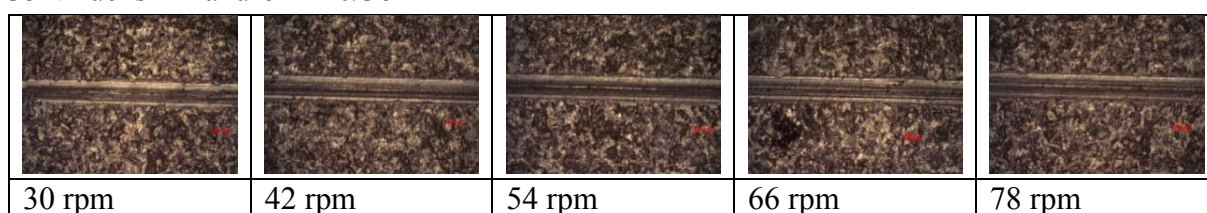
30N Dry



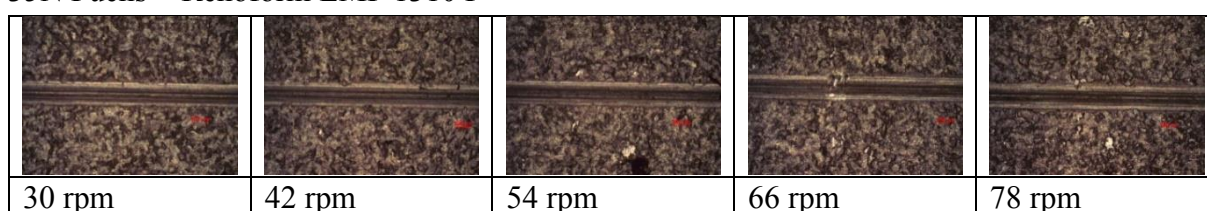
35N Fuchs



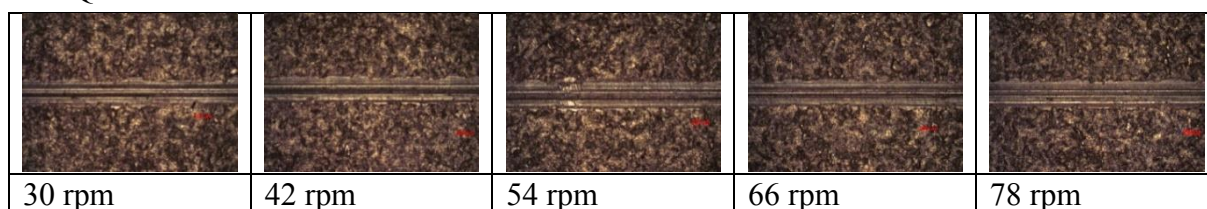
35N Fuchs + Hakuform 20/38



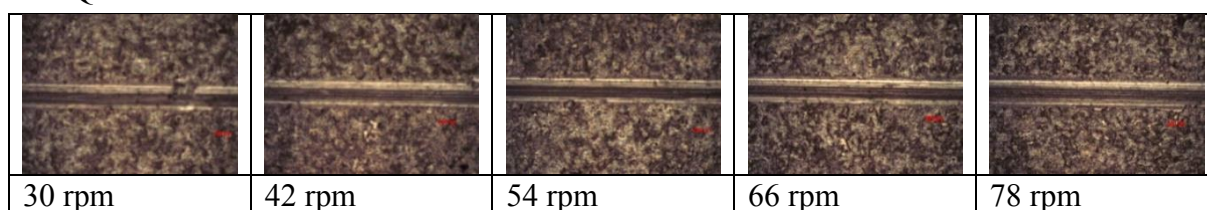
35N Fuchs + Renoform EMP 1310 P



35N Quaker



35N Quaker + Hakuform20/38



35N Quaker + Renoform EMP 1310 P

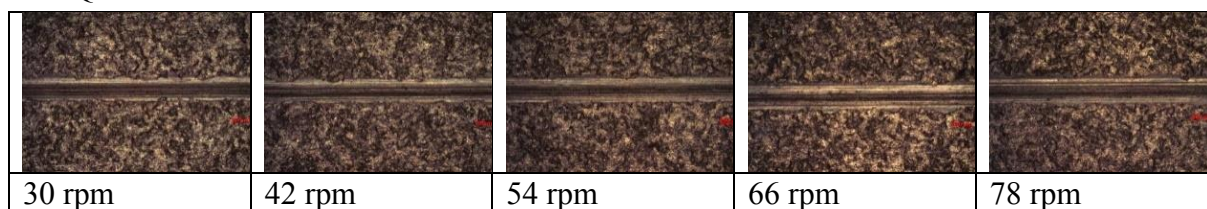


Figure A20 Pictures differences track length on sheet metal under 35 N

A 4. Pin-on-disk experimental test result, by coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 420"

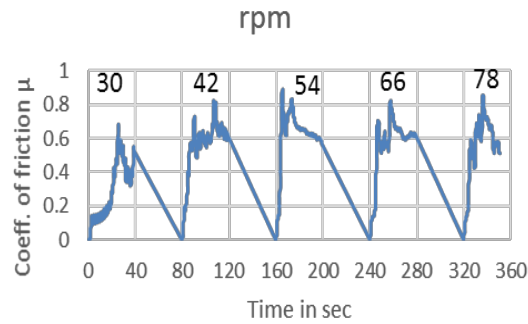
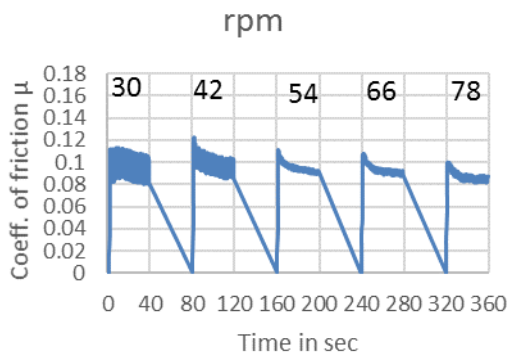
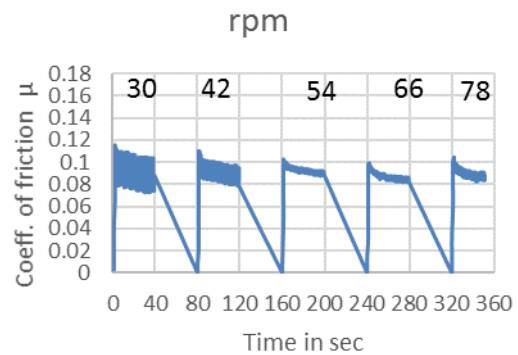


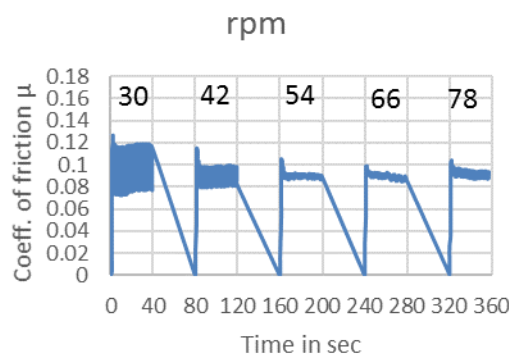
Figure A21 Dry test - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 420"



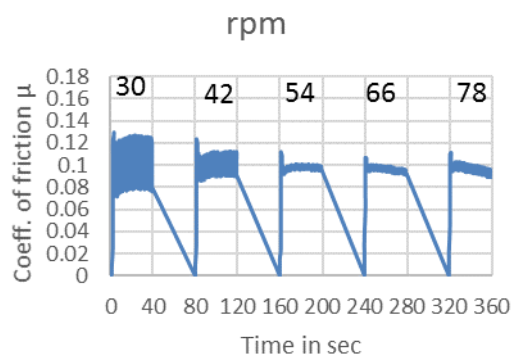
(a) Base lubricant Prelube A



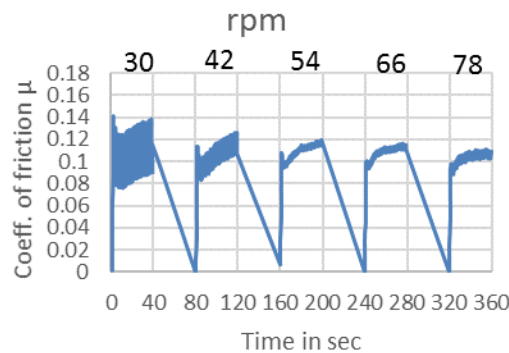
(b) Base lubricant Prelube B



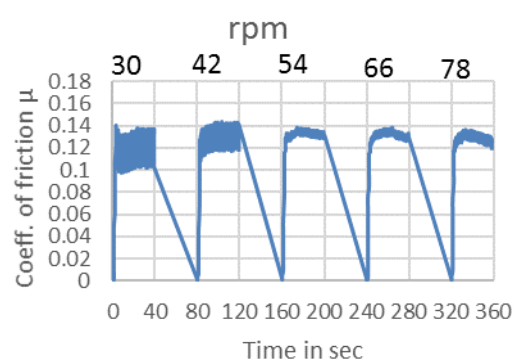
(a) Prelube A + Press oil 1



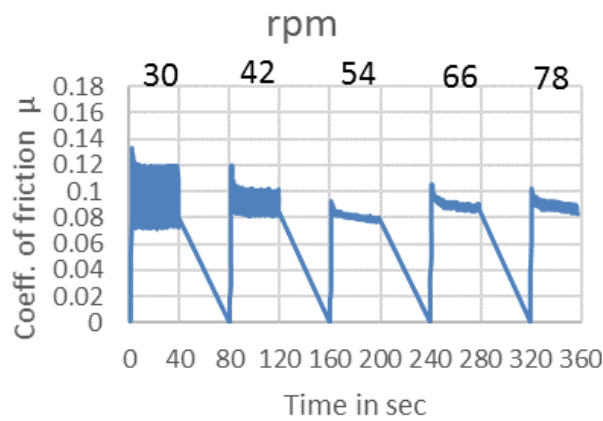
(b) Prelube B + Press oil 1



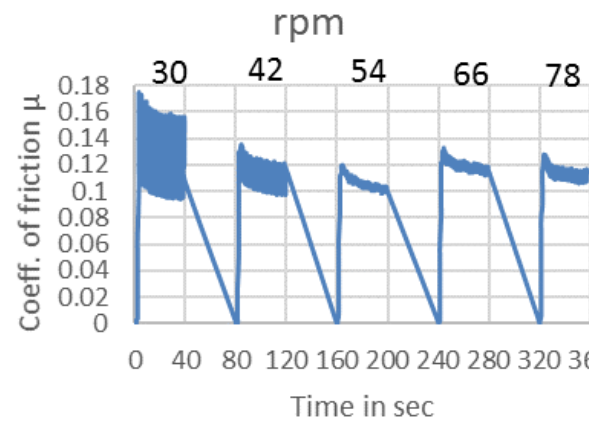
(a) Prelube A + Press oil 2



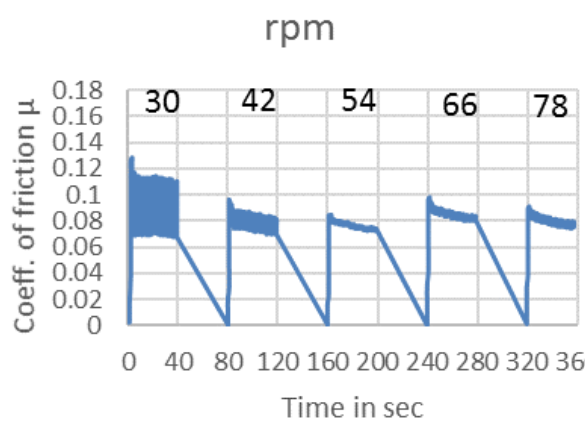
(b) Prelube B + Press oil 2



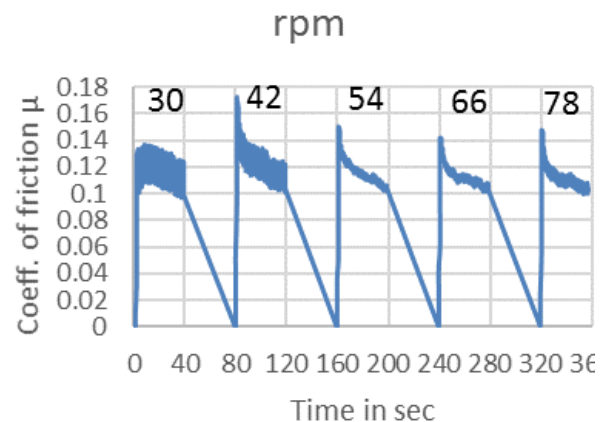
(a) Prelube A + Press oil 3



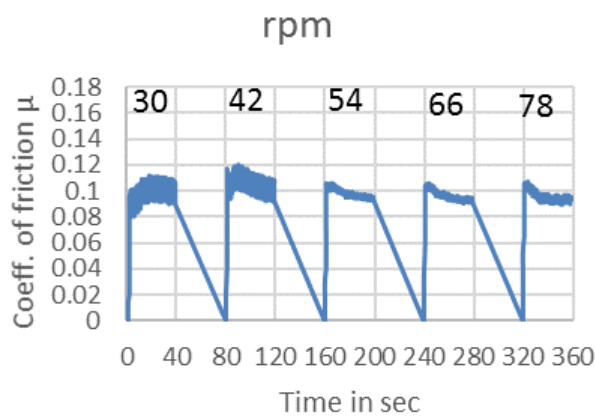
(b) Prelube B + Press oil 3



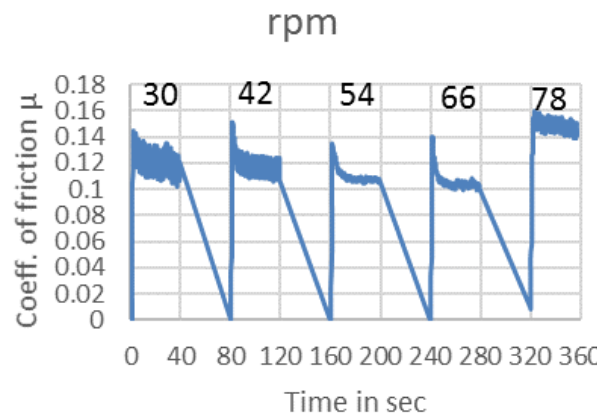
(a) Prelube A + Press oil 4



(b) Prelube B + Press oil 4



(a) Prelube A + Press oil 5



(b) Prelube B + Press oil 5

Figure A22 Lubricated condition - coefficient of friction with varying sliding velocity for "Cold Rolled HSLA 420"

During this PhD work, many experiments have been carried out. Although that has stated several times that the transferability of friction coefficients, measured in a certain situation, to another situation is low, some data is presented here as a first impression.

B. Surface preparation of tool steels

Tools designed for a particular application and production material thickness may not function if they are later used to perform an operation on a much thicker or harder blank material as they could be severely overloaded.

The following recommendations concerning design features, although very basic, are intended to avoid premature failure either in heat treatment or in use.

- use adequate overall dimension to ensure basic tool strength and support;
- avoid sharp corners – wherever possible, incorporate a generous fillet radius instead;
- wherever possible, avoid adjacent heavy and light sections in the tool;
- avoid potential stress raisers, e.g. machining marks, grinding marks and letter stamping;
- leave sufficient stock thickness between holes and surface edges;
- complicated tool shapes are often best built up from sections which are safer in heat treatment and easier to refurbish or replace.

The following four terms (grinded, polished, nitrided and quenched/tempered) are commonly used when it comes to surface preparation of tool steels. The essential characteristics of these methods are explained below.

B 1. Basic tool design

Grinded: General grinding recommendations are given below [89]. The use of correct grinding techniques will always have a positive influence on tool making and tool performance. The stress created locally in the tool surface by the combination of high temperatures, friction and pressure during the grinding operation can be kept to a minimum by:

- using properly dressed, free-cutting grinding wheels;
- restricting the wheel pressure/metal removal rate or depth of cut;
- using plenty of coolant.

Tools made from high alloy steel which have been tempered at low temperatures are particularly sensitive during grinding operations. Extra care is demanded here. As a rule of thumb, the harder the steel, the softer the wheel and vice-versa.

Under unfavourable grinding conditions the tool steel can be affected as follows:

- surface hardness is reduced (temper burn) and this will adversely affect wear resistance;
- hardening of the ground surface may take place and result in the formation of grinding cracks and problems with tool breakage and chipping;
- severe stresses are introduced into the tool and these can enhance the risk of failure.

After a rough grinding operation, it is important that a finish grinding is made so that the stress affected surface layer due to the rough grinding operation is removed.

It should be noted that the risk of surface cracking is high when grinded tools that have been overheated, over-soaked or under tempered during heat treatment. This is caused by the

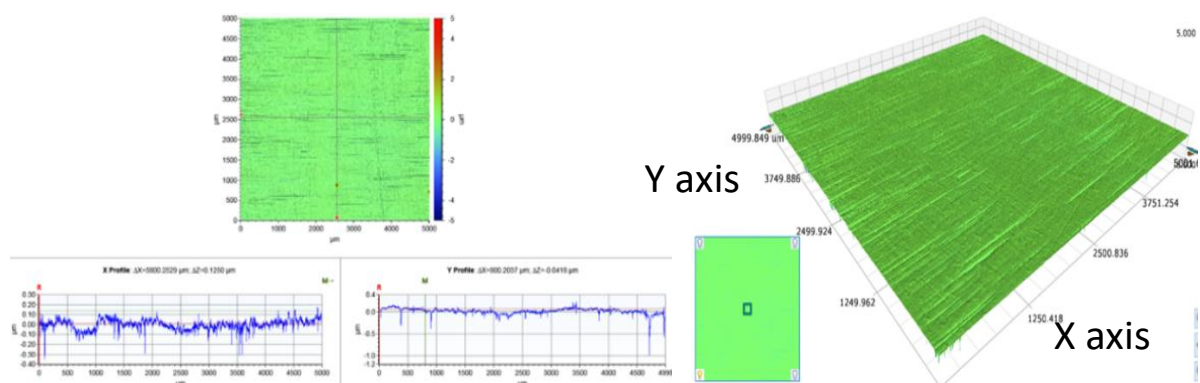
presence of the soft constituent retained austenite in the microstructure. The heat and pressure produced during grinding usually transform this into untampered martensite. The resultant very hard and brittle condition at the tool surface can lead to the formation of surface cracks. Grinding marks on the working surfaces of the tool can cause problems in service;

- they are potential stress raisers and can lead to chipping or flaking or even cracking;
- they can cause galling, especially if they are transverse to the direction of the metal flow.

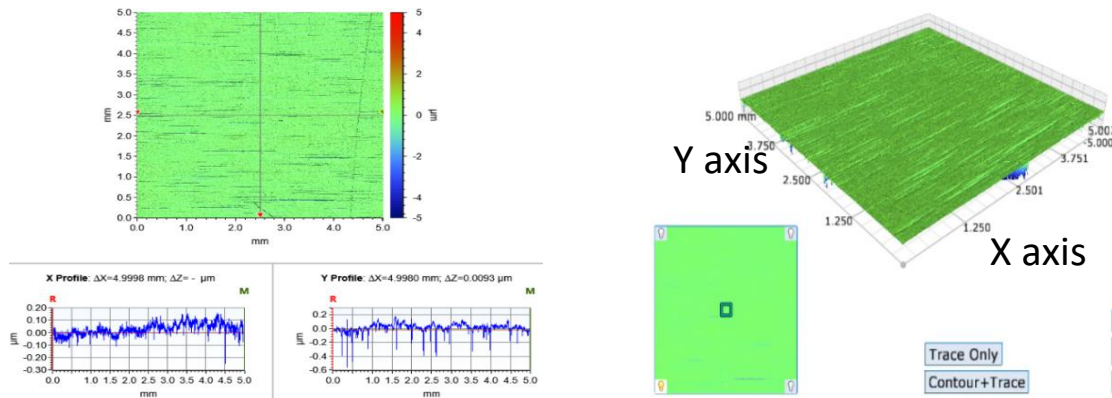
When the die surface is finish ground or reground, the feather edge which is created should be carefully removed by a light hand stoning operation. This will reduce the possibility of chipping or flaking of the cutting edge at the beginning of the production run. This is particularly important in tools being used at high hardness's for cutting of thin materials.

Surface map and profiles for Grinded surfaces are presented in Figure 4.11 and Figure 4.12.

Polishing: Most cold work applications do not need high gloss polished tool surfaces [90], but it is always advantageous to create well finished functional surfaces for a prolonged tool life. In forming operations where lubricants are involved a preparation strategy may consist of removing larger peak formations on the surface and preserving a controlled depth of valleys as lubrication pockets, which then will contribute to a reduced friction during forming. However, it is always important to consider the final tool steel surface quality in relation to the application. If a high-quality surface coating is going to be applied, then it is always recommended to perform high gloss polishing of the tool surface before the coating process. During the work, experience and technique of the polisher plays an extremely important role in achieving the desired surface finish. Surface map and profiles for Polished surfaces are presented in Figures B1 and B2.



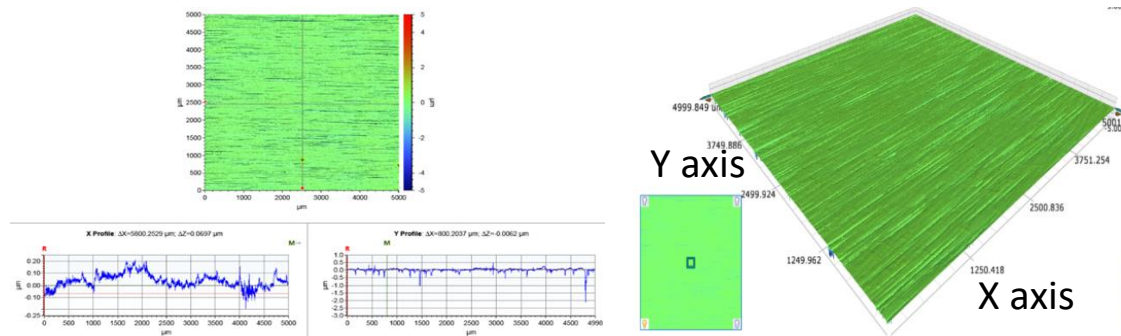
a) Before tests, X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = 0.1250 \mu\text{m}$
Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = -0.0418 \mu\text{m}$



b) After tests, X Profile: $\Delta X = 4.9998 \mu\text{m}$; $\Delta Z = - \mu\text{m}$

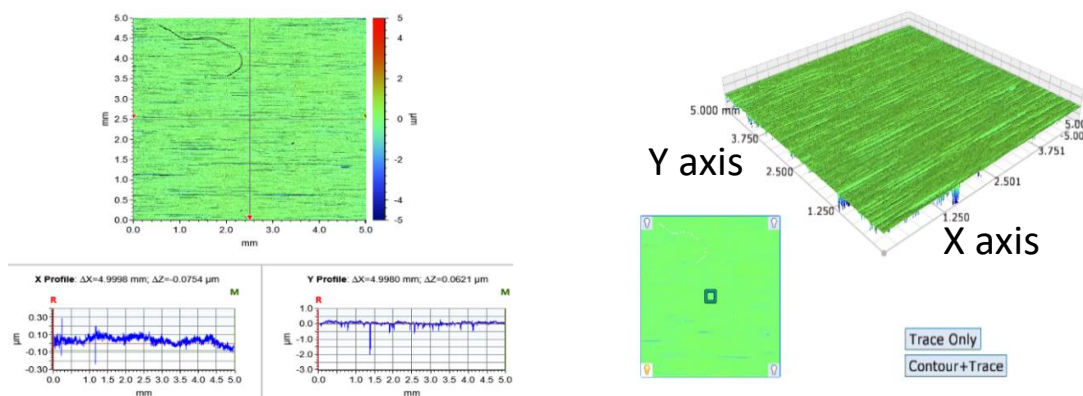
Y Profile: $\Delta X = 4.9980 \mu\text{m}$; $\Delta Z = 0.0093 \mu\text{m}$

Figure B1 3D analysis of a surface of a profile of Polished "L" tool



a) Before tests, X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = 0.0697 \mu\text{m}$

Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = -0.0062 \mu\text{m}$



b) After tests, X Profile: $\Delta X = 4.9998 \mu\text{m}$; $\Delta Z = - 0.0754 \mu\text{m}$

Y Profile: $\Delta X = 4.9980 \mu\text{m}$; $\Delta Z = 0.0621 \mu\text{m}$

Figure B2 3D analysis of a surface of a profile of Polished "R" tool

Nitriding: A process of chemical-thermal treatment in which the surface of a given metal or alloy is saturated with nitrogen in a special nitriding medium. The surface layer of the product, enriched with nitrogen, has in its composition dissolved nitrides and acquires increased corrosion resistance and the highest micro-hardness. According to “overview of the nitride hardening process” [91], the micro-hardness obtained by nitriding is similar to boronated, surpassing cementation and carbonitriding (slightly). So, nitride hardening is a means of imparting very high surface hardness to steel components. There are, of course, other processes which can be used to get high hardness but nitride hardening offers certain crucial advantages [91]:

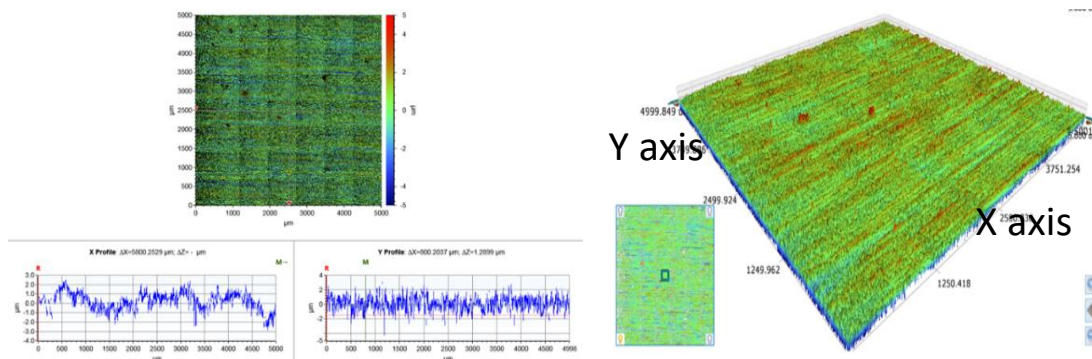
- low process temperature - Around 495° to 535° Celsius;
- lack of shock-inducing "quench" at cycle end - Nitride hardening utilises a slow, controlled heating and cooling rate at cycle end;
- the whole process takes place under a protective atmosphere, giving the finished product a clean, oxide-free finish.

In combination, these features confer great advantages to the manufacturer requiring wear resistance whilst maintaining component form and dimensional accuracy. In fact, many types of component can only be hardened by the nitriding process due to their complex or slender forms.

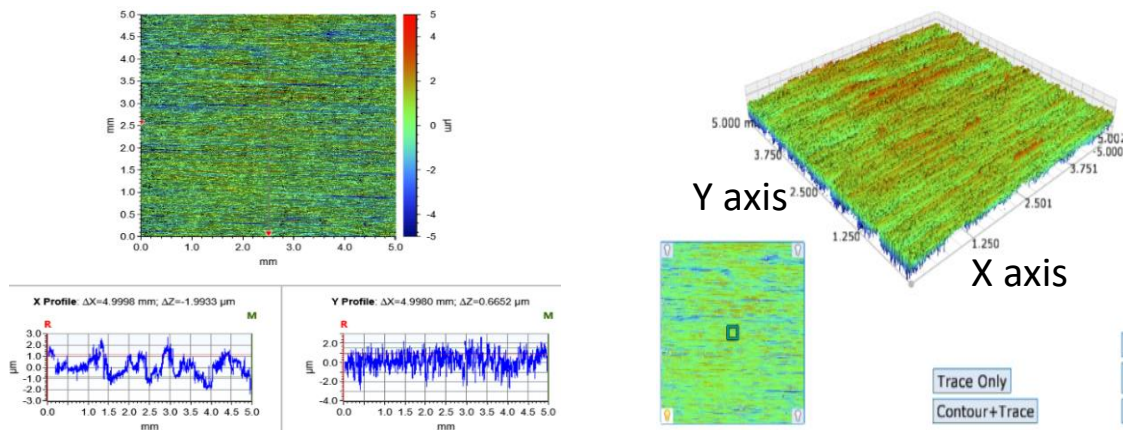
Another major benefit of the nitriding process is the ability to harden selected areas of the component, but of course the entire component can be hardened if preferred. This is achieved through the application of specialised masking paints to areas of the component that do not require hardening.

Very basically, the process works by the load components absorbing some of the nitrogen present in the furnace atmosphere (at the process operating temperature).

Virtually all steels nitride to some extent but to provide a useful increase in surface hardness certain amounts and types of alloying elements need to be present, generally chromium, molybdenum and in some cases aluminium, vanadium and tungsten. Surface map and profiles for Nitrided surfaces are presented in Figure B3 and Figure B4.

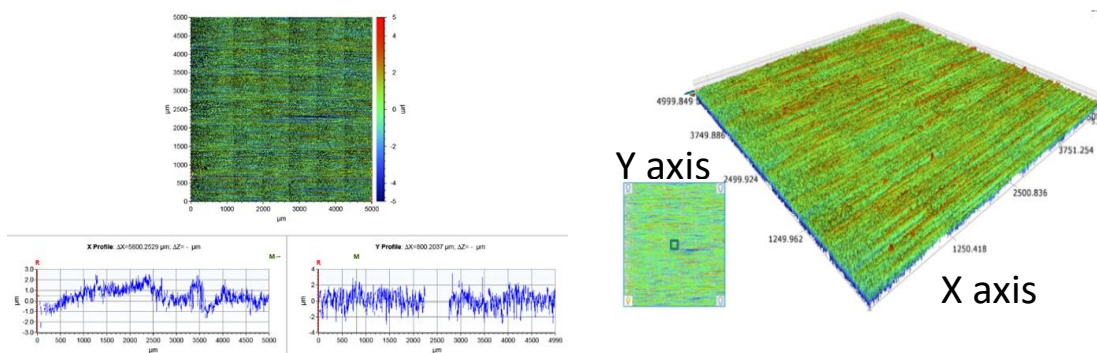


a) Before tests, X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = - \mu\text{m}$
Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = 1.2829 \mu\text{m}$

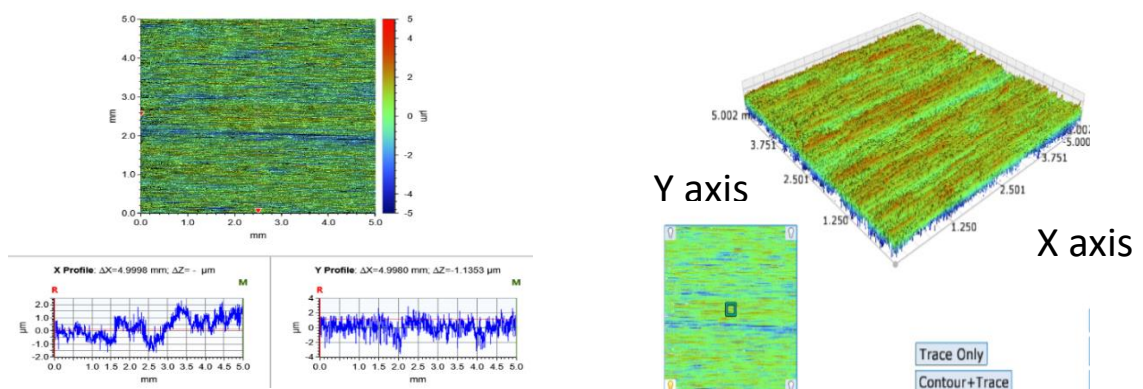


b) After tests, X Profile: $\Delta X=4.9998 \mu\text{m}$; $\Delta Z= - 1.9933\mu\text{m}$
Y Profile: $\Delta X=4.9980 \mu\text{m}$; $\Delta Z=0.6652 \mu\text{m}$

Figure B3 3D analysis of a surface of a profile of Nitrided "L" tool



a) Before tests, X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = - \mu\text{m}$
Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = - \mu\text{m}$



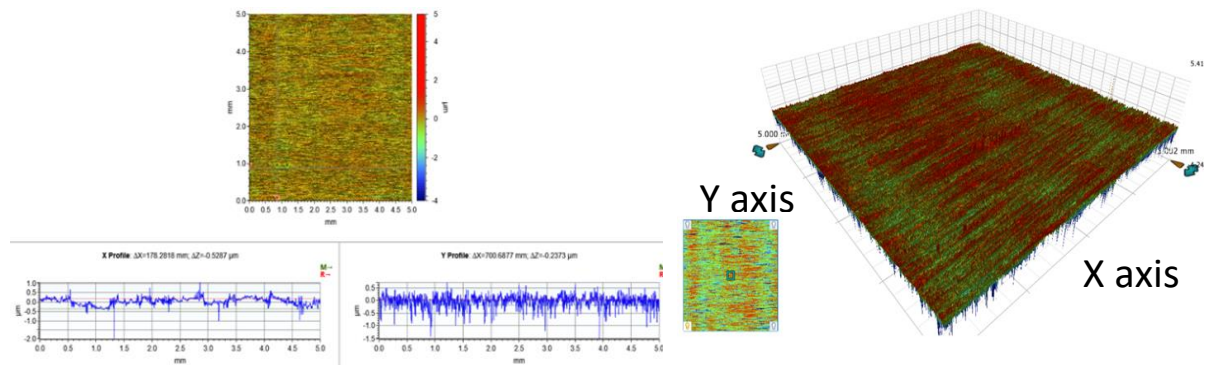
b) After tests, X Profile: $\Delta X=4.9998 \mu\text{m}$; $\Delta Z= - \mu\text{m}$
Y Profile: $\Delta X=4.9980 \mu\text{m}$; $\Delta Z=-1.1353 \mu\text{m}$

Figure B4 3D analysis of a surface of a profile of Nitrided "R" tool

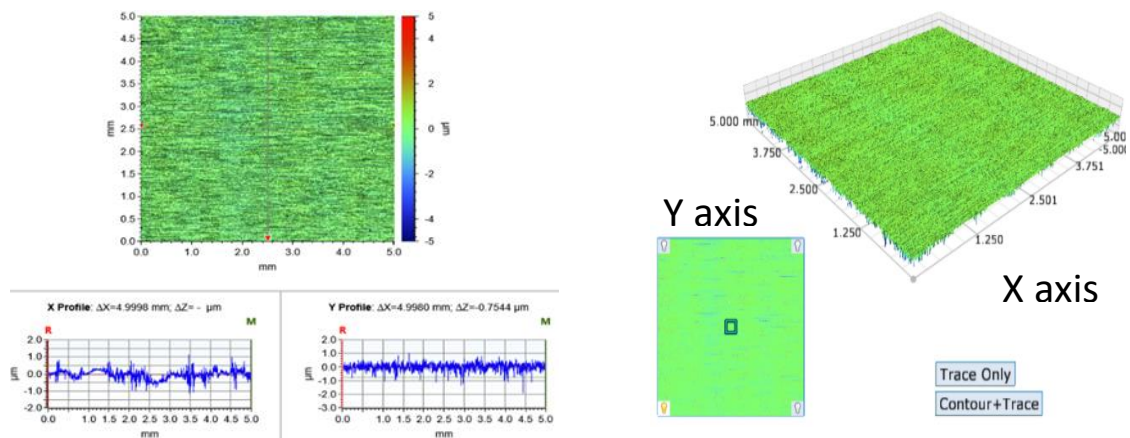
Quenching/tempering: Quenching and tempering provides the steel with high strength and ductility [89]:

Quenching and tempering consists of a two-stage heat-treatment process. Stage 1 includes hardening, in which the plate is austenitized to approximately 900 - 1200 °C and then quickly cooled. The material is water (air or oil) -quenched in a quench unit, in which the plate is clamped to avoid warpage. Stage 2 consists of tempering the material to obtain the desired material properties. Quenching and tempering achieves an extremely fine-grained and homogeneous microstructure. Quenched/tempered steel is characterized by high strength and good ductility.

3D surface measurement has given engineers, process designers, and quality control professionals a significantly improved toolkit for describing surfaces since three-dimensional measurements uniquely differentiate not only surface shapes but functionalities as well. All of which, ultimately, results in better surface performance. Surface map and profiles for Quenched/tempered surfaces are presented in Figure B5 and Figure B6.

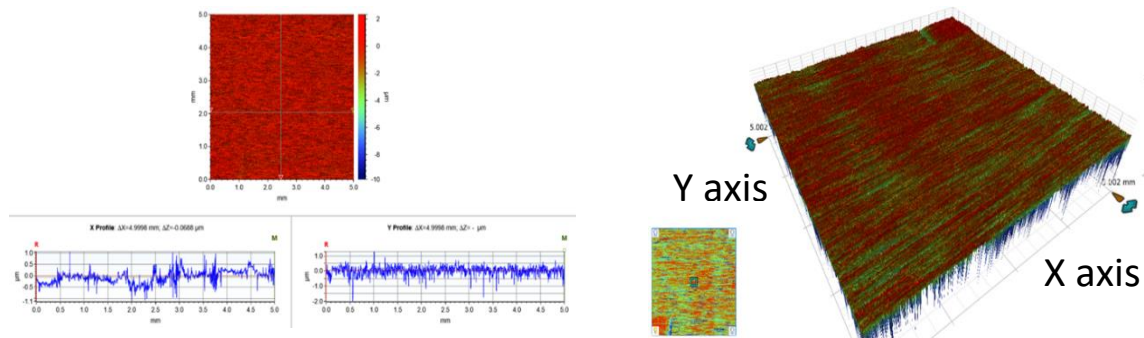


a) Before tests, X Profile: $\Delta X = 178.2818 \mu\text{m}$; $\Delta Z = -0.5287 \mu\text{m}$;
Y Profile: $\Delta X = 700.6877 \mu\text{m}$; $\Delta Z = -0.2373 \mu\text{m}$

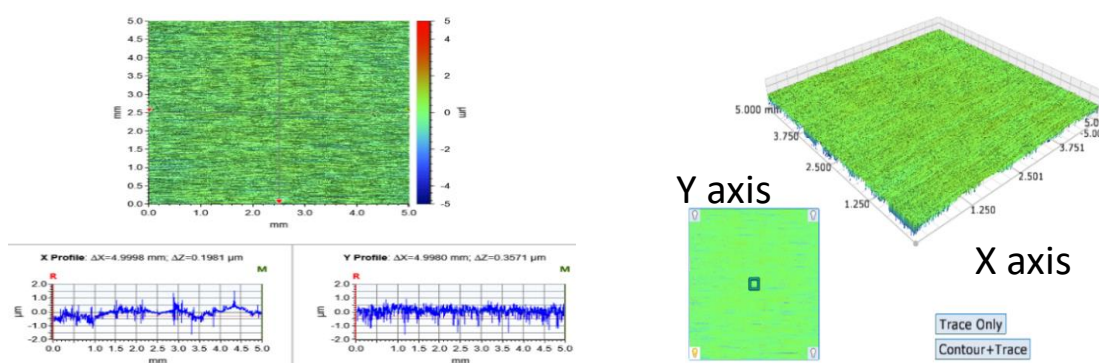


b) After tests, X Profile: $\Delta X = 4.9998 \mu\text{m}$; $\Delta Z = - \mu\text{m}$
Y Profile: $\Delta X = 4.9980 \mu\text{m}$; $\Delta Z = -0.7544 \mu\text{m}$

Figure B5 3D analysis of a surface of a profile of Quenched/tempered “L” tool



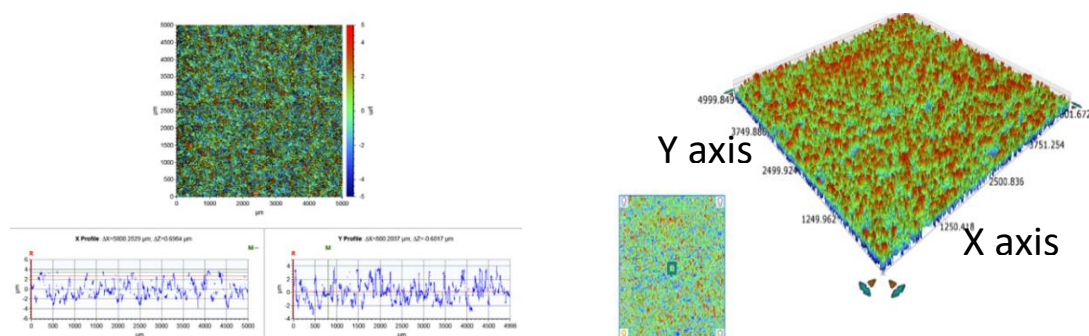
Top view: X Profile: $\Delta X = 4.9998 \mu\text{m}$; $\Delta Z = -0.0688 \mu\text{m}$;
Y Profile: $\Delta X = 4.9998 \mu\text{m}$; $\Delta Z = - \mu\text{m}$.



b) After tests, X Profile: $\Delta X=4.9998 \mu\text{m}$; $\Delta Z= 0.1981 \mu\text{m}$
Y Profile: $\Delta X=4.9980 \mu\text{m}$; $\Delta Z=-0.3571 \mu\text{m}$

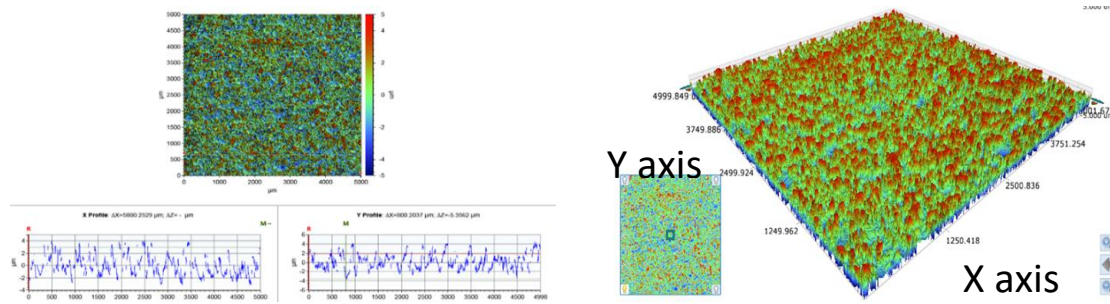
Figure B6 3D analysis of a surface of a profile of Quenched/tempered “R” tool

Surface map and profiles for HSLA 380 and HSLA 420 sheet steel surfaces are presented in Figure B7 and Figure B8.



Top view: X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = 0.6984 \mu\text{m}$;
Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = -0.6017 \mu\text{m}$.

Figure B7 3D analysis of a surface of a profile of steel sheet HC380LA, before test



Top view: X Profile: $\Delta X = 58000.2529 \mu\text{m}$; $\Delta Z = - \mu\text{m}$;

Y Profile: $\Delta X = 800.2037 \mu\text{m}$; $\Delta Z = -5.3562 \mu\text{m}$.

Figure B8 3D analysis of a surface of a profile of steel sheet HC240LA, before test

B 1.1. The surface parameters measured by Bruker's NPFLEX 3D optical microscope

The measurement of surface roughness parameters was carried out using the two available instruments Bruker's NPFLEX 3D optical microscope and contact measure device HOMMEL tester T500.

There are many surface roughness parameters that can be used to describe a particular case, as presented in Table B1. The 3D surface parameters helped to improve communication and allowed a process to control that traditional R parameters could not do alone.

Table B1 Description of surface roughness parameters

Symbols	Description	Symbols	Description
R_a	Roughness average	T_{pi}	Bearing ratio (micro)
$R_{z(DIN)}$	Mean peak-to-valley height	T_{pa}	Material ratio (macro)
R_{max}	Maximum peak-to-valley height	S_m	Mean peak spacing
$R_{z(ISO)}$	Ten point height	D	Peak density
R_y	Maximum roughness depth	L_o	Actual profile length
R_q	RMS roughness average	L_r	Profile length ratio
R_p	Mean peak height	Δ_a	Average profile slope
R_{pm}	Maximum peak height	Δ_q	RSM profile slope
R_v	Mean valley depth	λ_a	Average wavelength
R_{vm}	Maximum valley depth	Λ_q	RMS wavelength
R_{3z}	Mean third highest peak-to-valley height	R	Average roughness depth
R_{3zmax}	Maximum third highest peak-to-valley height	P_t	Total profile depth
R_k	Core roughness depth	R_{max}	Maximum roughness depth
R_{pk}	Reduced peak height	W	Average waviness depth
R_{vk}	Reduced valley depth	W_{max}	Maximum waviness depth
M_{r1}	Peak material ratio	W_t	Total waviness depth
M_{r2}	Valley material ratio	A_r	Roughness width
W_t	Total waviness depth	A_w	Waviness width
P_t	Total profile depth	S_k	Skewness
N_r	Normalized peak count	K_u	Kurtosis
P_c	Peak count		

In Tables B2 to B7 are presented all measured parameters of the different surfaces involved in this work. Tables B2 to B4 contain results of measures taken before tests.

Table B2 3D surface parameters, measured by optical microscope - Before tests

Measured surfaces	3D parameters						
	Sa nm	Sku	Sp nm	Sq nm	Ssk	Sv nm	Sz nm
Grinded "L"	183,667	8,11073	5620,476	250,2106	-1,21533	-3137,4	8757,875
Grinded "R"	190,5614	7,10527	9200,237	257,0182	-1,06783	-3165,96	12366,2
Polished "L"	38,34281	53,3633	3117,248	63,96977	-4,31856	-2216,37	5333,619
Polished "R"	61,78163	57,3877	8809,611	105,1137	-4,76044	-2640,03	11449,64
Nitrided "L"	762,1668	4,63167	16280,18	971,6445	-0,20725	-9090,04	25370,21
Nitrided "R"	797,9691	3,37654	8829,175	1009,055	-0,23337	-8262,69	17091,87
Quenched/tempered "L"	170,6865	9,03223	5367,395	235,5438	-1,12026	-4242,68	9610,072
Quenched/tempered "R"	200,9044	9,49096	2220,228	275,8953	-1,40466	-9913,43	12133,66
Steel sheet HC380LA	1230,477	2,76541	19017,44	1524,327	0,424852	-11600,3	30617,76
Steel sheet HC420LA	1278,101	3,04337	24665,43	1571,088	0,444911	-9759,33	34424,77

Table B3 2D surface parameters, X-direction measured by optical microscope - Before tests

Measured surfaces	2D parameters xx direction						
	A1 mm	A2 mm	H mm	Htp mm	LamdaA mm	LamdaQ mm	Mr1 %
Grinded "L"	1.56E-05	1,46E-05	0,000381	0,000101	0,003866	0,019166	1382,17
Grinded "R"	1.46E-05	1,62E-05	0,000432	0,000122	0,004545	0,02199	1258,37
Polished "L"	2.97E-06	4,79E-06	9,21E-05	2,74E-05	0,001701	0,016169	1100,55
Polished "R"	4.57E-06	5,05E-06	0,000103	2,75E-05	0,002117	0,024454	1289,26
Nitrided "L"	3.20E-05	5,13E-05	0,001855	0,000604	0,008941	0,022356	902,159
Nitrided "R"	3.72E-05	3,34E-05	0,001511	0,000484	0,00739	0,019255	1061,84
Quenched/tempered "L"	1.37E-05	1,59E-05	0,00041	0,000118	0,004028	0,018691	1183,44
Quenched/tempered "R"	1.42E-05	1,88E-05	0,000471	0,000135	0,004323	0,018887	1150,8
Steel sheet HC380LA	0.000123	3,52E-05	0,004306	0,001362	0,024095	0,06162	1470,58
Steel sheet HC420LA	0.000123	3,33E-05	0,004367	0,001393	0,025238	0,066833	1452,93

Table B3 Continuation

Measured surfaces	2D parameters xx direction						
	Mr2 %	R3z mm	Ra mm	Rc mm	Rda °	Rdq °	Rk mm
Grinded "L"	8803,96	0,000831	9,89E-05	0,000529	9,147162	2,718682	0,000253
Grinded "R"	8759,67	0,000904	0,000113	0,000577	8,938566	2,627839	0,000304
Polished "L"	8802,2	0,000199	2,52E-05	0,000127	5,294537	0,849438	6,85E-05
Polished "R"	8874,03	0,000203	2,76E-05	0,000134	4,574998	0,663346	6,87E-05
Nitrided "L"	8681,99	0,002703	0,000499	0,001552	20,08337	10,39928	0,001509
Nitrided "R"	8900,06	0,002303	0,0004	0,001327	19,46192	9,817684	0,001211
Quenched/tempered "L"	8770,79	0,000886	0,000109	0,000558	9,693702	3,00637	0,000294
Quenched/tempered "R"	8722,82	0,000986	0,000125	0,00061	10,36233	3,36149	0,000339
Steel sheet HC380LA	9260,88	0,005206	0,001121	0,003589	16,74552	8,151049	0,003405
Steel sheet HC420LA	9282,93	0,005267	0,001139	0,003578	16,25189	7,60993	0,003482

Table B3 Continuation

2D parameters xx direction							
Measured surfaces	Rku	Rmax	RPc	Rp	Rpk	Rpk*	Rq
		mm	1/Millimeter	mm	mm	mm	mm
Grinded "L"	8,62101	0,001612	10,11668	0,000858	0,000225	0,000734	0,000144
Grinded "R"	7,4661	0,001668	7,863125	0,00088	0,000231	0,000726	0,00016
Polished "L"	27,0887	0,000547	10,82833	0,000232	5,23E-05	0,000196	3,82E-05
Polished "R"	18,3414	0,000559	5,382561	0,000297	6,86E-05	0,000262	4,35E-05
Nitrided "L"	4,81789	0,004738	8,323553	0,002712	0,0007	0,001931	0,000645
Nitrided "R"	4,86366	0,004042	10,91551	0,002422	0,000691	0,001823	0,000526
Quenched/tempered "L"	8,00699	0,001687	9,855892	0,000896	0,00023	0,000746	0,000155
Quenched/tempered "R"	7,58218	0,001805	10,01307	0,000924	0,000246	0,00075	0,000176
Steel sheet HC380LA	2,76677	0,006762	4,831427	0,00381	0,00165	0,002292	0,001387
Steel sheet HC420LA	3,07278	0,007034	4,782178	0,004034	0,001663	0,002478	0,001406

Table B3 Continuation

2D parameters xx direction							
Measured surfaces	RS	Rsk	RSm	Rt	Rv	Rvk	Rvk*
	mm		mm	mm	mm	mm	mm
Grinded "L"	0,005578	-0,07348	0,057601	0,001764	0,000905	0,000241	0,000776
Grinded "R"	0,005354	-0,16423	0,06996	0,001823	0,000943	0,000259	0,000793
Polished "L"	0,007146	-1,58333	0,051361	0,000657	0,000425	7,90E-05	0,000393
Polished "R"	0,006637	-0,4416	0,079819	0,000652	0,000355	8,39E-05	0,000321
Nitrided "L"	0,010014	-0,09636	0,046231	0,005069	0,002357	0,000772	0,001629
Nitrided "R"	0,009097	0,191652	0,037477	0,00442	0,001998	0,000598	0,001386
Quenched/tempered "L"	0,006231	-0,21522	0,057192	0,00185	0,000954	0,000257	0,000809
Quenched/tempered "R"	0,006103	-0,35494	0,054458	0,001963	0,001039	0,000291	0,000875
Steel sheet HC380LA	0,009578	0,269129	0,143993	0,007325	0,003516	0,000924	0,001628
Steel sheet HC420LA	0,009808	0,317483	0,140037	0,007469	0,003435	0,000899	0,001509

Table B3 Continuation

2D parameters xx direction	
Measured surfaces	Rz
	mm
Grinded "L"	0,001203
Grinded "R"	0,001283
Polished "L"	0,000339
Polished "R"	0,000297
Nitrided "L"	0,003664
Nitrided "R"	0,003132
Quenched/tempered "L"	0,001289
Quenched/tempered "R"	0,001403
Steel sheet HC380LA	0,006004
Steel sheet HC420LA	0,006105

Table B4 2D surface parameters, Y-direction measured by optical microscope - Before tests

2D parameters yy direction							
Measured surfaces	A1	A2	H	Htp	LamdaA	LamdaQ	Mr1
	mm	mm	mm	mm	mm	mm	%
Grinded "L"	9.16E-06	3,11E-05	0,000643	0,000202	0,004377	0,015898	810,208
Grinded "R"	9.19E-06	3,21E-05	0,000667	0,000213	0,004497	0,016115	795,513
Polished "L"	2.61E-06	9,65E-06	0,000106	3,12E-05	0,002205	0,019686	948,065
Polished "R"	2.43E-06	1,84E-05	0,000179	5,10E-05	0,003215	0,0218	719,583
Nitrided "L"	3.58E-05	7,35E-05	0,002783	0,000957	0,01094	0,021382	819,48
Nitrided "R"	3.94E-05	6,98E-05	0,002939	0,001008	0,011409	0,021854	871,463
Quenched/tempered "L"	1.01E-05	2,93E-05	0,000594	0,000188	0,004087	0,015108	822,59
Quenched/tempered "R"	9.18E-06	3,53E-05	0,000687	0,000218	0,004499	0,015711	776,224
Steel sheet HC380LA	0.000119	3,47E-05	0,004255	0,00135	0,022729	0,057079	1467,27
Steel sheet HC420LA	0.000117	3,22E-05	0,004411	0,001437	0,024302	0,061882	1438,79

Table B4 Continuation

2D parameters yy direction							
Measured surfaces	Mr2	R3z	Ra	Rc	Rda	Rdq	Rk
	%	mm	mm	mm	°	°	mm
Grinded "L"	8533,98	0,001332	0,00018	0,000719	14,81686	5,517132	0,000505
Grinded "R"	8570,43	0,001366	0,000188	0,000743	15,00884	5,675412	0,000531
Polished "L"	8568,3	0,000282	3,24E-05	0,00025	5,256183	1,04032	7,79E-05
Polished "R"	8339,74	0,00048	5,68E-05	0,000395	6,332228	1,550692	0,000127
Nitrided "L"	8791,66	0,004044	0,000761	0,002602	25,0574	16,35623	0,002392
Nitrided "R"	8826,99	0,004228	0,000796	0,002719	25,13216	16,61989	0,002519
Quenched/tempered "L"	8579,79	0,001304	0,000168	0,000698	14,74945	5,512971	0,000469
Quenched/tempered "R"	8550,75	0,001469	0,000195	0,000783	15,60373	6,151463	0,000545
Steel sheet HC380LA	9260,65	0,005192	0,001107	0,00352	17,55609	8,710834	0,003376
Steel sheet HC420LA	9306,83	0,005382	0,00116	0,003593	17,20915	8,348403	0,003592

Table B4 Continuation

2D parameters yy direction							
Measured surfaces	Rku	Rmax	RPc	Rp	Rpk	Rpk*	Rq
		mm	1/Millimeter	Mm	mm	mm	mm
Grinded "L"	6,21459	0,002227	17,31742	0,000922	0,000226	0,000639	0,000243
Grinded "R"	6,83609	0,002392	17,15532	0,000947	0,000231	0,000651	0,000254
Polished "L"	48,7369	0,000918	7,131769	0,000295	5,51E-05	0,000249	5,65E-05
Polished "R"	31,3478	0,001314	6,58038	0,000341	6,73E-05	0,000259	9,36E-05
Nitrided "L"	3,75128	0,006692	13,66602	0,003428	0,000871	0,002186	0,00097
Nitrided "R"	3,29832	0,006556	13,92868	0,003364	0,000902	0,002055	0,001008
Quenched/tempered "L"	8,08878	0,00228	18,72806	0,001034	0,000245	0,000774	0,000231
Quenched/tempered "R"	8,04886	0,00252	18,02662	0,000967	0,000236	0,000663	0,000268
Steel sheet HC380LA	2,66297	0,006812	4,808515	0,003804	0,001604	0,002303	0,001368
Steel sheet HC420LA	2,69252	0,006886	4,538838	0,003841	0,001584	0,002221	0,001424

Table B4 Continuation

Measured surfaces	2D parameters yy direction						
	RS	Rsk	RSm	Rt	Rv	Rvk	Rvk*
	mm		Mm	mm	mm	mm	mm
Grinded "L"	0,007347	-1,00109	0,029338	0,002393	0,001471	0,000424	0,001249
Grinded "R"	0,007316	-1,06721	0,029612	0,002569	0,001623	0,000447	0,001387
Polished "L"	0,007706	-4,24551	0,115649	0,001039	0,000743	0,000134	0,000712
Polished "R"	0,008229	-3,79036	0,114077	0,00143	0,001089	0,000221	0,001044
Nitrided "L"	0,012696	-0,32523	0,043204	0,007136	0,003708	0,001208	0,002558
Nitrided "R"	0,011815	-0,23713	0,042127	0,007026	0,003662	0,001185	0,002453
Quenched/tempered "L"	0,007302	-1,03811	0,028288	0,002584	0,001551	0,000411	0,001341
Quenched/tempered "R"	0,007301	-1,31068	0,028497	0,002738	0,001771	0,000486	0,00153
Steel sheet HC380LA	0,009935	0,252147	0,137081	0,007246	0,003442	0,000915	0,001567
Steel sheet HC420LA	0,00974	0,276148	0,14161	0,007281	0,003439	0,00091	0,001468

Table B4 Continuation

2D parameters yy	
Measured surfaces	Rz
	mm
Grinded "L"	0,00186
Grinded "R"	0,001924
Polished "L"	0,000598
Polished "R"	0,000921
Nitrided "L"	0,005672
Nitrided "R"	0,00567
Quenched/tempered "L"	0,001878
Quenched/tempered "R"	0,00209
Steel sheet HC380LA	0,006031
Steel sheet HC420LA	0,006129

Tables B5 to B7 contain results obtained after tests.

Table B5 3D surface parameters, measured by optical microscope - After tests

3D parameters							
Measured surfaces	Sa	Sku	Sp	Sq	Ssk	Sv	Sz
	nm		nm	nm		nm	nm
Grinded "L"	186,4594	5,64346	7362,231	249,5324	-0,74063	-2839,13	10201,36
Grinded "R"	209,794	34,7579	14819,04	308,4181	-3,07555	-6361,84	21180,89
Polished "L"	38,42874	434,741	11179,56	72,04779	-8,68151	-6343,52	17523,08
Polished "R"	59,84386	9562,82	27449,43	126,9304	46,1223	-8710,58	36160,01
Nitrided "L"	698,0403	4,66202	35148,48	885,8019	-0,37784	-11983,5	47131,94
Nitrided "R"	710,0067	4,12847	35394,86	896,0492	-0,33023	-12867,9	48262,79
Quenched/tempered "L"	176,8881	11,873	14666,12	244,6092	-1,28038	-3818,7	18484,82
Quenched/tempered "R"	203.2775	10.9653	20090.95	277.0309	-1.18442	-3506.75	23597.7

Table B6 2D surface parameters, X-direction measured by optical microscope - After tests

2D parameters xx direction							
Measured surfaces	A1	A2	H	Htp	LamdaA	LamdaQ	Mr1
	mm	mm	mm	mm	mm	mm	%
Grinded "L"	1.89E-05	1,39E-05	0,000416	0,000106	0,003984	0,019365	1518,92
Grinded "R"	1.58E-05	1,96E-05	0,000472	0,000132	0,004847	0,023768	1211,68
Polished "L"	2.79E-06	3,79E-06	8,49E-05	2,52E-05	0,001786	0,021886	1126,52
Polished "R"	5.13E-06	5,89E-06	0,000107	2,94E-05	0,002021	0,025317	1200,23
Nitrided "L"	3.27E-05	3,01E-05	0,001376	0,000445	0,008081	0,023808	1105,35
Nitrided "R"	3.14E-05	2,59E-05	0,001201	0,000386	0,006969	0,020731	1121,08
Quenched/tempered "L"	1.35E-05	1,54E-05	0,000399	0,000115	0,003848	0,017916	1182,11
Quenched/tempered "R"	1.42E-05	1.80E-05	0.000463	0.000134	0.004208	0.018308	1155.12

Table B6 Continuation

2D parameters xx direction							
Measured surfaces	Mr2	R3z	Ra	Rc	Rda	Rdq	Rk
	%	mm	mm	mm	°	°	mm
Grinded "L"	8852,07	0,000855	0,000105	0,000555	9,466295	2,831284	0,000264
Grinded "R"	8741,42	0,000931	0,000125	0,000605	9,257777	2,754113	0,00033
Polished "L"	8860,06	0,000151	2,26E-05	0,000116	4,500976	0,575863	6,30E-05
Polished "R"	8923,91	0,000202	2,90E-05	0,000252	5,045193	0,712034	7,35E-05
Nitrided "L"	8930,6	0,002051	0,000365	0,001149	16,22236	7,173429	0,001114
Nitrided "R"	8968,11	0,001924	0,000318	0,001094	16,36499	7,236528	0,000965
Quenched/tempered "L"	8791,86	0,000873	0,000106	0,000537	9,860499	3,055207	0,000288
Quenched/tempered "R"	8742.17	0.000973	0.000123	0.000605	10.4633	3.405968	0.000335

Table B6 Continuation

2D parameters xx direction							
Measured surfaces	Rku	Rmax	RPc	Rp	Rpk	Rpk*	Rq
		mm	1/Millimeter	mm	mm	mm	mm
Grinded "L"	7,82584	0,001635	9,61238	0,000885	0,000249	0,00076	0,000152
Grinded "R"	10,3662	0,001831	7,334558	0,000943	0,000256	0,000774	0,000181
Polished "L"	42,2849	0,000443	7,742779	0,000193	4,84E-05	0,000161	3,45E-05
Polished "R"	26,7812	0,000733	7,744603	0,000405	0,00026	0,000368	4,98E-05
Nitrided "L"	7,14068	0,003693	6,169544	0,00223	0,000585	0,001673	0,000474
Nitrided "R"	8,24055	0,003554	8,914027	0,002198	0,000555	0,00172	0,000415
Quenched/tempered "L"	10,3651	0,00168	10,68833	0,000898	0,000226	0,000752	0,000151
Quenched/tempered "R"	7.89909	0.001836	10.42597	0.000933	0.000244	0.000761	0.000173

Table B6 Continuation

2D parameters xx direction							
Measured surfaces	RS	Rsk	RSm	Rt	Rv	Rvk	Rvk*
	mm		mm	mm	mm	mm	mm
Grinded "L"	0,005984	0,162398	0,059076	0,001789	0,000904	0,00024	0,000765
Grinded "R"	0,005979	-0,37392	0,074185	0,002058	0,001115	0,000308	0,000954
Polished "L"	0,007129	-1,26058	0,06602	0,000548	0,000355	6,72E-05	0,000324
Polished "R"	0,0067	-0,5747	0,080718	0,000807	0,000402	0,000102	0,000365
Nitrided "L"	0,006888	0,056621	0,053915	0,004184	0,001954	0,000555	0,001398
Nitrided "R"	0,006953	0,230323	0,044265	0,003894	0,001696	0,000493	0,001209
Quenched/tempered "L"	0,005993	-0,18031	0,052641	0,001851	0,000954	0,000251	0,000811
Quenched/tempered "R"	0.006265	-0.26808	0.052869	0.001946	0.001013	0.000284	0.00085

Table B6 Continuation

2D parameters xx direction	
Measured surfaces	Rz
	mm
Grinded "L"	0,001255
Grinded "R"	0,001355
Polished "L"	0,000246
Polished "R"	0,000343
Nitrided "L"	0,002733
Nitrided "R"	0,002617
Quenched/tempered "L"	0,001272
Quenched/tempered "R"	0.001392

Table B7 2D surface parameters, Y-direction measured by optical microscope - After tests

2D parameters yy direction							
Measured surfaces	A1	A2	H	Htp	LamdaA	LamdaQ	Mr1
	mm	mm	mm	mm	mm	mm	%
Grinded "L"	1.13E-05	2,72E-05	0,000672	0,000213	0,004451	0,016045	927,079
Grinded "R"	1.01E-05	4,18E-05	0,000713	0,000222	0,004938	0,018971	787,185
Polished "L"	2.48E-06	9,98E-06	0,000106	3,14E-05	0,00233	0,021737	945,72
Polished "R"	4.03E-06	2,05E-05	0,000173	4,66E-05	0,003066	0,024772	850,421
Nitrided "L"	2.86E-05	6,73E-05	0,002505	0,000873	0,010903	0,023163	783,353
Nitrided "R"	2.92E-05	6,51E-05	0,002579	0,000899	0,010908	0,022672	804,384
Quenched/tempered "L"	9.10E-06	3,16E-05	0,000617	0,000196	0,004242	0,015628	795,622
Quenched/tempered "R"	9.09E-06	3.66E-05	0.00071	0.000224	0.004721	0.016418	766.383

Table B7 Continuation

2D parameters yy direction							
Measured surfaces	Mr2	R3z	Ra	Rc	Rda	Rdq	Rk
	%	mm	mm	mm	°	°	mm
Grinded "L"	8663,93	0,001328	0,000184	0,000729	14,87814	5,546866	0,000531
Grinded "R"	8507,43	0,001466	0,000206	0,000792	15,04122	5,739937	0,000555
Polished "L"	8586,33	0,000284	3,32E-05	0,000264	5,129375	0,982964	7,85E-05
Polished "R"	8360,08	0,000492	5,55E-05	0,000429	6,498946	1,558047	0,000117
Nitrided "L"	8788,26	0,003888	0,000691	0,002236	22,8076	13,62579	0,002181
Nitrided "R"	8816,89	0,003935	0,000706	0,002302	23,30704	14,16712	0,002247
Quenched/tempered "L"	8568,13	0,001299	0,000175	0,000707	14,84199	5,578208	0,000489
Quenched/tempered "R"	8520,72	0,001469	0,000201	0,000799	15,32752	6,002302	0,000561

Table B7 Continuation

2D parameters yy direction							
Measured surfaces	Rku	Rmax	RPc	Rp	Rpk	Rpk*	Rq
		mm	1/Millimeter	Mm	mm	mm	mm
Grinded "L"	5,63178	0,002172	17,00398	0,000958	0,000244	0,000672	0,000247
Grinded "R"	17,9361	0,003245	15,45338	0,001002	0,000253	0,000684	0,000301
Polished "L"	46,2662	0,000933	6,037379	0,000273	5,22E-05	0,000225	5,88E-05
Polished "R"	63,2673	0,00161	6,167933	0,000489	0,000238	0,000415	0,000107
Nitrided "L"	4,12766	0,006022	12,8155	0,002948	0,000729	0,001788	0,000876
Nitrided "R"	3,67103	0,005962	13,28913	0,002927	0,000723	0,001742	0,00089
Quenched/tempered "L"	9,10843	0,002284	18,20659	0,000957	0,000229	0,000684	0,000242
Quenched/tempered "R"	6,92594	0,002574	16,56974	0,000983	0,000236	0,000667	0,000273

Table B7 Continuation

2D parameters yy direction							
Measured surfaces	RS	Rsk	RSm	Rt	Rv	Rvk	Rvk*
	mm		Mm	mm	mm	mm	mm
Grinded "L"	0,007589	-0,77941	0,029805	0,002351	0,001393	0,000408	0,001147
Grinded "R"	0,007584	-2,08008	0,032841	0,003502	0,002499	0,000559	0,002263
Polished "L"	0,007974	-4,48772	0,137832	0,001034	0,000761	0,000142	0,00073
Polished "R"	0,007952	-5,31317	0,133746	0,00188	0,00139	0,00025	0,001349
Nitrided "L"	0,008497	-0,37973	0,039227	0,006397	0,003449	0,00111	0,002428
Nitrided "R"	0,008597	-0,3275	0,038739	0,006319	0,003392	0,001092	0,002329
Quenched/tempered "L"	0,007154	-1,24183	0,028177	0,002623	0,001667	0,00044	0,00145
Quenched/tempered "R"	0,007471	-1,18076	0,030535	0,002741	0,001757	0,000494	0,001512

Table B7 Continuation

2D parameters yy direction	
Measured surfaces	Rz
	mm
Grinded "L"	0,001837
Grinded "R"	0,002169
Polished "L"	0,000619
Polished "R"	0,001007
Nitrided "L"	0,004877
Nitrided "R"	0,004997
Quenched/tempered "L"	0,001849
Quenched/tempered "R"	0.002092

B 2. Contact measurement results by HOMMEL tester T500

Measuring surface roughness and quality surfaces are traditionally estimated by the naked eye and measured by mechanical profilers for surface roughness, commonly described with the R_a , R_z and R_t values.

In Tables B8 to B25 all measured parameters of the different surfaces involved in this work. Tables contain results of measures taken before tests and after tests.

Table B8 Grinded “L” surface parameters - Before tests

Grinded “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.69	0.48	0.07	1.90	1.34	0.14
2	1.01	0.64	0.09	1.44	1.21	0.13
3	0.82	0.65	0.10	1.71	1.32	0.12
Average	0.84	0.59	0.09	1.68	1.29	0.13
Measured by optical microscope	1.61	1.20	0.09	2.23	1.86	0.18

Table B9 Grinded “L” surface parameters - After tests

Grinded “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.94	0.70	0.10	1.62	1.16	0.12
2	0.92	0.72	0.10	1.60	1.14	0.12
3	0.60	0.52	0.08	1.54	1.28	0.14
Average	0.82	0.65	0.09	1.59	1.19	0.13
Measured by optical microscope	1.63	1.25	0.10	2.17	1.83	0.18

Table B10 Grinded “R” surface parameters - Before tests

Grinded “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.75	0.66	0.11	1.63	1.28	0.14
2	0.57	0.50	0.09	1.30	1.19	0.13
3	1.12	0.81	0.12	1.60	1.15	0.13
Average	0.81	0.66	0.11	1.51	1.21	0.13
Measured by optical microscope	1.66	1.28	0.11	2.39	1.92	0.18

Table B11 Grinded “R” surface parameters - After tests

Grinded “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.76	0.68	0.10	1.70	1.30	0.14
2	1.12	0.78	0.10	1.76	1.38	0.14
3	0.74	0.56	0.08	1.14	1.00	0.12
Average	0.87	0.67	0.09	1.53	1.23	0.13
Measured by optical microscope	1.83	1.35	0.12	3.24	2.16	0.20

Table B12 Polished “L” surface parameters - Before tests

Polished “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.16	0.14	0.02	0.58	0.48	0.04
2	0.16	0.12	0.02	0.54	0.38	0.04
3	0.12	0.10	0.02	0.60	0.30	0.02
Average	0.15	0.12	0.02	0.57	0.39	0.03
4	0.42	0.28	0.04	1.18	0.72	0.06
5	0.40	0.26	0.02	1.02	0.80	0.06
6	0.46	0.36	0.04	-	-	-
Average	0.43	0.3	0.03	1.1	0.76	0.06
Measured by optical microscope	0.54	0.33	0.02	0.91	0.59	0.03

Table B13 Polished “L” surface parameters - After tests

Polished “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.18	0.14	0.02	0.92	0.42	0.02
2	0.16	0.14	0.02	0.44	0.30	0.02
3	0.14	0.12	0.02	0.16	0.12	0.02
Average	0.15	0.12	0.02	0.57	0.39	0.03
4	0.50	0.30	0.04	1.50	0.62	0.04
5	4.90	1.38	0.18	0.90	0.48	0.04
6	0.40	0.30	0.04	1.54	0.50	0.02
Average	1.93	0.66	0.09	1.31	0.53	0.03
Measured by optical microscope	0.44	0.24	0.02	0.93	0.61	0.03

Table B14 Polished “R” surface parameters - Before tests

Polished “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.16	0.12	0.02	0.12	0.10	0.02
2	0.26	0.16	0.02	0.24	0.14	0.04
3	0.32	0.20	0.04	0.16	0.12	0.02
Average	0.25	0.16	0.03	0.17	0.12	0.03
4	0.40	0.26	0.04	0.98	0.52	0.04
5	0.66	0.38	0.04	0.76	0.58	0.04
6	0.48	0.30	0.04	1.16	0.64	0.04
Average	0.51	0.31	0.04	0.97	0.58	0.04
Measured by optical microscope	0.55	0.29	0.02	1.31	0.92	0.05

Table B15 Polished “R” surface parameters - After tests

Polished “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.22	0.12	0.02	1.08	0.66	0.04
2	0.26	0.18	0.02	0.22	0.16	0.02
3	0.20	0.14	0.02	1.18	0.70	0.04
Average	0.23	0.15	0.02	0.83	0.51	0.03
4	0.34	0.24	0.04	1.08	0.72	0.06
5	0.34	0.26	0.04	1.06	0.72	0.06
6	0.36	0.30	0.04	0.66	0.52	0.06
Average	0.35	0.27	0.04	0.93	0.65	0.06
Measured by optical microscope	0.73	0.34	0.02	1.61	1.00	0.05

Table B16 Nitrided “L” surface parameters - Before tests

Nitrided “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	4.02	2.88	0.42	8.44	6.34	0.82
2	5.16	4.06	0.62	7.80	5.64	0.80
3	8.46	3.42	0.42	10.72	6.90	0.90
Average	5.88	3.45	0.49	8.99	6.29	0.84
Measured by optical microscope	4.73	3.66	0.49	6.69	5.67	0.76

Table B17 Nitrided “L” surface parameters - After tests

Nitrided “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	4.80	3.47	0.60	5.34	4.06	0.50
2	3.30	2.68	0.48	5.08	4.24	0.52
3	3.78	3.06	0.48	6.12	4.70	0.54
Average	3.96	3.07	0.52	5.51	4.33	0.52
Measured by optical microscope	3.69	2.73	0.36	6.02	4.87	0.69

Table B18 Nitrided “R” surface parameters - Before tests

Nitrided “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	4.60	3.28	0.54	5.42	4.80	0.68
2	2.98	2.50	0.38	8.30	5.34	0.64
3	3.36	2.88	0.36	5.94	5.44	0.68
Average	3.65	2.89	0.43	6.55	5.19	0.67
Measured by optical microscope	4.04	3.13	0.4	6.55	5.67	0.79

Table B19 Nitrided “R” surface parameters - After tests

Nitrided “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	3.82	2.62	0.48	5.46	4.20	0.56
2	3.92	3.08	0.48	5.86	4.32	0.58
3	2.42	2.10	0.32	4.44	3.92	0.54
Average	3.39	2.6	0.43	5.25	4.15	0.56
Measured by optical microscope	3.55	2.61	0.31	5.96	4.99	0.70

Table B20 Quenched/tempered “L” surface parameters - Before tests

Quenched/tempered “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	1.68	0.96	0.14	2.38	1.20	0.10
2	0.84	0.62	0.08	1.60	1.18	0.12
3	0.88	0.64	0.10	2.02	1.20	0.10
Average	1.13	0.74	0.11	2	1.19	0.11
Measured by optical microscope	1.68	1.28	0.10	2.28	1.87	0.16

Table B21 Quenched/tempered “L” surface parameters - After tests

Quenched/tempered “L”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.68	0.50	0.08	13.80	4.98	0.66
2	0.80	0.62	0.08	1.18	0.98	0.10
3	0.70	0.58	0.08	1.36	1.04	0.10
Average	0.73	0.57	0.08	5.45	2.33	0.29
Measured by optical microscope	1.68	1.27	0.10	2.28	1.84	0.17

Table B22 Quenched/tempered “R” surface parameters - Before tests

Quenched/tempered “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.84	0.66	0.10	2.58	1.40	0.12
2	1.32	0.90	0.10	1.56	1.26	0.14
3	0.60	0.56	0.08	1.46	1.22	0.12
Average	0.92	0.71	0.09	1.87	1.29	0.13
Measured by optical microscope	1.80	1.40	0.12	2.52	2.09	0.19

Table B23 Quenched/tempered “R” surface parameters - After tests

Quenched/tempered “R”	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	0.82	0.58	0.10	1.56	1.06	0.12
2	10.86	5.84	1.34	9.40	2.90	0.22
3	0.82	0.70	0.10	1.04	0.92	0.12
Average	4.17	2.37	0.51	4	1.63	0.15
Measured by optical microscope	1.83	1.39	0.12	2.57	2.09	0.20

Table B24 HC380LA sheet surface parameters - Before tests

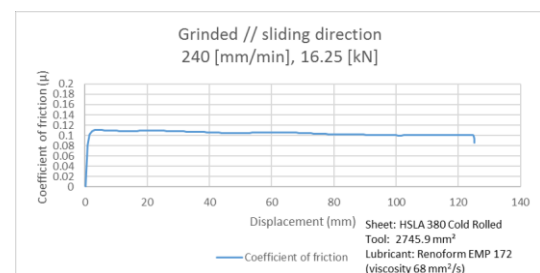
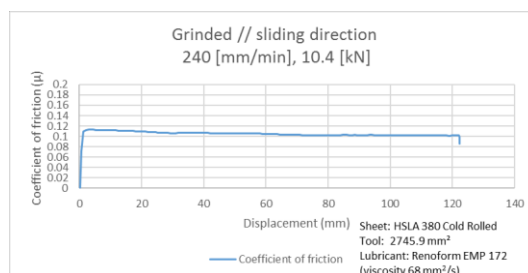
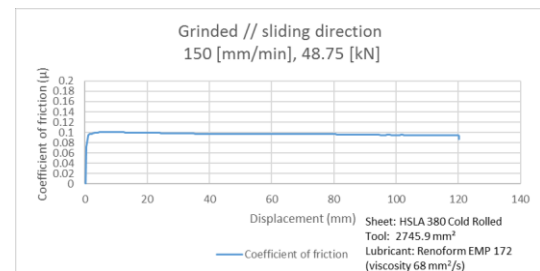
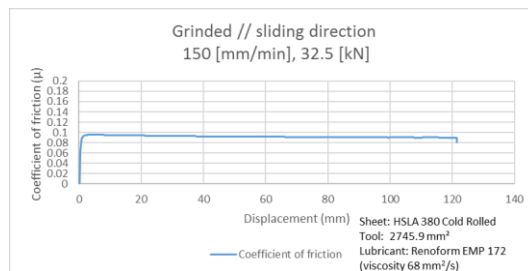
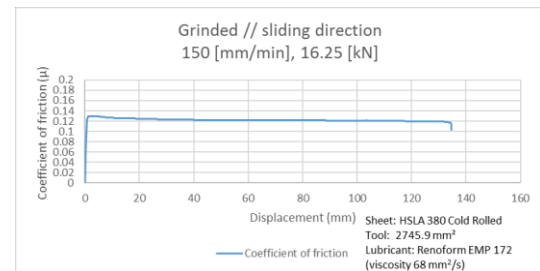
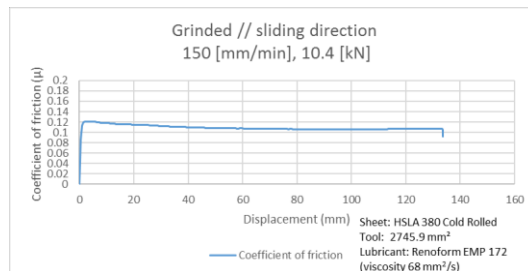
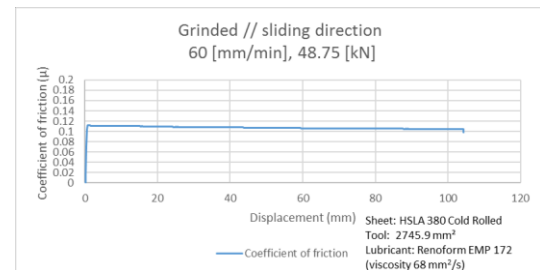
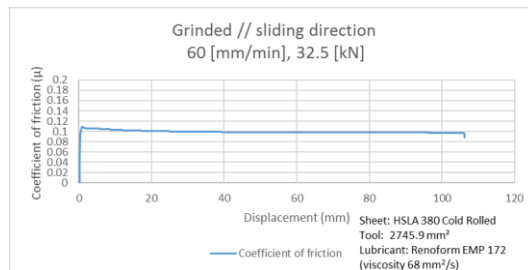
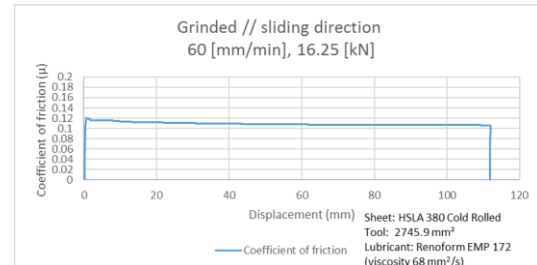
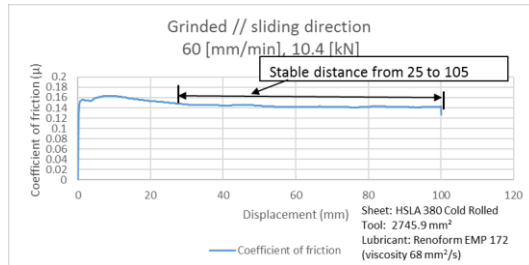
HSLA 380 sheet roughness	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	7.44	6.34	1.24	6.18	6.00	1.08
2	7.48	6.14	1.16	6.08	5.70	1.04
3	6.68	6.04	1.10	6.74	5.78	1.14
4	7.16	6.22	1.06	6.24	5.70	1.06
5	7.04	6.38	1.16	6.68	5.92	1.12
6	7.00	5.88	1.06	6.40	5.84	1.08
Average	7.13	6.17	1.13	6.39	5.82	1.09
Measured by optical microscope	6.76	6.00	1.12	6.81	6.03	1.10

Table B25 HC420LA sheet surface parameters - Before tests

HSLA 420 sheet roughness	Measurement <u>along</u> to sliding direction			Measurement <u>perpendicular</u> to sliding direction		
Order of tests	RmD μm	RzD μm	Ra μm	RmD μm	RzD μm	Ra μm
1	7.94	6.84	1.20	6.36	5.72	1.04
2	6.64	5.94	1.00	7.34	6.10	1.12
3	6.58	6.08	1.16	6.48	6.04	1.10
4	6.80	6.40	1.00	6.30	5.96	1.16
5	7.08	6.44	1.16	6.38	5.80	1.10
6	6.70	6.40	1.10	6.92	6.30	1.04
Average	6.96	6.35	1.1	6.63	5.99	1.09
Measured by optical microscope	7.03	6.10	1.13	6.88	6.12	1.16

C. Strip drawing test results

C 1. The coefficient of friction as a function of sliding speed and applied normal force



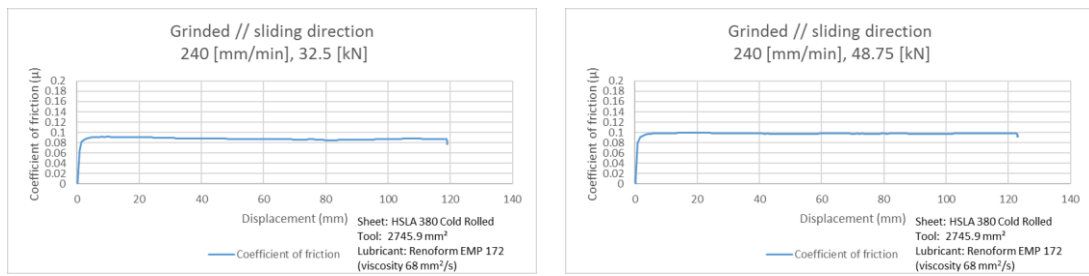
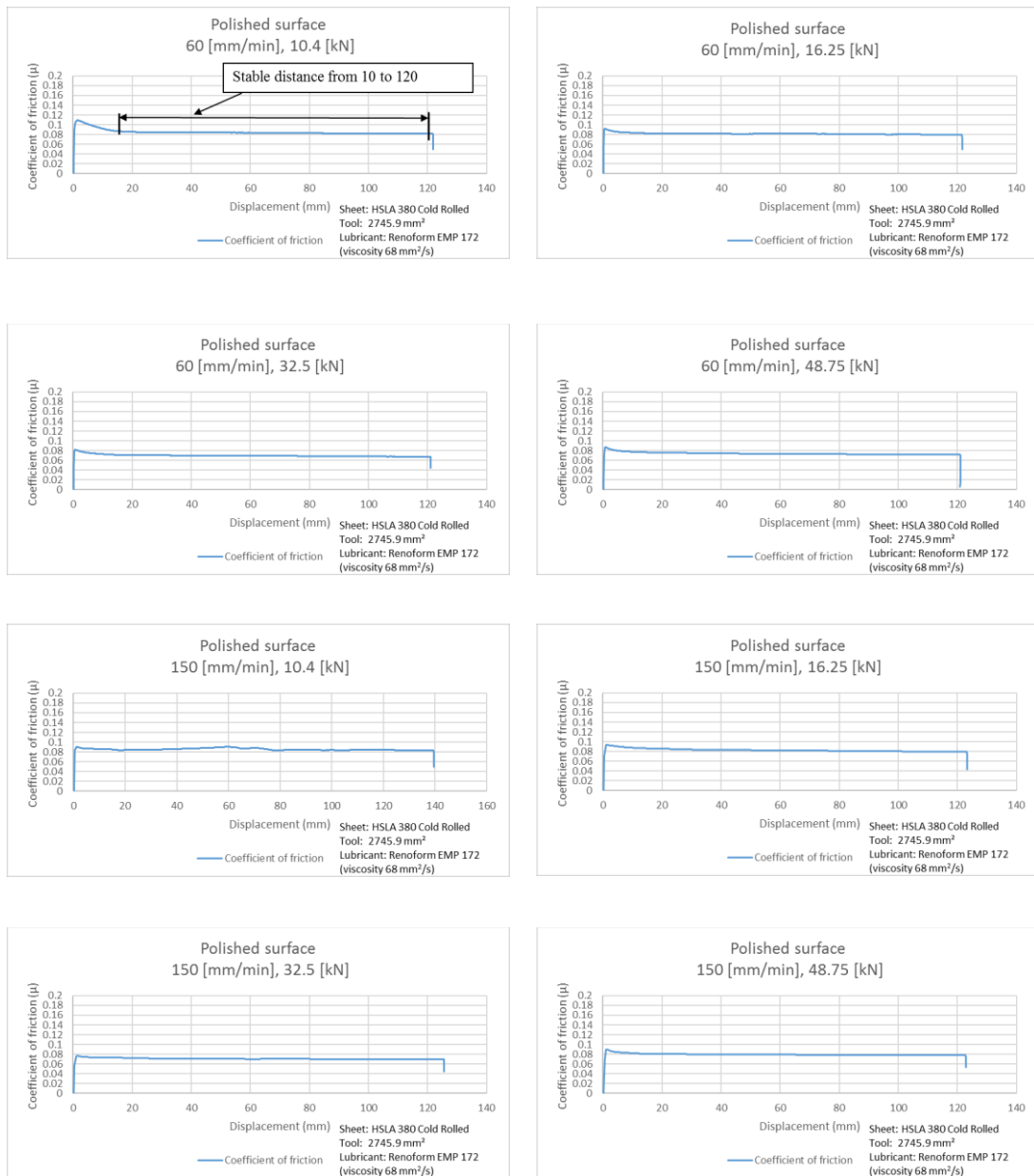


Figure C1 The coefficient of friction as a function of displacement at constant sliding speed and applied normal force for Grinded surface



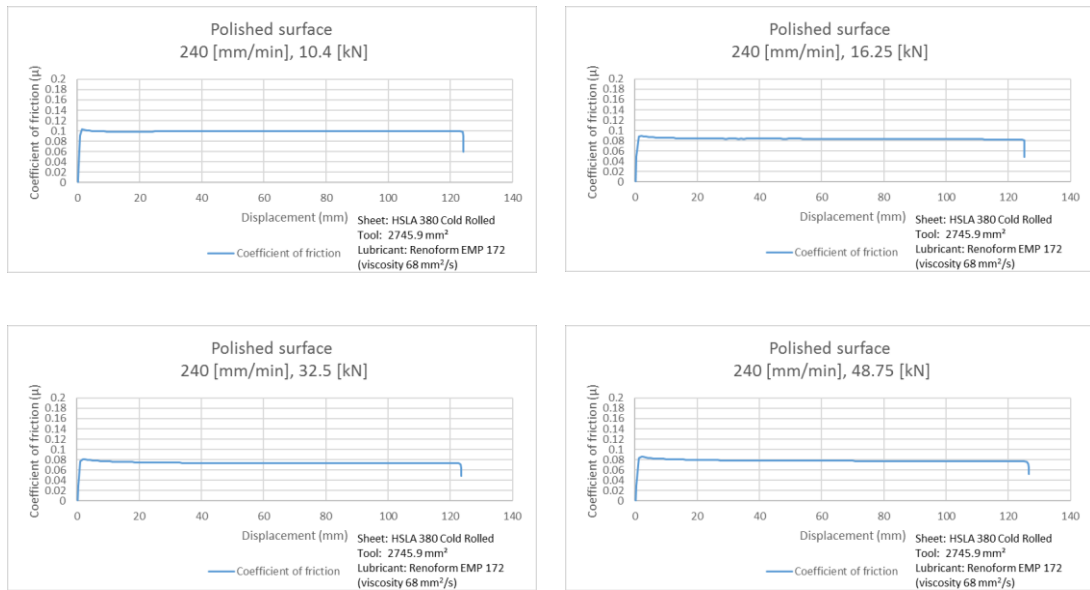
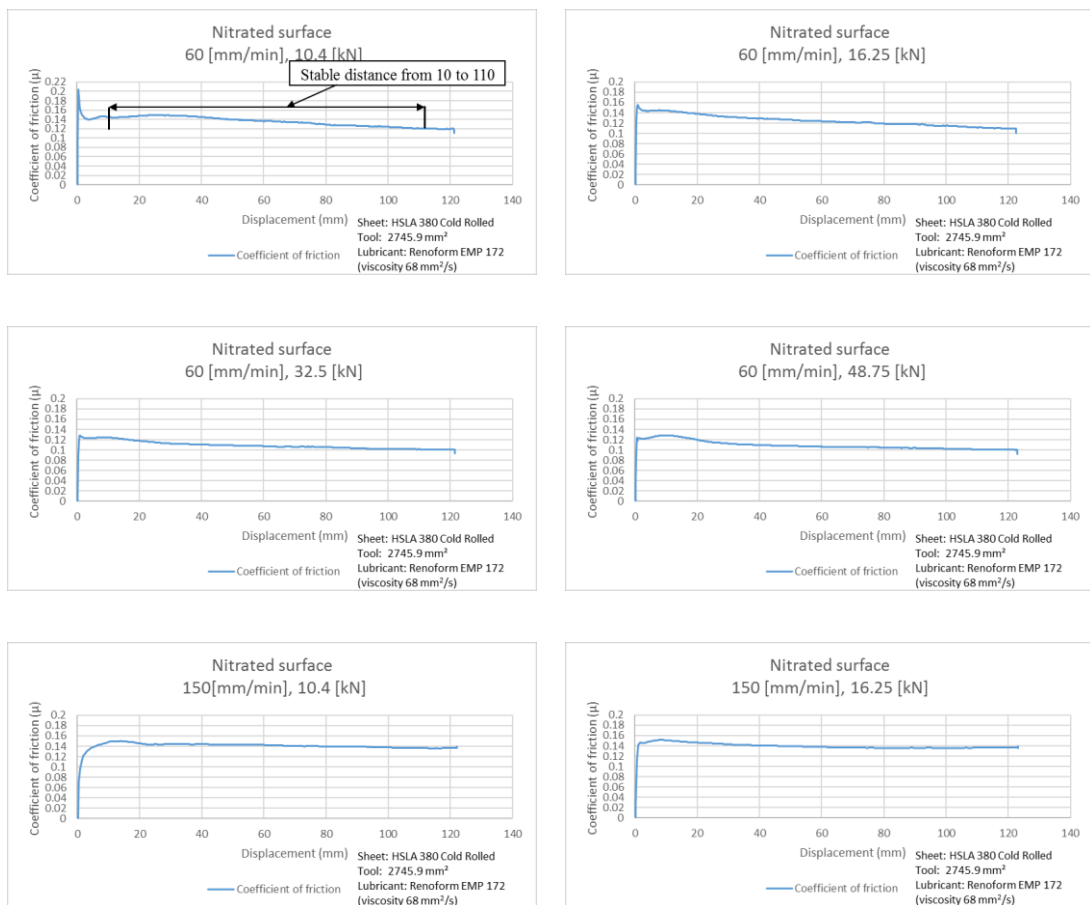


Figure C2 The coefficient of friction as a function of displacement at constant sliding speed and applied normal force for Polished surface



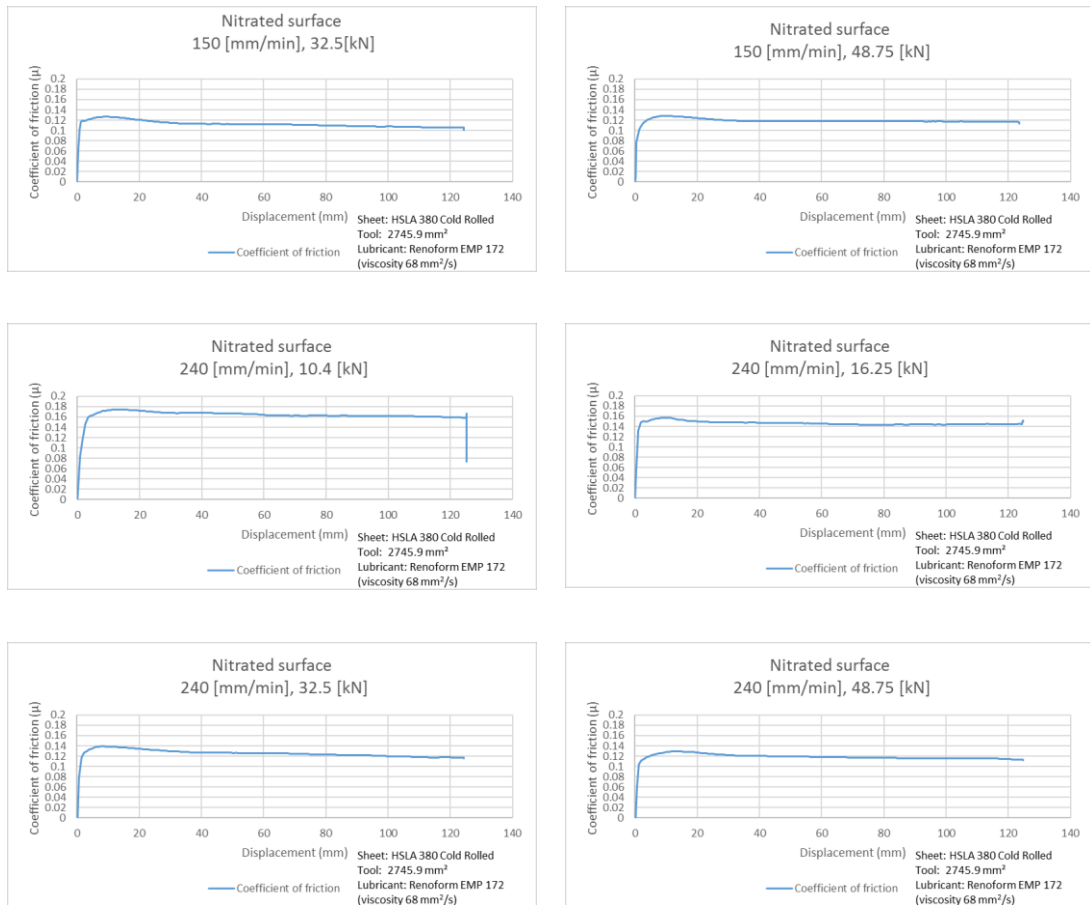


Figure C3 The coefficient of friction as a function of displacement at constant sliding speed and applied normal force for Nitrated surface

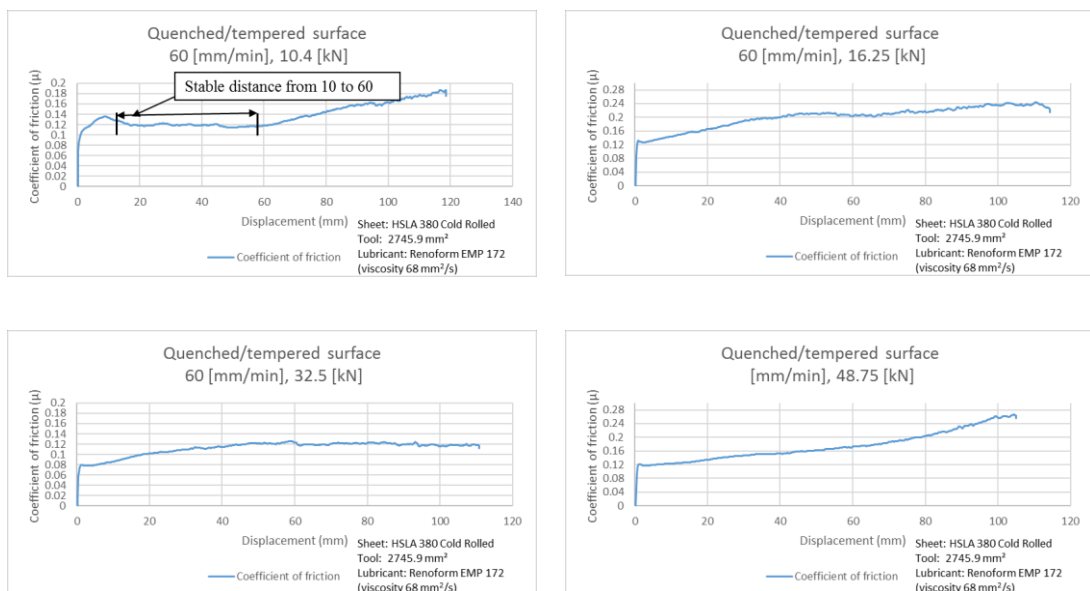
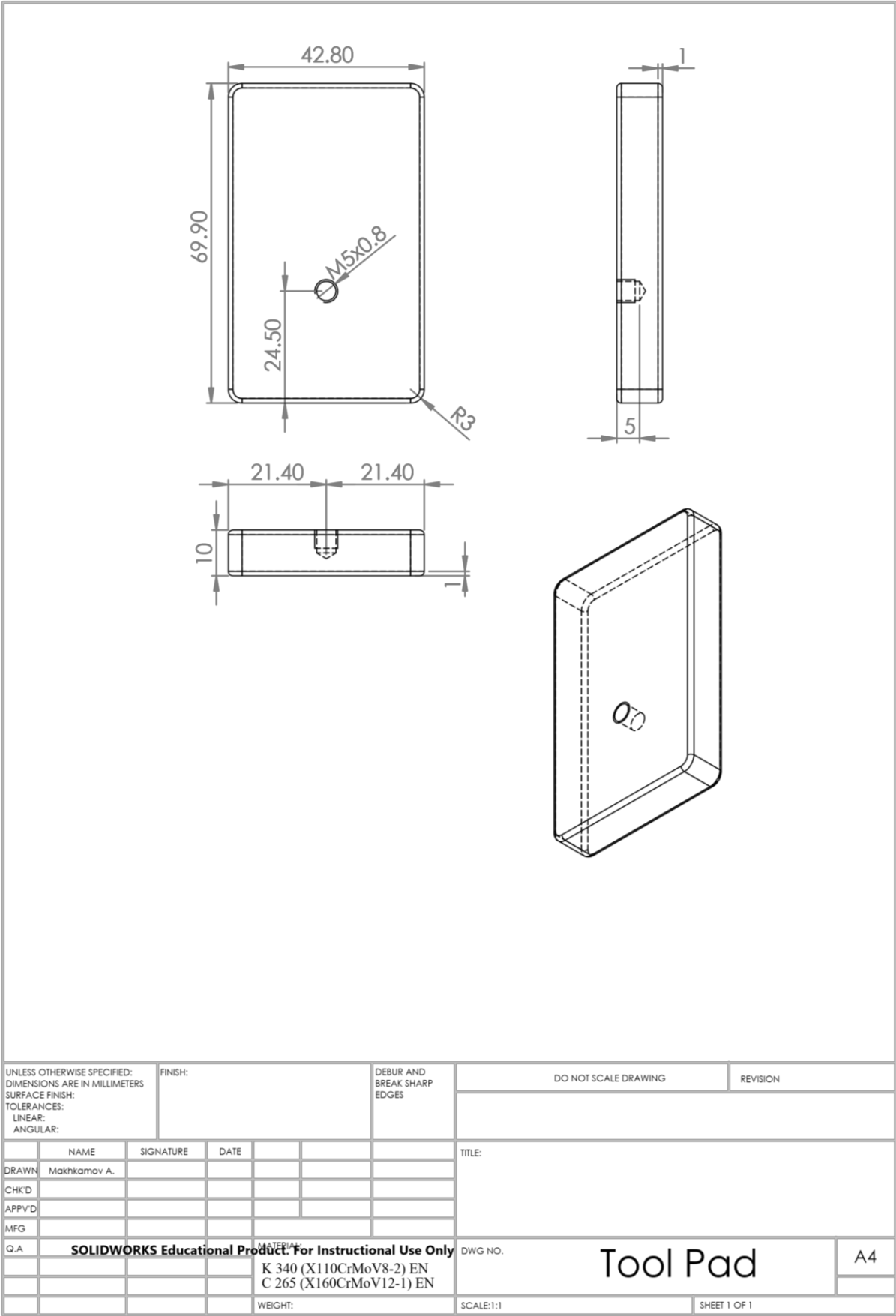
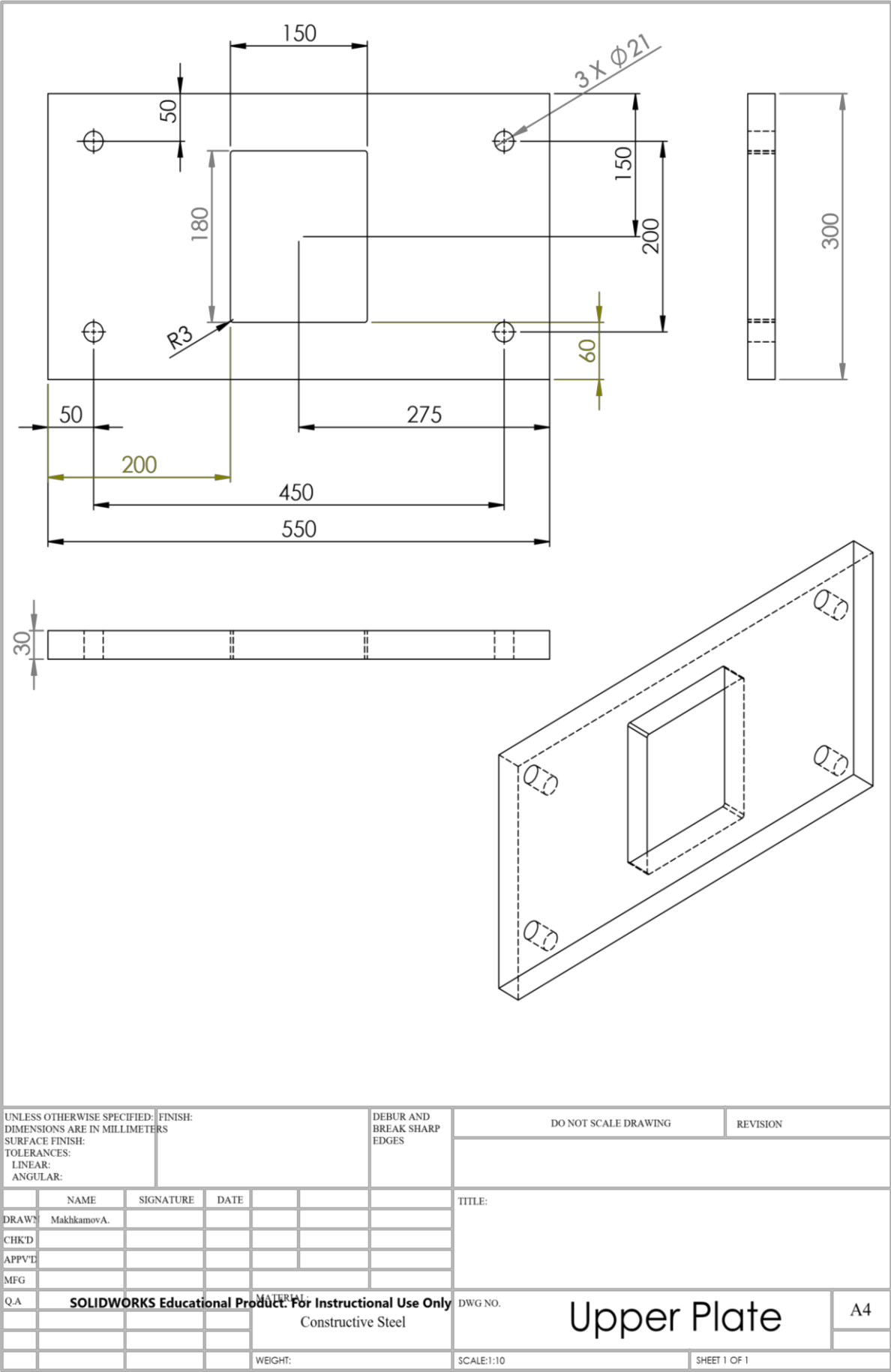
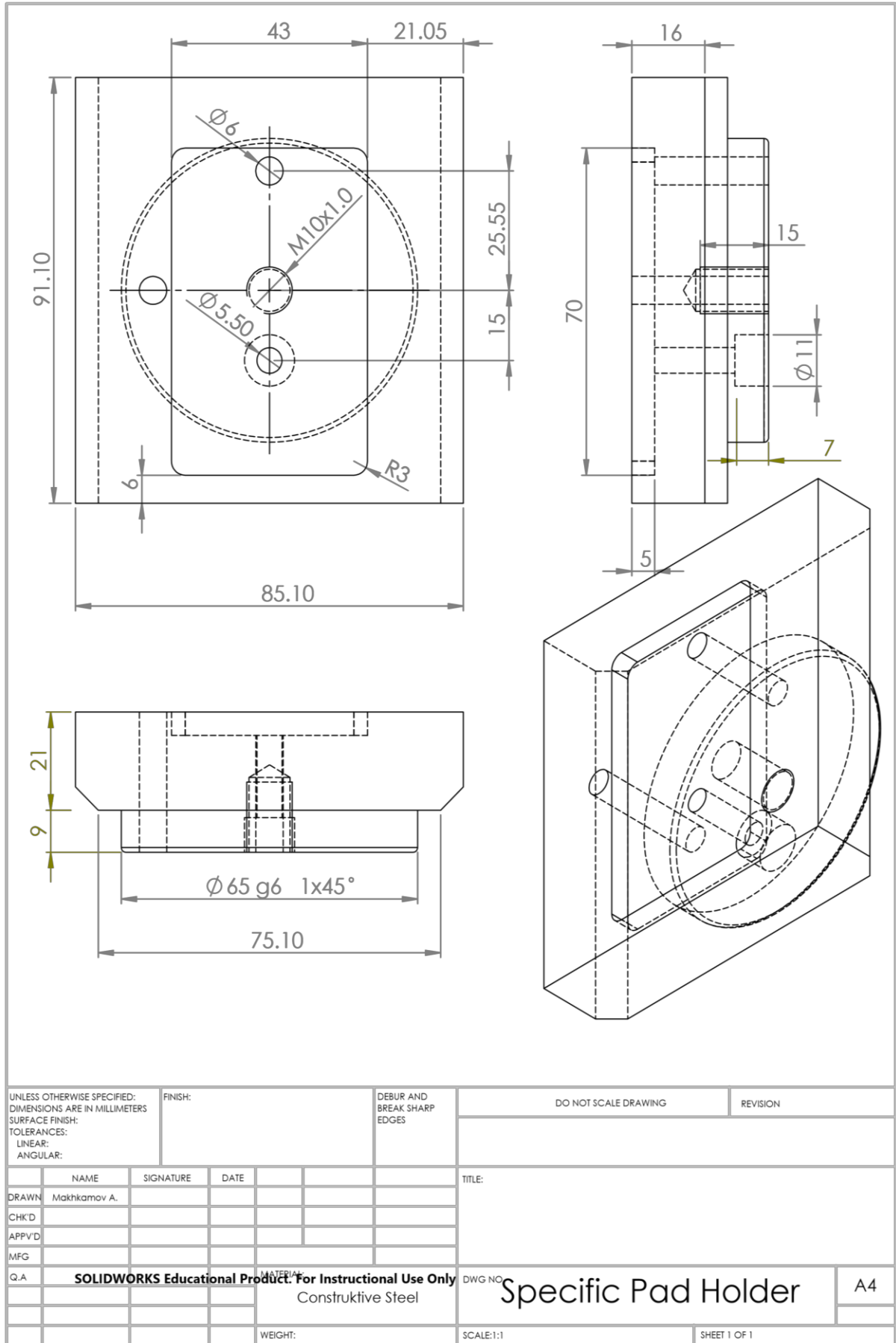


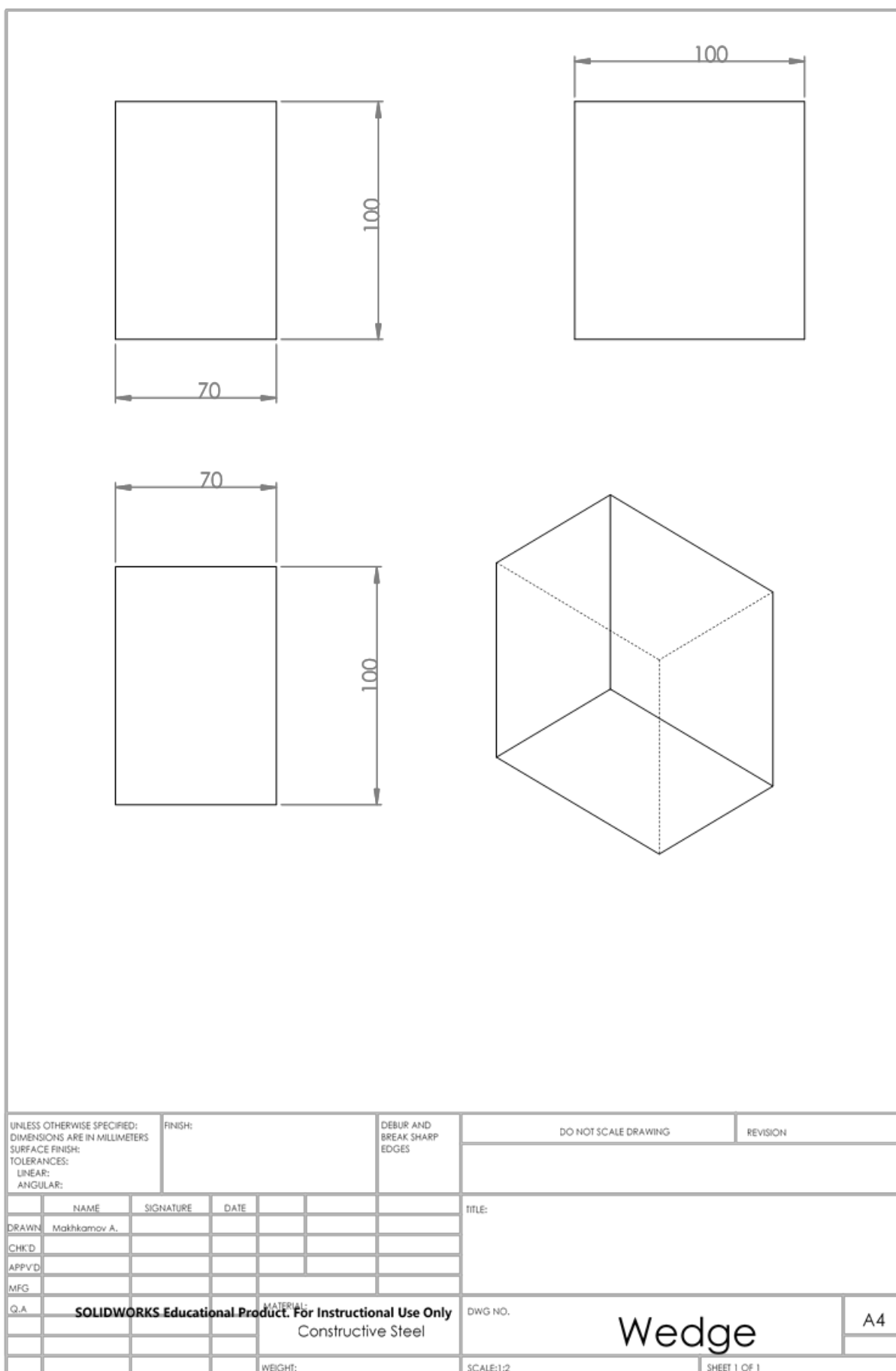
Figure C4 The coefficient of friction as a function of displacement at constant sliding speed and applied normal force for Quenched/tempered surface

C 2. Set of tools





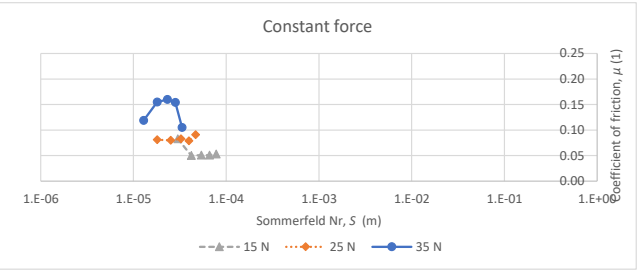
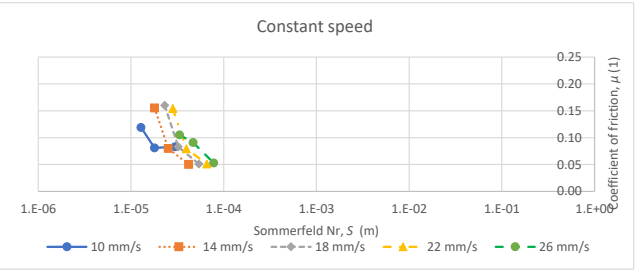
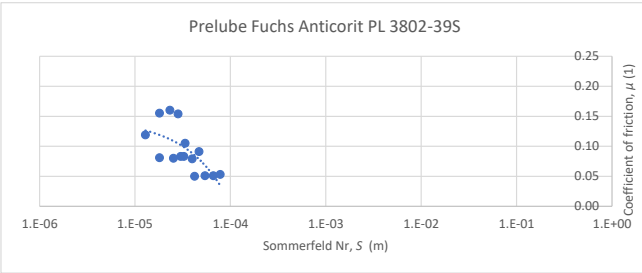




Prelube Fuchs Anticorit PL 3802-395

	Value	Unit
Lubricant's kinematic viscosity:	1.00E-02	cSt = mm2/s
Lubricant's density:		kg/m3
Lubricant's absolute viscosity:	0.0450	Pa.s
Force1	15	N
Force2	25	N
Force3	35	N
Speed1	1.00E-02	m/s
Speed2	1.40E-02	m/s
Speed3	1.80E-02	m/s
Speed4	2.20E-02	m/s
Speed5	2.60E-02	m/s

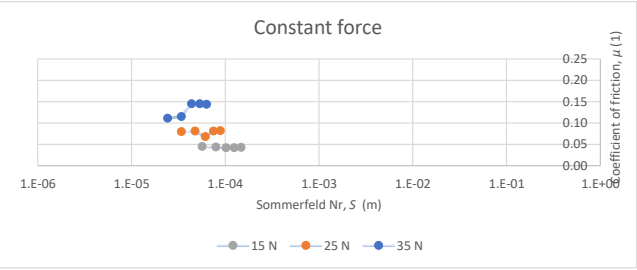
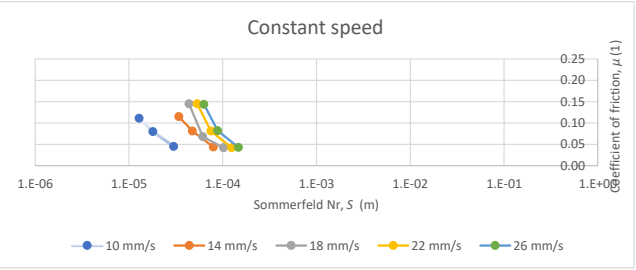
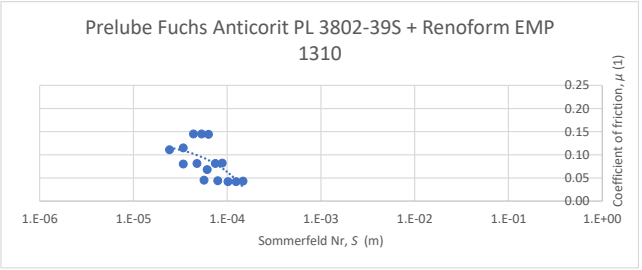
Speed	Force	Sommersfeld	Friction
1.00E-02	35	1.29E-05	0.119
1.00E-02	25	1.80E-05	0.081
1.00E-02	15	3.00E-05	0.083
1.40E-02	35	1.80E-05	0.155
1.40E-02	25	2.52E-05	0.08
1.40E-02	15	4.20E-05	0.05
1.80E-02	35	2.31E-05	0.16
1.80E-02	25	3.24E-05	0.083
1.80E-02	15	5.40E-05	0.051
2.20E-02	35	2.83E-05	0.154
2.20E-02	25	3.96E-05	0.079
2.20E-02	15	6.60E-05	0.051
2.60E-02	35	3.34E-05	0.105
2.60E-02	25	4.68E-05	0.091
2.60E-02	15	7.80E-05	0.053



Prelube Fuchs Anticorit PL 3802-395 + Renoform EMP 1310

	Value	Unit
Lubricant's kinematic viscosity:		cSt = mm2/s
Lubricant's density:		kg/m3
Lubricant's absolute viscosity:	0.0850	Pa.s
Force1	15	N
Force2	25	N
Force3	35	N
Speed1	1.00E-02	m/s
Speed2	1.40E-02	m/s
Speed3	1.80E-02	m/s
Speed4	2.20E-02	m/s
Speed5	2.60E-02	m/s

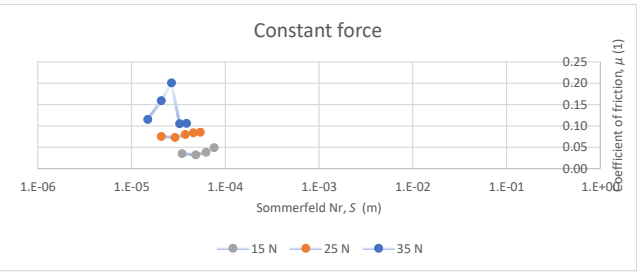
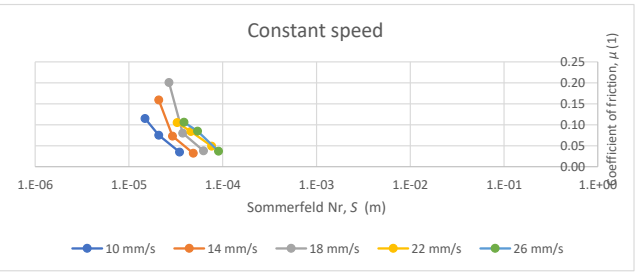
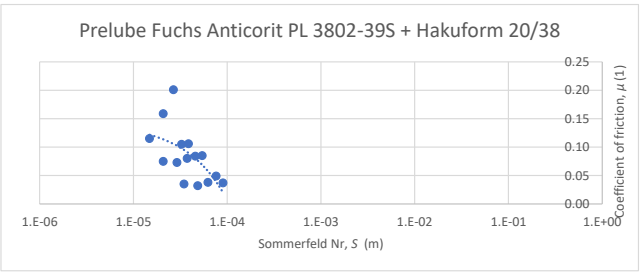
Speed	Force	Sommersfeld	Friction
1.00E-02	35	2.43E-05	0.111
1.00E-02	25	3.40E-05	0.08
1.00E-02	15	5.67E-05	0.045
1.40E-02	35	3.40E-05	0.115
1.40E-02	25	4.76E-05	0.081
1.40E-02	15	7.93E-05	0.044
1.80E-02	35	4.37E-05	0.145
1.80E-02	25	6.12E-05	0.068
1.80E-02	15	1.02E-04	0.042
2.20E-02	35	5.34E-05	0.145
2.20E-02	25	7.48E-05	0.081
2.20E-02	15	1.25E-04	0.042
2.60E-02	35	6.31E-05	0.144
2.60E-02	25	8.84E-05	0.082
2.60E-02	15	1.47E-04	0.043



Prelube Fuchs Anticorit PL 3802-395 + Hakuform 20/38

	Value	Unit
Lubricant's kinematic viscosity:		cSt = mm2/s
Lubricant's density:		kg/m3
Lubricant's absolute viscosity:	0.0520	Pa.s
Force1	15	N
Force2	25	N
Force3	35	N
Speed1	1.00E-02	m/s
Speed2	1.40E-02	m/s
Speed3	1.80E-02	m/s
Speed4	2.20E-02	m/s
Speed5	2.60E-02	m/s

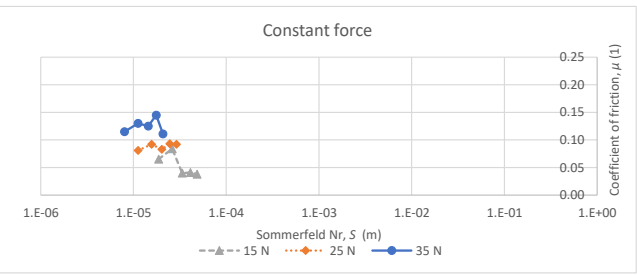
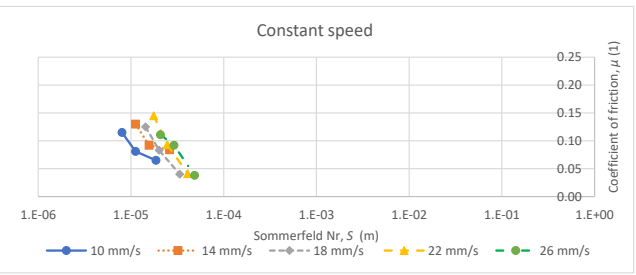
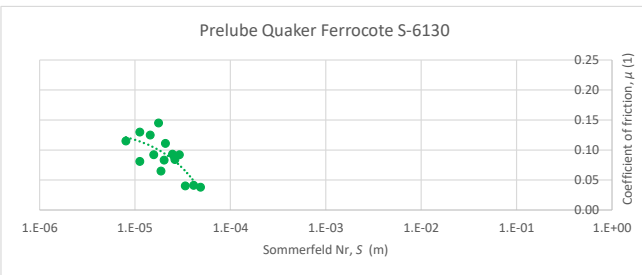
Speed	Force	Sommersfeld	Friction
1.00E-02	35	1.49E-05	0.115
1.00E-02	25	2.08E-05	0.075
1.00E-02	15	3.47E-05	0.035
1.40E-02	35	2.08E-05	0.159
1.40E-02	25	2.91E-05	0.073
1.40E-02	15	4.85E-05	0.032
1.80E-02	35	2.67E-05	0.201
1.80E-02	25	3.74E-05	0.08
1.80E-02	15	6.24E-05	0.038
2.20E-02	35	3.27E-05	0.105
2.20E-02	25	4.58E-05	0.084
2.20E-02	15	7.63E-05	0.049
2.60E-02	35	3.86E-05	0.106
2.60E-02	25	5.41E-05	0.085
2.60E-02	15	9.01E-05	0.037



Prelube Quaker Ferrocode S-6130

	Value	Unit
Lubricant's kinematic viscosity:		cSt = mm2/s
Lubricant's density:		kg/m3
Lubricant's absolute viscosity:	0.0280	Pa.s
Force1	15	N
Force2	25	N
Force3	35	N
Speed1	1.00E-02	m/s
Speed2	1.40E-02	m/s
Speed3	1.80E-02	m/s
Speed4	2.20E-02	m/s
Speed5	2.60E-02	m/s

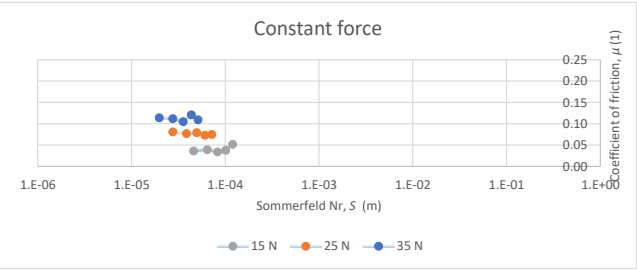
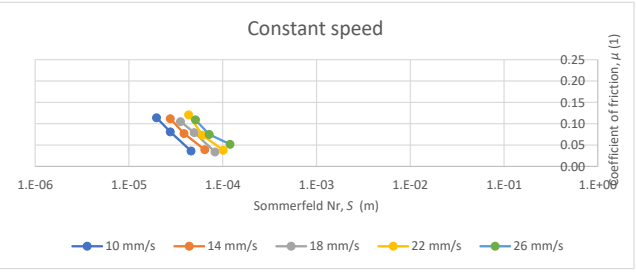
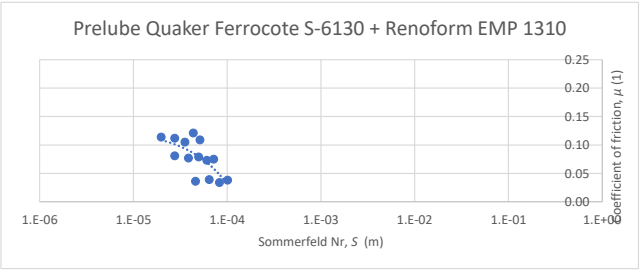
Speed	Force	Sommersfeld	Friction
1.00E-02	35	8.00E-06	0.115
1.00E-02	25	1.12E-05	0.081
1.00E-02	15	1.87E-05	0.065
1.40E-02	35	1.12E-05	0.13
1.40E-02	25	1.57E-05	0.092
1.40E-02	15	2.61E-05	0.084
1.80E-02	35	1.44E-05	0.125
1.80E-02	25	2.02E-05	0.083
1.80E-02	15	3.36E-05	0.04
2.20E-02	35	1.76E-05	0.145
2.20E-02	25	2.46E-05	0.093
2.20E-02	15	4.11E-05	0.041
2.60E-02	35	2.08E-05	0.111
2.60E-02	25	2.91E-05	0.092
2.60E-02	15	4.85E-05	0.038



Prelube Quaker Ferrocode S-6130 + Renoform EMP 1310

	Value	Unit
Lubricant's kinematic viscosity:		cSt = mm2/s
Lubricant's density:		kg/m3
Lubricant's absolute viscosity:	0.0690	Pa.s
Force1	15	N
Force2	25	N
Force3	35	N
Speed1	1.00E-02	m/s
Speed2	1.40E-02	m/s
Speed3	1.80E-02	m/s
Speed4	2.20E-02	m/s
Speed5	2.60E-02	m/s

Speed	Force	Sommersfeld	Friction
1.00E-02	35	1.97E-05	0.114
1.00E-02	25	2.76E-05	0.081
1.00E-02	15	4.60E-05	0.036
1.40E-02	35	2.76E-05	0.112
1.40E-02	25	3.86E-05	0.077
1.40E-02	15	6.44E-05	0.039
1.80E-02	35	3.55E-05	0.105
1.80E-02	25	4.97E-05	0.079
1.80E-02	15	8.28E-05	0.034
2.20E-02	35	4.34E-05	0.121
2.20E-02	25	6.07E-05	0.073
2.20E-02	15	1.01E-04	0.038
2.60E-02	35	5.13E-05	0.109
2.60E-02	25	7.18E-05	0.075
2.60E-02	15	1.20E-04	0.052



Prelube Quaker Ferrocode S-6130 + Hakuform 20/38

	Value	Unit
Lubricant's kinematic viscosity:		cSt = mm2/s
Lubricant's density:		kg/m3
Lubricant's absolute viscosity:	0.0370	Pa.s
Force1	15	N
Force2	25	N
Force3	35	N
Speed1	1.00E-02	m/s
Speed2	1.40E-02	m/s
Speed3	1.80E-02	m/s
Speed4	2.20E-02	m/s
Speed5	2.60E-02	m/s

Speed	Force	Sommersfeld	Friction
1.00E-02	35	1.06E-05	0.117
1.00E-02	25	1.48E-05	0.078
1.00E-02	15	2.47E-05	0.036
1.40E-02	35	1.48E-05	0.101
1.40E-02	25	2.07E-05	0.074
1.40E-02	15	3.45E-05	0.03
1.80E-02	35	1.90E-05	0.112
1.80E-02	25	2.66E-05	0.079
1.80E-02	15	4.44E-05	0.034
2.20E-02	35	2.33E-05	0.113
2.20E-02	25	3.26E-05	0.081
2.20E-02	15	5.43E-05	0.029
2.60E-02	35	2.75E-05	0.114
2.60E-02	25	3.85E-05	0.08
2.60E-02	15	6.41E-05	0.037

