

Micro-milling of cemented carbide with diamond coated tools

by

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Abstract

The micro-milling of brittle materials in a ductile cutting mode presents itself as a possible real industrial application of high value. It allows the production of complex 3D features with excellent finishing and small tolerances, and it may be applied to the manufacture of micro-injection moulds and dies. However, the cutting phenomena at microscopic level are different from what is seen at the macroscopic level, so the analysis of micro-machining should also be done by taking in account this scale effect. The presence of minimum uncut chip thickness, critical uncut chip thickness, size effect, elastic recovery and ploughing mechanisms are the main issues and difficulties in micro-milling. Besides that, there are limited reported details about the features of the layer where ploughing dominates. The present work provides a review of the main, current and available concepts about micro-milling. Additionally, an experimental study is conducted for two grades of cemented carbide, namely WC-15Co and WC-10Co, with two different tools: (i) a two-flute micro ball end mill and (ii) a micro ball end mill without cutting edges. An extensive experimental campaign was developed for a wide range of operative conditions. In these experiments, for each WC-Co grade, both depth of cut and cut width influence have been analysed. After the tests, the comparison of the real and the theoretical chip size was performed and chip formation revealed the occurrence of a ductile cutting mode for both tool geometries. An evaluation of the consequence of the size effects (that translates into defects of the machined surfaces) was done with a strong focus on the ploughing layer. The minimum uncut chip thickness and the critical uncut chip thickness were also under study through the analysis of the machined surfaces and generated chip morphology. It has been found that the ploughing layer formation prevails when the two-flute micro ball end mill is employed. However, this surface roughness detrimental layer seems to be less evident when using cutting tools without cutting edges. A brittle cutting mode seems also be present for both tool geometries, due to the defects saw in the machined surfaces. So, a combination of both cutting modes seems to exist, which may indicate a cutting mode in the ductile-to-brittle transition zone.

Keywords: Micro-machining, micro-milling, cemented carbide, WC-Co, uncut chip thickness, minimum uncut chip thickness, critical uncut chip thickness, brittle materials, ductile cutting mode, ploughing.

Resumo

A microfresagem de materiais frágeis num regime de corte dúctil apresenta um elevado valor industrial. Este processo permite a produção de superfícies 3D complexas com excelente acabamento e reduzidas tolerâncias, podendo também ser aplicada no fabrico de moldes e para ferramentas de microinjeção. No entanto, os fenómenos de corte que ocorrem ao nível microscópico são diferentes daqueles que ocorrem ao nível macroscópico, sendo o mais conhecido o chamado efeito de escala, que deve ser considerado no estudo na micromaquinagem. A existência da espessura mínima da apara, da espessura crítica da apara, dos efeitos de tamanho, da recuperação elástica e dos fenómenos de *ploughing* são os principais temas a entender no estudo da microfresagem. Além disso, há informação limitada na literatura existente até ao momento sobre as características da camada onde o *ploughing* domina. O presente trabalho primeiramente pretende apresentar uma revisão bibliográfica sobre os conceitos e avanços da microfresagem. Adicionalmente, é apresentado um estudo experimental conduzido em dois graus diferentes de metal duro, isto é, com diferentes percentagens de cobalto, WC-15Co e WC-10Co, e com duas ferramentas distintas, uma microfresa esférica com duas arestas de corte e uma microfresa esférica sem arestas de corte. Uma extensa matriz experimental foi desenvolvida para uma vasta gama de condições operacionais. Nestes ensaios, para cada um dos diferentes graus de metal duro, a influência tanto da profundidade de corte como da largura de corte foi analisada. Depois destes testes experimentais, foi feita uma comparação entre a média do tamanho real das aparas obtidas e o tamanho teórico das mesmas. A formação das aparas revelou a presença de um regime de corte dúctil para ambos as geometrias das ferramentas. Uma avaliação dos consequentes efeitos de tamanho (que se traduzem em defeitos nas superfícies maquinadas) foi realizada, tendo-se dado grande foco à investigação da camada onde predomina o fenómeno de *ploughing*. A espessura mínima da apara e a espessura crítica da apara foram também objeto de estudo através da análise das superfícies maquinadas e da morfologia das aparas geradas durante a maquinagem. Verificou-se que a formação da camada de *ploughing* prevalece quando se emprega a ferramenta com arestas de corte. No entanto, esta camada de rugosidade superficial prejudicial parece ser menos evidente quando se utilizam ferramentas de corte sem arestas de corte. Um regime de corte frágil parece também estar presente aquando do uso de ambas as geometrias das ferramentas, devido aos defeitos observados nas superfícies maquinadas. Assim, parece existir uma combinação de ambos os regimes de corte, o que pode indicar um regime de corte na zona de transição dúctil/frágil.

Palavras-chave: Micromaquinagem, microfresagem, metal duro, WC-Co, espessura mínima da apara, espessura da apara por cortar, espessura crítica da apara, materiais frágeis, regime dúctil de corte, *ploughing*.

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*Aos meus Pais e Avós,
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*To my Parents and Grandparents,
For the support since ever, effort and love.*

“Success is not final, failure is not fatal: it is the courage to continue that counts.”

Winston Churchill

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Acronyms

UCT - Uncut chip thickness

BUE - Build-up edge

MRR - Material removal rate

HCP - Hexagonal-close-packed

PCBN - Polycrystalline cubic boron nitride

ND - Natural diamond

SCD – Single crystalline diamond

PCD - Polycrystalline diamond

MCD – Microcrystalline diamond

NCD – Nanocrystalline diamond

CVD - Chemical vapor deposition

HFCVD - Hot filament CVD

MMC - Metal matrix composite

ISO - International organisation for standardisation

SEM – Scanning electron microscopy

Symbols

a_p	– Axial depth of cut
a_e	– Cut width
r_β	– Cutting edge radius
f_z	– Feed per tooth
v_c	– Cutting speed
n	– Rotation frequency
h	– Uncut chip thickness
$h_{\min}$	– Minimum uncut chip thickness
d_c	– Critical uncut chip thickness
R_a	- Average roughness of profile
R_q	- Root-Mean-Square roughness of profile
R_t	- Maximum peak to valley height of roughness profile
R_z	- Mean peak to valley height of roughness profile
$R_{\max}$	- Maximum peak to valley height of roughness profile within a sampling length
R_p	- Maximum peak height of roughness profile
R_v	- Maximum valley height of roughness profile
R_{sk}	- Skewness of roughness profile
R_{ku}	- Kurtosis of roughness profile
S_a	- Average height of selected area
S_q	- Root-Mean-Square height of selected area
S_z	- Mean height of selected area
S_p	- Maximum peak height of selected area
S_v	- Maximum valley height of selected area
S_{sk}	- Skewness of selected area
S_{ku}	- Kurtosis of selected area

Chemical elements

WC – Tungsten carbide

Co – Cobalt

WC-Co - Cemented carbide composed of WC and Co

WC-10Co - Cemented carbide with WC and 10% Co

WC-15Co - Cemented carbide with WC and 15% Co

Ni – Nickel

N - Nitrogen

SiC – Silicon carbide

TiC – Titanium carbide

TaC – Tantalum carbide

NbC – Niobium carbide

Al - Aluminium

AlCrN – Aluminium chromium nitride

TiN – Titanium nitride

CrN – Chromium nitride

TiAlN – Titanium aluminum nitride

TiB₂ – Titanium diboride

Chapter 1

Introduction

The manufacturing industry is constantly increasing the search for improvement of devices and components, with complex features, fabricated on a variety of materials, in particular by reducing the weight and dimensions of these. At same time, there is a search for quality improvement, which commonly translates into surface quality and part precision, in the machining domain. The manufactured functional components not only have to fit the costumers' specifications, but they should also be produced with the lowest manufacturing costs and, in some applications, with also lowest batch sizes possible [1]. Ensuring good quality parts in the processing of brittle materials is a very relevant topic in micro-machining given the possibility in attaining favourable ductile cutting conditions [2].

Nowadays, miniature components with high-precision geometrical features and tight dimensional tolerances are needed for a wide range of applications, such as in the aerospace, biomedical and military industries [3, 4]. Some examples are micro-scale heat sinks, implantable and *in vivo* medical and micro-fluidic devices as well as the miniaturization of common devices, such as actuators, motors, fuel cells, and gas turbines [4, 5]. Also important, is the manufacture of micro-injection moulds and dies, due to the exceptional finishing capabilities in production of 3D surface features through micro-milling, and the possibility of ductile cutting mode even for brittle workpiece materials such as WC-Co [1]. The growing demand for micro machined parts along the last two decades is also reflected by the huge increase of publications related to micro-machining field. Figure 1 shows that micro-milling is one of the most promising of micro-machining processes over the last years [6]. The latter can be characterized by any machining operation that involves removal of material on a scale of 1 to 999 μm [1]. Despite the similar kinetics between macro-milling and micro-milling, there are unique phenomena in micro-milling due to size effects. The size effects are phenomena that arise when the uncut chip thickness (UCT) is comparable to the dimension of cutting edge radius or when the scale of material removal is similar to the grain size. This phenomena include the existence of minimum UCT, critical UCT, elastic recovery and ploughing effects [2, 4, 7]. The minimum UCT is the minimum value of chip thickness from which chip is formed [7], while the critical UCT is the value of the depth of cut from which the brittle cutting mode starts to appear [8]. The ploughing is characterized by a high elasto-plastic deformation of the

machined surface. All these concepts related to size effects will be explained in more detail in chapter 2.

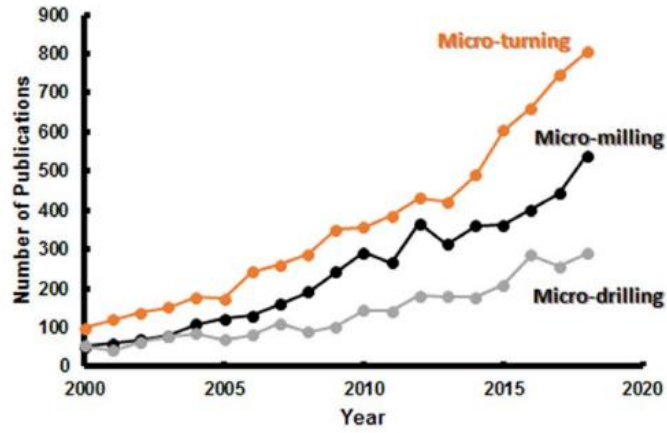


Figure 1 - Peer reviewed publication number evolution in the micro-machining topics, up to 2019 [6].

Equation (1) explains the reason why micro-milling machines require extremely high rotation frequencies to guarantee appropriate cutting speeds. For smaller tool diameters (D), higher rotation frequencies (n) are needed for a given cutting speed (V_c). In order to attain identical cutting speed values of macro-machining, the spindles of the machine tools used in micro-machining should have sub-micron spindle runout control, robust mechanical and thermal structure that is not influenced by vibration or thermal drift as well as a high resolution tool and positioning and feeding mechanisms [2, 9].

$$n = \frac{V_c}{\pi \cdot D} \cdot 1000 \quad (1)$$

Tool runout is a critical issue that affects the micro-milling process significantly. It is in part responsible for influencing the cutting force, tool life and surface integrity of the machined component. It is caused by the sum of the geometrical displacement errors of the machine-tool spindle, toolholder and tool axis from the ideal or theoretical axis of rotation. The sum of these errors yields a deviation between the theoretical and actual cutting edge trajectories [10].

A comparison between micro and macro-milling tools is highlight in Table 1.

Table 1 - Comparison between micro and macro-milling cutting tools, process details and attainable quality [11].

	Micro-milling tools	Macro-milling tools
Tool geometry requirement	Tool diameter	<1000 μm
	Tool diameter tolerance	0.1-5 μm
	Cutting edge radius	0.1-10 μm
	Length-to-diameter ratio	Approximately 10
	Structural symmetry	Unsymmetrical for micro-milling tools with small diameters
Process details and material removal principles	Uncut chip thickness	0.1-50 μm
	Tool runout	< 2 μm
	Specific cutting energy	>100 GPa
	Existence of elastic recovery?	Yes
	Is size effect relevant?	Yes
Applications and product quality	High-values fields	Optics, medical, nuclear, aerospace, biomedical, micro-electro-mechanical systems
	Applicable workpiece materials	Hard or soft materials, metals and alloys, plastics
	Required machined surface roughness (R_a)	10-100 nm
	Required dimension tolerance	0.1-5 μm
	Achievable feature size	10-5000 μm

1.1. Objectives and motivations

The micro-milling of cemented carbides with diamond cutting tools is a field in expansion. Nevertheless, there are still many unanswered questions, namely in what concerns the minimum UCT and critical UCT, i.e., the mechanisms of chip formation. Besides that, there are very few details on the features of the layer where ploughing dominates.

The lack of knowledge regarding the micro-milling of cemented carbides that are machined with diamond coated tools served as motivation to this research work. The aims of this research will be to enrich this field of micro-milling of brittle materials by:

- providing a review of the current and available concepts and information related to the micro-milling;
- performing an experimental study of the micro-milling process where the influence of WC-Co composition, tool geometry and cutting parameters are evaluated. The main size effects assessed are the minimum UCT, the critical UCT and the layer where ploughing

dominates. The performance of micro-milling experimental programs is very challenging as regards the objective of better understanding the mechanics of the cutting process. Therefore, it is also an objective of this study to develop and test best testing practices.

1.2. Palbit S.A.

Palbit S.A is a manufacturer of hard metal tools, founded in 1916, with focus in three business areas: (i) cutting tools, (ii) wear parts and (iii) rock tools. In relation to micro-machining processes, Palbit S.A uses the micro-milling process, laser machining and EDM processes to aid in-house production of press components (dies and punches), tools (such as milling cutters and drills) and diamond grinding wheels.

1.3. Document structure

This report is divided into five chapters which are briefly explained in this section for a global overview of this research work.

Chapter 1 introduces the micro-milling of cemented carbides and the evaluation of the size effects that are observed as the main subjects of this research work. It also includes the motivations and the goals of this work.

Chapter 2 focuses on the literature review. The characteristic phenomena of micro-machining and micro-milling are described. The main concepts are extensively explained, and some relevant authors' perspectives on the micro-milling phenomenon are reviewed.

Chapter 3 describes the experimental procedures and techniques, as well as all equipment and materials used. This section explains how the micro-machinability analysis (focusing on machined surface and chip morphology assessment) was performed.

Chapter 4 focuses on the discussion of the experimental results. Possible explanations for the obtained results are proposed and compared with what is reported by the literature, when possible.

Chapter 5 comprises the main conclusions of this work and the future works that arise for the continuation of this research topic.

Chapter 2

Literature review

In this chapter, some cutting fundamentals about micro-machining are presented. Since micro-machining involves different phenomena than those that occur at larger scales, understanding them is essential to take advantage of this process in its different applications.

2.1. Fundamentals of micro-cutting process

2.1.1. Size effect and ploughing effect

The size effect is a phenomenon that modifies the material removal and chip formation mechanisms at the microscale [10], and it is not correlated linearly with the tool's size reduction [2]. Even though it can be noticed in both macro- and micro-milling [11, 12] it becomes more challenging to control, promoting significant defects when removing material at the scale of micron. In micro-milling, often occurs an UCT comparable to the cutting edge dimension [4, 7, 13] and the UCT is comparable to the grain size of the machined material. For UCT in the same order of magnitude of grain size, chip formation might occur within a few or only a single grain of the material. Because of this, the workpiece material may not exhibit a homogenous response, which is reflected on the cutting forces and the surface quality [11, 14]. In contrast with conventional milling processes, where material can be considered to be homogeneous and isotropic, in the micro-milling process the workpiece material must be seen as heterogeneous and, in some cases, anisotropic. As the tool moves from one metallurgical phase to another, it is expected that the cutting process will behave differently. These changes manifest themselves as load variations in the process that may lead to higher levels of vibration and pronounced tool wear/ breakage. Wu et al. [14] studied the influence of grain size on cutting force and specific cutting energy concluding that smaller grain sizes result in a larger cutting force and specific cutting energy, due to the higher density of grain boundaries [10]. This conclusion was also reached by Ahmadi et al. [15] and Lauro et al. [16]. The latter authors have additionally reported that higher cutting forces are obtained for higher values of feed per tooth, f_z , for both small and large grain sizes. The specific cutting energy (U_t) is the energy required to remove a unit amount of material and it is calculated by the ratio of the cutting power (P_c) to the

material removal rate (MRR), equation (2). This ratio for simplification gives rise to the ratio between cutting force (F_c) and chip section (A_{chip}) [4]. Medina-Clavijo et al. [17] showed that specific cutting energy increases for lower values of UCT and they explain this by the dependence of the specific cutting energy on the tool geometry for microscales and on the strain hardening of the material. The compression of the material by the tool during the process promotes the increase of the work hardened layer.

$$U_t = \frac{P_c}{MRR} = \frac{F_c \cdot v_c}{V_c \cdot A_{chip}} = \frac{F_c}{A_{chip}} \quad (2)$$

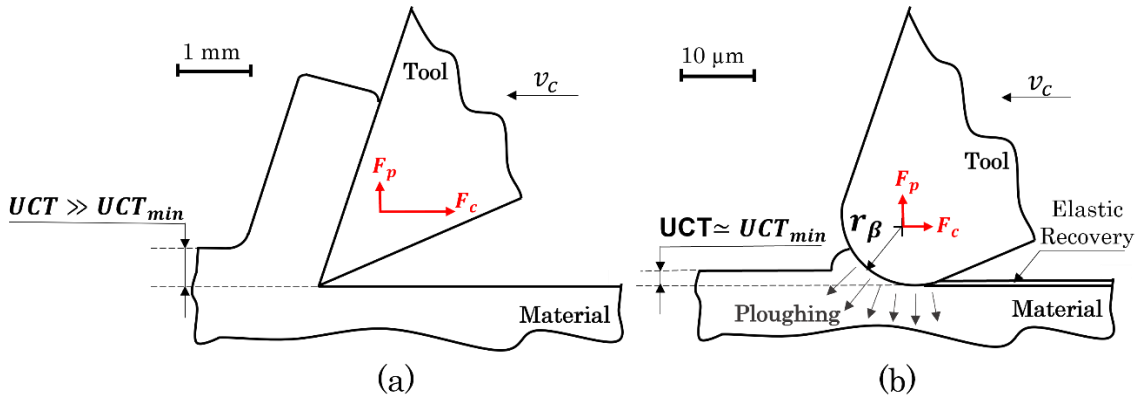


Figure 2 - Dominant cutting forces in (a) macro-milling and in (b) micro-milling, where F_p denotes the passive force, F_c the cutting force (adapted from [2]).

Figure 2 shows the main differences between micro- and macro-milling from the point of view of cutting forces. In micro-milling the magnitude of the cutting forces is smaller compared with the conventional milling, due to the size reduction. However, the ratio of cutting force, F_c , to the passive force, F_p , differs significantly, whereby the passive force has more significant effect on the chip removal process in micro-milling [2]. Due to the higher influence of passive force, the ploughing effect increases and becomes more dominant than shearing responsible for chip formation. Even though there is limited data regarding the ploughing effect on brittle materials, Chen et al. [18] have studied the ploughing in micro-milling of soft-brittle crystals and they showed that it is higher than shearing when the feed per tooth reaches values smaller than the cutting edge radius, r_β . This may result in poor surface quality due to the higher machined surface roughness. The authors also state the existence of higher specific cutting forces for smaller values of feed per tooth due to ploughing effect, mainly for micro end mills with a blunt cutting edge radius. Therefore, it is crucial to find out a good compromise between feed per tooth and tool stiffness, thus providing a shearing over than ploughing during cutting, ensuring a good surface quality.

In micro-machining, tool's strength decreases for smaller diameters, so the feed per tooth must be small enough to avoid tool deflection or breakage. Still, the tool cutting edge radius, r_β , which is approximately 1–20 μm for

both conventional and micro-milling [2], does not decrease in an identical proportion to the tool diameter. So, the tool cutting edge radius and the feed per tooth take on a similar scale, which can easily lead to the ploughing effect [19]. Oliveira et al. [12] noted that, in micro-milling, the size effect is observed through a huge increase of specific cutting force for feeds per tooth lower than tool cutting edge radius, reaching levels of grinding process when $f_z \cong r_\beta/10$. Chen et al. [20] not only observed an increase of cutting forces for higher values of cutting edge radius but also an increase of cutting forces for higher values of rake angle.

Gao et al. [21] examined the size effect in relation to the tool cutting edge radius and cutting parameters on specific cutting energy in micro-milling of heat resistant stainless steel (12Cr18Ni9). They showed that the specific cutting energy could be fully controlled by regulating the geometrical characteristics of the cutting tool, i.e., the cutting edge radius, and by the machining parameters recommended by their developed minimum UCT prediction model.

Table 2 summarises recent works related to the influence of cutting force and ploughing, the specific cutting energy and the grain size on the size effects.

Table 2 – Recent works related to the size effect and the ploughing effect.

Year	Author	Objective	Remarks
2003	Vogler et al. [3]	Microstructure-Level Force Prediction Model for Micro-milling of Multi-Phase Materials	The magnitude and the variation of cutting forces are affected by microstructure grain size and spacing of each phase that make part of material.
2012	Komatsu et al. [22]	Effect of Crystal Grain Size in Stainless Steel on Cutting Process in Micro-milling	The shearing force decreases in cutting of the ultra-fine-grained steel; meanwhile, the friction and/or the indentation forces increase.
2015	Oliveira et al. [12]	Comparison between the size effect behaviour in micro- and macro-milling	The size effect is observed through a higher specific cutting energy for feeds per tooth (f_z) lower than cutting edge radius (r_β), reaching levels of grinding process when $f_z \cong r_\beta/10$.
2015	Lauro et al. [16]	Specific cutting energy employed to study the influence of the grain size in the micro-milling of the hardened AISI H13 steel	The material with the highest grain size presented lower values of cutting forces in both directions and specific cutting energy compared with the material with the smallest grain size. In both cases, there was a reduction of the specific cutting energy with the increase of feed rate.
2016	Wu et al. [14]	Influence of the cutting edge radius and the material grain size on the cutting force in micro cutting	Smaller grain sizes result in a larger cutting force and specific cutting energy, due to the larger effect of grain boundaries. The cutting force increases with the increase of r_β and also with the increasing feed per tooth.
2018	Ahmadi et al. [15]	Microstructure effects on process outputs in micro scale milling of heat treated Ti6Al4V titanium alloys	Smaller grain size led to higher cutting force in micro-milling.
2017	Gao et al. [21]	Examined the size effect in relation to the tool edge radius and cutting parameters on specific energy in micro-milling	The specific cutting energy could be fully controlled by regulating the geometrical characteristics of the cutting tool and the machining parameters.

2019	Chen et al. [18]	Research on the ploughing force in micro milling of soft-brittle crystals	The ploughing is higher than sharing when the feed per tooth reaches values smaller than the cutting edge radius, which result in higher machined surface roughness. The specific cutting energy is higher for smaller values of feed per tooth due to the presence of ploughing effect.
2019	Wu et al. [23]	Experimental Investigation on Direct Micro-milling of Cemented Carbide	The cutting force components grow with the increasing feed per tooth and axial depth of cut.
2020	Chen et al. [20]	Design, optimization and manufacturing of polycrystalline diamond micro-end-mill for micro-milling of GH4169	The cutting forces components increase for higher cutting edge radius and higher rake angles.
2021	Medina-Clavijo et al. [17]	In-SEM micro-machining reveals the origins of the size effect in the cutting energy	The specific cutting energy is much higher for lower values of UCT, due to the dependence on the tool edge radius and the strain hardening of the material.

2.1.2. Minimum uncut chip thickness and chip formation

Chip formation is influenced, among others, by the workpiece, tool material, tool geometry, scale of machining (macro, micro, or nano) and the primary process parameters (cutting speed, feed rate, depth of cut) [2, 24]. In micro-machining, one of the primary factors affecting the chip formation is the minimum UCT. As represented in Figure 3, when the UCT, also called undeformed chip thickness, is below the minimum UCT, UCT_{min} , no chip is formed, and the material is forced under the tool and deformed. The chip formation only happens when it is accumulated a sufficiently large UCT by multiple tooth passes and so the UCT becomes higher than the minimum UCT. The effect of elastic recovery of the machined surface can significantly influence the flank face of cutting tools due to the high contact pressure [4, 25].

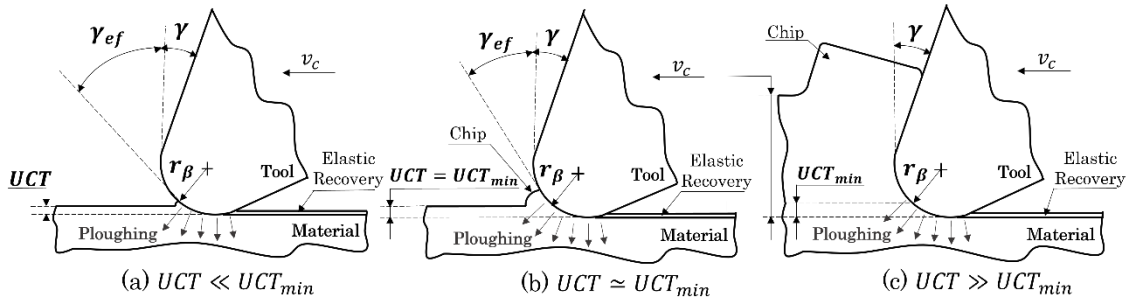


Figure 3 - Scheme of micro-chip removal mechanisms: (a) the uncut chip thickness (UCT) is smaller than the minimum chip thickness (UCT_{min}), (b) the value of UCT is approximately equal to the value of UCT_{min} , (c) the value of UCT is higher than the value of UCT_{min} (adapted from [2]).

Figure 3 additionally shows that as in micro-milling the UCT is usually less than cutting edge radius, only the bottom arc segment of cutting edge is actively in the cutting process, so the nominal rake angle, γ , is not fully engaged, resulting in an effective rake angle, γ_{ef} . Because of this, micro-

milling involves negative rake angles. The effective rake angle depends on the ratio between the UCT and cutting edge radius, becoming more negative for smaller ratios [26].

Figure 4 (a) and Figure 4 (b) show the variation of chip thickness with tool rotation for slot milling, using a micro ball end mill. For each tooth engagement and radial displacement (180°), the chip thickness increases from zero to its maximum value which is equal to feed per tooth, returning to null thickness at final engagement [11].

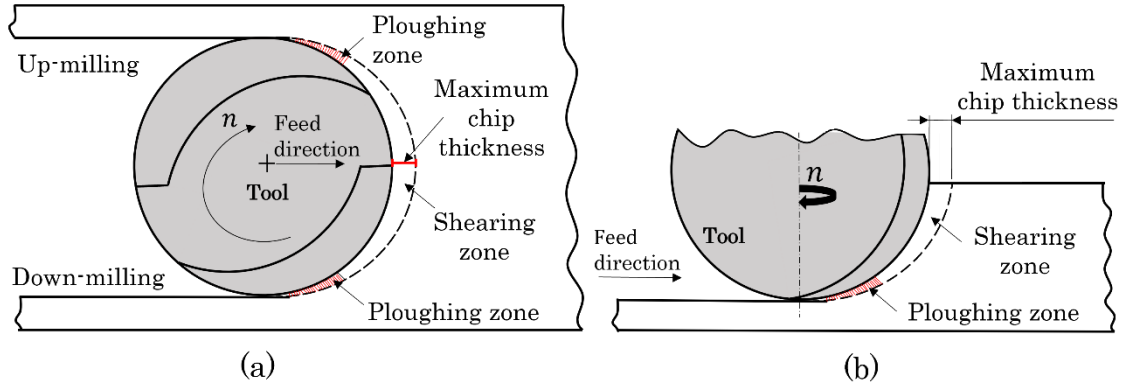


Figure 4 - Variation of chip thickness in slot milling with tool rotation: (a) top view; (b) side view (adapted from [24]).

The occurrence of ploughing is usually seen through the ratio of minimum UCT to cutting edge radius (UCT_{min}/r_β). Nowadays, there are analytical, numerical and experimental methods for estimation of this ratio in many materials. Balázs et al. [2] did a comparison between several methods used in the determination of UCT_{min}/r_β for different materials concluding that it commonly ranges between 0.14 and 0.48 in micro-milling. If the UCT/r_β gets smaller than the UCT_{min}/r_β , then the process parameters or the cutting tool must be changed, so that the ploughing effect is minimized and surface quality as well as machining efficiency are not compromised. Such can be achieved by the increase of the UCT/r_β ratio. The increase of feed per tooth also leads to the increase of UCT, and, thus, ploughing minimization. However, and especially when considering brittle materials, it is important that UCT does not increase excessively, given their tendency to fracture (unwanted non-ductile cutting) [27]. Brittle machining is undesirable in brittle materials due to the associated crack formation on the machined surface leading to poor surface quality and integrity. This topic is further explored in section 2.1.3. Shi et al. [28] determined the minimum UCT in micro-milling of Inconel 718 by acoustic emission signals and revealed that for feeds per tooth lower than minimum UCT the signal showed to be smaller, due to the presence of ploughing effect. Aslantas et al. [29] determined the minimum UCT of two titanium alloys in micro-milling by varying the feed per tooth and they reported that the specific cutting force increased for feeds per tooth smaller than the

cutting edge radius, due to ploughing. Sahoo et al. [24] reached to the same conclusion by micro-milling of P20 die steel.

In relation to the minimum UCT, Oliveira et al. [12] also noticed that this value guarantees chip formation, but not necessarily an adequate workpiece surface integrity. They studied the size effects on AISI 1045 steel machined by micro-milling. The authors verified that for values of $UCT < UCT_{min}$ no chip was formed and excessive ploughing with cracks was presented, while for $UCT > UCT_{min}$ there was (convenient) chip formation but also feed marks and evidence of side flow. According to the authors, the UCT that results in appropriate workpiece surface integrity while allowing for chip formation is between the minimum UCT and cutting edge radius.

Niu et al. [30] are among the few authors that compared the theoretical chip size with the experimental chip size, for experiments that involved micro-milling of aluminium 6082-T6 with a cemented carbide tool with a blunt cutting edge radius. They stated that as the feed rate increases, both theoretical UCT and measured chip length also increase. This effect is explained by the different relative size of ploughing zone with respect to the total chip size (Figure 4 (b)). However, there is a greater decrease in the experimental chip size compared to its real size with increasing feed rate, because the increased UCT leads to the likely chip breaking into pieces instead of forming continuous chips due to the higher size.

Table 3 summarises recent works related to the minimum UCT and chip formation.

Table 3 - Recent works related to the minimum chip thickness and chip formation.

Year	Author	Objective	Remarks
2015	Oliveira et. al [12]	Comparison between the size effect behaviour in micro- and macro-milling	The minimum UCT guarantees complete chip formation, but not necessarily adequate workpiece surface integrity. Another thickness above this critical value which minimizes the ploughing effect must exist and be used.
2017	Oliaei and Karpas [31]	Built-up edge effects on process output of titanium alloy micro-milling	It was not found a correlation between BUE and chip formation.
2018	Shi et al. [28]	Determination of minimum uncut chip thickness during micro-end milling Inconel 718 with acoustic emission signals and FEM simulation	The minimum UCT depends on the cutting tool geometry and the properties of machined material, and can be determined by acoustic emission signals. Micro-milling with feeds per tooth smaller than minimum UCT leads to lower acoustic emission signals which is caused by ploughing effect.
2020	Aslantas et al. [29]	An experimental analysis of minimum chip thickness in micro-milling of two different titanium alloys	The minimum UCT was determined by varying the specific cutting force. The specific cutting force increased for feeds per tooth smaller than cutting edge radius, due to the presence of ploughing.

2020	Sahoo et al. [24]	Determination of minimum uncut chip thickness and size effects in micro-milling of P20 die steel using surface quality and process signal parameters	Minimum UCT value depends upon the workpiece, cutting tool material and its geometry. The specific cutting force shows to be higher for feeds per tooth smaller than cutting edge radius, due to the presence of ploughing.
2020	Wu et al. [26]	Experimental Study on the Minimum Undeformed Chip Thickness Based on Effective Rake Angle in Micro-milling	The effective rake angle depends on the ratio of the UCT to tool cutting edge radius, so the calculation of minimum UCT can be based on the effective rake angle.
2021	Balázs et al. [2]	A review on micro-milling: recent advances and future trends	This work compares the values of ratio h_{min}/r_b between several methods in different materials and it report the range of 0.14 and 0.48 in micro-milling.
2021	Liu et al. [32]	Prediction of Nonlinear Micro-Milling Force with a Novel Minimum Uncut Chip Thickness Model	The minimum UCT divides the cutting zone into the shear region and the ploughing region, so it has a strong nonlinear effect on the cutting force of micro-milling.
2022	Wojciechowski, S. [25]	Estimation of Minimum Uncut Chip Thickness during Precision and Micro-Machining Processes of Various Materials	It is presented a critical review of the recent studies concerning the determination of minimum UCT during precision, ultra-precision, and micro-cutting.

2.1.3. Ductile cutting mode

Some conventional machining processes are used for final surface finishing of brittle materials, such as grinding, lapping and polishing. However, there are some disadvantages associated. Besides the poor grindability and the high manufacturing cost, these processes lack precision, due to the more challenging material removal control, which results in machined surface inaccuracies and, thus, high surface roughness. Subsurface cracking has also been reported as a possible outcome [8]. Micro-machining has the advantages of higher geometrical flexibility and precision for brittle materials and tight dimensional tolerances. Nevertheless, micro-machining may also cause cracks on the surface or in the subsurface if it occurs in brittle cutting mode, so the ductile cutting mode must be achieved.

Ductile cutting mode (also called ductile cutting regime, ductile cutting or ductile regime machining [9]), is a promising technique that has been studied over the past decades to overcome the problem of cracks when machining brittle materials. This concept was first seen in literature in 1954, where the material removal in abrasive wear of rock salt occurred due to the plastically deformed layer removal rather than a brittle fracture, although some cracking was still observed. Reproducible results of diamond grinding of glass in a ductile mode were firstly reported in 1976, which improved the surface quality and machining accuracy. Later, precision grinding of brittle materials in a ductile cutting mode had been extended to others, such as silicon and ceramics. In the 1990s, the improvement on

ultra-precision machining technology marked the progression to the application of ductile cutting mode to more advanced brittle materials, such as different types of carbides [8].

Figure 5 makes a comparison between ductile cutting mode and brittle cutting mode and it shows that the former suppresses the crack propagation by keeping an extremely high level of hydrostatic compressive stresses in the chip formation zone during material removal and continuous chips are formed. On the other hand, brittle cutting mode causes a significant cracks and their propagation, while chips are formed in a shape of brittle particles [1, 8].

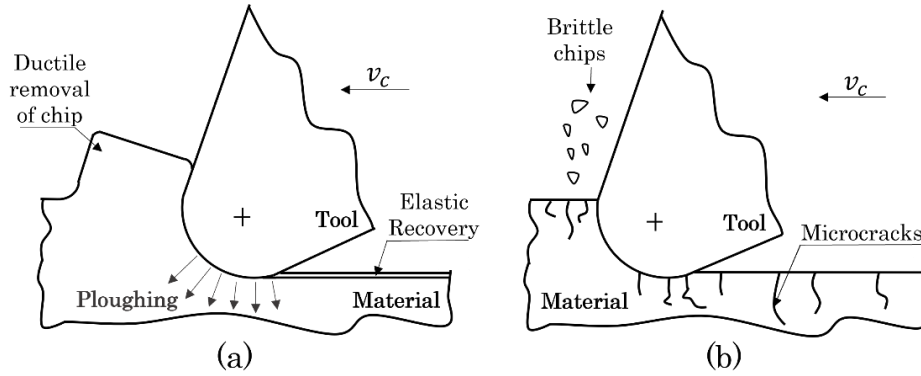


Figure 5 - Schematic illustration of two cutting modes for brittle materials: (a) Ductile cutting mode;

(b) Brittle cutting mode (adapted from [33]).

In micro-milling, ductile cutting mode is achieved when there is a lower UCT compared to cutting edge radius. So, for ductile machining of brittle materials, such as WC-Co, highly negative effective rake angle must be used in micro tools. It has been reported that there is a ductile-to-brittle transition in chip formation in brittle materials, which can be controlled if the UCT is below a certain threshold, the critical UCT [1, 8, 10, 34]. A diagram of brittle-to-ductile transition, based on Griffith fracture criterion, is presented in Figure 6. It suggests a ductile-to-brittle transition zone rather than a fixed threshold, for brittle materials.

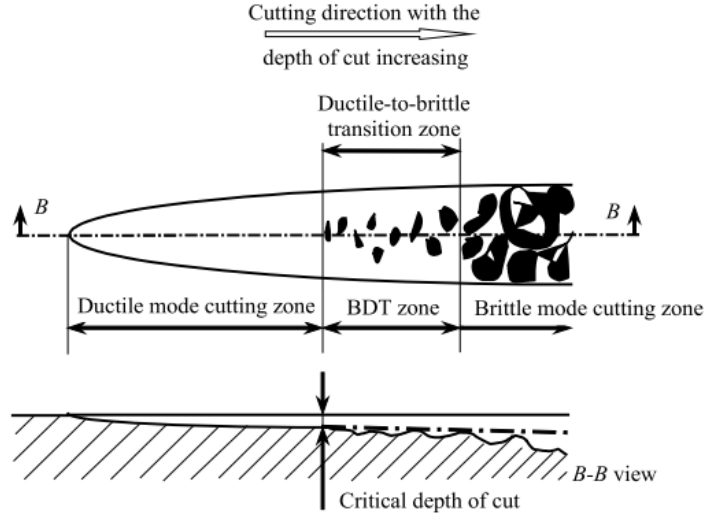


Figure 6 - Schematic diagram of brittle-to-ductile transition in grooving of brittle material [8].

Stanimirović, Z. and Stanimirović, I. [9] proposed the equation (3) that shows the critical UCT, the threshold below which ductile regime prevails.

$$d_c = A \left(\frac{E}{H} \right) \left(\frac{K_C}{H} \right)^2, \quad (3)$$

where d_c is the critical UCT (also known by critical depth of cut), E is the Young modulus, K_C is the fracture toughness and H is the surface microhardness. The constant A is material's brittle-ductile transition factor, which varies for different brittle materials [33].

Wu et al. [23] machined WC-15Co with a PCD micro end mill and they revealed that the critical UCT of this material is $1.49 \mu\text{m}$ for the cutting conditions tested. Brittle cracks and micro-pits emerged (the latter due to the pull out of broken WC grains) during brittle cutting mode (refer to Figure 7). These phenomena are the main causes of poor surface quality and high surface roughness. Chen et al. [35] performed experiments of micro-milling in a potassium dihydrogen phosphate crystal, which is a brittle material, reporting the existence of micro cracks and micro-pits in the brittle cutting mode. These last authors stated that for a ratio f_z/r_B of three, for the set of tested conditions, cracks and brittle areas dominated the entire surface, thus there was a total brittle cutting mode. Bian et al. [36] also demonstrated the defects on the machined surface of ZrO_2 ceramic that were originated in a brittle cutting mode. The defects were mainly micro-pits and micro cracks (refer to Figure 8), which occurred with increasing frequency due to tool wear evolution. Huo et al. [37] reported a partial ductile cutting mode when machining single-crystal silicon using a CBN micro end mill and a diamond coated WC micro end mill. The partial cutting mode was considered to exist only when few surface defects such as irregular streaks and micro-pits were left on the machined surface. When micro-pits dominated the entire surface, the authors considered that brittle

cutting mode was the main mechanism. The partial ductile cutting mode is related for other authors as a transition zone between the ductile cutting mode and the brittle cutting mode. Another example of such is the work conducted by Choong et al. [38] that addressed this transition zone and explaining it by the occurrence of partial brittle fracture. All mentioned authors relate cutting mode with feed per tooth. The ductile cutting mode is verified for lower values of feed per tooth and depth of cut.

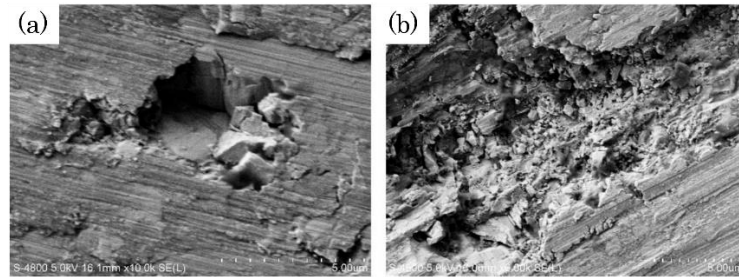


Figure 7 - Defects on the machined surface of WC-15Co: (a) micro-pit; (b) large pit [23].

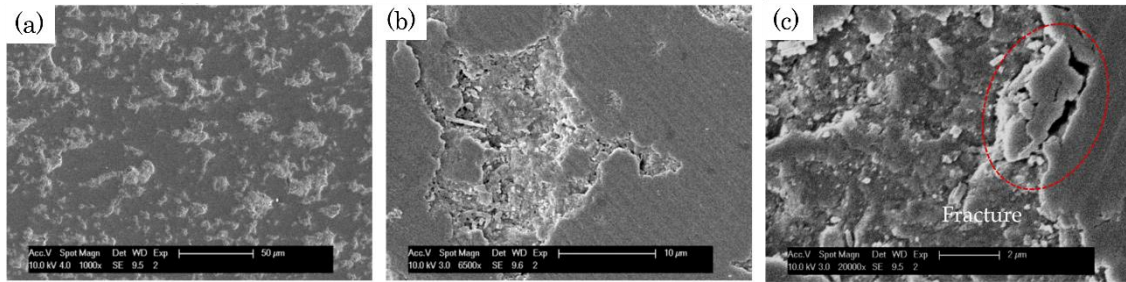


Figure 8 – Defects on the machined surface of ZrO_2 ceramic: (a) large areas of brittle failure; (b) specific damage area; (c) crack [36].

2.1.4. Surface finish

A good surface finish is desired in many applications, especially when the structural integrity of a certain component is under question (i.e. fatigue behaviour, contact pressure and wear, etc). Thus, many authors have been studying this parameter in micro-milling. Aslantas et al. [29] have demonstrated for two different titanium alloys that for UCT below $2\text{ }\mu\text{m}$, the surface roughness is higher and it increases with decreasing feed per tooth. This is caused by the excessive ploughing on the machined surface. Above minimum UCT the surface roughness increases with increasing feed per tooth. The authors also concluded that for the minimum UCT the surface roughness was only dependent on depth of cut for values higher than $150\text{ }\mu\text{m}$, noticing a roughness increase with increasing depth of cut. Wu et al. [34] studied the effect of feed rate and depth of cut on the surface roughness when micro-milling WC-15Co with a PCD tool. They concluded that the surface roughness increases with increasing feed rate and depth of cut. Another conclusion was that the surface roughness was less affected by the

machining parameters when the material was removed in ductile cutting mode. Nakamoto et al. [39] and Zhan et al. [40] also report an increase of surface roughness for higher values of feed per tooth. They also refer that the surface roughness of machined surface was not affected by the PCD tool wear, Figure 10. Moreover, Zhan et al. [40] also demonstrated that there is a minimum value of chip thickness (minimum UCT) below which surface roughness increases with decreasing feed per tooth and depth of cut (due to the ploughing effects) and above which surface roughness increases with increasing these parameters.

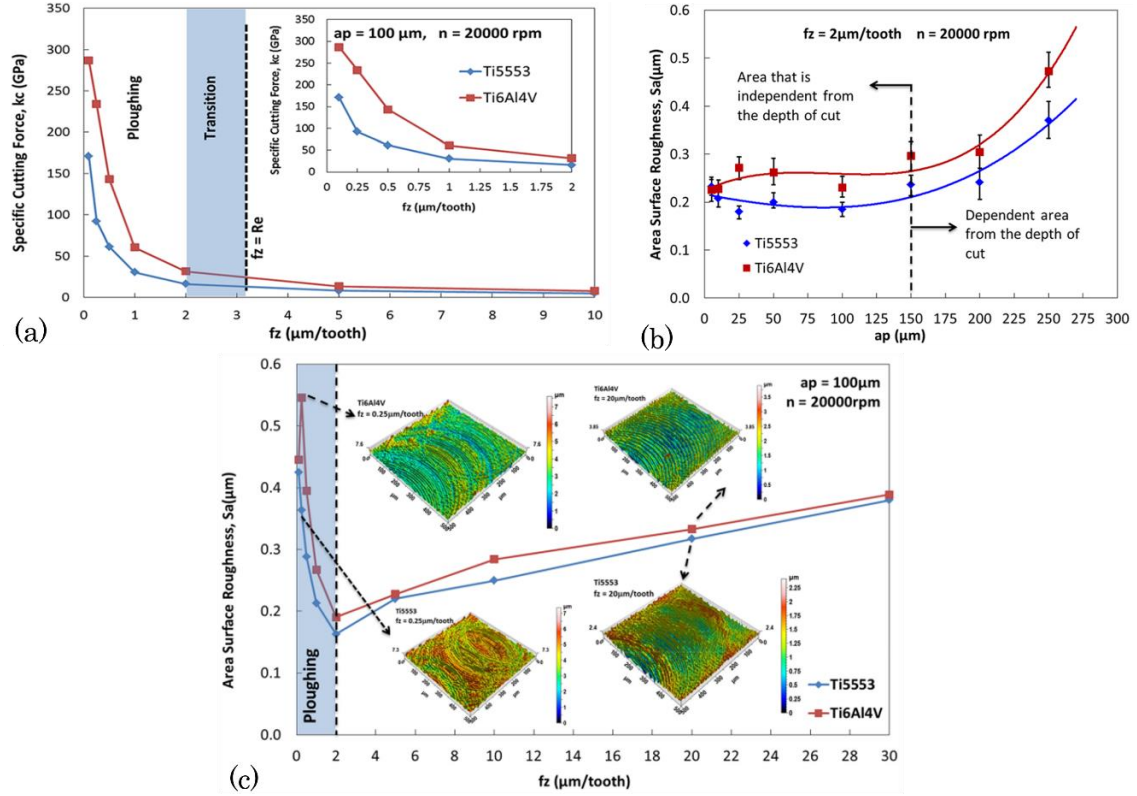


Figure 9 – Micro-milling of two different titanium alloys: (a) Variation of specific cutting force (k_c) with feed per tooth (f_z); (b) Variation of area surface roughness (S_a) depending on depth of cut (a_p); (c) Variation of area surface roughness (S_a) on feed peer tooth (f_z) [29].

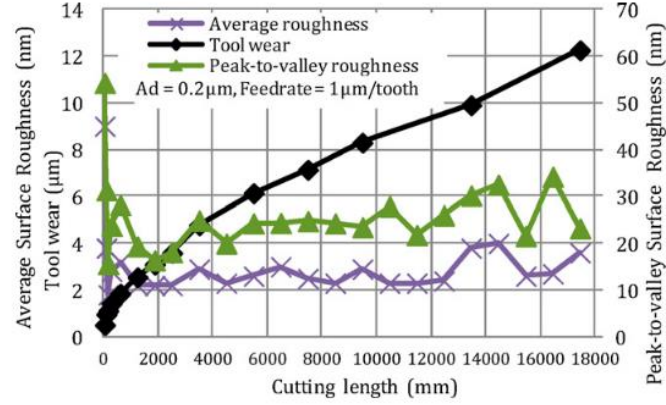


Figure 10 – Average surface roughness (R_a) and peak-to-valley (R_z) in accordance with progressive of tool wear [39].

In case of cemented carbides, some behaviour that may occur is the pulling of WC particles and tearing of soft phase, which induce pits, grooves and cracks on the machined surface, deteriorating surface quality. Cemented carbide is composed of the WC hard phase and the binder phase, so the tool alternately cuts the hard phase and the soft phase. When the material is separated from the workpiece surface to form chips, only a small part of the cut WC particle remains on the machined surface. The binding area of the remained part is very small as well and the binding force is not large enough to hold the WC particle. Under the action of cutting force, these WC particles may pull out from the machined surface, Figure 11 (a). Then, a cavity with the inverse shape of the pulled WC particle is generated. Therefore, the machined surface quality is deteriorated, and the surface roughness increases. When the WC grains are smaller or there is a higher Co content, pulling out of WC grains is more likely to occur, which may happen in both brittle and ductile modes [34].

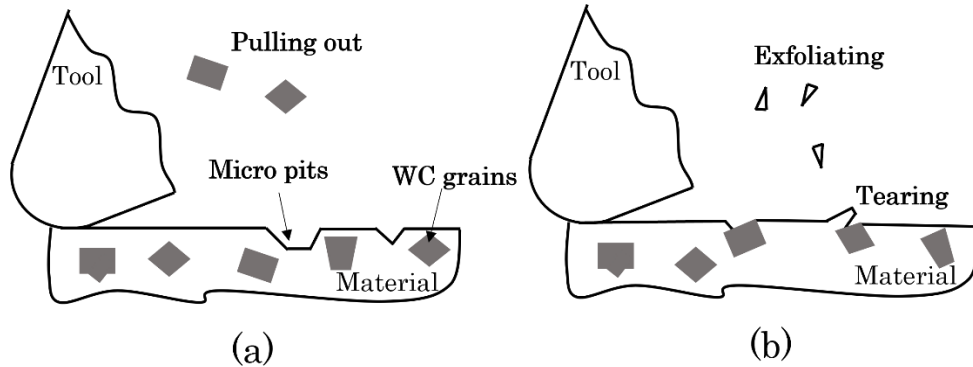


Figure 11 - Surface damage mechanism during micro-milling: (a) WC grain pull out; (b) tearing and exfoliating (adapted from [34]).

Figure 11 (b) shows the tearing and the exfoliating behaviours. The Co binding action is relatively weak (when compared to the cutting tool action), which can lead to tearing and exposition of WC particles. The lower Co content tends to promote tearing effect over pulling [34].

2.2. Micro-cutting tools

2.2.1. Micro-tool geometry

The geometry of end mills used in micro sizes is very similar to those used in macro sizes and, commercially, one, two or multi-fluted versions are available. The selection of tools must consider the intended machined features and highest possible tool stiffness and strength to avoid undesired vibrations and breakage. The two most important geometries that affect the micro-tool stiffness are the tool diameter and flute length. Equation (3) and Equation (4) show that the torsional stiffness, E_{tor} , decreases with the reduction of these two parameters, respectively [9].

$$E_{tor} = \frac{D_2^4 - D_1^4}{D_1^4} \quad [\%], \quad (3)$$

where D_1 is the higher tool diameter and D_2 is the lower tool diameter.

$$E_{tor} = \frac{L_2^{-2} - L_1^{-2}}{L_1^{-2}} \quad [\%], \quad (4)$$

where L_1 is the lower flute length and L_2 is the higher flute length.

A higher number of cutting edges often drastically reduces the stiffness of the cutting tool, therefore keeping it to a minimum feasible number is recommended for micro-milling. Still, for increasing cutting edges, a higher MRR is achieved [2]. For smaller values of tool diameter, the low stiffness of micro end mills imposes the usage of small depths of cut [41]. Fan et al. [42] have demonstrated by a finite element simulation analysis that a micro-milling tool with lower diameter breaks much more easily. They also showed that a two-flute micro end mill is weaker than a tool with a tapered body. The flutes that are presented in end mills are responsible for the chip evacuation and heat dissipation [43]. Suzuki et al. [44] showed that a tool with ten cutting edges reduces the tool temperature and the tool wear due to the interrupted cutting. Oliaei and Karpat [31] studied the influence of a tailored single edge micro end mill geometry in BUE formation, because a stable BUE protects the tool tip from rapid wear during micro-milling. It was concluded that a micro end mill with low clearance angle yielded the most stable condition in BUE formation. Yuan et al. [45] compared the performance of three PCD micro ball end mills with different number of cutting edges when micro-milling of cemented carbide. The authors concluded that the single edge tool with spherical flank face can avoid the phenomenon of chip blocking and depositing when compared with other solutions. Finally, Oliaei and Karpat [46] proposed an alternative to the commercially available PCD end mill having hexagonal geometry with flat bottom. The proposed hexagonal geometry showed to improve the MRR and the surface roughness when machining silicon in a ductile cutting mode.

Figure 12 shows possible micro-milling tools geometries for cemented carbides.

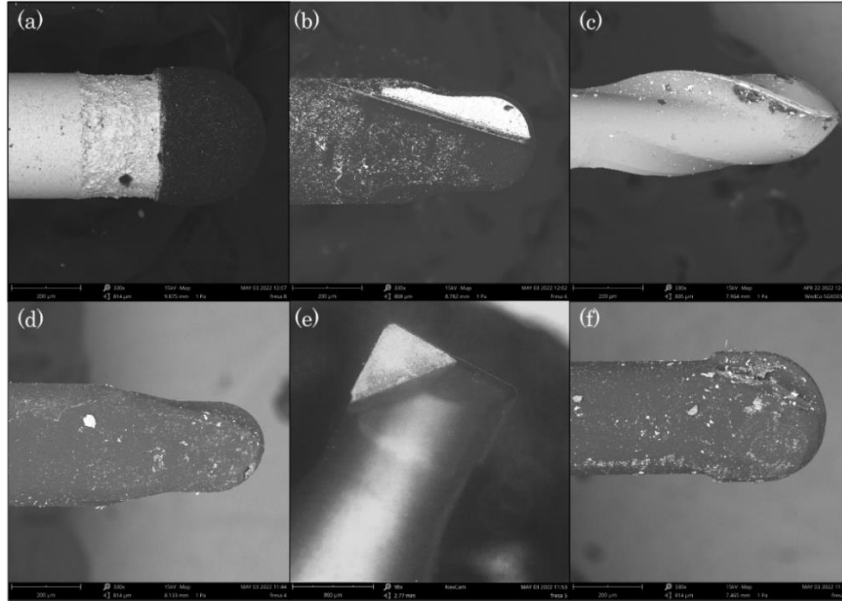


Figure 12 - Micro-milling cutters geometries for cemented carbides: (a), (b), (d) and (f) micro ball end mill; (c), (e) micro end mill.

Table 4 presents a summary of the available research work on the influence of micro-milling geometrical features.

Table 4 - Summary of some works where different geometries of micro-milling cutters are presented.

Year	Author	Tool design	Optimization target	Remarks
2003	Fang et al. [42]	Two-flute, triangular, D-shaped tool	Tool failure mode and improved tool life	Micro-cutters with lower diameter are more easily broken. Two-flute tool is eight times weaker than tapered triangular tool and twelve times weaker than tapered D-shaped tool. D-shaped tool experience accelerated tool wear, due to zero clearance angle.
2013	Suzuki et al. [44]	Tool with 10 round edges of 0.5 mm radius and tool with 10 sharp edges	Machine micro aspheric ceramic molds precisely and efficiently	The interrupted cutting makes the tool temperature and tool wear reduced. It was demonstrated that hard and brittle materials can be cut ultra-precisely and efficiently.
2017	Oliaei and Karpát [31]	Single edge micro end mill	Promote BUE formation	A micro end mill with low clearance angle yielded the most stable condition in BUE formation. A stable BUE protects the tool tip from rapid wear during micro-milling.
2018	Oliaei and Karpát [46]	Hexagonal geometry	Improve ductile mode machining of silicon	The designed tool demonstrated to be capable of producing a surface roughness in the order of nanometers, while ductile cutting mode machining of silicon.
2020	Yuan et al. [45]	PCD micro ball-end mills: double-edged conical surface, single-edged hemispherical and spherical	Achieve high quality milling of tungsten carbide micro-lens array	PCD micro ball-end mill with the single-edged and spherical flank face can avoid the phenomenon of chip blocking and depositing and can also fully exert the grinding characteristics of PCD materials to obtain relatively better processing quality.

2.2.2. Materials for micro-milling cutters

Micro-milling allows high-precision machining of complex parts and high quality of hard material structures. However, some challenges remain during the micro-machining of hard materials, namely tool vibration, wear and breakage which are more pronounced than in macro-machining, due to the higher specific cutting energy promoted by the size effects. So, from a mechanical point of view, it is essential that the micro-milling tool has: (i) high hardness for a smaller wear, (ii) high stiffness to increase the accuracy of machined surfaces, (iii) good impact toughness to overcome interrupted impacts in micro-milling processes and (iv) a high flexural strength to reduce tool breakage. Good heat resistance, small thermal expansion (to maintain the tool dimensions), good thermal conductivity (to dissipate the heat generated during the process) and a good chemical inertness (to reduce chemical reactions between tools and workpiece) [11].

The materials usually employed in micro-milling cutters are cemented carbide, polycrystalline cubic boron nitride (PCBN), natural diamond (ND) and its synthetics variants, namely single crystalline diamond (SCD) and polycrystalline diamond (PCD). The toughness and the hardness of these materials are compared in Figure 13.

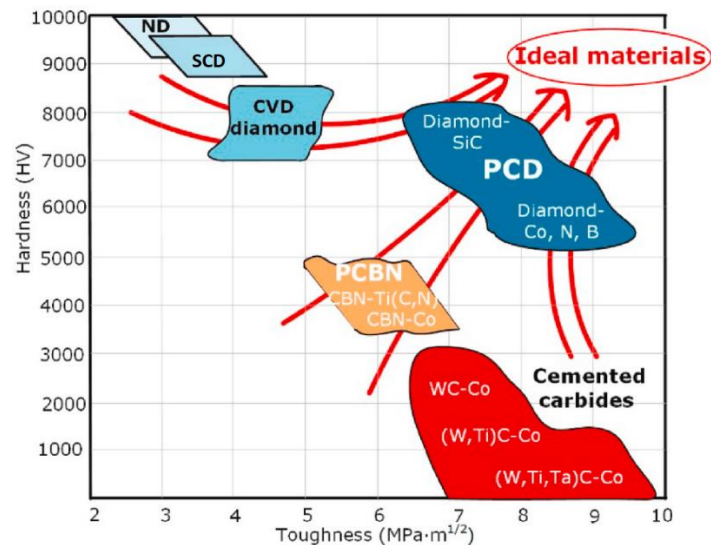


Figure 13 - Toughness and hardness of micro-milling cutter materials: non-ultrahard materials primarily including cemented carbides, and ultra-hard materials including PCBN, ND, SCD, CVD diamond, and PCD (adapted from [11]).

Cemented carbide

The cemented carbide, also known as hard metal or sintered carbide, is mainly used in machining tools and moulds in industry. It is a metal matrix composite (MMC) containing ceramic grains and a metallic binder, in which the brittle refractory carbides can be, for example, particles of WC, TiC, TaC and NbC, and the soft binder metal is often Co and, sometimes, Ni.

Chemical bonding is especially favourable in the case of WC and Co, because the wetting angle of Co on WC is zero, so there is an excellent wettability between both [8, 47, 48].

Figure 14 shows the crystal structure of a cemented carbide composed of a Co bonding phase and a WC hard phase. It is a simple hexagonal-close-packed (HCP) structure with two atoms per unit cell.

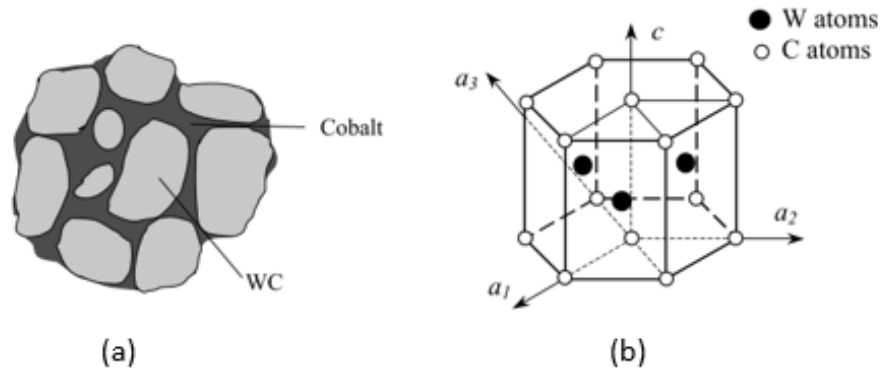


Figure 14 – (a) Schematic diagram of WC grains bonded by Co; (b) Simple hexagonal structure of cemented carbide crystal [8].

Some of its excellent mechanical properties are: superior strength, high hardness, relatively good fracture toughness, heat resistance, high resistance to abrasion and wear. The carbide phase provides hardness and wear resistance, while the ductile binder contributes to the toughness necessary for most applications. Due to its very high hardness, cemented carbide has very poor machinability [8, 34, 47, 48].

The cemented carbide properties depend not only on the WC phase and binder percentages, but also on its microstructure, such as WC grain size [47]. The range of some properties of WC-Co are shown in Table 5.

Table 5 - Properties of WC-Co (estimate made with the lower and upper limit values for cemented carbide with 72% and 96% WC, from the reference [48]).

Properties of WC-Co	Range
Young's modulus, E [GPa]	468 - 686
Shear modulus [GPa]	188 - 279
Hardness, H [HV]	814 - 2 150
Fracture toughness, K_{Ic} [$MPa \cdot m^{1/2}$]	6 - 24
Density, ρ [kg/m^3]	12 600 – 15 300
Thermal conductivity [$W \cdot m^{-1} \cdot ^\circ C^{-1}$]	57 - 98

The manufacture of WC-Co involves a power metallurgy process, which steps are powder compaction tooling, powder ball milling, powder atomization, powder pressing and forming, sintering and post-sinter forming [8].

Polycrystalline Cubic Boron Nitride (PCBN)

PCBN is composed by micro CBN powders with sizes between 0.1 and 100 μm and metallic or ceramic binders (Co, Al, Ni or TiC). It is the second hardest substance after diamond, so its main advantages are the high wear resistance, high temperature stability and its heat resistance, which allows for its usage in dry micro-milling. The lower cost and thermal resistance of PCBN micro-milling tools make them a good alternative to diamond tools under particular solicitations [11].

Diamond and its variants

Diamond and its variants may be used in micro-milling cutters with cutting edge radius lower than 0.1 μm to machine brittle materials or non-ferrous metals, due its extreme high hardness and strength. Its high price and poor machinability are the main challenges to its implementation in more applications. Apart from ND, the other diamond variants are synthetic. The SCD is produced from graphite powders under high temperature and pressure. The PCD is a solution to improve the toughness and reduce the costs. Its composition consists of micro diamond powders with metallic or ceramic binders (Co, SiC, N) [11]. Compared to PCD, chemical vapor deposition (CVD) diamond possesses higher hardness and wear resistance, due to the absence of a binder phase. Because of these features, CVD diamond might be used for achieve smaller cutting edge radius to reduce size effects, while at the same time tool life is not compromised easily [49].

2.2.3. Coatings for cemented carbide tools

The coatings applied to cemented carbide micro-milling cutters may be classified into metal and diamond coatings. Some metal coatings are TiN, CrN, AlCrN and TiAlN. For materials that are difficult to be machined, the metal coatings with Al are recommended, because they enhance the coating hardness and prolong the tool life, due to the lower tool wear [11]. Coating is a cost-effective solution that requires minimal material volume and reduces the tool wear, and, consequently, increases the tool life. Aurich et al. [50] are an example of authors who reinforced this idea through an experimental research where WC-Co micro-milling tools with different diameters were coated with TiB_2 . They reported that the advantage of using coatings was especially evident with the smaller tool diameters in terms of tool life. Nonetheless, the cutting edge radius of micro end mills increases by thin films deposition, which might lead to excessive blunt cutting edges [6]. The blunt cutting edge is detrimental to the process outcomes because it negatively affects the minimum UCT and the ploughing effect, as it leads to their increase. This hinders the attainment of a good workpiece surface

quality. In addition, tool life may also be compromised, due to the higher required cutting forces [2]. Therefore, it is necessary to optimize the coating thickness of the coated micro end mill to reduce the size effects. Sahoo, P. and Patra, K. [51] demonstrated by micro-milling of P-20 steel that a TiAlN coated tool exhibited better machinability performance than an uncoated WC micro end mill, due to the former's high hardness and low coefficient of friction values. Their investigation showed also that TiAlN coated tools with higher coating thickness values revealed reverse performance due to the size effects.

Diamond coatings are preferred for WC-Co micro-milling cutters, because they offer lower coating defects and better machined surface quality [11]. Diamond coatings minimize tool wear, chip adhesion and poor surface finish due to their favourable mechanical and tribological properties, such as high hardness, chemical inertness, low adhesion to many materials and low friction [5]. The diamond coating deposition technique is usually the chemical vapor deposition (CVD), where diamond grains are formed on the substrate to be coated by a chemical reaction between hydrogen and carbon-containing gas, in a reaction chamber. The gas is activated and decomposed by certain energy source, such as hot filament, microwave plasma or direct current. The CVD technique that uses hot filament as the energy source is called Hot Filament CVD (HFCVD). The size of CVD diamond grains can be reduced to several micrometres, due to the re-nucleation during diamond growth [11, 52]. Chae et al. [53] investigated the effect of the grain size of diamond films for coating of WC-Co cutting tool inserts. The authors concluded that the larger grain size of microcrystalline diamond (MCD) comparing to nanocrystalline diamond (NCD) led to the formation of interfacial porosity due to the inability of diamond crystals to conform to the surface topography of WC-Co. NCD allowed the porosity elimination and a higher surface coverage, leading to higher adhesion and interfacial toughness. Silva et al. [54] tested a coating in a micro ball end mill of WC-7Co to machine a WC-15Co workpiece with an average grain size of 3 μm . The tested coating had a multilayer architecture, alternating between sub-microcrystalline (SMCD) and NCD layers. It was shown that multilayer CVD diamond coatings with SMCD and NCD layers are effective in preventing delamination by the layer-wise progressive wear of the diamond coating. Wang et al. [55] compared diamond coatings of identical thickness with different morphologies, namely MCD, SMCD, NCD and MCD/NCD layer. They were applied on WC-Co end mills and used for high-speed milling of graphite in the absence of cutting fluids. MCD shows much higher adhesion strength than SMCD and NCD coatings. MCD/NCD multilayer coatings exhibited the lowest friction coefficient and highest wear resistance, producing the best cutting performance.

Chapter 3

Experimental procedure and details

The increased complexity of the micro-milling process relatively to macro-milling imposes the need of further research given the necessity of enhancing micro-machinability, understanding especially in what regards surface quality and ploughing effects, which were highlighted topics of the conducted research work.

In micro-milling the similar scale of the cutting edge radius of the tool, the feed per tooth and the depth of cut can easily lead to ploughing effect, which may be responsible for excessive plastic deformation of the machined surface. This can result in micro-cracks due to stresses that are created by the tool compression during the process [56]. Therefore, the choice of cutting parameters must be chosen carefully in order to avoid both excessive ploughing and brittle cutting mode.

This experimental study aims at exploring the size effects that emerge of the micro-milling of WC-Co with micro ball diamond coated tools. It tries to identify the minimum UCT and the critical UCT, as well as the layer where the ploughing dominates, for a given set of machining conditions. The research comprises the study of two WC-Co grades, WC-10Co and WC-15Co, and two different tools, a two-flute micro ball end mill and a micro ball end mill without cutting edges. This chapter introduces the details of the studied tools and WC-Co grades, along with all the required setups. The experimental techniques and procedures are also described.

3.1. Experimental approach plan

The final experiments that led to the surfaces to be studied were preceded by a surface preparation composed of two operations, with the goal of equalizing initial micro-milling conditions for all experiments. Two previous operations (roughing and a finishing) ensured a flat surface and a better surface quality before the third operation in which a wide range of parameters was analysed. The sequence of these three operations and the micro-milling conditions for each one is shown in Figure 15.

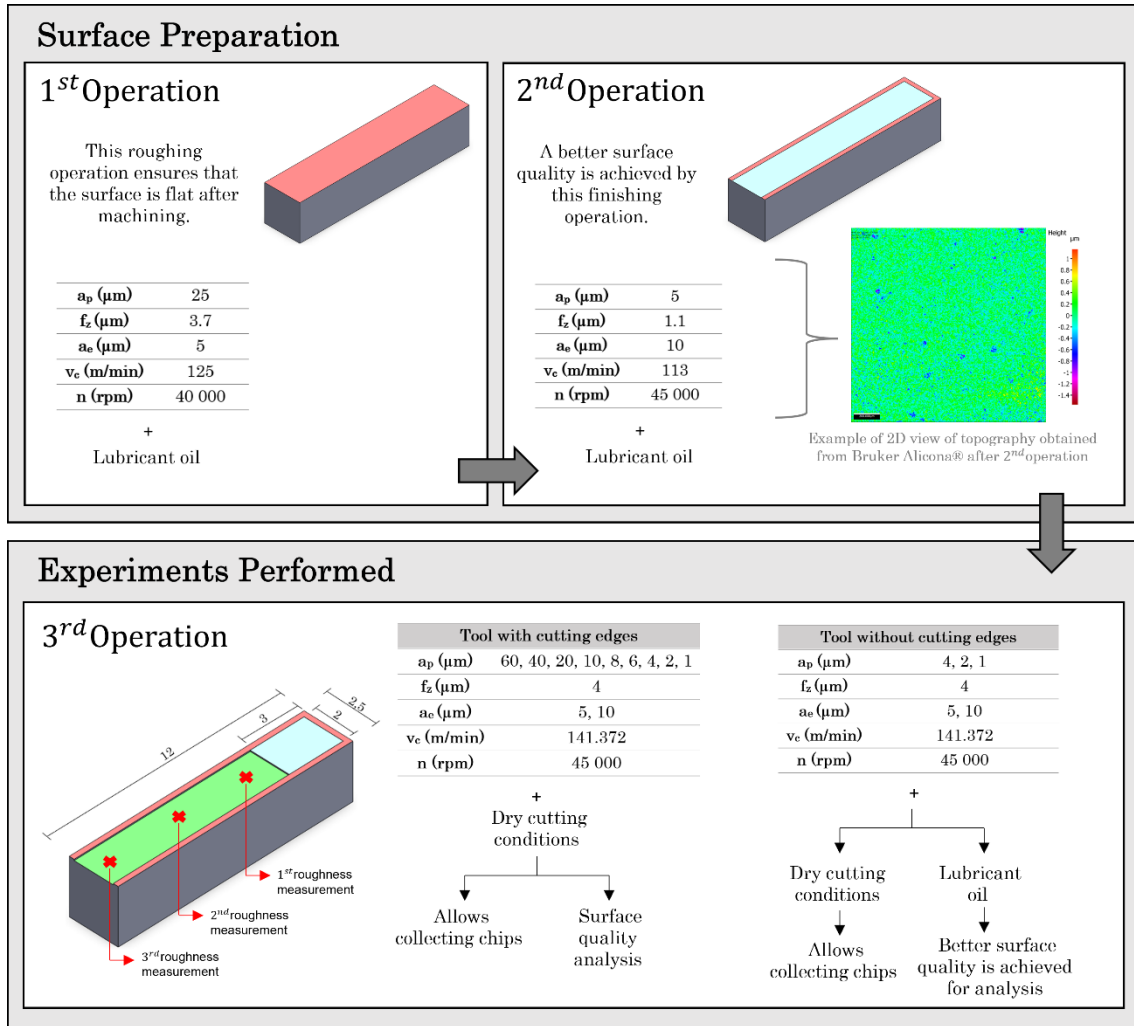


Figure 15 – Operations performed and their milling conditions.

The cutting conditions for the surface preparation stage (first and second operations) were based on the minimum roughness results out of a wide range of cutting parameters ($S_a=0.176$ μm for the WC-15Co grade and $S_a=0.128$ μm for the WC-10Co grade). After obtaining the best possible roughness value at the end of the second operation, the cutting conditions were then defined. For each set of cutting conditions, the roughness parameters were measured in three areas of 1.5x1.5 mm each: in the beginning, in the middle and in the end of the total machining area. An average the three roughness measurements was considered.

A list of cutting parameters configuration was defined for the third operation (refer to Table 6), which was used to study the minimum UCT and the critical UCT, as well as the ploughing effect on the machined surfaces. Two tools were employed in this experimental campaign: (i) a two-flute micro ball end mill and a (ii) micro ball end mill without cutting edges. The cutting parameters f_z , v_c and n are constants. Only the a_p and the a_e take different values depending on the test. All experiments were performed under dry cutting conditions to allow collecting the generated chips. However, experiments 37 to 48 were repeated with lubricant oil, given the

very poor generated surface quality without it. For that reason, roughness values analysis was based only on the repeated experiments with lubricant oil, in the case of experiments 37 to 48.

Table 6 - Experimental micro-milling matrix.

Test No.	Tool (*)	Workpiece	a_p (μm)	f_z (μm)	a_e (μm)	v_c (m/min)	n (rpm)
1	(1)	15% Co	60	4	5	141.372	45 000
2	(1)	15% Co	40	4	5	141.372	45 000
3	(1)	15% Co	20	4	5	141.372	45 000
4	(1)	15% Co	10	4	5	141.372	45 000
5	(1)	15% Co	8	4	5	141.372	45 000
6	(1)	15% Co	6	4	5	141.372	45 000
7	(1)	15% Co	4	4	5	141.372	45 000
8	(1)	15% Co	2	4	5	141.372	45 000
9	(1)	15% Co	1	4	5	141.372	45 000
10	(1)	15% Co	60	4	10	141.372	45 000
11	(1)	15% Co	40	4	10	141.372	45 000
12	(1)	15% Co	20	4	10	141.372	45 000
13	(1)	15% Co	10	4	10	141.372	45 000
14	(1)	15% Co	8	4	10	141.372	45 000
15	(1)	15% Co	6	4	10	141.372	45 000
16	(1)	15% Co	4	4	10	141.372	45 000
17	(1)	15% Co	2	4	10	141.372	45 000
18	(1)	15% Co	1	4	10	141.372	45 000
19	(1)	10% Co	60	4	5	141.372	45 000
20	(1)	10% Co	40	4	5	141.372	45 000
21	(1)	10% Co	20	4	5	141.372	45 000
22	(1)	10% Co	10	4	5	141.372	45 000
23	(1)	10% Co	8	4	5	141.372	45 000
24	(1)	10% Co	6	4	5	141.372	45 000
25	(1)	10% Co	4	4	5	141.372	45 000
26	(1)	10% Co	2	4	5	141.372	45 000
27	(1)	10% Co	1	4	5	141.372	45 000
28	(1)	10% Co	60	4	10	141.372	45 000
29	(1)	10% Co	40	4	10	141.372	45 000
30	(1)	10% Co	20	4	10	141.372	45 000
31	(1)	10% Co	10	4	10	141.372	45 000
32	(1)	10% Co	8	4	10	141.372	45 000
33	(1)	10% Co	6	4	10	141.372	45 000
34	(1)	10% Co	4	4	10	141.372	45 000
35	(1)	10% Co	2	4	10	141.372	45 000
36	(1)	10% Co	1	4	10	141.372	45 000
37	(2)	15% Co	4	4	5	141.372	45 000
38	(2)	15% Co	2	4	5	141.372	45 000
39	(2)	15% Co	1	4	5	141.372	45 000
40	(2)	15% Co	4	4	10	141.372	45 000
41	(2)	15% Co	2	4	10	141.372	45 000
42	(2)	15% Co	1	4	10	141.372	45 000
43	(2)	10% Co	4	4	5	141.372	45 000
44	(2)	10% Co	2	4	5	141.372	45 000
45	(2)	10% Co	1	4	5	141.372	45 000
46	(2)	10% Co	4	4	10	141.372	45 000
47	(2)	10% Co	2	4	10	141.372	45 000
48	(2)	10% Co	1	4	10	141.372	45 000

* (1) two-flute micro ball end mill

(2) micro ball end mill without cutting edges

Figure 16 shows one of the four workpieces that has areas machined with different cutting conditions (in the third operation). Figure 17 shows a representation of how the third operation occurs. From this representation, it is possible to see clear that the amount of material removed at each tool pass is greatly reduced.

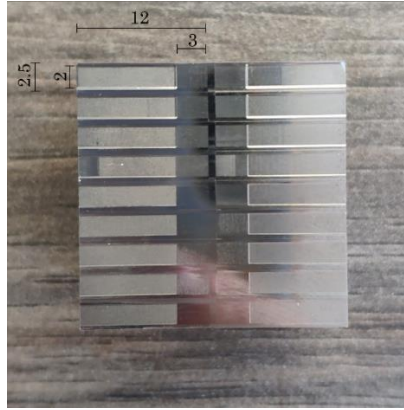


Figure 16 – Workpiece with machined areas that were performed with different cutting conditions.

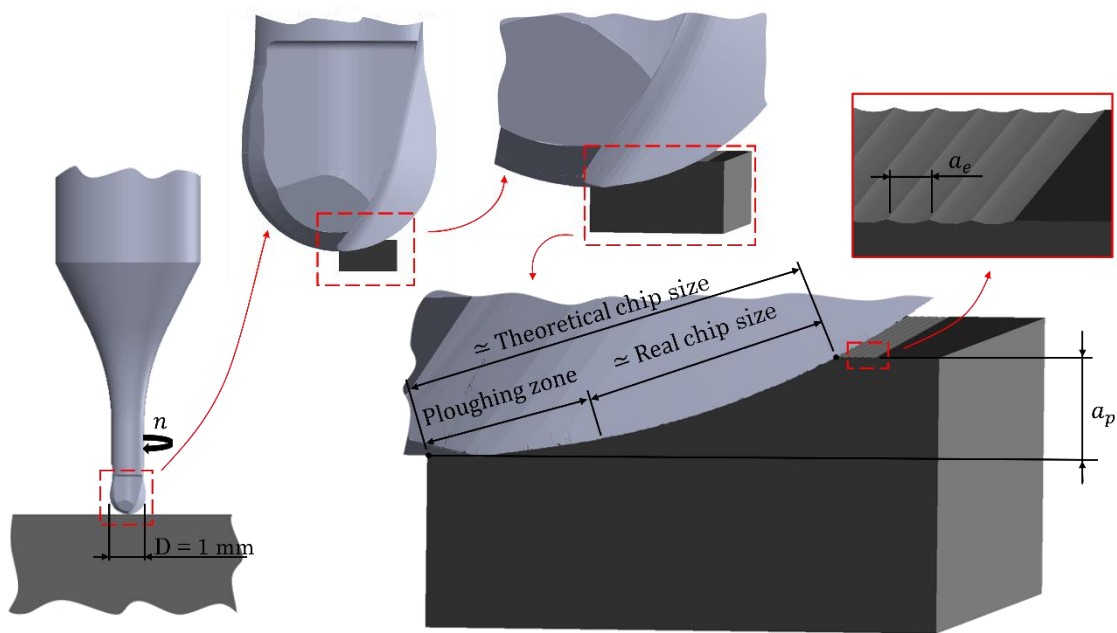


Figure 17 – Micro-machining process characterization using two-flute micro ball end mill tool.

In micro-milling, the chips collected in each experiment are extremely small, due to the lower depths of cut and feeds per tooth. The feed per tooth corresponds to the maximum thickness dimension that a chip can have, despite its variation along tooth radial displacement. In the so-called ploughing zones, there is no chip formation due to the $UCT < UCT_{min}$. This way, the chip size that may be observed with an appropriate equipment would not be the theoretical chip size, presented in Table 7 for the different cutting depths used in the tests of this study and for a micro ball end mill with a diameter of 1 mm. The real chip size depends on the machining conditions and the composition of the material machined. For WC-Co grades

with lower percentage of Co, a smaller chip size is expected to be obtained. This is because materials with lower Co content are more brittle, incrementing chips fragmentation.

Table 7 – Theoretical chip size for different values of cutting depth and for a micro ball end mill with a diameter of 1 mm.

ap (μm)	Theoretical chip size (μm)
60	250
40	200
20	150
10	100
8	90
6	80
4	70
2	50
1	40

3.1. Workpiece materials

Cemented carbide is a metal matrix composite (MMC), composed by a brittle and harder ceramic phase and a softer metallic binder phase. Its excellent mechanical properties are quite relevant to applications in which high hardness is required, such as the cutting tools and moulds industry. The range of properties of cemented carbides are high and they depend on the harder and softer phase percentages, on additives and on their microstructure, such as grain size.

The micro-milling experiments were performed in two different WC-Co material grades, with a different percentage of Co: (i) 15% and (ii) 10%. The material properties of both workpieces are shown in Table 8.

Table 8 - Properties of the workpiece materials (WC-Co) used in the experiments.

Properties	Workpiece with 15% Co	Workpiece with 10% Co
Hardness [HV10]	1160 $\pm$ 40	1385 $\pm$ 40
Transverse Rupture Strength	3270, Type B	3100, Type B
Fracture toughness [MPa $\cdot$ m ^{1/2}]	$\geq$ 20	13.8
Grain Size [μm]	3	3
Co [wt%]	15	10
TaC+NbC+TiC [wt%]	0.7	0.7

Both material grades used in the experiments are formed by 0.7% of gamma phase (γ -phase). This is a phase formed during sintering and composed by metal carbides, namely TiC, TaC and NbC, which are WC grain growth inhibitors. They improve the hardness and the fracture toughness, as well as the wear resistance [57]. Figure 18 shows an example of γ -phase circumscribed by a red dotted line in the WC-15Co material, after a surface polishing and etching with Murakami solution. It was verified that the size of this γ -phase is not always uniform.

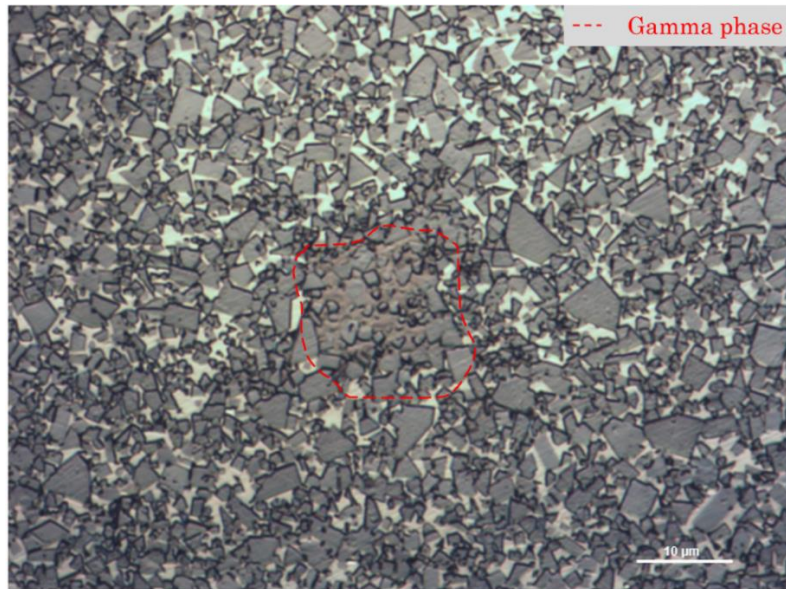


Figure 18 – Optical microscopy image of γ -phase in the WC-15Co material at a magnification of 100x.

Figure 19 shows that although in WC-10Co grade there is an equal percentage of γ -phase compared to WC-15Co grade, it is dispersed in the WC-10Co material in smaller areas.

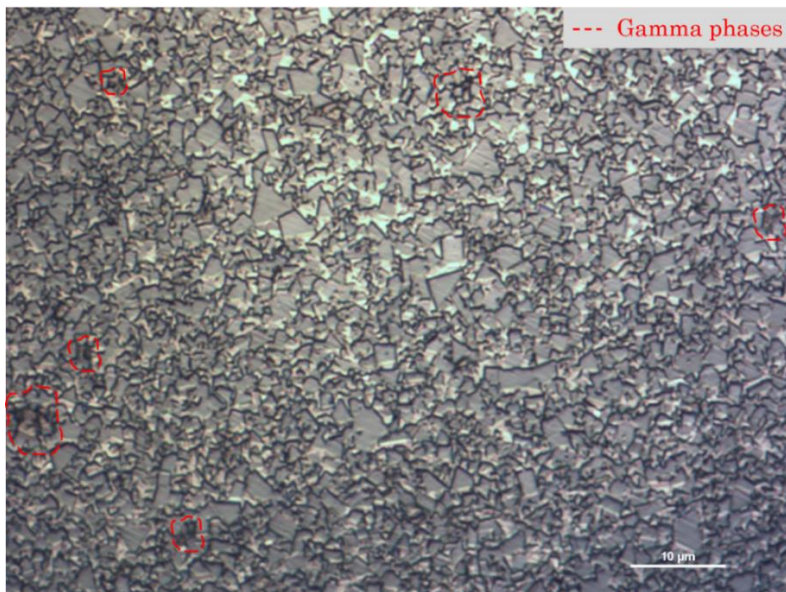


Figure 19 – Optical microscopy image of γ -phases in the WC-10Co material at a magnification of 100x.

3.2. Machine tool and cutting tools

The machine tool used to perform the machining operations in this study was a Makino® iQ500 vertical 4-axis micro-milling machine. Its technical specifications are shown in Table 9. Programming all tests of this study was performed in Mastercam®2021.



Figure 20 - Makino® iQ500 micro-milling machine [58].

Table 9– Technical specifications of the Makino® iQ500 [58].

Dimension of the work axes	X:600 mm; Y:500 mm; Z:300 mm
Table working area	800 x 500 mm
Maximum table load	300 kg
Spindle speed	≤45 000 rpm
Spindle taper hole	HSK-E32
Feed rate	X, Y: 1-16 000 mm/min; Z: 1-8 000 mm/min
Tool storage capacity	40 tools
Maximum tool diameter	20 mm
Scale feedback	0.00125 μm
Least input increment	0.0001 mm

The micro-milling operations were done using three distinct tool geometries, as illustrated in Figure 21: (a) a two-flute micro ball end mill; (b) a micro ball end mill without cutting edges; (c) six-flute micro end mill. Their specifications are described in Table 10, according to the parameters shown in Figure 21.

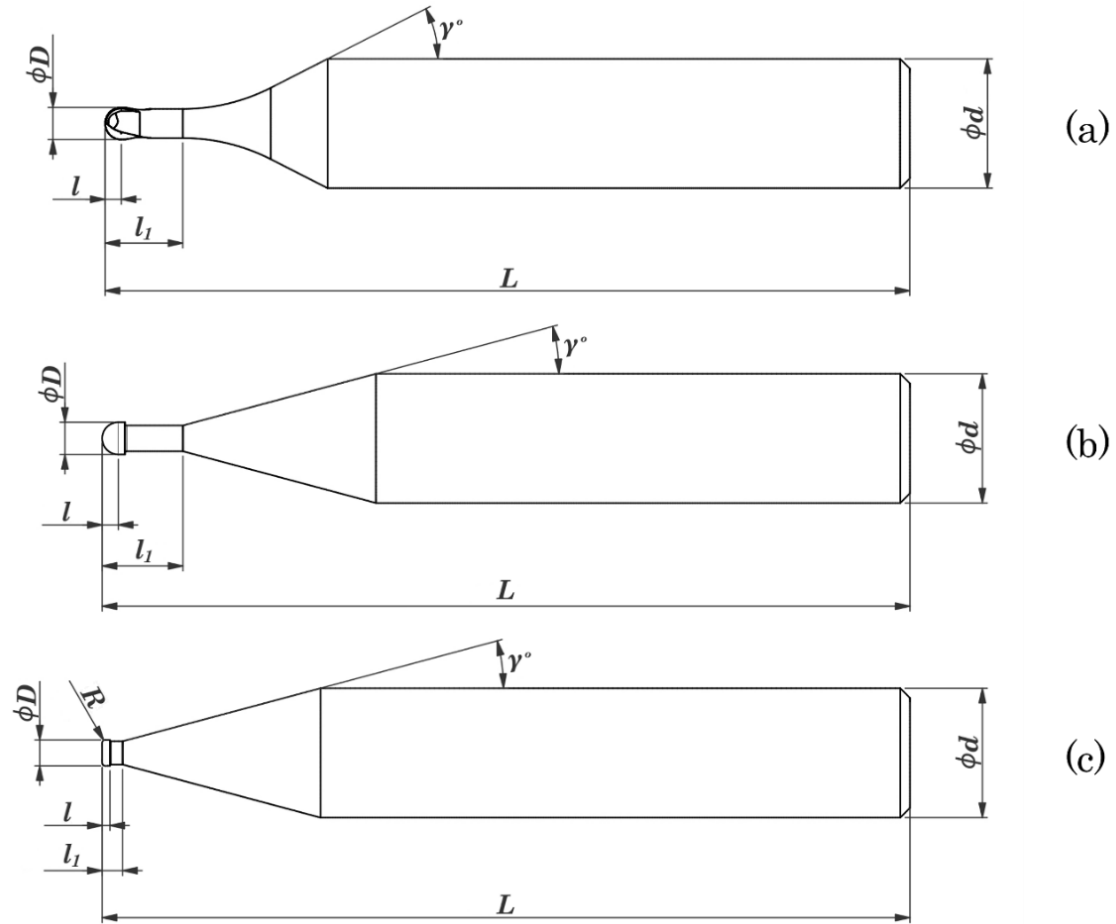


Figure 21 – Dimensions of micro-milling cutters used to study the cemented carbide micro-milling process: (a) Two-flute micro ball end mill; (b) Micro ball end mill without cutting edges; (c) Six-flute PCD micro end mill.

Table 10 – Micro-milling cutters specifications.

Symbol	Definition	Two-flute micro ball end mill	Micro ball end mill without cutting edges	Six-flute PCD micro end mill
$\varnothing D$	Nominal diameter	1.0	1.0	0.8
$\varnothing d$	Shank diameter	6	4	4
Z	Number of flutes	2	0	6
ℓ	Length of cut	0.5	0.5	0.24
ℓ_1	Effective length	2.5	2.5	0.8
L	Overall length	50	50	48
γ°	Neck taper angle	40°	15°	15°
γ	Rake angle	-1°	----	----
r	Cutting edge radius	0.0232	----	----
R	Corner Radius	----	----	0.1

*All dimensions are in millimetres

**The cutting edge radius of two-flute micro ball end mill was measured in Bruker Alicona®, according to what is described ahead in this sub-chapter.

The two-flute micro ball end mill was employed in the first operation to rough the surfaces and in the second operation the six-flute PCD micro end mill was employed to improve surface quality. Finally, in the third operation two different tools was studied, a two-flute micro ball end mill and a micro ball end mill without cutting edges. Table 10 shows the rake angle and the cutting edge radius of the two-flute micro ball end mill but not for the six-flute PCD micro end mill, given that such tool was only used to prepare the surface (equalizing initial micro-milling condition) and this study does not address the influence that it has on the studied size effects. Figure 22, Figure 23 and Figure 24 illustrate the geometrical details of selected tools.

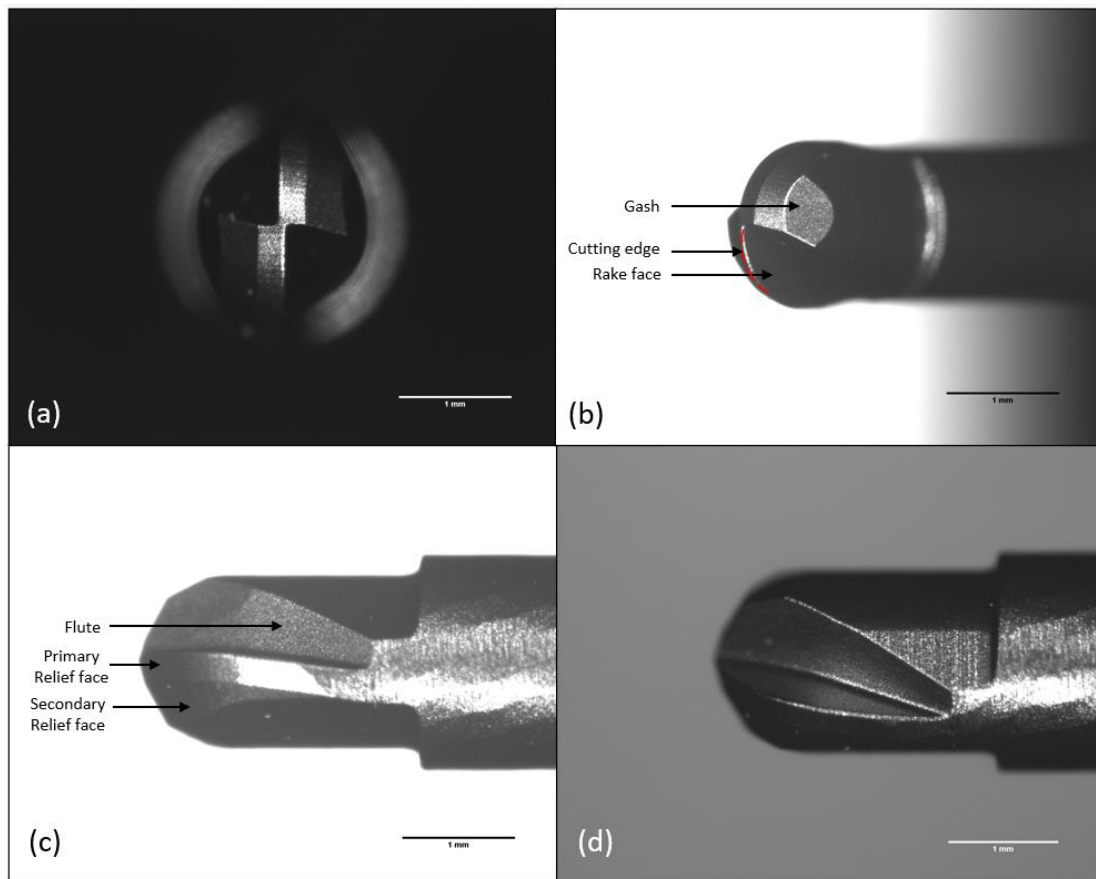


Figure 22 – Geometry description of two-flute micro ball end mill: (a) front view; (b)(c)(d) side view.

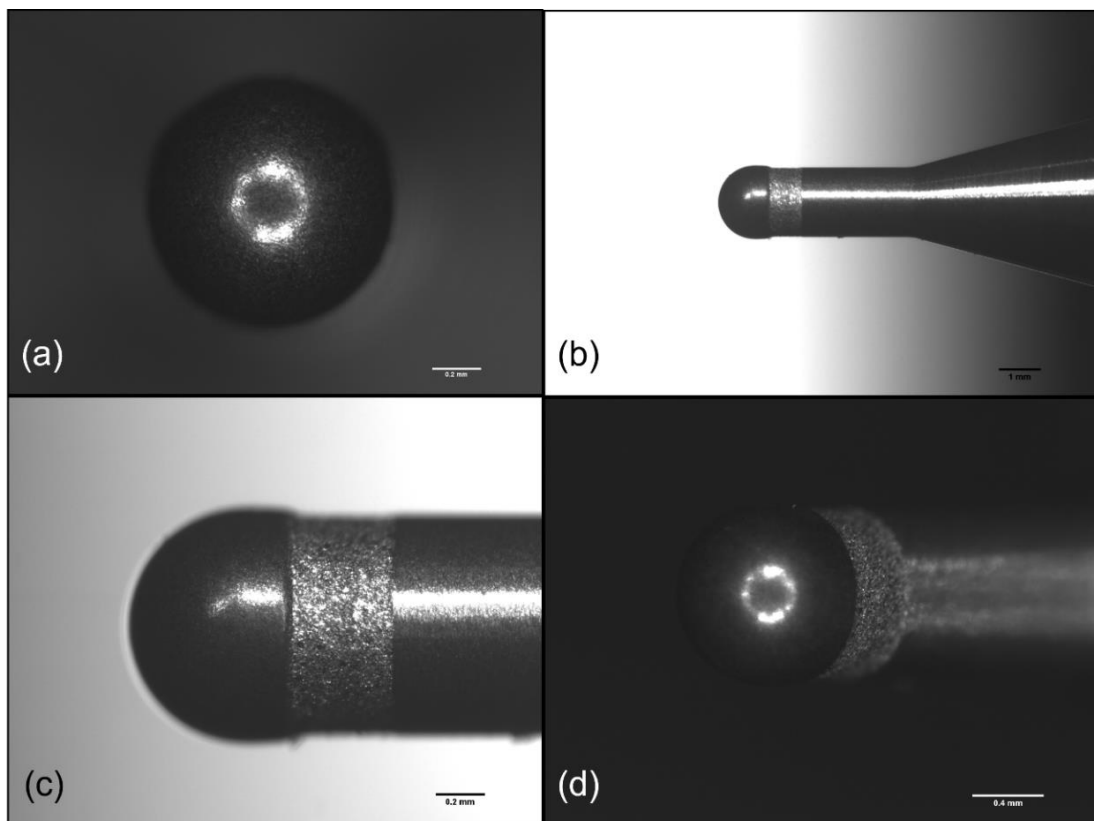


Figure 23 - PCD micro ball end mill: (a) front view; (b)(c)(d) side view.

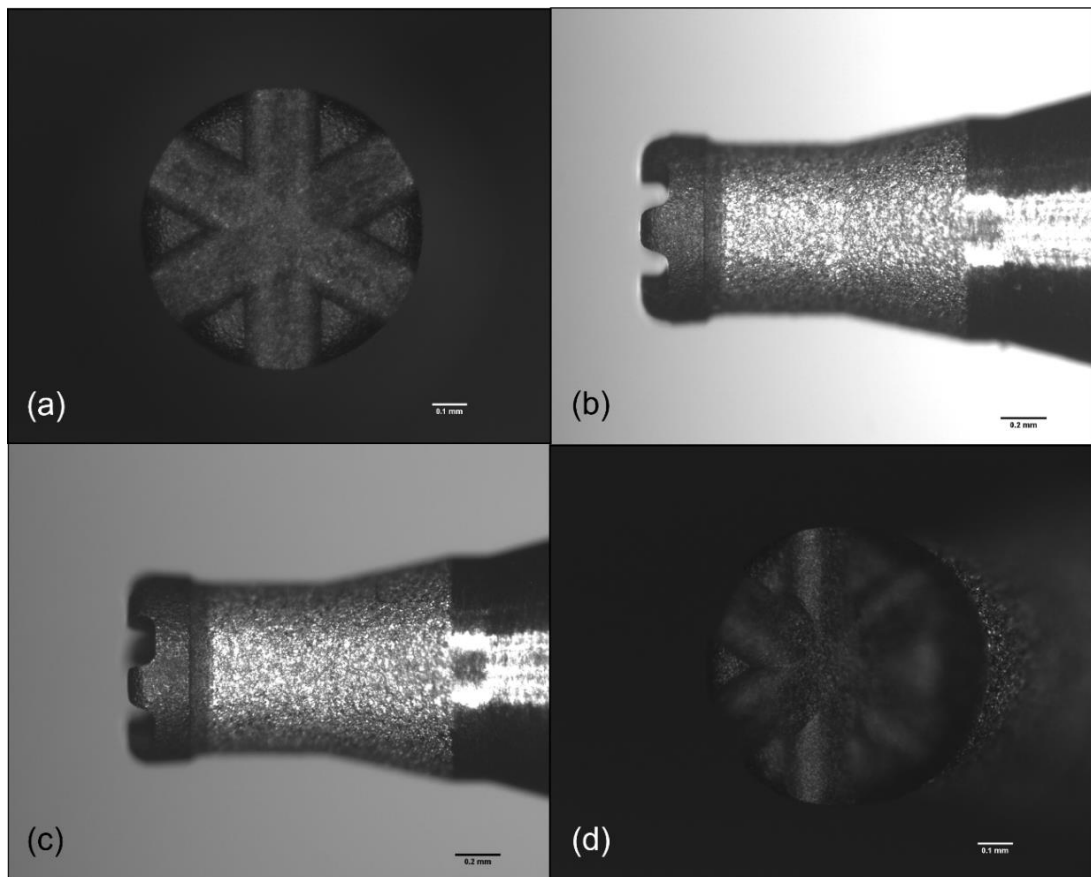


Figure 24 – Six-flute PCD micro end mill: (a) front view; (b)(c)(d) side view.

As the micro-milling process involves the ploughing effect, which may happen when the cutting edge radius is higher than UCT, it is important to know the cutting edge radius of the tool that will be studied, namely the two-flute micro ball end mill. Due to not having cutting edges, the micro ball end mill was not submitted to this measuring process. The cutting edge radius of two-flute micro ball end mill was measured in Bruker Alicona®. A three-dimensional portion of the tool was scanned, Figure 25 (a), and the cutting edge radius measured through profile (2D) analysis, Figure 25 (b). This profile was obtained from the view through the cut of a section in a cutting edge radius zone.

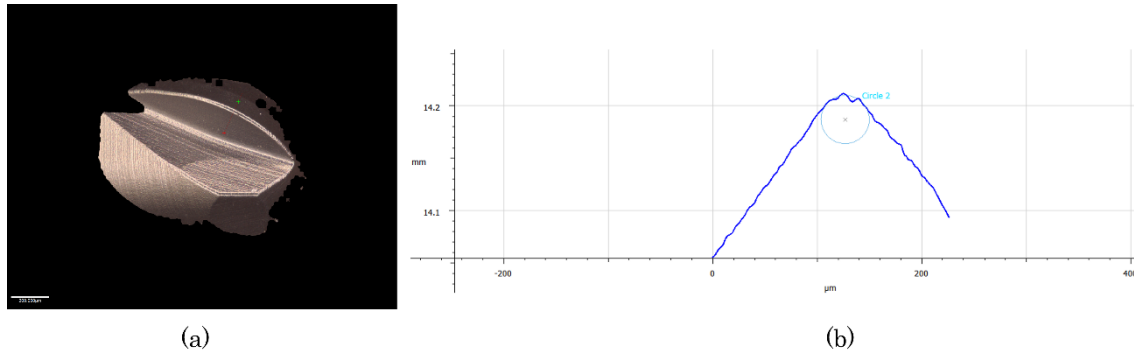


Figure 25 -Two-flute micro ball end mill in Bruker Alicona®: (a) 3D scanned portion; (b) profile form measurement of cutting edge radius.

The measurement resulted in a cutting edge radius of $23.197 \mu\text{m}$. The two-flute micro ball end mill is a WC-Co tool with 5.5% Co and a grain size equal to $1.5 \mu\text{m}$. Its coating thickness is $16 \pm 1 \mu\text{m}$, which was analysed by SEM on a cross-section. Figure 26 shows a cross section of the three coating layers, two with nanocrystalline diamond (with a thickness of 5 and $3.5 \mu\text{m}$) and other between these of microcrystalline diamond (which has a thickness of $7.5 \mu\text{m}$). The coating roughness was measured by optical profilometry on an area of $175 \times 130 \mu\text{m}$ (S_a of $0.195 \mu\text{m}$).

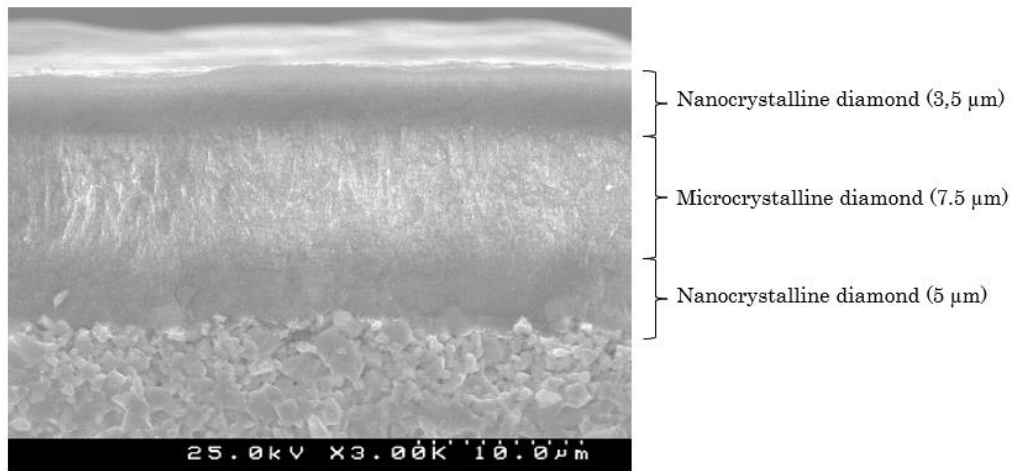


Figure 26 - Coating composition of HFCVD tool.

During the experimental tests an inspection of the final condition of the tools was carried out. In the two-flute micro ball end mill has been observed chipping and delamination in the coating as well as abrasion of substrate for less than 25 minutes of cutting. In the PCD tool no evidence of these was observed up to 100 minutes of cutting time. Figure 27 shows the delamination/ abrasion of coating and substrate of the two-flute tool after a usage time of 25, 50, 75 and 100 min.

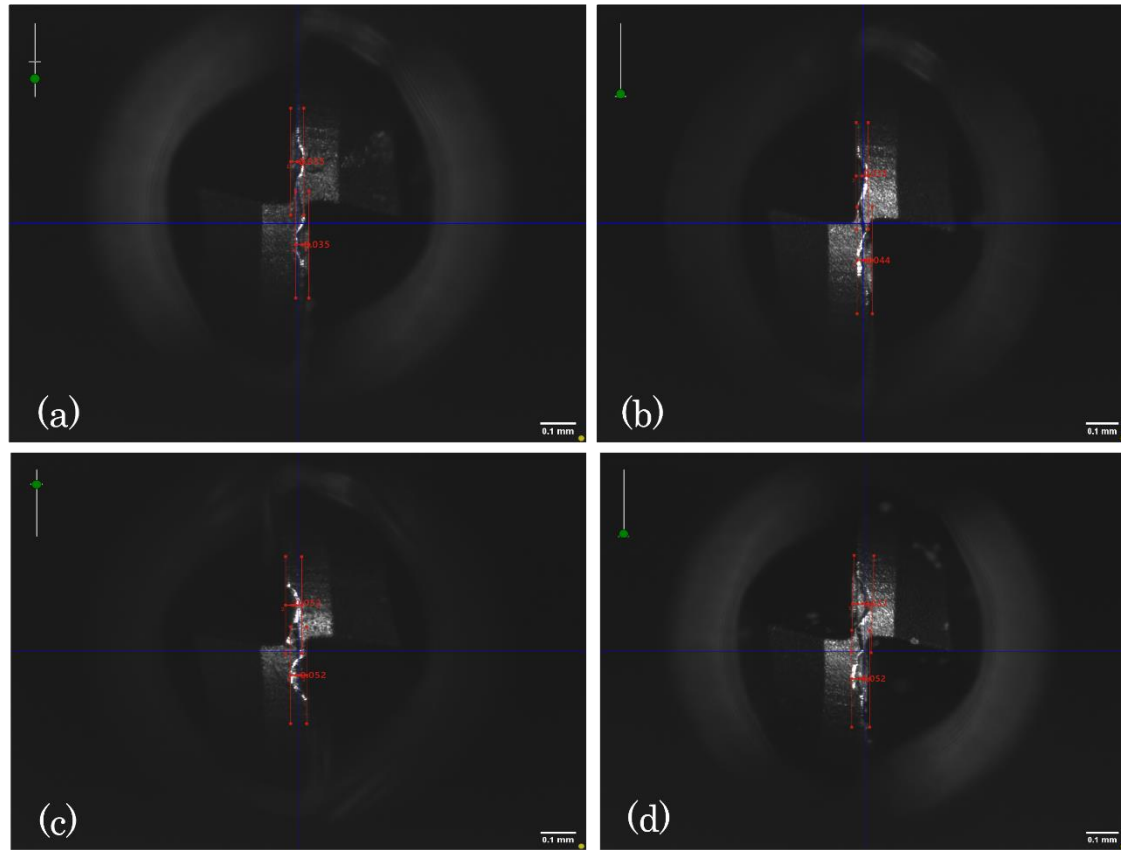


Figure 27 – Delamination/ abrasion of coating and substrate observed in two-flute micro ball end mill after a usage time of: (a) 25 min; (b) 50 min; (c) 75 min; (d) 100 min.

3.3. Machined surfaces and chips analysis

The morphology and the roughness of the machined surfaces was measured with the Bruker Alicona® InfiniteFocusSL which uses an optical, non-contact and 3D measurement system, based on focus-variation. Figure 28 shows an example of the measuring process for one of the micro-milled surfaces. Colour images with high contrast and depth of focus are also achieved [59]. Scanning electron microscopy (SEM) was also used to observe possible defects in the machined surface and the chips formed during machining. The observation of the machined surface is crucial to understand if there are any characteristic defects that can be associated with the brittle cutting mode. The chips formed during the cutting process also indicate the cutting mode, so their observation is also essential. This research work uses two different SEM's, Phenom Pro Desktop® and FEI Quanta 400 FEG ESEM / EDAX Genesis X4M®. Before their observation in SEM, samples were cleaned in an ultrasonic cleaner equipment. This procedure reduces the probability of visualizing external factors such as dirt (due to samples manipulation) during their analysis.

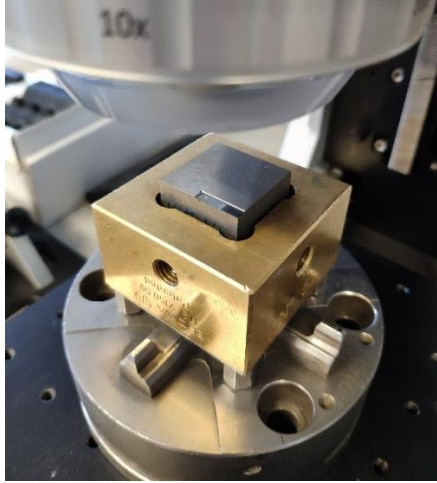


Figure 28 - Roughness measurement of a workpiece in the Bruker Alicona®.

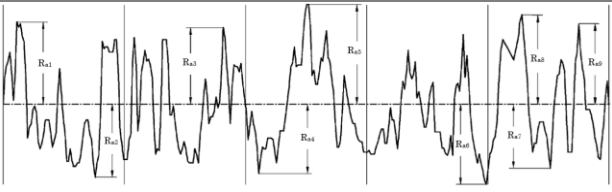
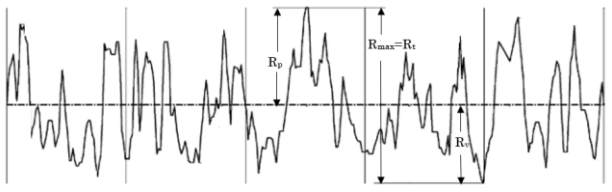
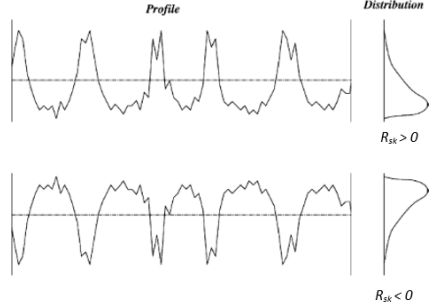
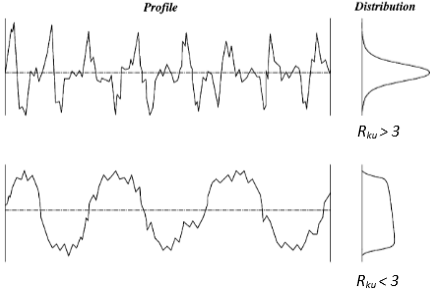
3.3.1. Roughness parameters

The surface roughness evaluation is crucial to control the properties and the function of technical surfaces, because it has implications in applications that involve surface contact with effects on wear, friction and fluid dynamics, for example [60]. The methods used to analyse the surface roughness are the 2D profile method and the 3D area method. The first method is the most used, due to being quicker, simpler and easier to interpret. Still, the areal method provides a more complete representation of the topographical features [61, 62].

2D profile parameters

The parameters mostly used to measure the surface roughness in 2D profile method are R_a , R_q , R_z and R_{max} . However, the real surface geometry is challenging to characterize, so a finite number of parameters cannot provide a full description. Thus, to obtain a more accurate description in profile method, more parameters must be used, like the skewness and the kurtosis. The skewness, R_{sk} , is used to measure the symmetry of the profile about the mean line. If there are a similar number of peaks and valleys, meaning a symmetrical height distribution, $R_{sk}=0$. The R_{sk} is positive if there is a significantly high quantity of high peaks and it is negative if there are deep scratches. The Kurtosis, R_{ku} , describes the sharpness of the probability density of profile. If $R_{ku}<3$ there are few high peaks and low valleys. However, if $R_{ku}>3$ then there are a lot of high peaks and low valleys [63]. The definition and a measurement scheme of these parameters can be seen in Table 11.

Table 11 –Roughness parameters in 2D profile method.

Symbol	Definition	Measurement scheme
R_a	Average roughness of profile	 Figure 29 - Definition of R_a (adapted from [63]).
R_q	Root-Mean-Square roughness of profile	
R_t	Maximum peak to valley height of roughness profile	 Figure 30 - Definition of R_{max}, R_t, R_p and R_v (adapted from [63]).
R_z	Mean peak to valley height of roughness profile	
R_{max}	Maximum peak to valley height of roughness profile within a sampling length	
R_p	Maximum peak height of roughness profile	
R_v	Maximum valley height of roughness profile	
R_{sk}	Skewness of roughness profile	 Figure 31 - Definition of R_{sk} (adapted from [63]).
R_{ku}	Kurtosis of roughness profile	 Figure 32 - Definition of R_{ku} (adapted from [63]).

The cut-off (λ_c), also called sample length, is the length used for identifying the irregularities characterizing the profile or the area analysed. The choice of its value influences the value of roughness parameters, so the standard ISO 4288 recommends different cut-offs according to R_a , for non-periodic profiles, which can be seen in Table 12 [1].

Table 12 - Recommended roughness cut-off values according to ISO 4288 [1].

R_a (μm)	Cut-off - λ_c (mm)	Sampling length - λ_c (mm)/ L
<0.02	0.08	0.08/0.4
>0.02-0.1	0.25	0.25/1.25
>0.1-2	0.8	0.8/4
>2-10	2.5	2.5/12.5
>10	8	8/40

3D areal surface textures parameters

The areal surface texture parameters are introduced by the standard ISO 25178-2:2012 and they resulted from technological advances and the emergence of new instruments and software [64]. The standard ISO 25178-2 presents some areal parameters which do not have any equivalent profile parameter [64]. However, some areal parameters equivalent to the profile parameters are described in Table 13.

Table 13 - Areal surface texture parameters.

Symbol	Definition
S_a	Average height of selected area
S_q	Root-Mean-Square height of selected area
S_z	Mean height of selected area
S_p	Maximum peak height of selected area
S_v	Maximum valley height of selected area
S_{sk}	Skewness of selected area
S_{ku}	Kurtosis of selected area

3.3.2. Chip analysis

The chips that resulted from the machining operations are extremely important towards a better understanding of the cutting mode and generated surface features for different cutting conditions within each tool. They were collected with a carbon ribbon immediately after each machining operation. A carbon ribbon was used because it is a magnetic conductor, so it allows the sample analysis to be more stable in SEM. After the chip images from SEM were collected, the size measurement of about one hundred chips was taken in ImageJ® and an average of these measurements was done. This process was done for each experiment in this work and the measurement was taken along the axial depth of cut, a_p . An example on how

the measurement of the size of each needle-shaped chip generated by the two-flute micro ball end mill is done is shown in Figure 33. Here the identification of the axial depth of cut is facilitated by noticing the striation marks on the back surface of the chips, which is not in contact with the rake face of the tool. These striation marks are due to the compression and shear forces on the chip when removing the material.

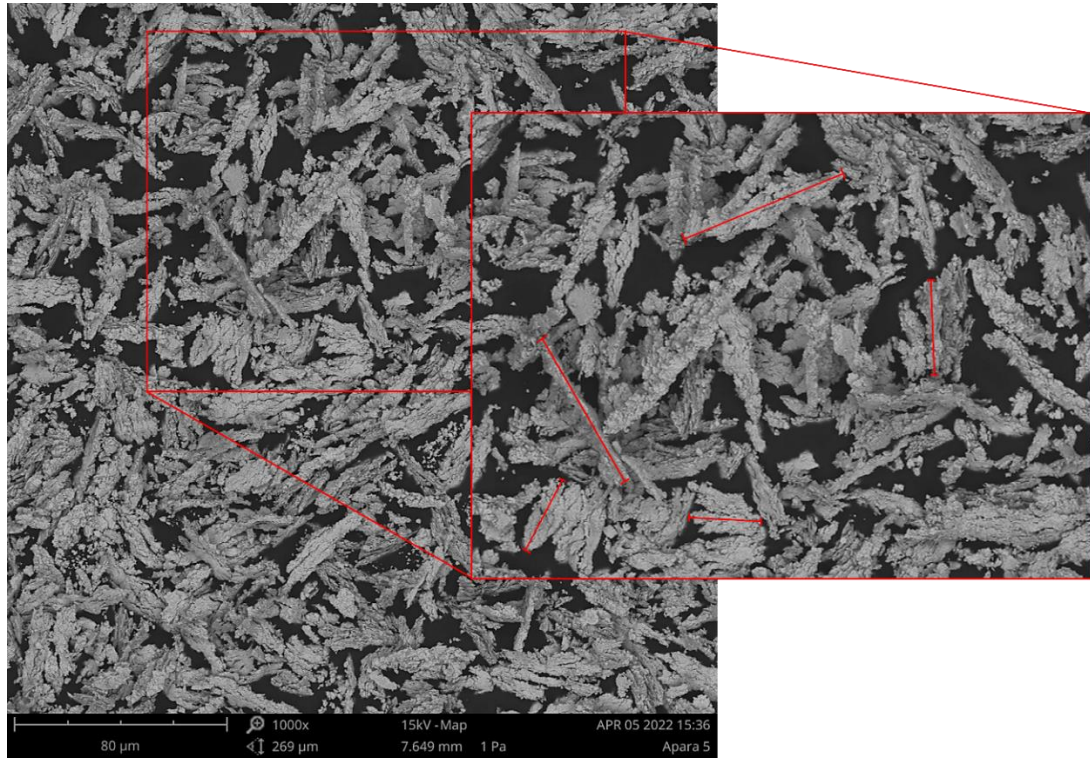


Figure 33 – Measurement in ImageJ® of the chips generated by the two-flute micro ball end mill.

As it will be further discussed in section 4.3.1., the chips formed by micro-cutter without cutting edges have a different geometry and appearance comparatively to the chips produced by two-flute micro-cutter. Figure 34 demonstrates how the size of chips originated with the tool without cutting edges is collected.

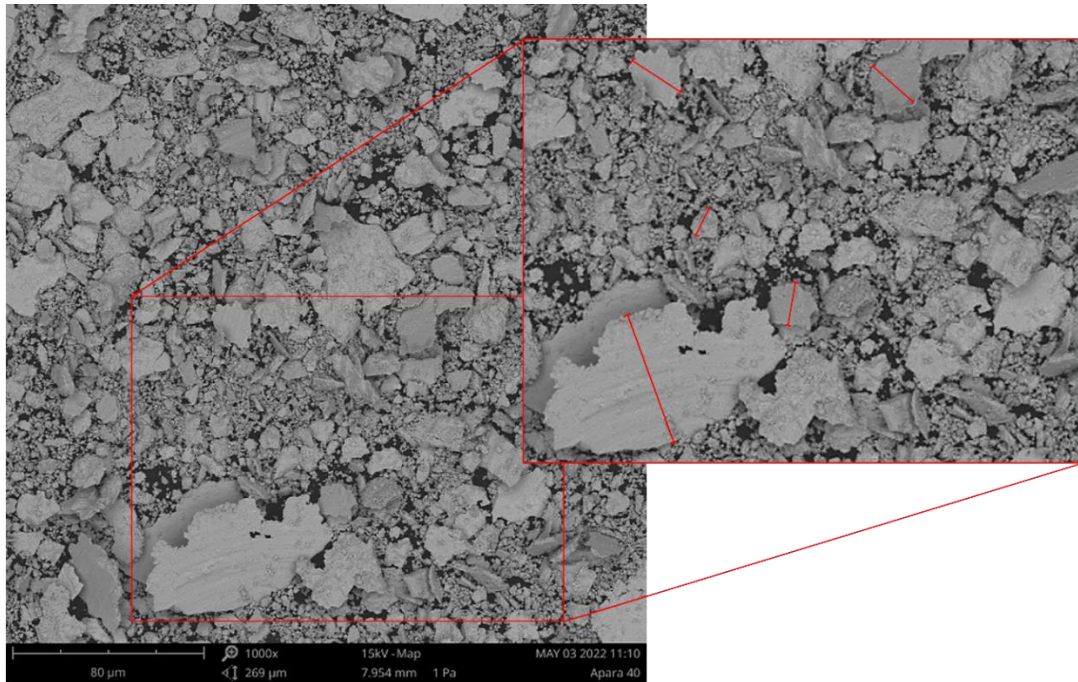


Figure 34 – Measurement in ImageJ® of the chips generated by the micro-cutter without cutting edges.

As the chips generated by tool without cutting edges do not show striation marks in the back surface of the chips, the identification of the measurement direction is not so easy. In this case, tool scratch marks, as seen in Figure 34, were helpful. It is important to highlight that the results of these chips measurement correspond to an average of several (>100) measurements for each test.

Chapter 4

Experimental results and discussion

4.1. Introduction

This chapter will be focused on the main observations and results obtained from the micro-milling experiments, their analysis and discussion. Section 4.2. presents the results obtained from the experimental setup performed with the tool with cutting edges, whereas in section 4.3. analogous results are shown for the tool without cutting edges. Each of these two sections comprises the discussion for both materials studied, namely WC-15Co and WC-10Co materials. Besides, the results obtained from observation of the collected chips (from each machining operation) and the topography of each machined surface will be presented and discussed. Lastly, it is also an aim of this study to identify possible changes in machined surfaces that may occur within distinct values of depth of cut and cut width.

4.2. Milling cutter with cutting edges

4.2.1. Chips formation and their size

Chip formation consistently occurred regardless of cutting conditions and WC-Co grade, when the two-flute micro ball end mill was employed. Thus, in a given portion of the a_p values employed, the minimum UCT was reached with the tool used. Figure 35 and Figure 36 show a representative selection of WC-15Co and WC-10Co collected chips, respectively, for each tested condition of micro-milling. For both material grades and operative conditions (a_e and a_p) small chip fragments can be observed. The fragments can be resultant from chips that get into the tool path (interference, as dry cutting process does not clear the process zone), during the micro-milling process. From both figures it is also possible to observe that the needle shaped chips formed with the two-flute micro ball end mill have a flat rather than curled appearance for both WC-Co grades. While the chip surface that does not contact the rake surface of the tool shows striation marks due to the intense compressive and shear stresses, the chip's back surface (that contacts the rake face) is smoother, as shown in Figure 37. This smooth chip back surface aspect is a good indicator of the presence of the ductile cutting

mode, as concluded by Bian et al. [36]. Besides, brittle cutting mode does not completely dominate the chip formation mechanism, otherwise only fine material particles could be seen and no chips could be perfectly detached, as referred by Liu et al. [65].

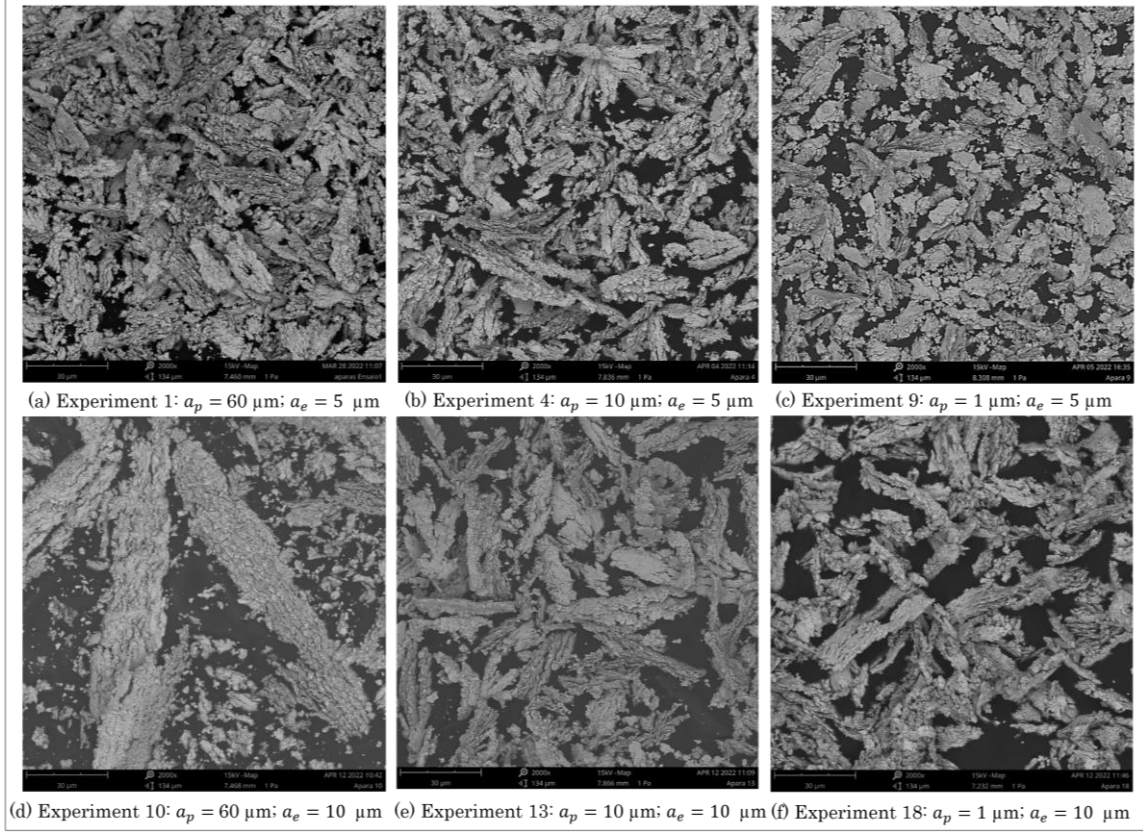


Figure 35 - SEM images with an amplification of 2000x of the collected WC-15Co chips.

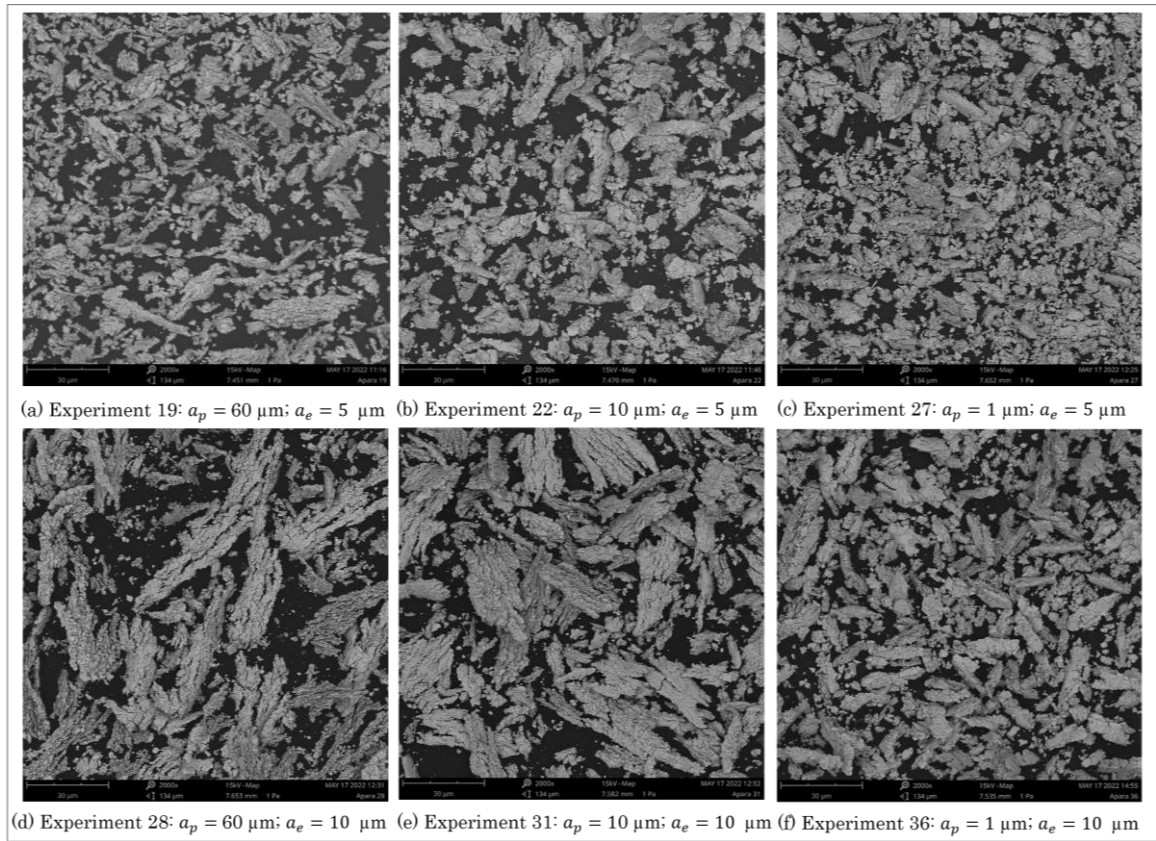


Figure 36 - SEM images with an amplification of 2000x of the collected WC-10Co chips.

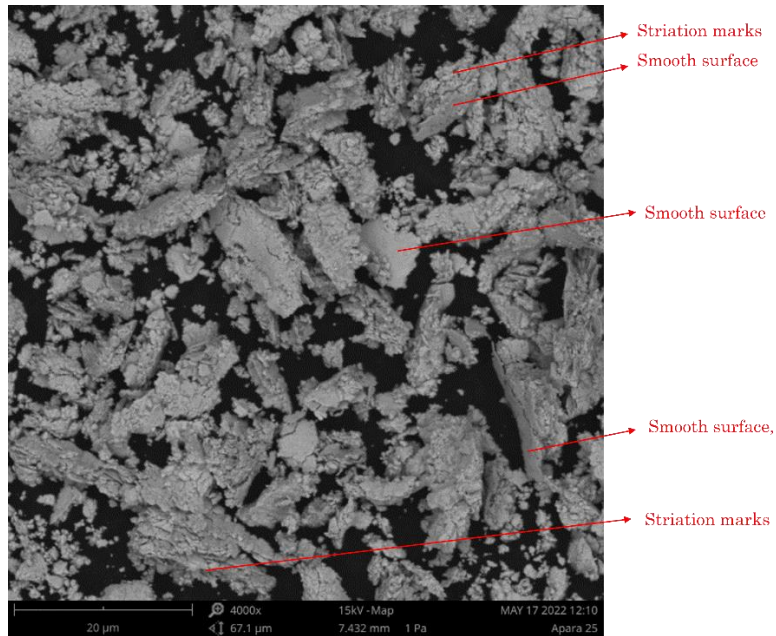


Figure 37 - Characterization of the WC-Co chips formed with the two-flute micro ball end mill (experiment 25: $a_p=4 \mu\text{m}$; $a_e=5 \mu\text{m}$).

Figure 38 shows the chip average size in function of operative conditions for both WC-15Co and WC-10Co materials. A relation between chip size and a_p can be noticed. Despite some scatter, it is verified that chip size increases

with increasing a_p , which reinforces the idea inferred by Figure 35 and Figure 36. Scatter to the increasing trend might be resultant from chip fragmentation degree. Even though a representative sample of chips was selected (>100), average chip size will certainly be influenced by that phenomenon. The collection of the chips was done carefully to avoid their damage and the analysis sample was chosen meticulously to have the best possible representation of the population.

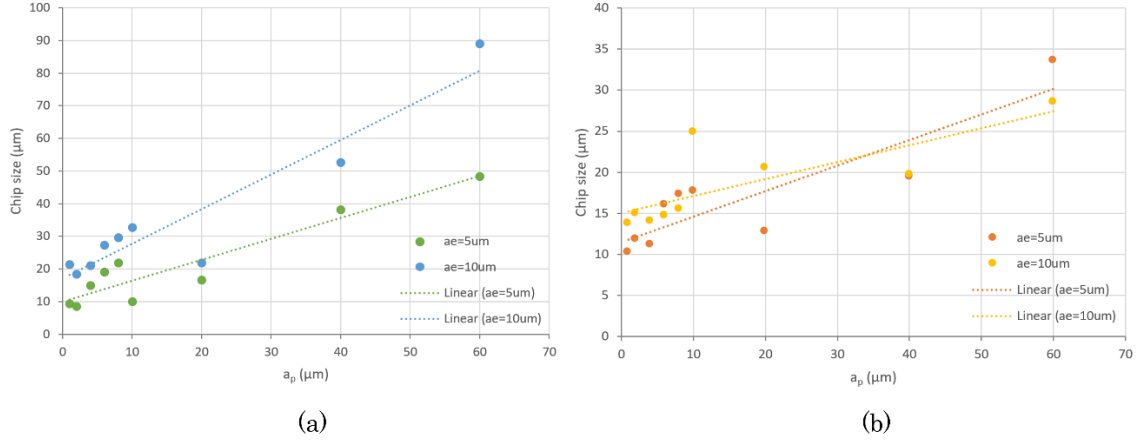


Figure 38 - Variation of chip size with the depth of cut, a_p , for cut widths, a_e , of 5 μm and 10 μm , for the workpiece material: (a) WC-15Co; (b) WC-10Co.

Table 14 presents the average of the measured chip size for each experiment with two-flute micro ball end mill and it also compares these values with the theoretical chip size for each a_p value.

Table 14 – Theoretical and real chip size in function of Co percentage, a_e and a_p .

a_p	Theoretical chip size	Real chip size							
		15%Co, 5 μm		15%Co, 10 μm		10%Co, 5 μm		10%Co, 10 μm	
		Measured	% to theoretical	Measured	% to theoretical	Measured	% to theoretical	Measured	% to theoretical
60	250	48.46	19.38	89.04	35.62	33.71	13.48	28.55	11.42
40	200	38.22	19.11	52.62	26.31	19.42	9.71	19.71	9.86
20	150	16.49	10.99	21.90	14.60	12.70	8.47	20.63	13.75
10	100	10.05	10.05	32.65	32.65	17.69	17.69	24.86	24.86
8	90	21.87	24.30	29.59	32.88	17.27	19.19	15.44	17.15
6	80	19.17	23.96	27.32	34.15	15.99	19.99	14.76	18.45
4	70	15.00	21.43	20.99	29.99	11.25	16.07	14.01	20.01
2	50	8.44	16.88	18.49	36.98	11.85	23.7	14.92	29.84
1	40	9.27	23.18	21.30	53.25	10.26	25.65	13.79	34.47

Figure 38, supported by Table 14, makes it clear that the average chip size is smaller for the WC-10Co grade than for the WC-15Co grade. This is because cemented carbides with lower Co content are more brittle, so their

chips break more easily. It is also important to note that for an increasing a_p , the real chip size in relation to its theoretical size decreases. From Table 14 it is also possible to see that the average chip size is higher for an a_e of 10 μm than 5 μm , which can be explained by Figure 39. Ductile chip formation is only possible when there is a sufficient value of thickness, t_0 . Variation of a_e leads to the variation of ploughing zone, which consequently influences the percentage of chip that is submitted from ploughing conditions. Final chip cross section size depends on both f_z and a_e . The larger these values are, the thicker the chip will be.

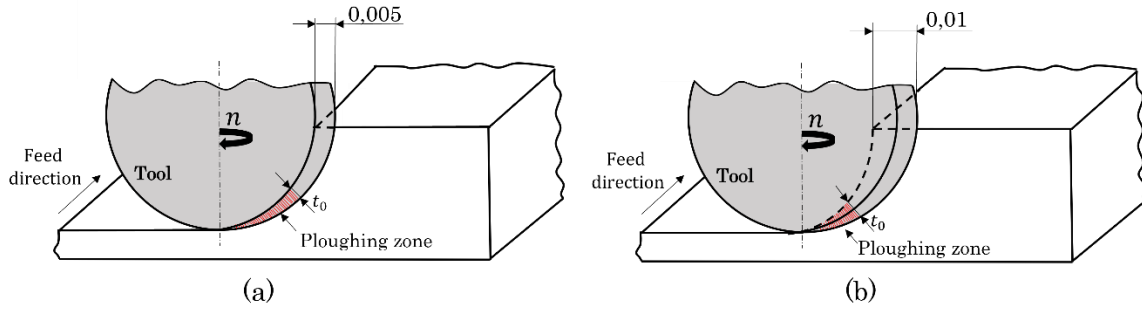


Figure 39 – Ploughing zone for an: (a) $a_e=5 \mu\text{m}$; (b) $a_e=10 \mu\text{m}$.

Figure 40 shows an illustration of the depth of cut from which the ploughing zone begins (L) for a given a_p value. From a depth of L there is no ductile chip formation. Figure 41 shows the L parameter for each tested a_p value, for both WC-CO grades and for both tested a_e value (5 and 10 μm). The L parameter was calculated using the average of measured chips size (demonstrated in Table 14).

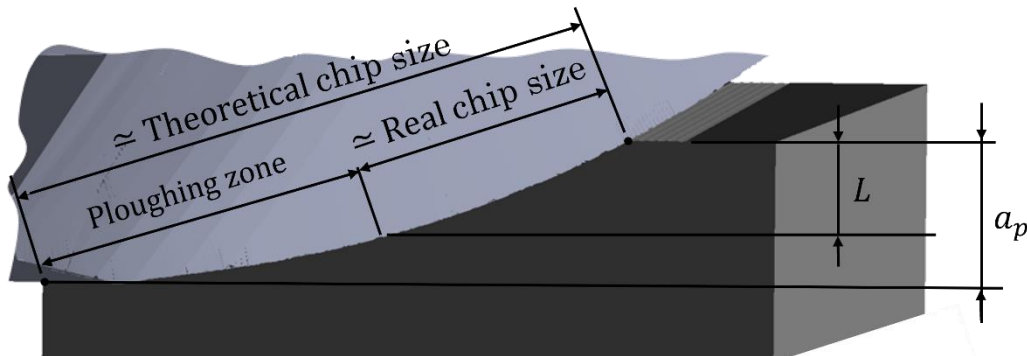


Figure 40– Illustration of the depth of cut from which the ploughing zone begins (L).

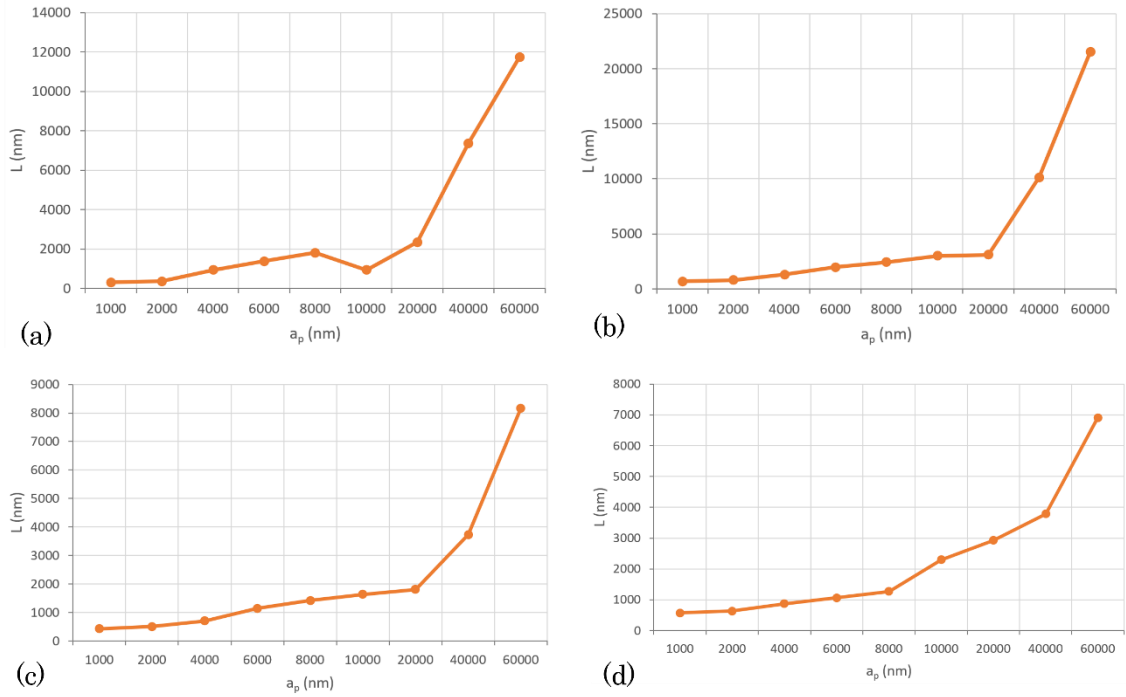


Figure 41 – Depth of cut from which ploughing zone begins (L) for a total depth of cut (a_p): (a) WC-15Co and $a_e=5\mu\text{m}$; (b) WC-15Co and $a_e=10\mu\text{m}$; (c) WC-10Co and $a_e=5\mu\text{m}$; (d) WC-10Co and $a_e=10\mu\text{m}$.

The tendency of L parameter has showed to be different below the value of cutting edge radius ($r_\beta=23.197\ \mu\text{m}$). When $UCT < r_\beta$ the L value becomes much lower than $a_p - L$, i.e., the ploughing zone. Thus, when $UCT < r_\beta$ the size effects have more impact in chip formation, including the ploughing effects.

4.2.2. Topography

Surface topography was analysed through the measurement and monitoring of different areal roughness parameters. Figure 42 presents the results of those measurements for both WC-15Co and WC-10Co materials within the tested operative conditions. Figure 42 (a) and Figure 42 (b) show that the S_a and the S_q , respectively, are generally higher for an a_e of $5\ \mu\text{m}$, except for an a_p of $8\ \mu\text{m}$ for the WC-15Co material. Besides, these parameters do not change significantly with the a_p values, for each WC-Co grade and operative conditions. This observation might indicate that the parameters S_a and S_q are independent from the a_p for the tested cutting conditions. Aslantas et al. [29] reached this conclusion by micro-milling of titanium alloys. The authors referred the existence of an a_p value below which S_a is independent of a_p . Figure 42 (c) reveals an increasing pattern of S_v parameter with increasing a_p for the WC-15Co material when machined with an a_e of $5\ \mu\text{m}$, which seems indicate that deeper micro-pits are originated by these conditions for the referred WC-Co grade. Figure 42 (d) also shows higher values of S_p parameter for the WC-15Co material with an

a_e of 5 μm . Figure 42 (d) demonstrates that the WC-15Co surface machined with an a_e of 5 μm has a higher asymmetry. This asymmetry is mainly composed of peaks, which may have origin in an intense ploughing effect on the surface. Finally, Figure 42 (f) demonstrates that both materials have always sharp peaks for all tested cutting conditions.

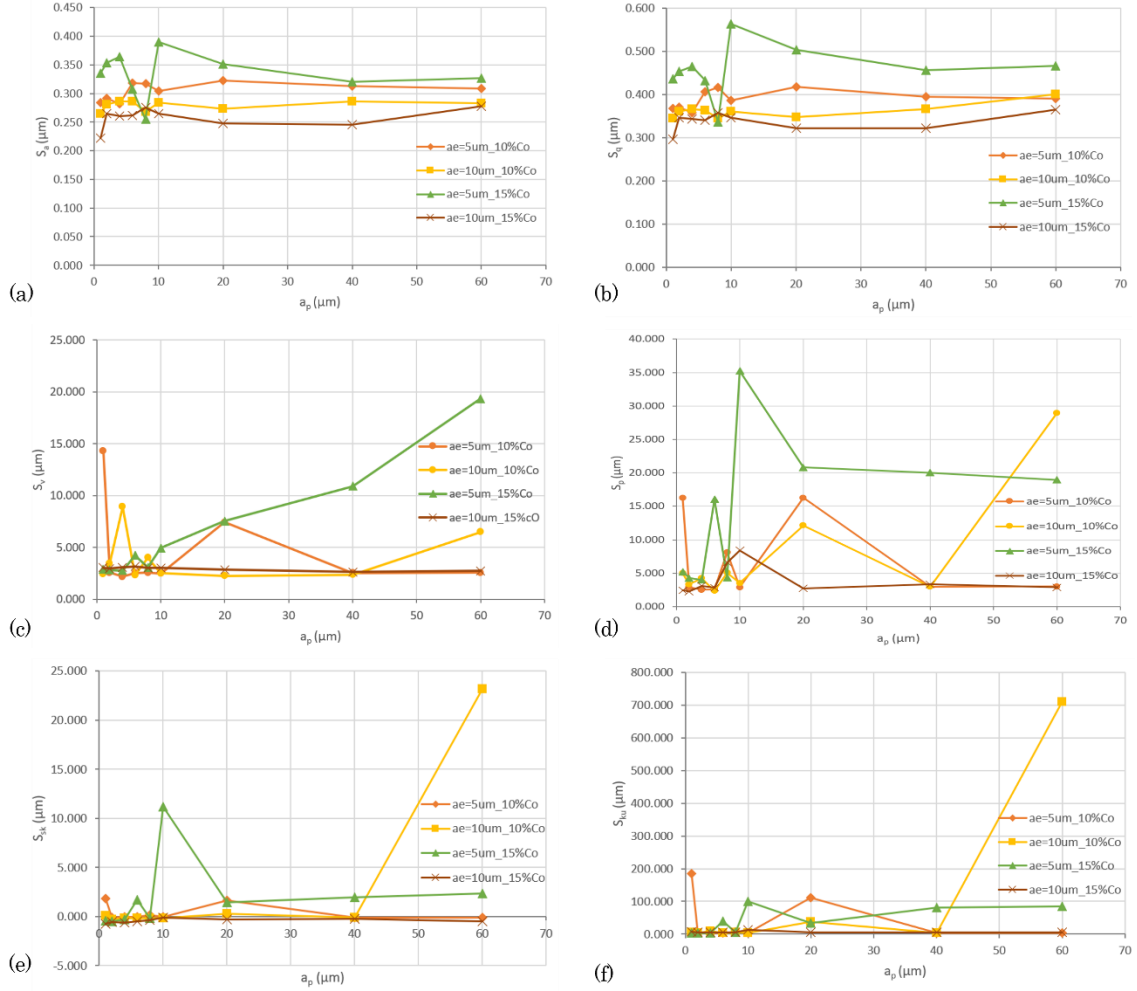


Figure 42 - Roughness parameters obtained from the experiments performed with different cutting depths, a_p , and for cut widths, a_e , of 5 μm and 10 μm , for the WC-15Co and WC-10Co materials: (a) S_a ; (b) S_q ; (c) S_v ; (d) S_p ; (e) S_{sk} ; (f) S_{ku} .

Figure 43 (a) and Figure 43 (b) show the topographical data of WC-15Co surfaces machined with an a_p of 6 and 4 μm , respectively. While for an a_p of 4 μm a wavelike pattern machined surface can be noticed, the same is not valid for the larger a_p condition (6 μm).

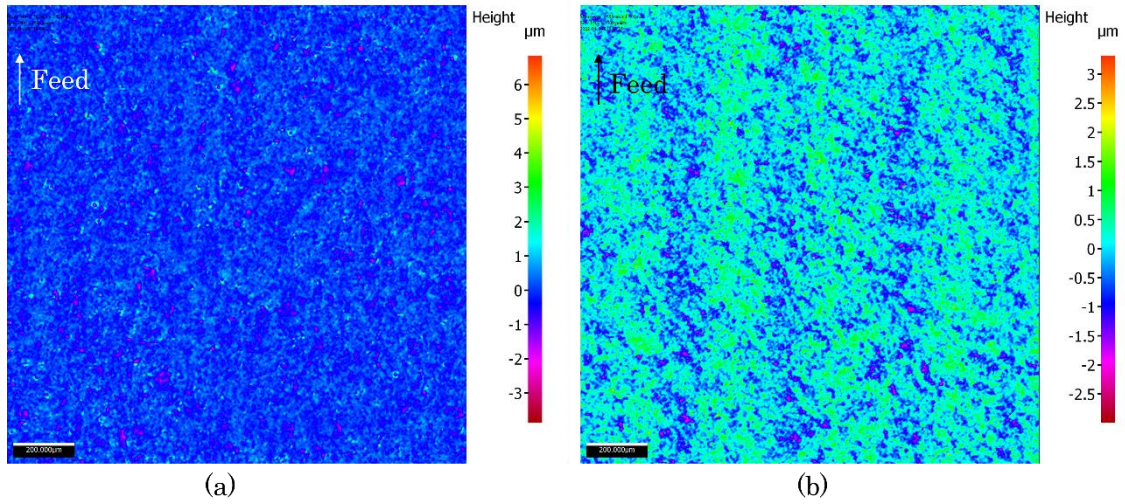


Figure 43 - Topographical images of the machined surface of WC-15Co material in the (a) experiment 6 ($a_p=6 \mu\text{m}$, $a_e=5 \mu\text{m}$) and in the (b) experiment 7 ($a_p=4 \mu\text{m}$, $a_e=5 \mu\text{m}$).

4.2.3. Machined surface characterization using SEM

The observation of the machined surfaces and resultant chip morphology was performed through Scanning electron microscopy (SEM). Figure 44 shows the transition between a non-machined and machined areas by a two-flute micro-milling cutter passage, after first operation of surface preparation.

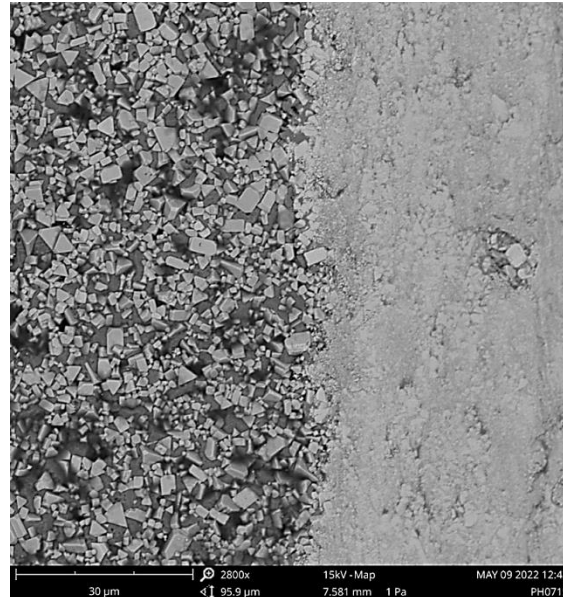


Figure 44 - WC-15Co material top view of a transition zone between machined and non-machined zone, on the left and on the right respectively.

A higher machined area with the roughing operation conditions can be seen in Figure 45, where surface cracking and some micro-pits on the

surface are shown. The image also demonstrates that below the observed thin layer of deformed materials, the WC grains do not seem to undergo morphological changes, meaning that the mechanical behaviour of the original material is maintained. This is valid for both WC-15%Co and WC-10%Co materials. In some of these micro-pits, an EDS analysis (refer to Figure 46) revealed the existence of Ti, Ta and Nb (characteristic elements of the WC-Co γ -phase, which is rich in TiC / TaC and NbC). Unlike cobalt this γ -phase does not undergo plastic deformation (due to its very high hardness) being consequently pulled off the machined surface. Such surface defects were verified in almost all experiments, in both WC-15Co and WC-10Co materials. Still, it is important to note that the selected parameters for the first operation were carefully selected based on surface roughness minimization and thus, it is believed that this current initial condition has a relatively small number of defects (refer to Figure 45 (a)) with minimal impact of further operations (second and third).

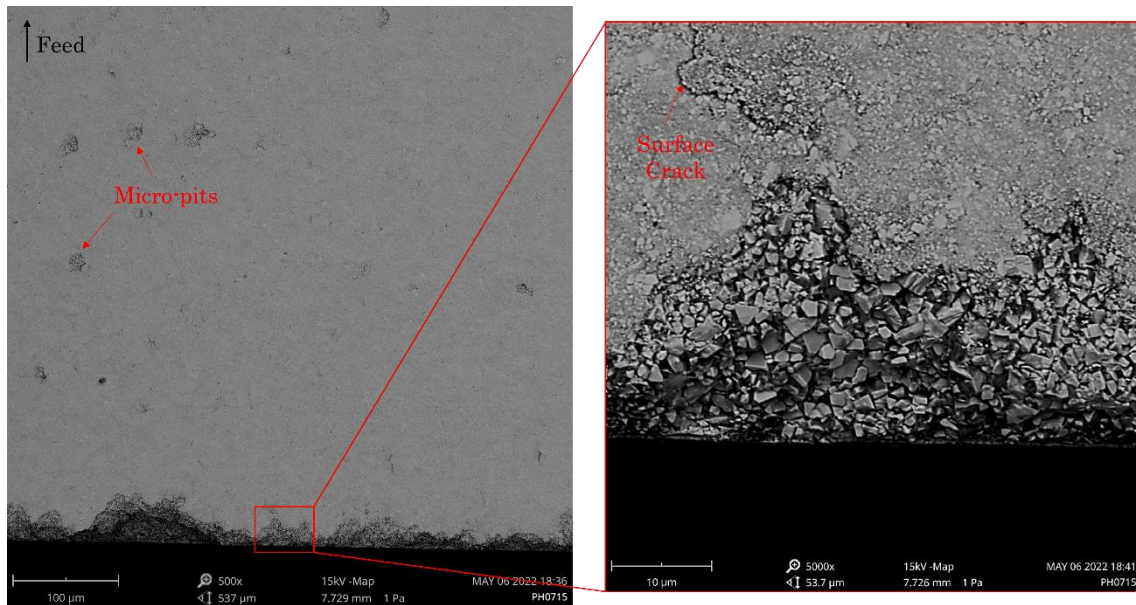


Figure 45 - Top view of the initial machining area of the WC-15Co material after being machined with a two-flute micro ball end mill in the first surface preparation roughing operation.

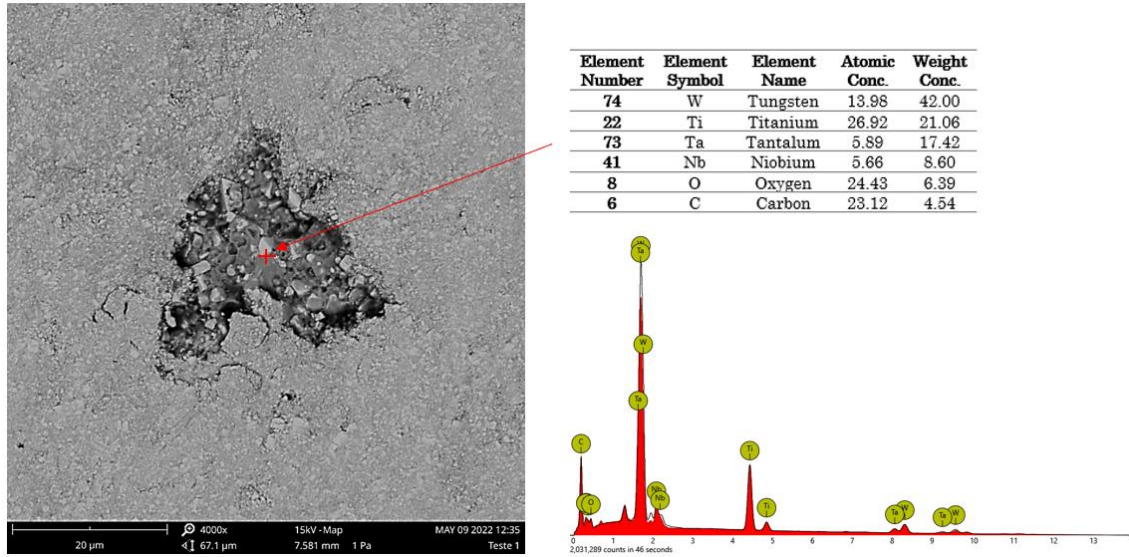


Figure 46 –EDS analysis of a γ -phase in the machined surface.

Figure 47 and illustrate the deformation phenomenon that occurs in WC-15Co and WC-10Co materials, respectively, for all conditions tested (after third operation). The surface obtained from the experiments showed the evidence of ploughing, which is responsible for the size effects, as referred by the literature. Figure 47 (a) shows some tool marks and, for the lower a_p values, these marks can originate not only from the third operation but also from surface preparation (first and second operations). This is because the reduced material removal in the last operation may not be able in some places to completely remove the marks left by the previous tools, as well as other surface defects like micro-pits. Figure 47 (b) demonstrates the presence of some cracked WC grains below the thin ploughing layer.

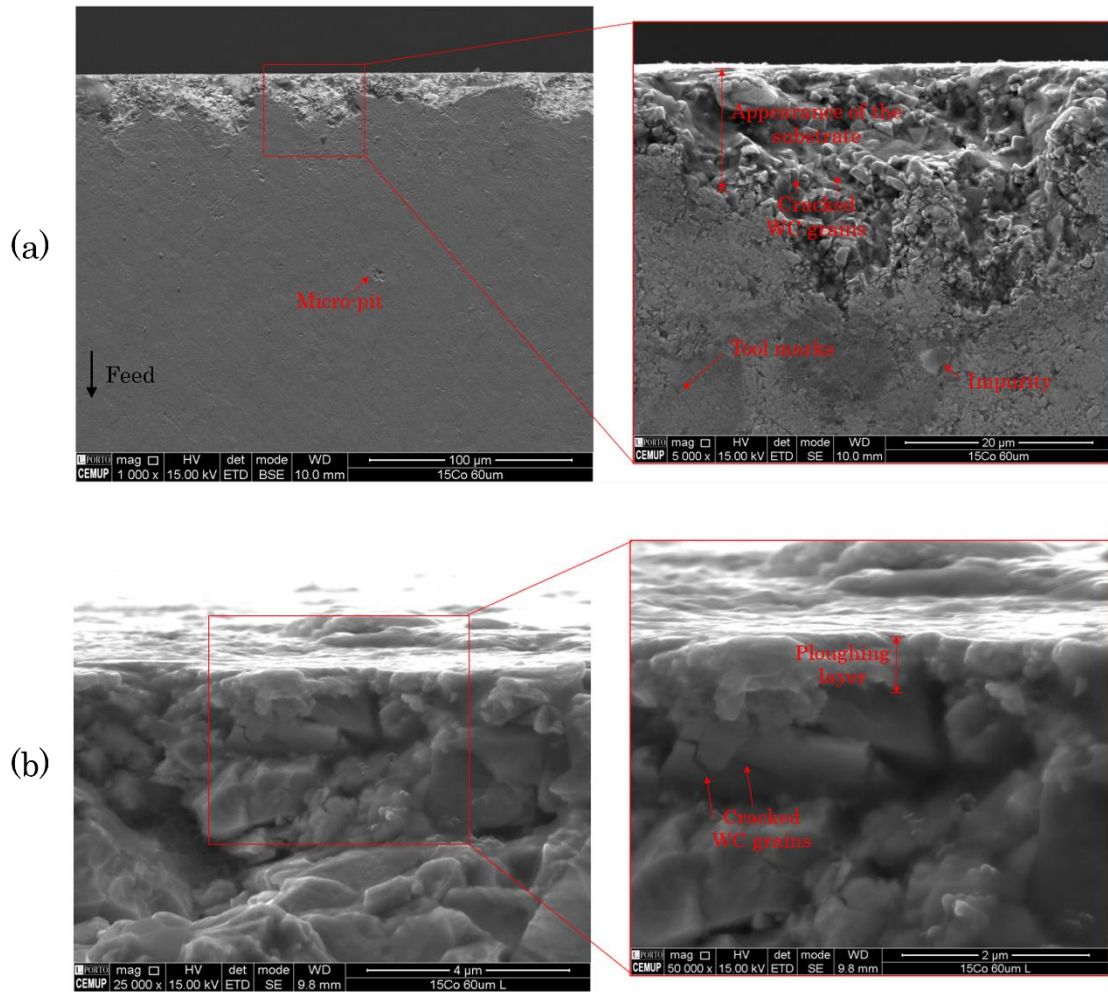


Figure 47 – SEM images of WC-15Co surface after being machined under the conditions of experiment 1 ($a_p=60 \mu\text{m}$, $a_e=5 \mu\text{m}$): (a) top view; (b) side view.

The same operative conditions in micro-milling of WC-10Co material cause similar superficial defects when compared to the WC-15Co material. Figure 48 (a) shows the presence of tool marks, surface cracks and micro-pits. The surface cracks seem to be more intense in material with less percentage of Co. As the WC-10Co material has higher hardness than WC-15Co material, its capacity of plastic deformation is lower. Figure 48 (b) shows what seems to be a layer where the ploughing effect is present. Below this ploughing layer some cracked WC grains can be observed.

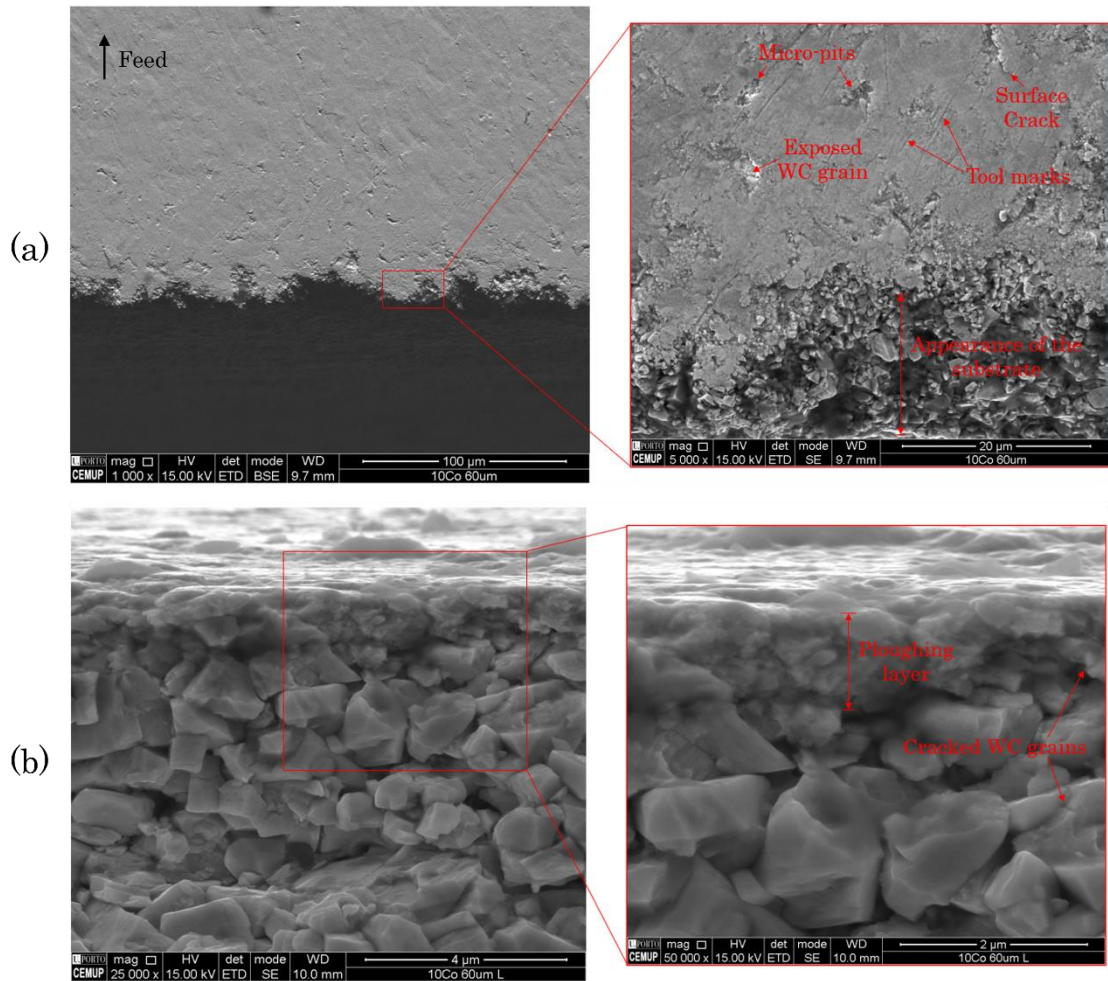


Figure 48 – SEM images of WC-10Co surface after being machined under the conditions of experiment 19 ($a_p=60\text{ }\mu\text{m}$, $a_e=5\text{ }\mu\text{m}$): (a) top view; (b) side view.

In both tested WC-Co grades the delimitation of the ploughing layer limits and its thickness revealed to be a challenging task. Although, this layer appears to have a thickness in the nanometre range. The SEM analysis seems to show that the ploughing layer is a combination of Co with a small fragments of WC grains, as demonstrated in Figure 49, where white parts correspond to the WC grains, and the grey zones correspond to the Co. This morphology of ploughing layer appears to be valid for both material grades. Since both material grades have a grain size of $3\text{ }\mu\text{m}$, this may indicate that machining leads to fragmentation of WC grains on removal. Similar fragmentation of the ploughing layer was observed for machining with an a_p of $1\text{ }\mu\text{m}$, as shown in Figure 50, where grains with a size lower than $1\text{ }\mu\text{m}$ seem to exist.

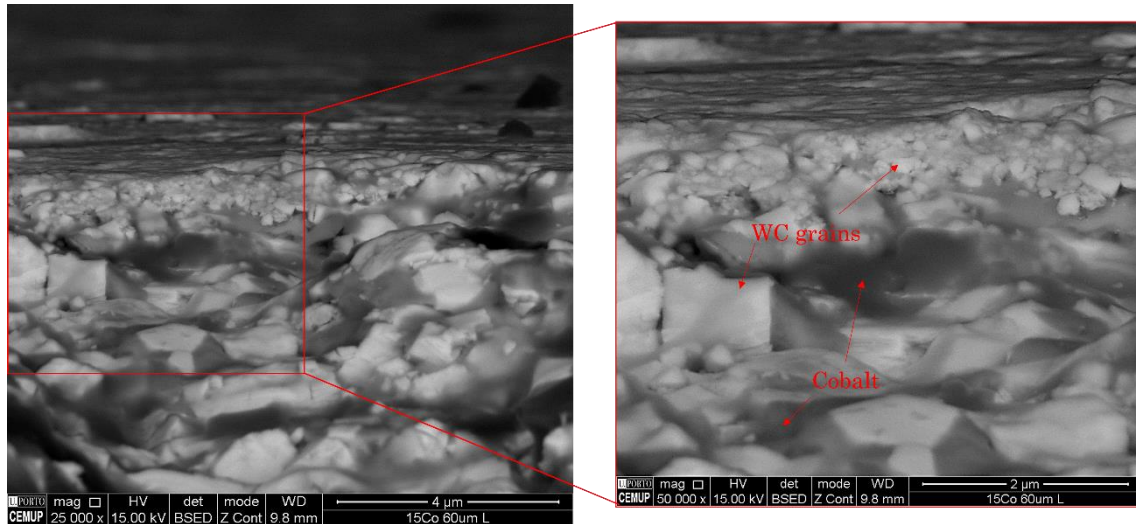


Figure 49 - Ploughing layer in WC-15Co material, in a machining with an a_p of 60 μm .

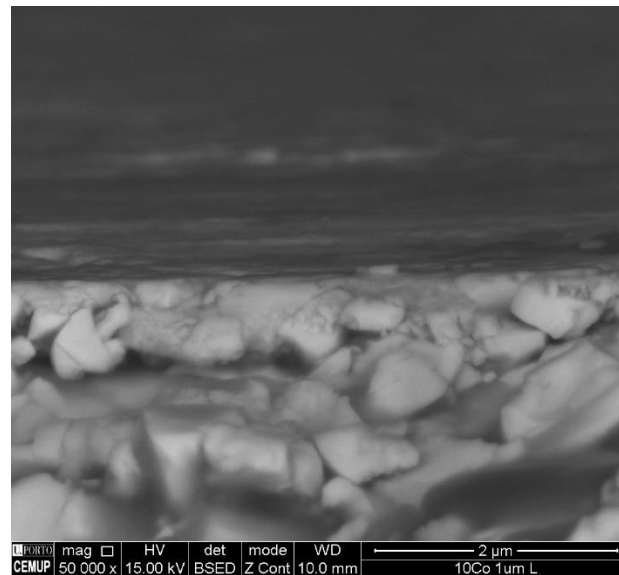


Figure 50 - Ploughing layer in WC-10Co material, in a machining operation with an a_p of 1 μm .

4.2.4. Summary of results discussion

Chip formation consistently occurred for both materials and the full range of tested operative conditions, so the minimum UCT was reached in all parameters combination. The SEM observation of the chips also perfectly showed needle shapes besides small particles observed, meaning that brittle cutting mode does not dominates. Moreover, the chips back surface which slides out from the tool's rake face seem to be smooth, which is also an indicator of the presence of the ductile cutting mode.

Looking to the roughness parameters, there is no increasing trend in roughness with increasing a_p . The topographical images and the pictures collected from SEM do not reveal any pattern for higher a_p and a_e values,

which is valid for both machined materials. SEM images additionally show that some cavities (micro-pits) are originated by the pull out of some WC grains, but others appear to be formed by the pull out of the γ -phase, which is dispersed on the surface and can have different shapes and sizes. A small quantity of these cavities is already present before the third operation. The SEM images also demonstrate the formation of a thin layer where the plastic deformation is dominating, due to ploughing effect, for all experiments. In this ploughing layer the WC grains are fragmented. Some cracks were also observed.

Concluding, a ductile cutting mode appears to be present, although some brittle cutting mode may also exist. Since chip collection was always possible in all tests, the minimum UCT was surpassed thus its determination was not possible. Thus, experiments with a_p values lower than $1\text{ }\mu\text{m}$ may be performed to determine the a_p value from which the ploughing zone completely dominates, i.e., the a_p value from which no chip formation occurs. In relation to the critical UCT, its determination was not possible and revealed to be extremely difficult. However, a combination of both cutting modes seems to occur, which may indicate a cutting mode in the ductile-to-brittle transition zone.

4.3. Milling cutter without cutting edges

4.3.1. Experimental results

Chip formation consistently occurred using the ball end mill tool (without cutting edges), regardless of Co percentage. Figure 51 and Figure 52 show a representative selection of collected chips in both cemented carbides with 15% and 10% Co, respectively, for each tested condition in micro-milling.

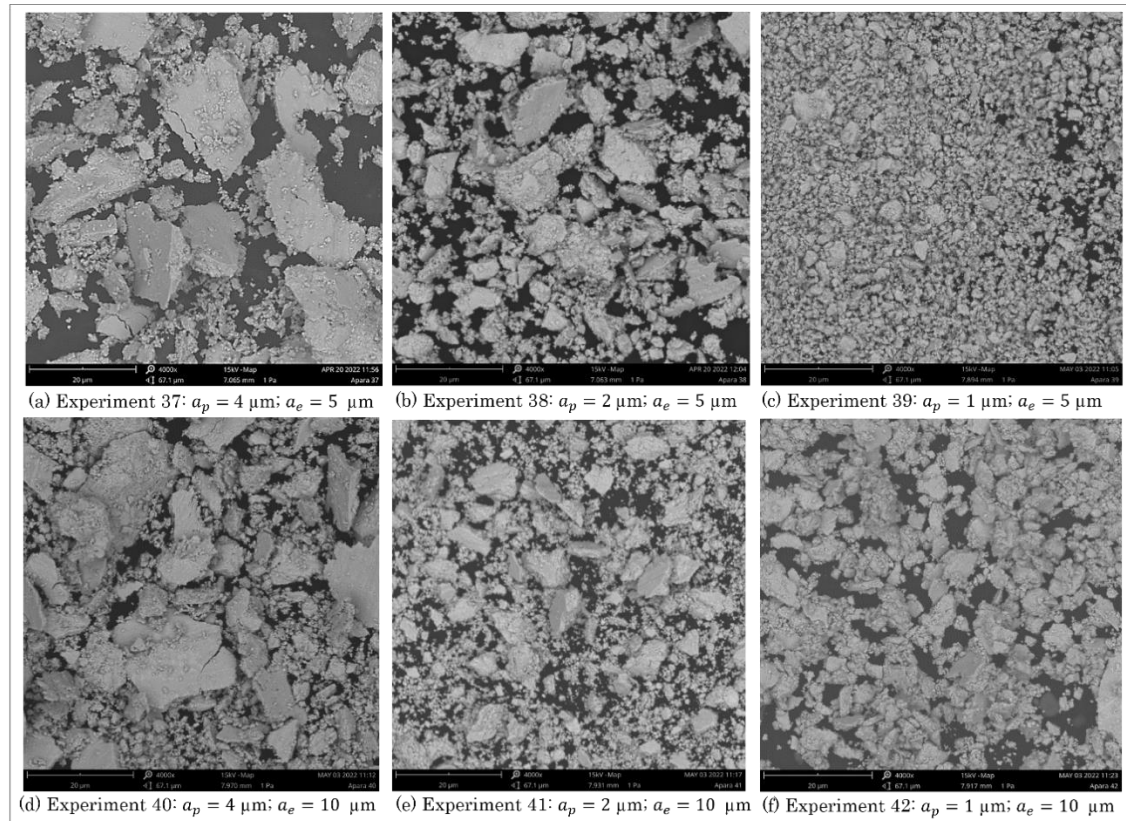


Figure 51 - SEM images with an amplification of 4000x of the collected WC-15Co chips.

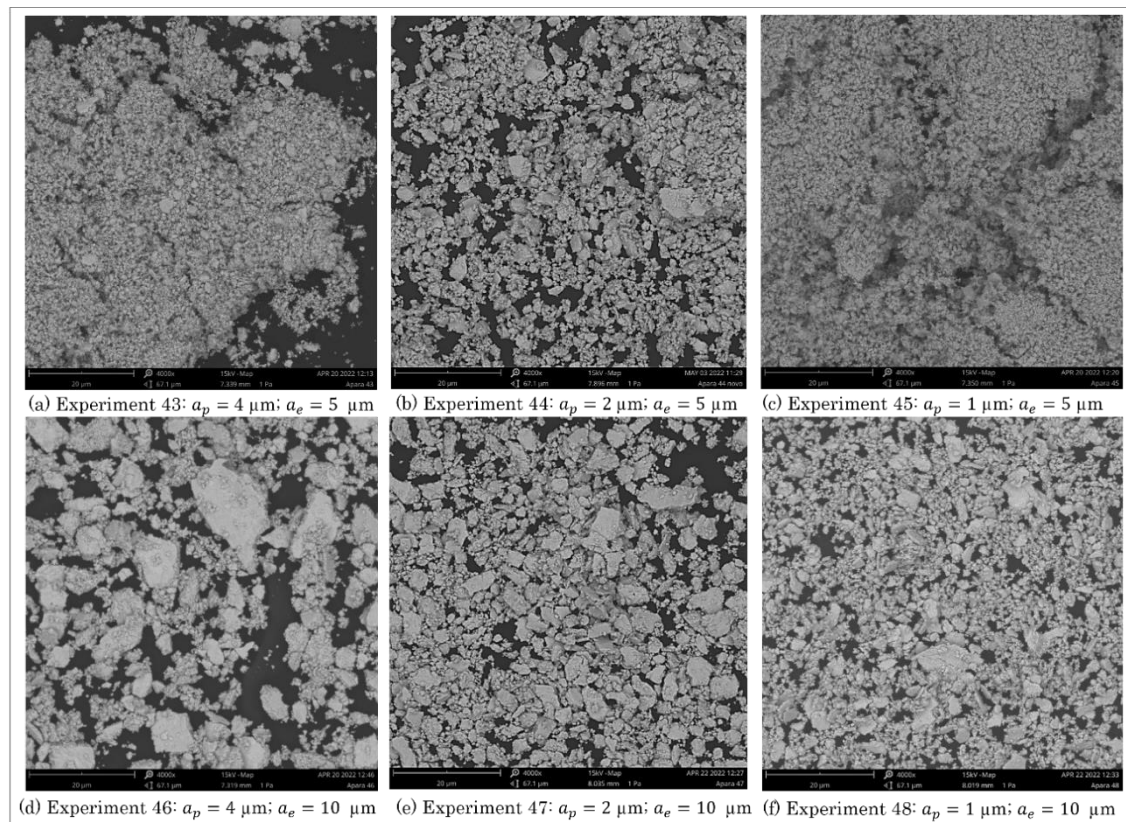


Figure 52 - SEM images with an amplification of 4000x of the collected WC-10Co chips.

Chip morphology analysis shows that, in contrast to chips formed by the two-flute cutter, these do not show back surface striation marks. The chips appear to be fragments of material that are pulled from the surface due to the high tangential pressures of the cutting tool. The occurrence of well-defined chip formation and its consistent morphology with the imposed cutting parameters means that minimum UCT has been exceeded and ductile cutting mode seems to be present. However, for WC-10Co grade with an a_e of 5 μm , the relatively smaller chips (refer to Figure 51 (c)) may indicate that for those operative conditions the cutting mechanism is rather close to the brittle mode. It is verified that there is an increase of the chip size with the increasing a_p for both materials used in the tests 36 to 48 (refer to Table 6). The chips formed in the WC-10Co material are smaller than in WC-15Co material. This effect may be related with the higher hardness of WC-10Co material, which hinders plastic deformation. Figure 53 shows the chip average size in function of operative conditions for both WC-15Co and WC-10Co materials. Figure 53 (a) demonstrates that average chips size seems to be independent of a_e value in WC-15Co grade, while Figure 53 (b) shows that in WC-10Co grade the average chip size has no significant variation between different values of a_p for an a_e equal to 5 μm .

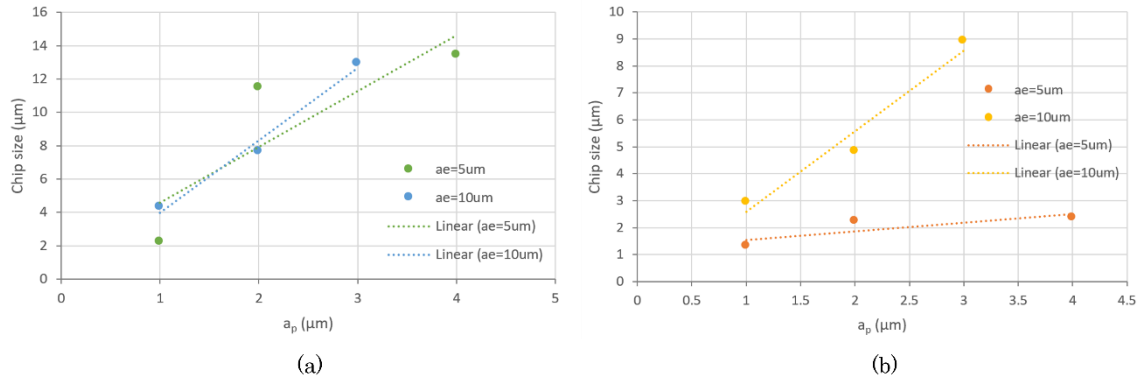


Figure 53 - Variation of chip size with the cutting depth, a_p , for cut widths, a_e , of 5 μm and 10 μm , for the material of: (a) WC-15Co; (b) WC-10Co.

4.3.2. Topography

Figure 54 shows the results of roughness measurements for both WC-15Co and WC-10Co materials and for each experiment with different a_p and a_e values.

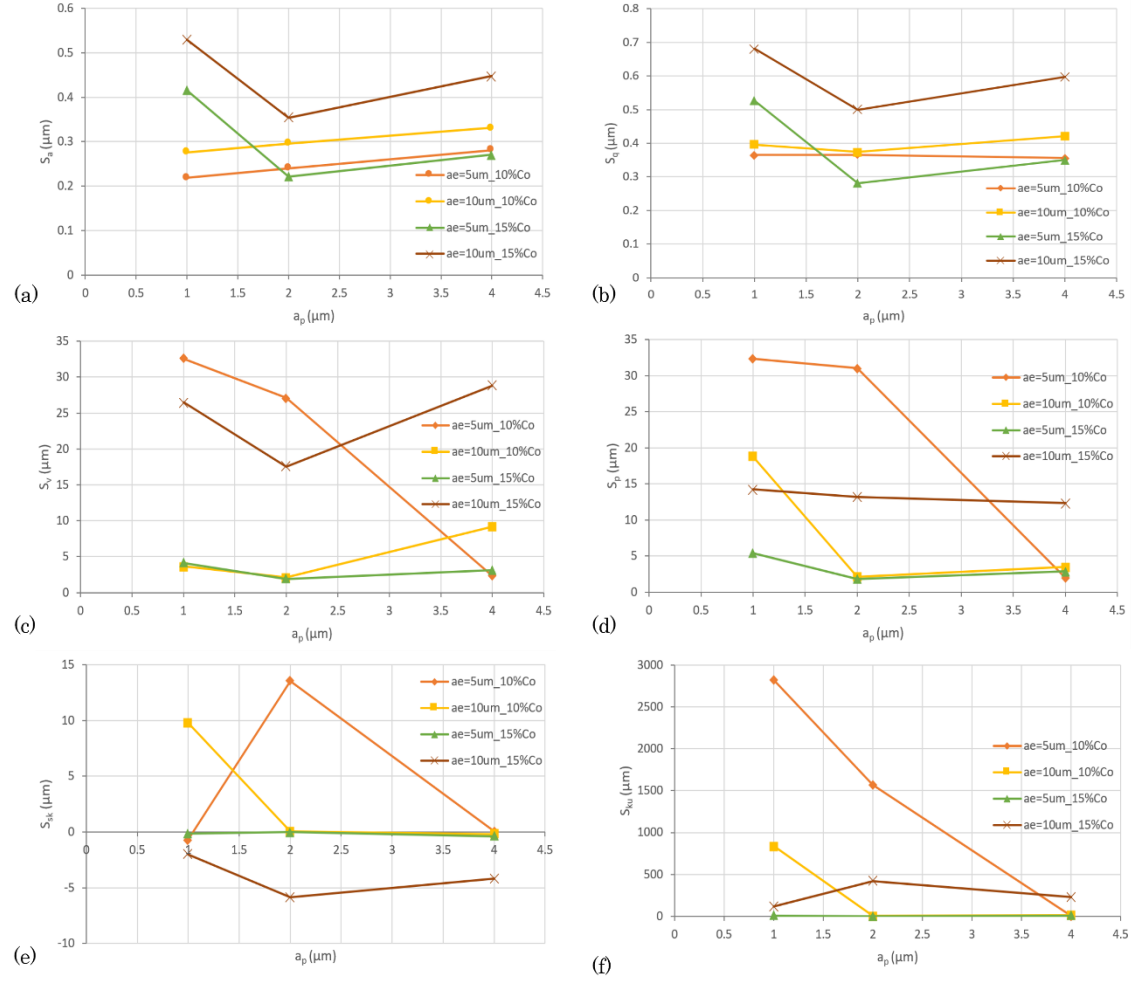


Figure 54 - Roughness parameters obtained from the experiments performed with different cutting depths, a_p , and for cut widths, a_e , of 5 μm and 10 μm , for the WC-15Co and WC-10Co materials: (a) S_a ; (b) S_q ; (c) S_v ; (d) S_p ; (e) S_{sk} ; (f) S_{ku} .

Higher values of a_e seems to result in higher values of S_a and S_q for both WC-Co grades, as demonstrated by Figure 54 (a) and Figure 54 (b), respectively. The higher S_a and S_q noticed in the WC-15Co for an a_p smaller than 2 μm may indicate a transition threshold value from which ploughing is increasingly detrimental to surface roughness. For WC-10Co grade, the S_a appears to increase with increasing a_p , which may indicate that the ploughing does not have as much influence as on the other WC-Co grade for smaller tested values of a_p . The S_q does not vary significantly for WC-10Co. Figure 54 (c) and Figure 54 (d) show that deeper micro-pits and higher peaks, respectively, are originated in the WC-10Co with an a_e of 5 μm and in the WC-15Co with an a_e of 10 μm . Figure 54 (e) reveals the expected symmetry of the WC-15Co material with an a_e of 5 μm , however for an a_e of 10 μm this material seems to have a high asymmetry with many valleys, meaning defects occurrence. Lastly, Figure 54 (f) shows that both materials have sharp peaks for all cutting conditions. Figure 55 shows that the topographical images of the machined surfaces do not follow an equal visual appearance for all tests. While some machined surfaces have a wavy pattern as in experiment 37 (a_p of 4 μm and WC-15Co material), Figure 55 (a),

others do not show any evident pattern, such as in experiment 39 (a_p of 1 μm and WC-15Co material), Figure 55 (b).

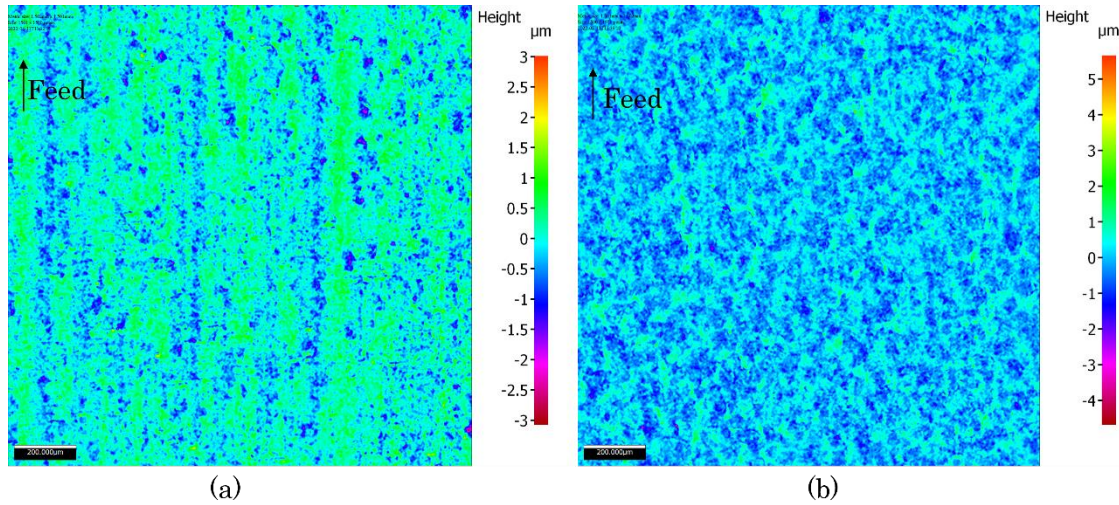


Figure 55 - Topographical images of the machined surface of WC-15Co material in the (a) experiment 37 ($a_p=4 \mu\text{m}$, $a_e=5 \mu\text{m}$) and in the (b) experiment 39 ($a_p=1 \mu\text{m}$, $a_e=5 \mu\text{m}$).

4.3.3. Machined surface characterization using SEM and optical microscopy

The operations of surface preparation may induce micro-pits and surface cracking on the machined surface, which remain after the third operation. Similarly to what was observed for the previously analysed tool, some cavities were originated due to pulling γ -phase by action of the tool. Finally, it was concluded that the tools used in the first two operations seem to give rise to a layer where plastic deformation dominates, which is called the ploughing layer.

Figure 56 (a) demonstrates the WC-15Co material surface after the third machining operation with cutting conditions of experiment 37 ($a_p=4 \mu\text{m}$, $a_e=5 \mu\text{m}$). A magnification of 1000x shows that, for the machining conditions imposed, the material appears to be compressed when the tool passes and dragged along the surface. These induce defects such as cavities and tool marks. Lower magnification did not reveal any pattern on the defects. A magnification of 5000x enables a more clearly understanding of the entire grains below the machined surface. The observed WC grain integrity resultant from the micro ball end mill contrasts with the severely cracked and fragmented WC grains resultant from the mill with cutting edges.

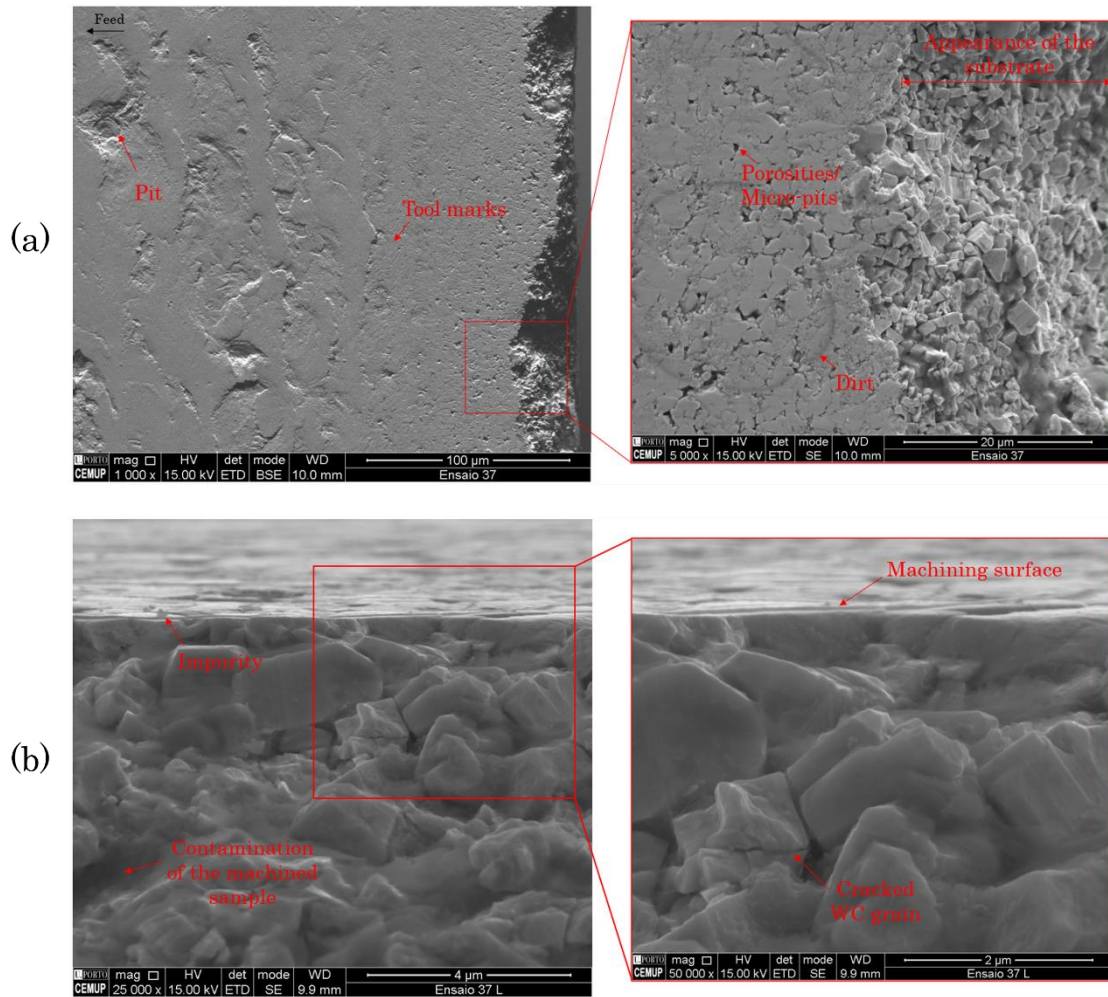


Figure 56 – SEM images of WC-15Co surface after being machined under the conditions of experiment 37 ($a_p=4\ \mu\text{m}$, $a_e=5\ \mu\text{m}$): (a) top view; (b) side view.

From the side view of WC-15Co material samples, Figure 56 (b), ploughing layer formation is not evident. Some cracked WC grains were observed below the machined surface.

Figure 57 (a) shows the top view of WC-10Co surface after machining with the cutting conditions of experiment 43 ($a_p=4\ \mu\text{m}$, $a_e=5\ \mu\text{m}$). Compared to the WC-15Co material surface in analogous machining conditions, the WC-10Co material surface shows less plastic deformation. Here, micro-pits and a huge quantity of tool marks are visible, but the material appears not to be so dragged along the surface. This can be explained by the lower content of Co and thus higher hardness of the WC-10Co. The magnification of 5000x also allows to see in this WC-Co grade the entire grains below the machined surface. In this WC-Co grade was not also possible to identify any ploughing layer from the side view, as demonstrated in Figure 57 (b).

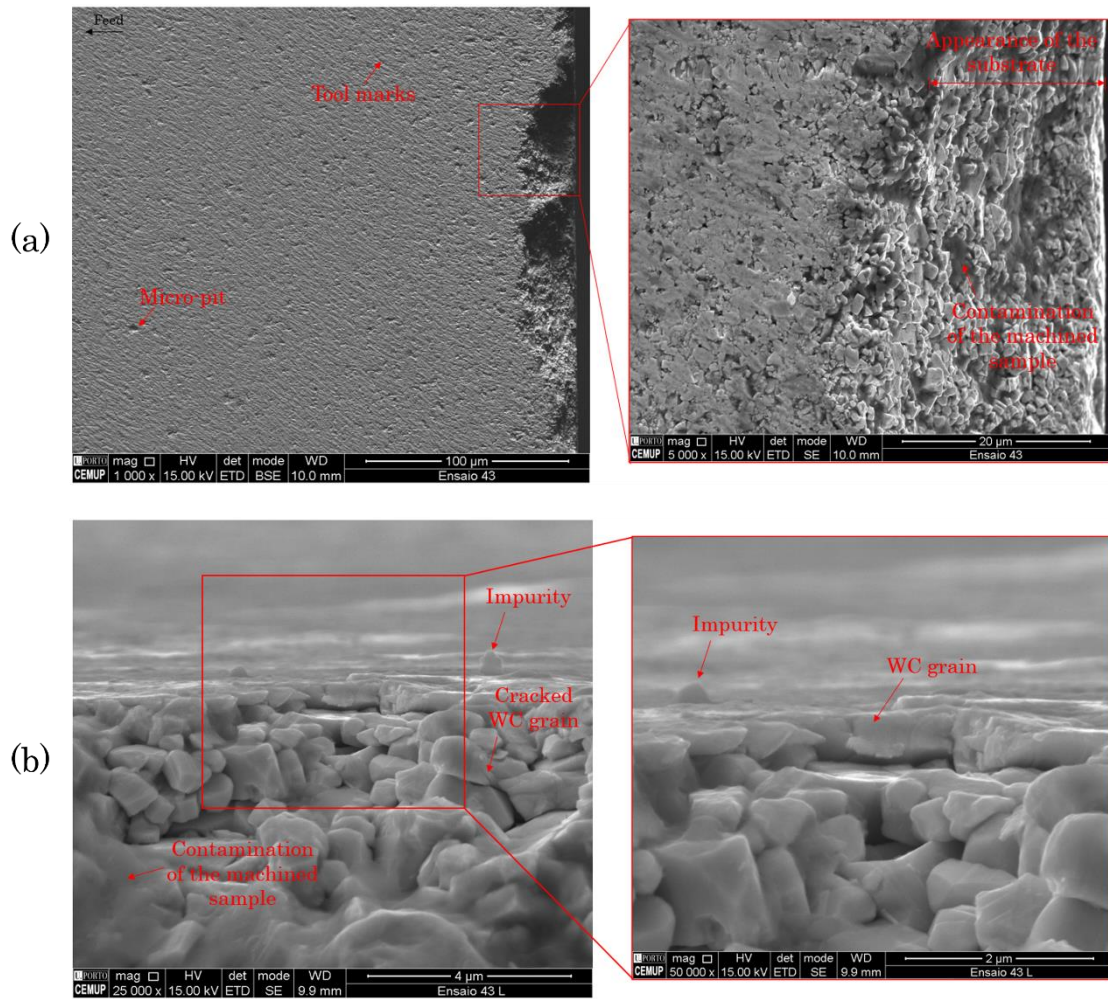


Figure 57 – SEM images of WC-10Co surface after being machined under the conditions of experiment 43 ($a_p=4\ \mu\text{m}$, $a_e=10\ \mu\text{m}$): (a) top view; (b) side view.

4.3.4. Summary of results discussion

Chips were collected in all experiments conducted with the ball mill (without cutting edges). This is an indicator that all tested values of a_p are higher than minimum UCT. From chip morphology observation, it was possible to verify that the average chip size increases with the increasing a_p . WC-Co composition seems to have a significant influence on the ductile cutting mode, due to brittleness variation and, thus, eventual shifting of the ductile cutting mode in the a_p domain. As the shape of all chips is perfectly visible and not only small particles are identified, a ductile cutting mode seems to be present in both WC-Co grades.

From the roughness results there seems to be a higher influence of the ploughing in the WC-15Co grade than in the WC-10Co grade, which was confirmed by the SEM images of top view of machined surfaces. The lower surface quality may be explained by the excessive plastic deformation at the ploughed layer, resultant from workpiece compressive stresses and chips

fragments that were dragged along its surface and possibly welded again to it. This may be explained by the higher content of Co in this WC-Co grade. However, in both studied WC-Co grades when it is seen the side view of the samples no ploughing layer is identified. The topographical images and the pictures collected from SEM do not show any pattern with the increasing a_p , for both tested values of a_e and for both machined materials. It is important to remind that the two operations of surface preparation already induced some micro-pits and surface cracking on the machined surface that remained after the third operation.

In sum, chips were collected from all performed tests and the minimum UCT was not determined. However, minimum UCT is expected to be close of an a_p of 1 μm in the WC-10Co grade with an a_e of 5 μm . This is explained by the extremely low chips size (almost the size of what could be fragmented chip particles), for this value of a_p , while for the above a_p values the chips size is higher. A ductile cutting mode seems to be present, although some brittle cutting mode may also exist, due to the observed defects. The determination of critical UCT was not possible for any experiment.

Chapter 5

Conclusions and future works

5.1. Conclusions

The present master's dissertation comprises two main groups. Firstly, focusing on the most recent and available data, micro-milling of brittle materials has been reviewed, with a special focus on cemented carbides. Then, an experimental research was drawn and carried out. This comprises the study of WC-10Co and WC-15Co grades, and two different micro ball end mills, one with two flutes and another without cutting edges. The main conclusions of the experimental research performed is summarised next.

- Optical microscopy enabled the identification of γ -phases on the WC-Co grades, which was confirmed by composition analysis, using X-ray spectroscopy (EDS). Due to its higher hardness, this phase is commonly pulled out of the surface by the action of the cutting tool, resulting in surface defects (micro-pits). Although in WC-10Co grade there is an equal percentage of γ -phase compared to WC-15Co grade, its distribution seems to be less dispersed (grouped in smaller areas) for the former material grade.
- Due to consistent chip formation for all performed experiments, an UCT threshold could not be identified. However, it is expected to be close of an a_p of 1 μm in the WC-10Co grade with an a_e of 5 μm and with micro ball end mill without cutting edges.
- The consistently smaller chip size when compared to its theoretical size prediction means that there is a theoretical minimum UCT, even though it was not fully attained within the testing range.
- The average chip size is smaller for the WC-10Co material than for the WC-15Co material, for both tested micro-cutters. A possible reason is the lower Co content of the former material grade and, thus, its relatively higher brittleness (lower toughness).
- For the two-flute micro ball end mill, the average chip size is higher for an a_e of 10 μm than 5 μm , due to the lower ploughing zone for the first a_e value.

- The roughness parameters do not change significantly with the variation of a_p values for the tool with cutting edges, regardless of material grade and operative conditions. However, the roughness results for the tool without cutting edges seems to reveal a higher influence of the ploughing in the WC-15Co material than in the WC-10Co grade for values of a_p below 2 μm . The higher S_a and S_q noticed in the WC-15Co grade for an a_p smaller than 2 μm may indicate a transition threshold value from which ploughing is increasingly detrimental to surface roughness.
- The very high sensitivity of the machined surfaces when submitted to micro-milling is illustrated by the arbitrary occurrence of either pattern-like features or no pattern at all for identical conditions with a_p differing only 3 μm . Moreover, no strong tendency could be found for a_p variation.
- Ploughing phenomenon and defects, such as micro-pits, were already saw in the two preliminary surface preparation operations. For small a_p values, these defects originated in these two first operations remain in the third operation, for both micro-cutters and for both materials. Because of this, it is difficult to identify what was originated by each operation.
- The observation under SEM reveals what seems to be a ploughing layer for all a_p values, for both WC-Co grades with the two-flute micro ball end mill. However, the machined surfaces with cutter without cutting edges do not show clear ploughing layer or at least its extension is of sub-grain size.
- Ductile cutting mode is present in all tests of experimental matrix, however some brittle cutting mode seems also coexist, leading to mix regime. Chip section is not uniform meaning that we could have brittle regimes for some extension and ductile for other extension of the uncut chips. The same applies for the minimum cutting size.

5.2. Future works

Despite the attempt of surface preparation (with a first and second operations) and thus equalization of the micro-milling initial stage, it has been noticed that some defects have been inflicted, which hindered results analysis. Because of this, other methods for surface preparation should be explored in order to minimize the associated error to previously inflicted defects (due to surface preparation), making it less challenging to identify

ideal machining conditions that lead to less micro-pits, tool marks and surface cracking. To complement this work and in order to determinate the minimum UCT, it is also proposed as future work to carry out experimental tests for a_p values less than 1 μm . A comparison of surface quality and induced size effects under dry cutting conditions or lubricant oil might also be interesting.

The scientific knowledge would be enriched by the use of more advanced techniques of surface characterization, in order to be able to clearly and accurately identify more details about the features of ploughing layer.

Finally, it could still be interesting to perform an experimental matrix with only one of the studied materials, the two-flute micro ball end mill and one of the a_e values, where the f_z would be varied in two or three levels, in order to verify if the increasing f_z lead to a decrease of ploughing effect and roughness, for the same cutting conditions, as referred in the literature. The analysis of useful life of the tools may also be helpful.

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