

**Faculdade de Engenharia da Universidade do Porto**



## **Hard turning of Inconel 718 using PCBN tools**

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### **Master Dissertation**

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*Não é o destino, é a viagem*

# Abstract

Inconel 718 is widely used in critical components in the aerospace and nuclear industry, owing to its combination of high strength, resistance and stability at extreme temperatures. However, known difficulties on machining this alloy are closely correlated with its outstanding properties combined with the natural tendency for work hardening and low thermal conductivity, resulting in rapid tool wear mainly due to adhesion and abrasion, even when small material removal rates are considered.

Polycrystalline cubic boron nitride (PCBN) tools have successfully emerged for finishing operations of superalloys, yet the knowledge of involved wear mechanisms remains limited. In this study, instrumented turning experiments have been employed to evaluate the machinability of Inconel 718 alloy, supplied in different heat treatment stages. With the goal of numerically simulate the metal cutting process, a simple but effective characterization of the alloy has been performed allowing the assessment of flow stress at quasi-static conditions. Cutting load, chip morphology and tool wear analysis were performed for distinct operative conditions.

It was found that tool life was highly sensitive to cutting speeds but also affected by the workpiece mechanical properties. At lower cutting speeds notch wear significantly impacted tool integrity, whereas at higher cutting speeds flank wear was the primary failure mode of the tool. Flank wear of tools with TiN based binder outperformed TiC by almost 30% and had consistent behaviour when machining. Numerical simulation of metal cutting processes using DEFORM™ 2D/3D commercial was performed. Estimated cutting force reasonably correlated with the experimental results, however passive forces were highly underestimated.



# Resumo

O Inconel 718, devido às suas excelentes propriedades mecânicas, resistência e estabilidade a altas temperaturas, é amplamente usado em componentes críticos na indústria aeroespacial e nuclear. A combinação destas propriedades excepcionais com uma tendência natural de encruamento e baixa condutividade térmica geram diversas dificuldades durante a maquinagem desta superliga, resultando num desgaste rápido da ferramenta devido a fenómenos de abrasão e difusão, mesmo com baixas taxas de remoção de material.

Recentemente ferramentas de nitreto cúbico de boro policristalino começam a ser utilizadas em operações de acabamento, no entanto o conhecimento dos mecanismos envolvidos no desgaste das mesmas permanece limitado. De forma a avaliar a maquinabilidade do Inconel 718 e o modo de desgaste das ferramentas, foram realizadas operações de torneamento instrumentadas em duas superligas com diferentes estados de tratamento térmico. Com o objetivo de simular numericamente o processo foi também realizado uma caracterização simples, mas que se revelou efetiva na avaliação da tensão de escoamento do material em condições quase estáticas. Os testes instrumentados permitiram a medição das forças envolvidas na operação de torneamento bem como a análise da morfologia da peça e do desgaste da ferramenta.

A vida útil da ferramenta revelou-se altamente sensível à velocidade de corte, mas também as propriedades mecânicas da peça a maquinar. O uso de menores velocidades de corte favorece o aparecimento do desgaste tipo entalhe que fragiliza a aresta de corte e a integridade da ferramenta. Por outro lado, com o uso de velocidades de corte superiores, o desgaste de flanco torna-se na principal causa de falha da ferramenta. O desgaste do flanco em ferramentas de PCBN com ligante TiN foi cerca de 30% inferior às ferramentas que tinham como TiC como ligante. Foi realizada simulação numérica do processo de corte com recurso ao software DEFORM<sup>TM</sup> 2D/3D, tendo-se obtido uma estimativa numérica da força de corte correlacionada razoavelmente com os resultados experimentais, no entanto, as forças passivas foram altamente subestimadas.

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## Abbreviations

|                 |                                     |
|-----------------|-------------------------------------|
| ALE             | Arbitrary Lagrangian-Eulerian       |
| AMS             | American Society for Metals         |
| BCT             | Body-Centered Tetragonal            |
| BUE             | Built-up edge                       |
| CBN             | Cubic Boron Nitride                 |
| CEL             | Coupled Lagrangian-Eulerian         |
| CVD             | Chemical vapor deposition           |
| EBSD            | Electron backscatter diffraction    |
| EDS             | Energy Dispersive Spectroscopy      |
| FCC             | Face-Centered Cubic                 |
| FEA             | Finite Element Analysis             |
| FEM             | Finite Element Method               |
| HCP             | Hexagonal Close-Packed              |
| HSM             | High-Speed Machining                |
| HRC             | Hardness Rockwell C                 |
| IN718           | Inconel 718                         |
| JC              | Johnson-Cook                        |
| MRR             | Material removal rate               |
| PCBN            | Polycrystalline Cubic Boron Nitride |
| PCD             | Polycrystalline diamond             |
| SEM             | Scanning electron microscope        |
| TiC             | Titanium carbide                    |
| TiN             | Titanium nitride                    |
| TW <sub>f</sub> | Tool flank wear rate                |

## Symbols

|       |                |
|-------|----------------|
| $a_p$ | Depth of cut   |
| $f$   | Feed           |
| $F_c$ | Cutting force  |
| $F_f$ | Feed force     |
| $F_p$ | Passive force  |
| $v_c$ | Cutting speed  |
| $T$   | Temperature    |
| $t_c$ | Chip thickness |

## Greek Symbols

|                        |             |
|------------------------|-------------|
| $\bar{\sigma}$         | Flow stress |
| $\bar{\epsilon}$       | Strain      |
| $\dot{\bar{\epsilon}}$ | Strain rate |

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# Chapter 1

## Introduction

### 1.1 Project framework and motivation

Inconel 718, hereinafter referred to IN718, is one of the most important alloys among the nickel and nickel-based alloys due to its outstanding properties under high temperature conditions, being widely used as a material for aviation, turbines and nuclear power plant applications. However, it is considered one of the least machinable materials due to peculiar characteristics such as low thermal conductivity, high tendency to work hardening and high affinity with cutting tool materials [1, 2]. Recently, PCBN cutting tools have received a great deal of attention as a material for cutting tools to achieve high performance machining of IN718. Several studies have found PCBN a suitable solution for machining of this alloy, despite the lack of research regarding tool wear [3, 4]. This topic goes in line with the scope of the Hi-rev project, particularly in what concerns finding advanced cutting tool solutions for hard-to-machine ferrous alloys (such as the Ni-based alloys), which constitute a significant share of complex functional components in automotive applications.

### 1.2 Palbit - Corporate Presentation

Palbit S.A. was founded in 1992 under the name *Minas e Metalurgia* to grant the exploitation of the Mines of lead sulphide of Palhal (Portugal). Currently it is specialized in producing hard metal, ultra-hard metal and ceramic cutting tools and operates in three business areas (Cutting Tools, Wear Parts and Rock Tools). Palbit is certified by ISO 9001:2015 & NP 4457:2007 standards and aims to answer customers' requests with qualified technicians, research and constant developments and cutting-edge technology.

Palbit is present in 5 continents, through distributors, agents and subsidiaries, exporting more than 90% to over 70 different countries. Meets the customer needs by having a large

portfolio of standard products with over 7000 references available offering tooling solutions for a wide industry range such as aerospace and defence, railway, automotive and power generation.

The company makes use of last generation equipment in conjugation with an experienced technical team in order to deliver a high-quality product. Palbit is focused on improving their R&D capabilities in order to remain competitive.

### 1.3 Objectives

The objective of this dissertation is to study the machinability of IN718 alloy through longitudinal turning instrumented tests using PCBN cutting tools. These results will also be used as experimental validation to a numerical simulation of metal cutting processes using DEFORM™ 2D/3D commercial FEM software. To achieve the final goal of the present study many intermediate steps were involved, that can be described as follows:

- Literature review on the topics this work would involve, particularly on machining with PCBN tools, IN718 alloy and finite element cutting simulation;
- Material characterization namely chemical analysis, hardness measurements, microstructural observation, using optical and scanning electron microscopy and experimental compression tests with the purpose of input information for simulation;
- Instrumented turning experiments; study of the influence of different cutting conditions in the resulting cutting forces, tool wear and chip formation;
- Development of a material constitutive law, from the quasi-static compression tests, for experimentally tested alloy;
- Three dimensional numerical simulations, using Deform™ 2D/3D, and comparison with existing experimental data.

### 1.4 Structure of this dissertation

This dissertation is composed of seven different chapters, divided as follows:

- **Introduction:** a brief description of the project's framework and motivation, and the main objectives of this dissertation;
- **Hard machining of Ni-based alloys:** literature review on machining of Ni-based alloys, focusing on the IN718 and suitable cutting tool materials, in particular the PCBN. A review of both experimental and numerical state-of-the-art studies are covered within the scope of this chapter;

- **Metal cutting mechanics and numerical modelling:** Given the goals of assessing the machinability and numerically modelling the cutting process, this literature review chapter focuses on (i) the fundamentals of metal cutting, such as the process mechanics and chip formation as well as (ii) finite element modelling in machining with relevance to the identification of material behaviour, friction and tool wear modelling.
- **Experimental procedure:** a description of the material characterization procedure is performed and a presentation of the followed stages during experimental tests, including equipment used and conditions tested;
- **Experimental results and discussion:** analysis of the results from the turning experiments, particularly cutting forces, specific cutting pressure, tool wear and chip analysis;
- **FEM simulation with DEFORM™:** Inconel 718 material constitutive law identification; analysis of results from the 3D cutting simulations and comparison with experimental results, including cutting forces and chip formation;
- **Conclusions and future work:** summary of the main conclusions of the work and listing of possible future works.

# Chapter 2

## Hard machining of Ni-based alloys

### 2.1 Introduction

Machining is a subtractive manufacturing process in which excess material is removed from a starting workpiece to achieve the desired final geometry [5]. In its broad definition, hard machining is the machining of parts with a hardness of above 45 HRC, although most frequently the process concerns hardness of 58 to 68 HRC [6]. Hard turning process emerged due to the development of new materials with higher mechanical properties. This process is a good alternative to precise grinding operations, as these ones had been the conventional solution to finishing hardened parts, which are costly and have a smaller productivity when compared to hard turning [1].

Nickel-based superalloys are the material of choice for applications that require a combination of excellent mechanical strength and heat resistant properties, for example in turbine components that are required to operate above 800 °C. Superalloys are able to retain their stiffness, strength, toughness and dimensional stability at higher temperatures than other structural materials [7, 8]. IN718 causes several difficulties in machining due to its low thermal conductivity, high strength, and considerable work hardening effect [9]. Machining IN718 culminates into two frequent problems: the short tool life due to the work hardening and abrasion properties of the alloy, and the metallurgical damage to the workpiece due to the very high cutting forces which also gives rise to work hardening, surface tearing and distortion in finally machined components due to induced stresses [10]. Although being rather challenging at an industrial level, machining processes try to combine high material removal and low tool wear rates with great surface quality, thus establishing the need for further research.

The development of nickel superalloys such as IN718 had a sustained growth in the last years, as illustrated in Figure 2.1. Additionally, it shows the increase in the number of

publications about hard turning as this topic is emerging as alternative to grinding operations. At the same time simulation of turning processes is increasing its importance along the researchers. This work aims at interconnecting these three topics with the objective of understanding the difficulties of machining this alloy and identify appropriate operating conditions with regards to cutting parameters and tool wear scenarios, when processing IN718 using polycrystalline cubic boron nitride (PCBN) tools. Additionally, the numerical modelling of the cutting process is developed in order important machinability outputs, such as cutting forces and tool wear while and correlating those to the experimental results.

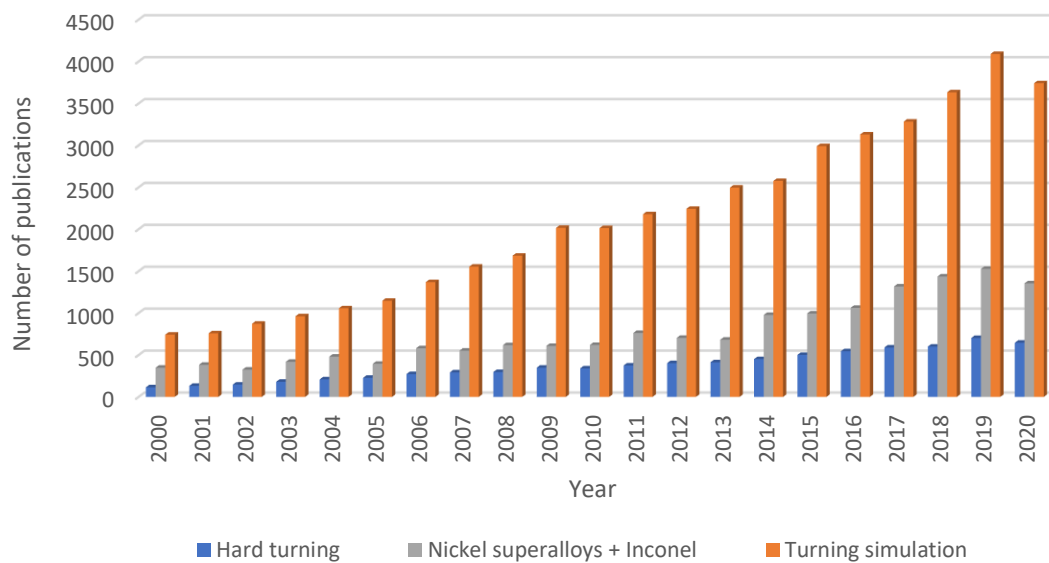


Figure 2.1 - Number of scientific published articles, in SCOPUS, focusing on hard turning, nickel superalloys or Inconel and turning process simulation over time.

## 2.2 Cutting tools

Cutting tools play a significant role in material machining and should have characteristics which vary according to the material to be machined. Tools should have pressure resistance, bending strength and toughness, edge strength, inner bonding strength, high temperature strength, oxidation resistance, small propensity to diffusion and adhesion, abrasion resistance and a reproducible wear behaviour [11]. Although several different tool materials are available today (Figure 2.2), the six most important groups are: carbides, ceramics, polycrystalline cubic boron nitrides (PCBNs), polycrystalline diamonds (PCDs), solid or thick film diamond (SFDs or TFDs) and high speed steel (HSS) [12, 13].

In order to achieve better results, cutting tools can be submitted to coating such as titanium nitride (TiN), which was introduced in the 1980s, titanium carbonitride (TiCN), and titanium aluminium nitride (TiAlN) [13]. The present literature review focuses on PCBN tools given they

will be assessed in experimental tests and often seen as an emerging solution for hard turning Ni-based alloys.

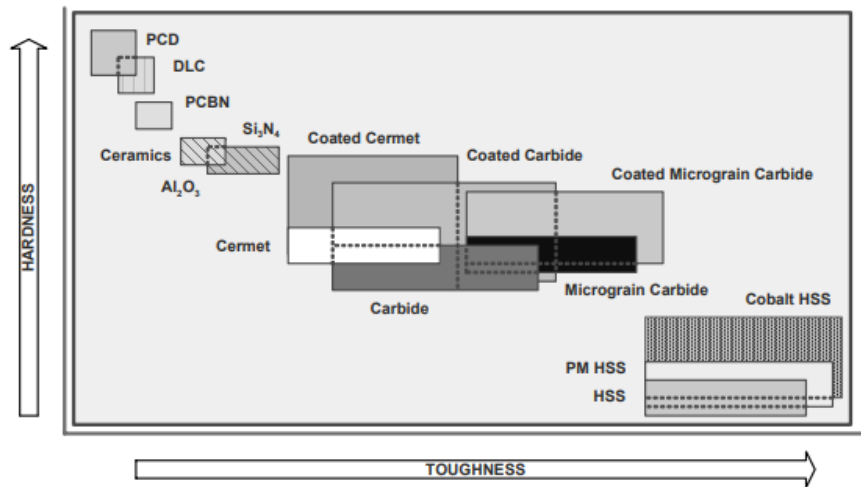


Figure 2.2 - Relative hardness and toughness levels of common cutting tool materials [12].

The main parameters that describe the turning tool structure typically include tool angles and cutting edge parameters. With regards to the main turning tool angles, the radial rake angle, axial rake angle and the cutting edge angle briefly define the relative workpiece-tool position, as exemplified in Figure 2.3.

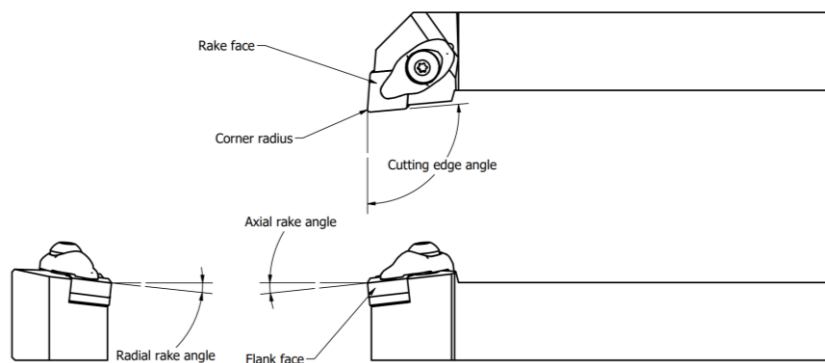


Figure 2.3 - Geometric elements of a combination tool/toolholder.

The cutting edge of turning tool can be characterized by the tool nose radius, the cutting edge radius, in addition to the cutting edge preparation. Bigger tool nose radius increases the strength of the insert, while improving the surface quality and cutting stability, hence allowing to work with higher cutting feeds and giving better resistance to chipping. In contrast, a small nose radius has the advantage of a smaller chattering tendency due to smaller passive forces, although the formation of notch wear is much more likely, particularly in hard materials [1, 11].

Different cutting edges can be prepared to improve the tool cutting performance such as chamfered edged, honed edge, wiper edge, as illustrated in Figure 2.4. The cutting edge

geometry can significantly affect the material deformation within the primary and secondary cutting zones including the chip formation and its evacuation, as well as the machined surface. Edge preparation without honing (Figure 2.4-a)) result in a sharp cutting edge and, thus, incapable of withstanding very high cutting forces, being particularly recommended for machining aluminium alloys and non-ferrous materials (typically for PCD cutting tools). Edge honing preparation (Figure 2.4-b)) is recommended for heat-resistant superalloys as the honing has a strengthening effect the edge, giving resistance to chipping and fracturing. Chamfered edge preparation (Figure 2.4-c)) is commonly used in PCBN tools and the desired choice for cast iron. A combination of chamfered and honed edge preparation (Figure 2.4-d)) achieves the higher edge strength being the first choice when turning hard materials. This preparation achieves more resistance to chipping and fracture than the chamfered one, resulting in more predictable tool life and a consistent surface finish despite promoting higher cutting forces.

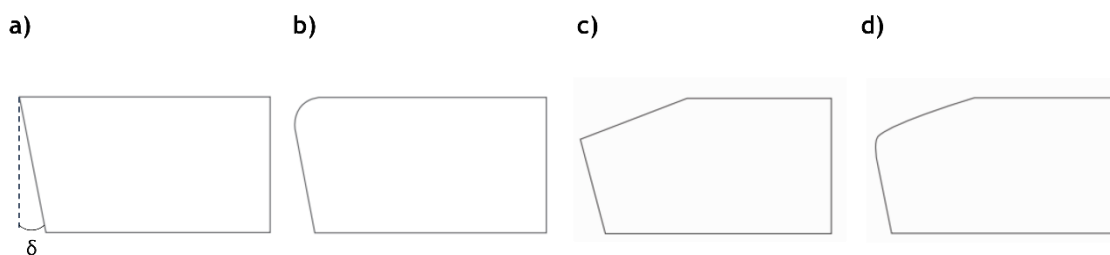


Figure 2.4 - Edge preparation a) edge without honing, b) edge honing, c) chamfer d) edge with chamfer and honing (adapted from Palbit S.A.).

Turning inserts can also be classified through their clearance angle ( $\delta$ ) (i.e., the angle between the rake and flank face): a negative insert has a clearance angle of  $0^\circ$  while a positive insert has a clearance angle  $>0^\circ$ . Positive turning inserts are single sided, achieve lower cutting forces and are the first choice for internal turning and for external turning of slender components. Alternatively, negative turning inserts can be double and/or single sided, have high edge strength and are the first choice for external turning under heavy cutting conditions.

### 2.2.1 PCBN as cutting tool material

Cubic boron nitride (CBN) is the hardest cutting tool material after diamond and has many similar, but not identical, properties. Its hardness varies with the orientation of the test surface relative to the crystal lattice: between 40 and 55 GPa (4000 and 5500 HV) [14]. Modern grades of PCBN (polycrystalline cubic boron nitride) allowed to introduce hard machining operations which may replace grinding operations, given their lower productivity [15]. A major advantage of cubic boron nitride, when compared with diamond is its greater stability at high temperatures in air or in contact with iron and other metals, since in normal atmosphere a protective layer of boron oxide ( $B_2O_3$ ) prevents oxidation up to  $1,300^\circ\text{C}$  [16]. Moreover, CBN keeps its good mechanical strength when subjected to higher temperatures than other tool

materials, combined with excellent abrasion resistance [14]. There is evidence of interaction between PCD and iron starting at 900°C. Contrary to this, below 1300°C no interaction was detected between iron and PCBN, both on low (50%) and high (85%) CBN tools [17].

PCBN tools are usually divided into three categories according to their CBN content: low content CBN (50%-65%), high content CBN (80%-90%) and more recently, binder-less sintered CBN which does not include any binder [13]. Several research has been done to find the most appropriate tool material for turning Ni-based alloys at higher cutting speeds. Criado et al. [4] compared the performance of PCBN (50% CBN) and carbide tools when machining Inconel 718. Cutting speeds between 4 to 6 times higher and a lower depth of cut were used with PCBN tools, according to recommendations provided by the manufacturer, leading to a lower tool life but with an increase in machined volume, when compared to WC cutting tools. Moreover, PCBN tools achieved an average surface roughness of 0.2-0.8  $\mu\text{m}$ , about 4-6 times lower than with the carbide tool. Finishing operations in turning usually have demanding tolerances and higher values of roughness may not be acceptable highlighting the suitability of PCBN tools were found suitable for finishing operations in Inconel 718. Dudzinski et al. [18] stated that although carbide tools can be used to machine Inconel at low cutting speeds ( $v_c = 20\text{-}30\text{ m/min}$ ) for an enhanced productivity (higher cutting speeds), ceramic tools consist of a more appropriate choice. There is a common agreement that carbide tools show higher resistance to crater wear, but the achievable cutting speeds are lower than with ceramic tools.

Costes et al. [19] analysed the influence of CBN content when finishing Inconel 718 finding that the percentages of CBN content in the range between 45% and 60% and cutting speeds between 250 m/min and 300 m/min lead to the best behaviour concerning tool durability and surface quality. Bushlya et al. [20] compared the performance of both coated and uncoated PCBN (50% CBN) with whisker-reinforced alumina tools in high-speed turning of Inconel 718, finding that tool life was highly sensitive to the cutting speed. Whisker-reinforced alumina tool life was lower than both coated and uncoated PCBN and it was also found that the advantageous coating on the PCBN tools has a cutting-speed-limited effect. Cutting forces were also higher in whisker-reinforced alumina tool than in PCBN tools. Coated PCBN tool achieved slightly higher cutting forces than uncoated tool despite its higher tool life at  $v_c = 250\text{ m/min}$ . Soo et al. [21] tested five different coatings on a PCBN tool (65% CBN) on high-speed turning of Inconel 718. The longest tool life (8.8 min) was achieved when turning at 200 m/min using the titanium silicium nitride (TiSiN) coated insert, which was 40% higher than the uncoated insert counterpart. It was also found that coatings have a cutting-speed-limited effect since no benefits were found in coatings when operating at cutting speeds higher and around 300 m/min.

Khan et al. [22] reported that a 0.2 mm/rev feed rate and a cutting speed of 300m/min offered good productivity/material removal rate when turning IN718. However, in titanium nitride (TiN) coated PCBN inserts, as the cutting speed was increased to 300 and 350m/min no significant performance in tool wear were noticed due to rapid oxidation of the coating layer, which is in line with [20, 21]. This cutting speed limited coating benefit is expected, given that diffusion processes appear especially when high cutting speeds are used, as demonstrated in

Figure 2.5, thus leading to high temperature and pressure in the contact zone provide an ideal setting for diffusion processes between the material and cutting tool material.

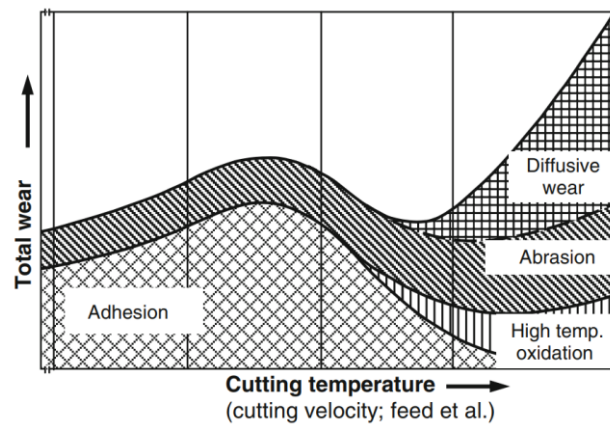


Figure 2.5 - Causes of wear in cutting processes (adapted from [23]).

Bushlya et al. [24] also tested TiN coated PCBN tools against uncoated counterparts finding that coated result in loads about 10% higher than the uncoated ones. TiN coated PCBN tools had a relatively lower performance in terms of roughness because cutting forces typically play a detrimental role in surface roughness. Despite this, higher tool life was accomplished by TiN coated tools in compliance with other authors. Both Khan et al. [22] and Bushlya et al. [24] concluded that with an increase of speed to 300 m/min and above the coating provides no benefits in terms of tool life. Experimental tests showed that low content CBN tools with TiN binder correspond to excellent wear resistance because the ceramic binder phase has much better chemical stability with respect to nickel [25, 26]. From the research done by the previous authors it seems that PCBN tools with between 45-65% of CBN content are suitable for hard machining IN718.

Understanding tool wear mechanism and its impact on the effectiveness of machining operation is crucial. The wear generally occurs over time and is a gradual failure in a cumulative process that affects tool life. Usually, tool wear rate depends on cutting time, as represented in Figure 2.6. Initially, there is a period characterized by a rapid initial wear followed by a uniform wear rate that results in a wear region that evolves linearly with cutting time. When the tool is reaching its limit cutting time wear rate accelerates, typically leading to a tool failure.

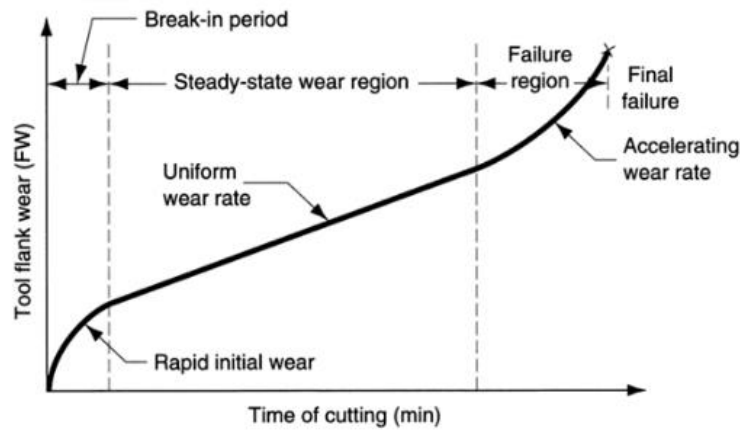


Figure 2.6 - Tool wear as a function of cutting time (adapted from [5]).

Excessive tool wear may lead to increased cutting forces and temperatures, decreased accuracy of produced parts and poor surface finish. On the social and economic side worn tools also endanger the operator and machine, risking even higher repair costs or prolonged down times.

Different types of tool wear can be identified in Figure 2.7. Crater wear is caused by mechanical abrasion due to chip sliding resulting in a concave section on the rake face of the tool. This tool chip interface is characterized by high temperatures and stresses. Flank wear is also caused by abrasion, but this time from the contact of the tool flank face and the newly generated work surface. Notch wear is similar to flank wear but in an extreme condition. It is triggered by abrupt transitions of mechanical and thermal stress usually when the newly generated surface is harder and/or more abrasive than the removed material. Comb cracks are a form of damage of the cutting edge due to thermal alternating stresses that cause the material to expand and contract. Chipping, build-up edge (BUE) and plastic deformation may also occur in the tool during cutting [11, 27].

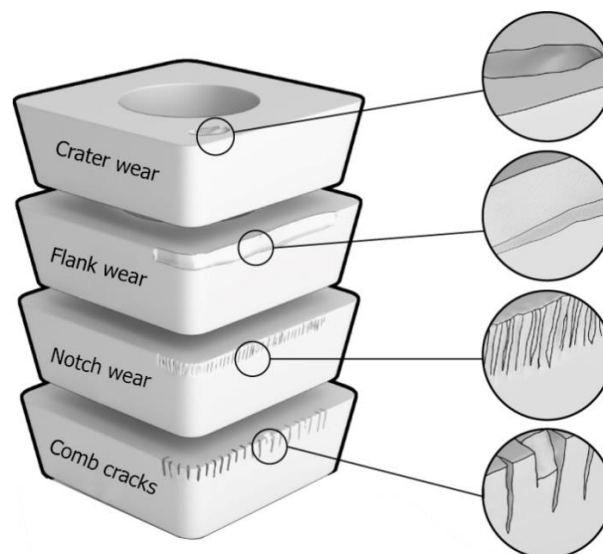


Figure 2.7 - Tool wear types, adapted from [27].

Different tool wear mechanisms are also present in cutting with the main ones being abrasion, diffusion and adhesion. Abrasion or mechanical wear occurs at both low and high cutting speeds and it's caused by the friction between the workpiece and the tool. Small particles penetrate the surface of the cutting tool material producing micro cutting. Diffusion occurs when atoms transfer between tool-workpiece, due to high temperatures and pressure. The diffusion of atoms can lead to a potential reduction of the wear resistance of cutting tools given their depletion of certain alloying elements. This wear mechanism particularly occurs when high cutting speeds are used resulting in high temperatures in the contact zone. Adhesion may occur when two materials are forced into contact under high pressure and temperatures until they bond together. The tool-chip interface can form metallic bonds in the form of spot welds [11].

Understanding and predicting the effect of the cutting process parameters in tool life and wear is crucial with simulation being helpful to help solve these challenges. Several authors have made research in this topic. Costes et al. [19] reported adhesion and diffusion as dominant wear mechanisms in turning Inconel 718 with CBN tools at cutting speeds of 250 m/min, 350 m/min and 450 m/min. The workpiece under high temperatures and stresses, plasticized itself superficially, so the alloy spread on the contact area between the insert and the workpiece (rake and flank faces) leading to new compounds with different physical characteristics on the insert. Regarding diffusion wear mechanisms, Bushlya et al. [25] also reported that both under high pressure and temperature boron and nitrogen diffuse from CBN into Inconel 718 while forming their solid solutions. Chemical reaction triggers the formation of nitrides of Ti and Nb and borides of Cr, Mo, and Nb. The same authors additionally found that the presence of titanium carbide binder (TiC) in PCBN is an obstacle to further diffusional loss of the CBN phase. Despite the diffusional loss of carbon, TiC remains more stable than CBN and acts as an inert obstacle to further diffusional loss of the CBN phase. The results attained make it possible to explain the significantly lower wear rate of PCBN tools with low-CBN content and ceramic binders compared to grades with high-CBN.

In fact, several researchers concluded that above cutting speeds of 100 m/min, diffusion due to high cutting temperature is a dominant factor for promoting crater wear. Thus, at the cutting speed of 300 m/min and 500m/min, the dominant factor for worsening crater wear completely changes from mechanical wear to thermal wear, and PCBN inserts with a low CBN content and TiC or TiN-based ceramic binder phase shows excellent crater wear resistance due to its superior heat resistant property and chemical stability [25, 26, 28].

### *2.2.2 Other cutting tool materials*

There is a growing interest in the scientific community regarding the use of efficient solutions for the machining of heat-resistant nickel-based alloys. Although recent advances and

research on machining Inconel with PCBN tools as stated in the previous chapter there are other tool materials that can be used to machine Inconel.

Cemented carbides (WC-Co) are a low-price alternative that despite having limited low cutting speeds (20 - 80 m/min) and poor thermo-chemical stability still offer a good balance between cost and performance being the most used cutting tool material in the industry [29, 30]. Several research indicate that PCBN inserts have a much shorter tool life than carbide tools, but it is worth noting that cutting speeds allowed for PCBN are almost 5x higher resulting in more attractive productivity scenarios [4, 31, 32]. Cemented carbide tool life is also sensitive to cutting parameters, decreasing when cutting speeds increase, that lead to higher temperatures and the diffusion of Nickel and Iron into the Cobalt matrix of WC-Co tools [33]. These tools are usually available with a wide range of coatings and tool wear can be divided into two periods: first the protective coating layer makes wear increase slowly and a second period when coating disappears and carbide is exposed both crater and adhesion happen [34].

Ceramics, such as alumina ( $\text{Al}_2\text{O}_3$ ) based composites, offer until 10x faster cutting speeds than carbides although with a decrease in tool life [30]. At higher cutting speeds (100-300 m/min) ceramic tools also experience flank wear and adhesion that can be minored using high pressure cooling (HPC) [35]. Cooling strategy regarding ceramic tools is still an interesting research theme since ceramic tools have around ten and five times lower thermal conductivity when compared to carbides and PCBN, respectively [30]. SiC whisker reinforced alumina tools showed a good performance in the speed range of 100-250 m/min but when exceeding 300m/min diffusion (or reaction) between Si in the tool and Inconel 718 caused larger wear [36, 37].

## 2.3 Superalloys

Superalloys demonstrate an impressive combination of mechanical strength and heat resistant properties being able to retain their stiffness, strength, toughness and dimensional stability at higher temperatures than other structural materials [7, 8].

The number of available materials is growing at a fast pace as new alloys are developed with unique (i.e., customized for particular applications) or improved properties. Nevertheless, it is estimated that, at this stage, only around one hundred types of metallic alloys, composites, polymers and ceramics have the combination of essential properties needed for aerospace applications [7].

Iron-based superalloys are characterized by both high temperature and room-temperature strength and resistance to creep, oxidation, corrosion, and wear. Due to their low thermal expansion at high temperature, they are suitable for components that require tight dimensional tolerances. These alloys can be divided further in three types: alloys strengthened by a martensitic type of transformation, alloys that are austenitic and are strengthened by a

sequence of hot and cold working and austenitic alloys strengthened by precipitation hardening. Iron based superalloys are less expensive than cobalt or nickel-based superalloys [38-40].

Nickel-based superalloys, such as the Inconel 718, are the material of choice for turbine components that are required to operate above 800°C. These alloys have an outstanding resistance against creep and stress rupture at high temperature combined with good resistance to oxidation and corrosion. Creep resistance has a special role in engine parts in order to avoid their seizure and failure. Nickel superalloys withstand to creep until approximately 70% of their melting temperature while most materials experience creep at temperatures of 30-40% of their melting temperature. Furthermore, Ni-based alloys can tolerate average temperatures of 1050°C with occasional exposure to temperatures as high as 1200°C which is in the region of the melting point of the material. Nickel based superalloys contain at least 50% by weight of nickel however they may contain more than ten types of alloying elements. Niobium, molybdenum, tungsten and aluminium enhance the creep resistance. Chromium has the same effect has in iron-based superalloys: improving corrosion and oxidation resistance. Wear resistance increases with carbon content and oxidation resistance improves with chromium content. Nickel superalloys achieve their strength by solid solution hardening or the combination of solid solution and precipitation hardening [39, 41]. These replace titanium in most applications where the service temperature exceeds 600°C [42]. The stress-rupture strength of different alloys is shown in Figure 2.8.

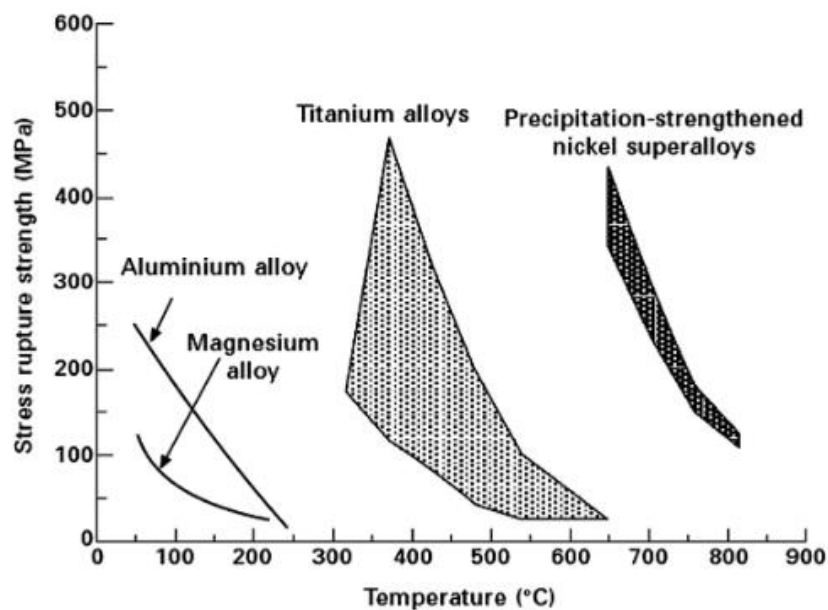


Figure 2.8 - Stress-rupture strength of different alloys [42].

Cobalt-based superalloys generally have better corrosion resistance than nickel-based and iron-nickel alloys in hot atmospheres. Alloying elements are used to harden the cobalt by solid solution or precipitation strengthening. However, the precipitation hardening in cobalt does not provide the same high-temperature strength as in precipitation-hardened nickel-based

alloys. Cobalt super alloys typically contain chromium levels, in addition to metal carbides and refractory metals, to develop resistance to corrosion that usually happens in the surrounding area of exhaust high temperature gases [39, 40].

The high-speed machining (HSM) concept and its desirable speeds differs on each material/process combination. For example, if the work material being machined is a nickel-based alloy is considered as HSM cutting this alloy at 50-500 m/min, while for aluminium, HSM range starts at 1300 m/min [43]. Figure 2.9 demonstrates that nickel-based alloys have the lowest range, which can be seen as a good indicator of their poor machinability, especially at high speed operative conditions.

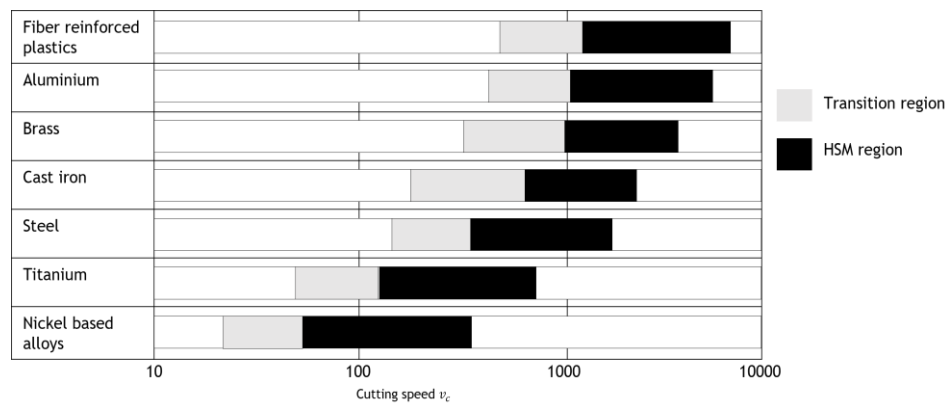


Figure 2.9 - Cutting speeds for HSM, adapted from [43].

### 2.3.1 Inconel 718 composition and microstructure

Inconel 718 is a nickel-chromium-iron superalloy. Nickel is used as base element due to its ability to preserve high concentrations of alloying elements in solid solution and high thermal stability at an adequate cost [44]. Moreover, nickel is stable in the FCC from room temperature to its melting point so that there are no phase transformations that would produce expansions and contractions which could be critical in high-temperature components. Low diffusion rates in FCC enhances the microstructural stability at elevated temperatures [2]. In Table 2.1 typical chemical composition of Inconel 718 is presented.

Table 2.1 - Main alloying elements (wt %) in IN718 [44].

| Element | wt %          |
|---------|---------------|
| Ni      | 50.00-55.00   |
| Cr      | 17.00-21.00   |
| Fe      | balance (~19) |
| Nb      | 4.75-5.50     |
| Mo      | 2.80-5.50     |
| Ti      | 0.65-1.15     |

|    |           |
|----|-----------|
| Al | 0.20-0.80 |
| C  | 0.08 max  |

Table 2.2 summarises Inconel 718 various phases which form either during solidification or during subsequent aging heat treatments.

*Table 2.2 - Summary of Inconel 718 phases [2, 45-47].*

| Phase                             | Crystal Structure | Composition                                | Comments                                                                   |
|-----------------------------------|-------------------|--------------------------------------------|----------------------------------------------------------------------------|
| Gamma ( $\gamma$ )                | FCC               | Table 2.1                                  | Matrix of the alloy                                                        |
| Gamma Prime ( $\gamma'$ )         | FCC               | $\text{Ni}_3(\text{Al, Ti, Nb})$           | Strengthening phase                                                        |
| Gamma Double Prime ( $\gamma''$ ) | BCT               | $\text{Ni}_3\text{Nb}$                     | Principal strengthening phase                                              |
| Delta ( $\delta$ )                | Orthorhombic      | $\text{Ni}_3(\text{Nb, Ti})$               | Observed in overaged alloy, detrimental mechanical properties              |
| Laves                             | HCP               | $(\text{Ni, Fe, Cr})_2(\text{Nb, Mo, Ti})$ | Brittle and detrimental to mechanical properties                           |
| MC-carbide                        | Cubic             | $(\text{Nb, Ti})\text{C}$                  | If carbon and boron are present improves high-temperature creep properties |

Gamma ( $\gamma$ ), the matrix material, has an FCC structure and consists of the solid solution elements: nickel, chromium, iron, columbium, molybdenum, titanium, and aluminium.

Gamma Prime ( $\gamma'$ ) is an  $\text{A}_3\text{B}$  compound where A atoms are primary nickel and B are niobium, titanium, and aluminium. Gamma prime has a spherical shape and appears as small dots within the gamma matrix [48].  $\gamma'$  contribute also to the strength of the alloy, but to a lesser degree than the Gamma Double Prime ( $\gamma''$ ) precipitates [49, 50].

Gamma Double Prime ( $\gamma''$ ) displays a disc-shaped morphology, with the thickness often as small as 10 nm and the diameter of about 50 nm [2]. Its strengthening is mainly due to the coherency strains induced by the tetragonal  $\text{Ni}_3\text{Nb}$  precipitate  $\gamma''$  forming in the nickel  $\gamma$  matrix [49, 50].

Delta ( $\delta$ ) phase precipitates with an orthorhombic structure during heat treatment or results from over aging of the  $\gamma''$  phase. This phase forms as large needles in the grains and at the grain boundaries as shown in Figure 2.10. Delta is invariably incoherent with  $\gamma$ , and therefore does not give strength even when present in significant quantities [2].

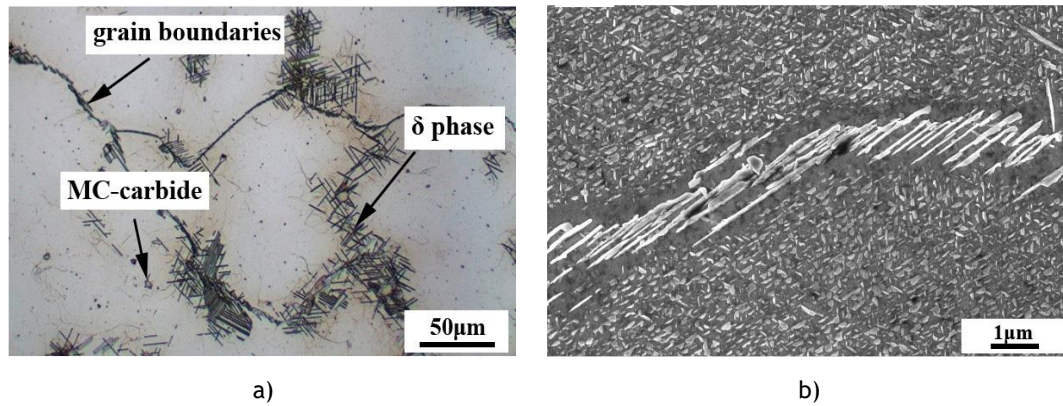


Figure 2.10 - Optical microstructures of the IN718: a)  $\delta$  precipitation at grain boundaries, b) detail of  $\delta$  precipitation shaped as large needles [51].

Laves phase appear as round massive particles and is found in heavily cores of segregated areas. This brittle phase is harmful to the mechanical properties such as ductility. Thus, it removes alloying elements required for precipitation hardening and therefore tend to reduce strength [48].

### 2.3.2 Heat treatments

Inconel 718 is a heat treatable alloy, thus, enabling different strength and ductility configurations. Table 2.3 shows the two common heat treatment specifications for Inconel alloy 718 according to American Society for Metals although slight temperature variations of these methods are often used.

Table 2.3 - Heat Treatment Specifications for Inconel 718 [52].

| Standart      | Product               | Temperature range                                                                                                                                                                                               |
|---------------|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| AMS 5662/5663 | Bars, Forgings, Rings | Solution anneal at 925-1010°C followed by rapid cooling, plus precipitation hardening at 720°C for 8 hours, furnace cool to 620°C, hold at 620°C for a total aging time of 18 hours, followed by air cooling.   |
| AMS 5596      | Sheet, Strip, Plate   |                                                                                                                                                                                                                 |
| AMS 5589      | Seamless Tubing       |                                                                                                                                                                                                                 |
| AMS 5664      | Bars, Forgings, Rings | Solution anneal at 1040-1065°C followed by rapid cooling, plus precipitation hardening at 760°C for 10 hours, furnace cool to 760°C, hold at 760°C for a total aging time of 20 hours, followed by air cooling. |
| AMS 5597      | Sheet, Strip, Plate   |                                                                                                                                                                                                                 |
| AMS 5590      | Seamless Tubing       |                                                                                                                                                                                                                 |

Figure 2.11 - Transformation-time-temperature diagram of IN718 alloy [53] shows a time-temperature-transformation (TTT) curve of Inconel 718. Gamma prime ( $\gamma'$ ) phase begins to form at 650°C within reasonable periods of time (50 minutes). Both  $\gamma'$  and  $\gamma''$  are metastable, undergoing a slow transformation into  $\delta$  at temperatures in excess of 650°C, leading to limit

the use of IN718 at higher operating temperatures. Laves phase forms at temperatures in excess of 980°C which limits the temperature usage [48].

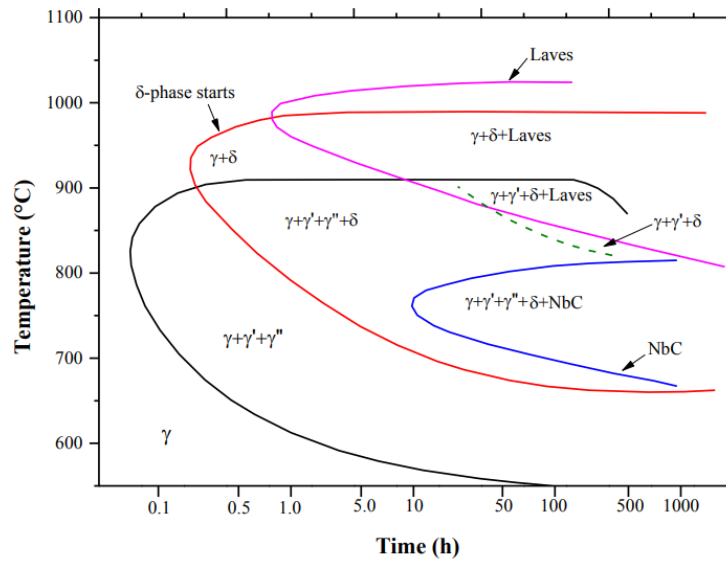


Figure 2.11 - Transformation-time-temperature diagram of IN718 alloy [53].

## 2.4 FEM simulation

Metal cutting process simulation enables the testing of different parameters without the need for expensive experimental work. In the last three decades, FEM has been progressively applied to metal cutting simulations. An increase in computation power and widely available FEM programs lead to the development and spread of finite element analysis (FEA) through metal cutting studies [54].

There is a wide range of topics in turning processes that can be studied with numerical simulation. Inconel 718 machining parameters and their influence on the tool life, cutting temperatures and forces, chip formation and surface finish have been studied from various authors. MacGinley and Monaghan [55] used FORGE software to compare the cutting process outputs of orthogonal turning Inconel 718 with uncoated, single-coated TiN, TiC, and Al<sub>2</sub>O<sub>3</sub> and double-coated TiN/Al<sub>2</sub>O<sub>3</sub> tungsten carbide tools achieving that finite element analysis can be adapted to effectively model a metal-cutting process. Moreover, distinctive shear zones were produced using both positive and negative rake cutting tools and a negative rake tool without a chip breaker produced the greatest magnitude of equivalent stress. Yadav et al. [56] used DEFORM to estimate flank wear and material removal rate in turning of Inconel 718, using CVD coated tungsten carbide cutting tools. Flank wear calculation was performed through calibration of the Usui's model. After validating numerical simulation with experimental data, was achieved that the relative error between experimental and simulation predicted value of flank wear and material removal rate was below 7%.

Attanasio et al. [57] implemented a subroutine on DEFORM<sup>TM</sup> with the objective to simulate drill flank wear during drilling of Inconel 718. This material was defined by a Johnson Cook constitutive model and the written subroutine was applied after cutting process reached the thermo-mechanical steady state. After force and temperature reach steady state, identification of rake, flank and cutting edge nodes is done followed by calculation of the local rake ( $\gamma$ ), clearance ( $\alpha$ ) angles and tool wear amount for each node. Tool geometry and mesh are then updated and define the new worn tool geometry. Later a similar approach was once again followed by Attanasio et al. [58] to simulate tool wear in drilling Inconel 718 under flood and cryogenic cooling conditions. Results of both studies had a good agreement between experimental and simulated results in addition to adopting a useful procedure for researchers and workers in cutting field.

Two cutting models, using Lagrangian and Coupled Eulerian-Lagrangian (CEL) approaches, were investigated by da Silva and Outeiro [59] to simulate the orthogonal cutting of Inconel 718 on Abaqus, defined by a constitutive law that considered effects of strain hardening, temperature and strain rate (stress triaxiality and Lode angle) developed by da Silva et al., [60]. Experimental tests were made with uncoated carbide tools and allowed the authors to conclude that Lagrangian and CEL approaches can reasonably simulate the chip geometry and chip compression ratio. The frequency of cutting force obtained by the Lagrangian approach is closer to the experimental frequency of chip segmentation than the CEL approach, both simulated cutting temperature and cutting forces are slightly higher for the CEL approach and both Lagrangian and CEL approaches can reasonably predict the residual stresses in the cutting direction.

Jafarian et al. [61] implemented a user subroutine in the DEFORM<sup>TM</sup> software to simulate microstructural changes including grain refinement and hardness variation in orthogonal cutting of Inconel 718 alloy. The grain refinement was predicted by using the Zener-Hollomon equation while microhardness variation induced in the surface and subsurface of the machined workpiece was predicted by Hall-Petch equation. By testing seven constants for the Johnson-Cook constitutive model it was found that the material model has a significant effect on the results of the simulation.

Lotf et al. [62] used DEFORM to estimate the wear of ceramic and coated carbide tools in turning of Inconel 625. Usui's tool wear model was calibrated according to experimental data showing predicted and experimental values are in good agreement. Furthermore, the simulation results indicate that tool wear rate is higher in the areas in which temperature and stresses are concentrated which increase as the depth of cut increases.

Investigation regarding mechanical and thermal loads when machining Inconel 718 with a PCBN tool was also made by Agmell et al. [63], using ABAQUS commercial code. The material was defined according to a Johnson-Cook constitutive law and a coupled Eulerian-Lagrangian (CEL) formulation was made to predict cutting forces, chip formation and thermal loads. The tool temperature predicted by the FEM model, correlated with the experimentally determined.

Moreover, the presented numerical model simulated the principal stress at the notch wear region of the tool, which correlated with the notch wear experimentally observed.

Even if Johnson-Cook material model is the most widely used strength model in metal cutting simulations, several authors focused improving constitutive models for this alloy. Various authors conducted experimental tests in order to calculate and calibrate material parameters for the Johnson-Cook constitutive model while others adapted and proposed modified versions of that model [64-66]. Calamaz et al. [67] proposed a tangent hyperbolic (TANH) model that adds a new term to the conventional Johnson-Cook equation to consider strain softening at elevated temperatures and strain rates. Sima & Ozel [68] further modified the TANH material model by introducing an  $S$  exponent to better control (TANH) function for thermal softening. Still, the numerous experimental studies regarding Inconel and PCBN tools there is a clear lack of coupled simulation/experimental analysis when hard turning Inconel with PCBN tools, which serves as motivation for the present research.

# Chapter 3

## Metal cutting mechanics and numerical modelling

### 3.1 Analytical model

Machining is a subtractive manufacturing process in which excess material is removed from a workpiece to achieve the desired final geometry [5]. There are two different approaches regarding machining, conventional and non-conventional machining. In the first one the material is removed from a workpiece in the form of a chip by the action of a sharp cutting tool. In non-conventional machining there is no direct contact (that results in mechanical cutting) between the machine tools and the workpiece.

Given the scope of this dissertation, conventional machining fundamentals will be briefly reviewed. Given its simplification of the cutting process and close correspondence to the longitudinal turning process, orthogonal cutting is usually applied, whereas the former can be seen as an experimental characterization test, useful for the benchmark of operative conditions and calibration of numerical models, the latter is an industrial operation, susceptible to instrument and conduct in laboratory-controlled environment yielding a more representative portrayal of the cutting mechanism.

#### 3.1.1 *Orthogonal cutting model*

The complex geometry and dynamics of machining operations, impose its three-dimensional nature. The orthogonal cutting model enables the simplification of this 3D problem into a two-dimensional modeling analysis.

By definition, orthogonal cutting uses a wedge-shaped tool in which the cutting edge is perpendicular to the direction of cutting speed. This cutting method is characterized by a uniform process along the cutting edge for what it is typically considered a 2D problem (Figure

3.1). The tool in orthogonal cutting has only two elements of geometry: ( $\alpha$ ) rake angle and ( $\delta$ ) clearance angle. The tool forces into the material, creating a chip by shear deformation along a shear plane oriented at an angle ( $\phi$ ) with the surface of the work. This chip is characterized by a width ( $w$ ), uncut chip thickness ( $t_0$ ) and chip thickness ( $t_c$ ) [5].

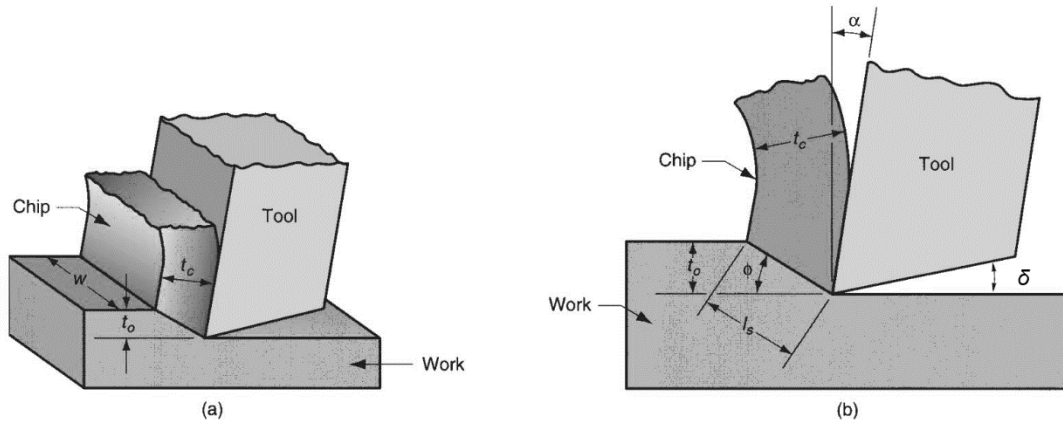


Figure 3.1 - Orthogonal cutting: (a) as a 3D process and (b) how it reduces to 2D in the side view, adapted from [5].

The chip formation process involves intense plastic deformation concentrated in different locations of the cutting zone. Intense plastic deformation is focused in the primary shear zone (Figure 3.2). This region defines a shear plane oriented at an angle ( $\phi$ ) where the behaviour of the material within this region is controlled by shear stress and compressive stresses. Secondary shear results from friction between the chip and the tool as the chip slides along the rake face of the tool [5].

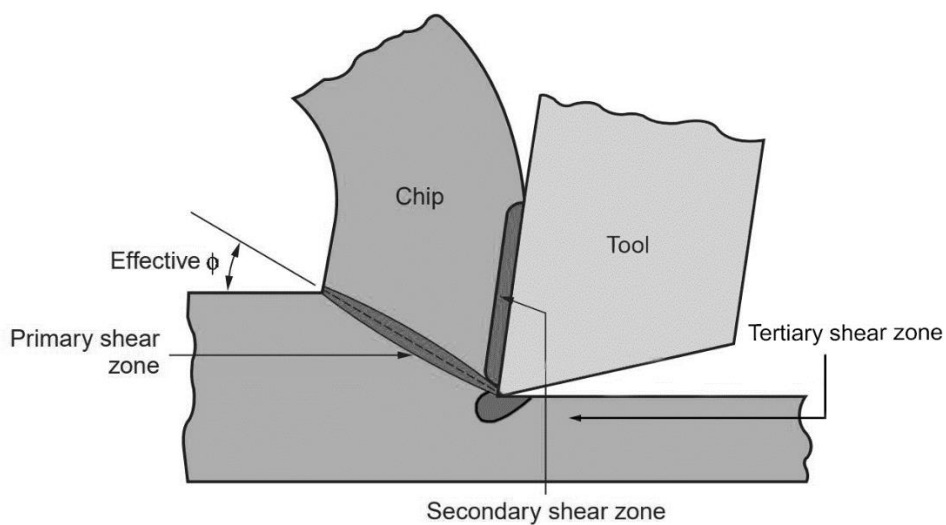


Figure 3.2 - Primary, secondary and tertiary shear zone, adapted from [5].

Chip formation during metal cutting depends on the type of material being machined and the cutting conditions of the operation. Four types of chips can be effortlessly distinguished [5]:

- **Discontinuous chip:** Typical from processes with brittle materials (e.g., cast irons) machined at low cutting speeds. High tool-chip friction and large feed and depth of cut promote the formation of this chip type. Usually, the surface finish is very rough [69].
- **Continuous chip:** Typical from processes with: i) ductile materials cut at high speed and relatively small feeds and depths; ii) sharp cutting edge in the cutting tool and iii) low tool-chip friction. This continuous chip leads to lower vibrations and better surface finish although, a chip breaker might be needed to avoid problems regarding chip disposal and/or tangling about the tool [69].
- **Continuous chip with built-up edge:** Typical from processes with ductile materials at low to medium cutting speeds. Friction between the tool and chip tends to cause portions of the work material to adhere to the rake face of the tool near the cutting edge. This phenomenon is called a built-up edge (BUE) and happens cyclically since the material builds up on the tool and periodically brakes off. BUE formation reduces the life of the cutting tool and decreases the surface quality [69].
- **Serrated chips:** Typical from processes involving difficult to machine metals such as nickel-base super alloys, austenitic stainless steels and titanium alloys. This semi-continuous chip is produced by a cyclical chip formation of alternating high shear strain followed by low shear strain [69].

On the secondary shear zone, the forces acting against the chip by the tool can be separated into two mutually perpendicular components: friction force (F) and normal force to friction (N) as seen in Figure 3.3. These two forces can be related, according to the Coulomb friction law, through the coefficient of friction,  $\mu$ , or the friction angle,  $\beta$  [69]:

$$\mu = \frac{F}{N} = \tan \beta \quad 3.1$$

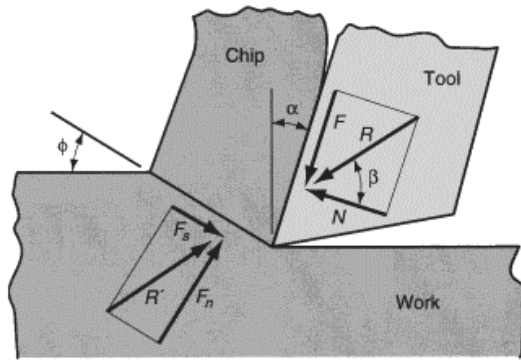


Figure 3.3 - Forces acting on the chip in orthogonal cutting [5].

Eugene Merchant defined an equation which defines the general relationship between rake angle, tool-chip friction, and shear plane angle [5]. When the rake angle increases ( $\alpha$ ), shear angle increases ( $\phi$ ) and when friction decreases ( $\beta$ ), shear angle increases.

$$\phi = \frac{\pi}{4} - \frac{\beta}{2} + \frac{\alpha}{2} \quad 3.2$$

Merchant equation must be considered an approximate relationship rather than an accurate mathematical equation because assumes that the shear strength of the work material is constant, unaffected by strain rate and temperature [5]. Some authors proposed alternative equations for shear angle relationships shown at Table 3.1.

Table 3.1 - Shear angles according to several authors adapted from [69].

| Author         | Equation                                                                                                                                       |
|----------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| Ernst-Merchant | $\phi = \frac{\pi}{4} - \frac{\beta}{2} + \frac{\alpha}{2}$                                                                                    |
| Stabler        | $\phi = \frac{\pi}{4} - \beta + \frac{\alpha}{2}$                                                                                              |
| Lee-Shaffer    | $\phi = \frac{\pi}{4} - \beta + \alpha$                                                                                                        |
| Hucks          | $\phi = \frac{\pi}{4} - \frac{\alpha \tan(2\mu)}{2} + \alpha$                                                                                  |
| Shaw et al.    | $\phi = \frac{\pi}{4} - \beta + \alpha \pm \eta$                                                                                               |
| Sata           | $\phi = \frac{\pi}{4} - \alpha \pm \frac{\alpha - 15^\circ}{2}$                                                                                |
| Kroonenberg    | $\phi = \text{acot} \left[ \frac{e^{\mu(\frac{\pi}{2} - \alpha)} - \sin \alpha}{\cos \alpha} \right]$                                          |
| Oxley          | $\phi = a \tan \left[ 1 + \frac{\pi}{2} - 2\phi + \frac{\cos 2(\phi - \alpha)}{\tan \beta} - \sin 2(\phi - \alpha) \right] - (\beta - \alpha)$ |

Atkins [70]

$$F_c = \left( \frac{\tau_y w v}{Q} \right) t_0 + \frac{R_w}{Q} \quad Q \text{ is the friction correction given by}$$

$$Q = [1 - (\sin \beta \sin \phi / \cos(\beta - \alpha) \cos(\phi - \alpha))]$$

The orthogonal model can be used to approximate turning if the feed in this operation is small relative to depth of cut. Figure 3.4 shows how orthogonal cutting can be seen as an elemental representation of the turning process, where the tool's cutting edge is perpendicular to the feed motion. Table 3.2 summarizes the nomenclature conversion between the interchangeable operations.

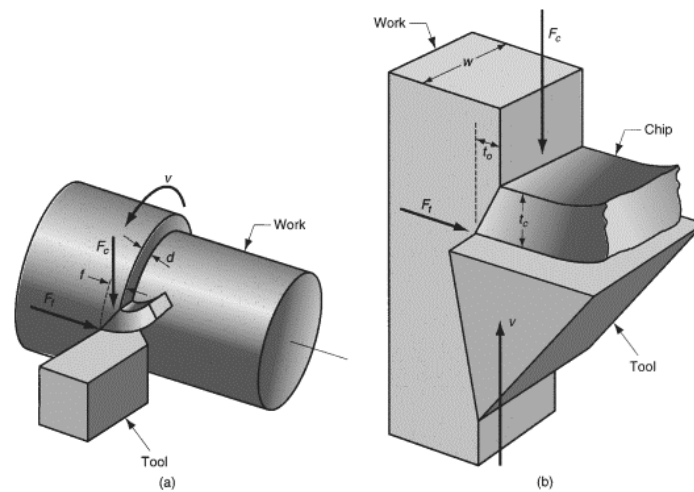


Figure 3.4 - Approximation of turning by the orthogonal model: (a) turning; and (b) the corresponding orthogonal cutting [5].

Table 3.2 - Parameter conversion: longitudinal turning vs orthogonal cutting adapted from [5, 69]

| Longitudinal Turning | Orthogonal cutting         |
|----------------------|----------------------------|
| Feed $f$             | Uncut chip thickness $t_0$ |
| Depth $d$            | Width of cut $w$           |
| Cutting speed $v$    | Cutting speed $v$          |
| Cutting Force $F_c$  | Cutting Force $F_c$        |
| Feed Force $F_f$     | Thrust Force $F_t$         |

Still, the orthogonal cutting model has some limitations when applied to cylindrical turning. Cylindrical turning is a 3D process with variable cutting speed ( $v_c$ ) along the cutting edge. Furthermore, this cutting edge usually has a small radius that leads to a three-dimension cut.

The feed, which corresponds to the chip thickness before cut  $t_0$ , is not momentaneous but rather the result of the workpiece rotation [69].

When machining hard materials the cutting process mechanisms (chip formation, heat generation, tool wear) differ from those observed in machining soft materials. Negative rake angle and tool corner radius lead to an remarkable increase in passive force [1]. Forces in turning can be divided into three components as detailed in Figure 3.5 where  $F_c$  is the cutting force,  $F_f$  is the feed force and  $F_p$  is the passive force. The resultant force (R) is given by the equation 3.3.

$$R = \sqrt{F_c^2 + F_f^2 + F_p^2} \quad 3.3$$

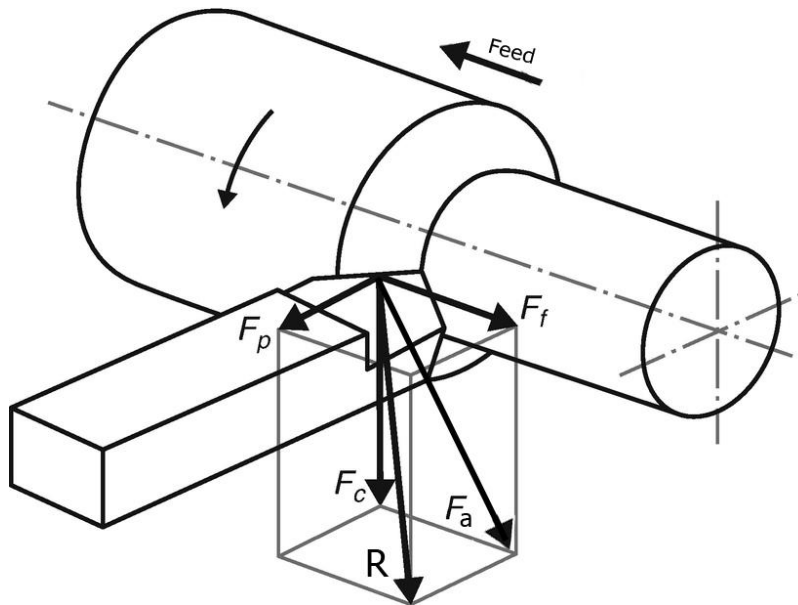


Figure 3.5 - Force components in turning, adapted from [71].

## 3.2 Finite Element Modelling in machining

Finite Element Modeling (FEM) is the most used numerical technique employed in metal machining, other numerical methods being the Finite Differences Method (FDM), Boundary Elements Method (BEM) and meshless methods [72, 73]. The principle of FEM is to transform a continuous model, in which each element has an infinite number of freedom degrees, into a discrete model where an element has a finite number of freedom degrees. This method is widely used and available in commercial software such as *Abaqus*<sup>TM</sup>, *DEFORM*<sup>TM</sup> 2D/3D or *Thirdwave AdvantEdge*.

The principle of FEM described before, i.e., the replacement of a continuum by finite elements forming a mesh, is called discretization. Each finite element aims to be simpler in geometry therefore easier to analyse than the real model. Furthermore, each finite element has nodes where it connects to other elements, problem initial and boundary conditions are applied, and the degrees of freedom are calculated [72].

Some difficulties are associated with modelling machining processes. Even on low cutting speeds, the machining process achieves very high strain rates (above of  $10^5 \text{ s}^{-1}$ ) and plastic deformation rates (0.1 and 3) [74]. Moreover, energy involved on the process, plastic deformation and friction lead to a temperature increase (higher than  $1000^\circ\text{C}$  are usual on the tool interface) which may induce material softening [74]. Simultaneously, heat transfer dynamics should also be taken into account resulting in non-linear coupling thermo-mechanical analyses.

### 3.2.1 Model Formulation

Continuum-based finite element modelling is based in one of two primary mathematical formulations: Eulerian and Lagrangian [75]. In the Eulerian approach the finite element mesh is spatially fixed and covers a control volume while in the Lagrangian approach the elements are attached to the material. The arbitrary Lagrangian-Eulerian (ALE) and coupled Lagrangian-Eulerian (CEL) formulations have also been proposed with the intention to combine the advantages of the two above-mentioned methods [72].

#### 3.2.1.1 Eulerian formulation

In the Eulerian approach the finite element mesh is spatially fixed and the material flows through a control volume. Eulerian formulation needs no re-meshing since there is no element distortion involved in the analysis. The main advantage of this formulations is the reduced computational time due to the few elements required for modelling the workpiece and the chip. On the downside, is only suitable for the simulation of steady-state machining process when the early stages of chip formation are not of interest and with continuous chip since no

chip breakage criterion can be incorporated in the model for the simulation of discontinuous chip formation.

More recently it is considered that Eulerian set up FEM models do not correspond to the real deformation procedure encountered in real metal cutting processes, as the chip thickness, a major outcome of the process cannot be assumed physically [72].

#### 3.2.1.2 Lagrangian formulation

In the Lagrangian approach the elements are attached to the material. If the material is deformed due to the actions of the cutting tool the mesh will deform too. Lagrangian formulation allows for simulations from transient chip formation to steady-state conditions and modelling of both segmented and continuous chips morphologies, although it requires a criterion for separation of the chip from the workpiece. Two different approaches, explicit or implicit, can be followed. In explicit approach, the displacement of the workpiece and the attached mesh, is a function of the time step and can be related to the material removal rate whereas in an implicit formulation the size of the time step has no influence on the stability of the solution. During simulation large mesh distortion due to the plastic deformation may cause convergence issues. Pre-distorted meshes and re-meshing techniques are applied in order to overcome these problems at the cost of longer computing time. Updated Lagrangian analysis has overcome the disadvantage of a chip separation criterion by applying continuous remeshing and adaptive meshing, not requiring a chip separation criterion [76].

#### 3.2.1.3 Arbitrary Lagrangian-Eulerian formulation (ALE)

The arbitrary Lagrangian-Eulerian formulation has also been proposed with the aim to combine the advantages of the two methods. In this formulation, the mesh is neither attached to the material nor fixed in space, so it is allowed to arbitrarily move relative to the material with the total displacement being the sum of a Lagrangian displacement increment and a Eulerian displacement increment. The ALE formulation has two major drawbacks. Often the ALE formulation needs a complete re-meshing. The re-mapping of state variables may be performed inaccurately resulting in a drawback compared to the updated Lagrangian. When the re-map is performed inaccurately, the history of the material is not taken into account properly [54, 72].

Despite ALE advantages, it still requires some assumptions about the initial chip geometry and cannot accurately model the chip morphology [77]. Because of the relative displacement between the mesh and the material, an ALE model with pure Lagrangian boundaries does not lead to a chip with a geometry close to the experimental one when segmented (or saw-toothed) chip is observed, contrary to a Lagrangian mode [78].

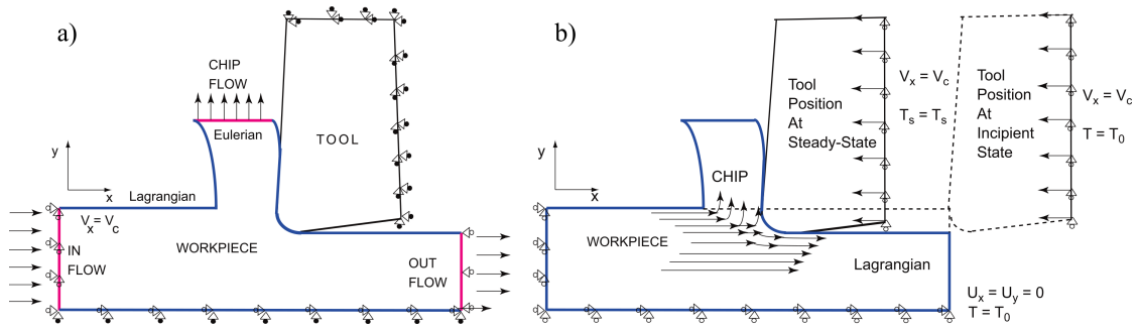


Figure 3.6 - FE simulation model for ALE formulation with: (a) Eulerian and Lagrangian boundary conditions, and (b) pure Lagrangian boundary conditions [79].

### 3.2.1.4 Coupled Lagrangian-Eulerian formulation (CEL)

The Coupled Lagrangian-Eulerian formulation (CEL) was developed to overcome ALE disadvantages. This formulation was typically used to study fluid-structure interactions. This type of model is composed of a volume represented by a Eulerian mesh in which the Eulerian material “flows” and interacts with Lagrangian part(s) [78]. In orthogonal cutting the Eulerian workpiece is represented by a non-translating and material deformation independent mesh while the cutting tool is modelled according to a Lagrangian formulation. The use of Eulerian formulation in the workpiece can lead to smaller computing time and mesh distortions were observed with the ALE model were avoided [80].

## 3.2.2 Constitutive Models

Constitutive models describe the material responses to different mechanical and/or thermal loading conditions, which provide the stress-strain relations to formulate the governing equations, together with the conservation laws and kinematic relations [81].

When machining the elastic strain is much lower than the plastic strain [72]. The flow properties of the workpiece material and the corresponding equations in FEM have been studied. These equations describe the flow stress or instantaneous yield strength at which work material plastically deforms, in function of strain and, depending on the model complexity, other variables such as temperature and strain rate.

### 3.2.2.1 Power law

This model proposes a power law relation to determine flow stress as a function of strain, strain-rate and temperature. The constitutive power law can incorporate the effects related to strain hardening, strain rate sensitivity and thermal softening [82].

$$\bar{\sigma} = \sigma_0 \left( \frac{\bar{\epsilon}}{\bar{\epsilon}_0} \right)^n \left( \frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right)^m \left( \frac{T}{T_0} \right)^\tau \quad 3.4$$

Where  $T$  is temperature,  $\bar{\epsilon}$  is strain, and  $\dot{\bar{\epsilon}}$  is strain-rate. The experimentally determined exponents  $n, m, \tau$  are the strain, strain-rate and temperature sensitivity, respectively [75].

### 3.2.2.2 Oxley

This model was proposed by Oxley who achieved that flow stress can be expressed as work-hardening behaviour. Both  $\sigma_0$  and  $n$  are written as functions of a velocity-modified temperature, in which temperature and strain-rate are linked into a single equation as given in Eq 3.6.

$$\bar{\sigma} = \sigma_0 \bar{\epsilon}^n \quad 3.5$$

$$T_{MOD} = T \left[ 1 - v \log \left( \frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right) \right] \quad 3.6$$

where  $\sigma_0$  is the strength coefficient,  $n$  is strain-hardening index,  $T$  is temperature,  $v$  is a constant,  $\bar{\epsilon}$  is strain, and  $\dot{\bar{\epsilon}}$  is strain-rate [75]. This model has been widely utilized in slip-line modelling of low and medium carbon steels. Later Oxley's model got extended to Johnson Cook material model by introducing a modified strain hardening exponent  $n_{eq}$  in place of  $n$ . The exponent  $n_{eq}$  can be calculated using the JC model constants  $A$ ,  $B$  and  $n$  using the Eq 3.7 [83].

$$n_{eq} = \frac{nB\epsilon_{AB}^n}{A + B\epsilon_{AB}^n} \quad 3.7$$

### 3.2.2.3 Johnson-Cook

This model was proposed for metals subjected to large strains, high strain rates and high temperatures accomplishing great success due to the simplicity and availability of parameters of various materials of interest [84]. It is also the most widely used in machining simulations due to its simplicity and because it is defined through simple interpolation of experimental data [85].

This model describes flow stress as a product of strain, strain-rate and temperature dependent terms as given in Eq. 3.8,

$$\bar{\sigma} = \underbrace{[A + B(\bar{\epsilon})^n]}_{\text{Strain hardening}} \underbrace{\left[1 + C \ln\left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0}\right)\right]}_{\text{Strain rate hardening}} \underbrace{\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]}_{\text{Thermal softening}} \quad 3.8$$

where the parameter  $A$  is the initial yield strength of the material at room temperature,  $\dot{\bar{\epsilon}}$  is the equivalent plastic strain rate normalized with a reference strain-rate  $\dot{\bar{\epsilon}}_0$ ,  $T_0$  is the room temperature,  $T_m$  is the melting temperature of the material, and  $B$ ,  $C$ ,  $n$  and  $m$  are model parameters. The parameters  $n$ ,  $m$  and  $C$  are the strain-hardening exponent, thermal softening exponent and strain-rate sensitivity, respectively [75].

The material constants ( $A$ ,  $B$ ,  $C$ ,  $n$  and  $m$ ) of Eq. 3.8 are determined using mechanical characterization tests (typically compressive loading is used, due to the higher strains involved) [86]. At high temperature the uncoupled nature effects of strain, strain rate, and deformation are the main problem of the Johnson-Cook model [87].

#### 3.2.2.4 Zerilli-Armstrong

Zerilli and Armstrong proposed dislocation mechanics-based constitutive relations for different crystalline structures, in which the effects of strain hardening, strain rate hardening, and thermal softening based on the thermal activation analysis were incorporated into constitutive relations [87]. Face-centred cubic (FCC) and body cubic centred (BCC) have different formulation models, as given in Eq. 3.9 and Eq. 3.10 respectively [88]:

$$\bar{\sigma} = B_0 + B_1(\bar{\epsilon})^n \exp(-B_3T + B_4T \ln \dot{\bar{\epsilon}}) \quad (\text{FCC}) \quad 3.9$$

$$\bar{\sigma} = B_0 + B_2 \exp(-B_3T + B_4T \ln \dot{\bar{\epsilon}}) + B_3 \bar{\epsilon}^n \quad (\text{BCC}) \quad 3.10$$

In these equations  $B_0$  to  $B_6$  and  $n$  are undetermined coefficients. The  $n$  parameter is derived from a strain hardening power law in an attempt to better account for the effects of dynamic recovery and the consequent saturation of the stress-strain curve at large strains.

The model considers dislocation mechanisms but not the effects of deformation conditions, which does not agree with practical situation. An improved model was proposed in order to predict flow stress in the process of high temperature deformation [89]:

$$\bar{\sigma} = (B_1 + B_2(\bar{\epsilon})^n) \exp \left[ - \left( B_3 + B_4 \bar{\epsilon} \right) T^* + (B_5 + B_6 T^*) \ln \left( \frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right) \right] \quad 3.11$$

where  $\bar{\sigma}$  is a von Mises flow stress in MPa,  $\bar{\epsilon}$  is equivalent plastic strain,  $\dot{\bar{\epsilon}}$  is the strain rate,  $\dot{\bar{\epsilon}}_0$  is the reference strain rate,  $T^* = T - T_{ref}$  with  $T$  and  $T_{ref}$  being the present experimental and reference temperatures. The effects of strain hardening, strain rate hardening and thermal

softening on the hot deformation behaviour of metallic materials are comprehensively considered in this modified Zerilli-Armstrong equation [90].

### 3.2.3 Friction Models (Coulomb, Shear and Hybrid model)

Friction occurs at the physical interface between two surfaces in contact in a form of tangential reaction force between two surfaces in contact [91]. Although the contact conditions at the tool-chip and tool-workpiece interfaces are complex, many known FE metal cutting simulations use simple Coulomb friction condition. Moreover, the friction coefficient is frequently assumed to be constant over these interfaces [54]. Coulomb friction model simplifies the frictional phenomena as the friction force ( $F_F$ ) is proportional to the normal force ( $F_n$ ) with  $\mu$  as a frictional factor:

$$F_F = \mu F_n \quad 3.12$$

This friction model cannot handle the environment of zero velocity, so it does not specify the friction force for zero velocity [91]. Furthermore, when the normal stresses increase and surpass a critical value, this equation fails to give accurate predictions [72].

In order to solve the limitations found in the Coulomb's friction law, the constant friction law or simply the Prandtl Law, assumes that the shear stress is proportional to the force required for plastic deformation of the material, resulting in the following equation [92]:

$$F_F = mk \quad 3.13$$

In this equation, the friction factor or proportionality factor ( $m$ ) ranges from 0 (zero friction conditions) to 1 (maximum friction conditions usually with occurrence of the adhesion phenomenon),  $k$  corresponds to the maximum shear stress of the material. In addition, hybrid models, also present in the DEFORM commercial code were developed conjugating both Coulomb and Prandtl friction models, establishing constant values throughout the process at the contact interface. Coulomb or Prandtl model use is defined by the following criteria [92]:

Use of Coulomb friction:

$$\mu p < mk \rightarrow F_F = \mu F_n$$

Use of Prandtl friction:

$$\mu p \geq mk \rightarrow F_F = mk$$

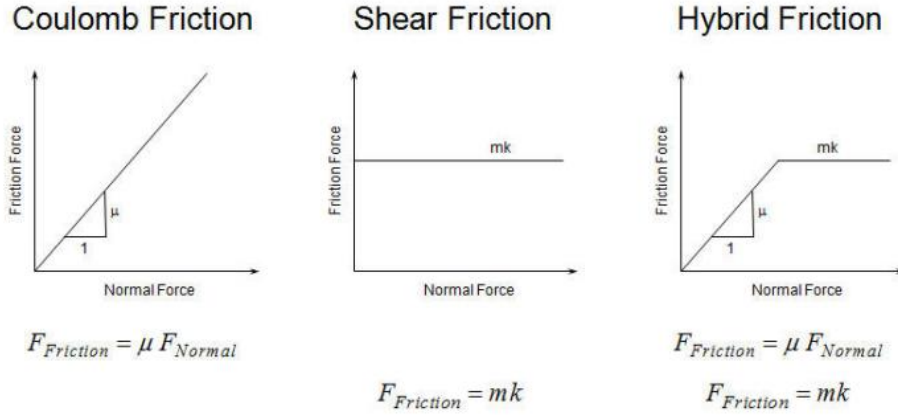


Figure 3.7- Friction models present in DEFORM™ software.

### 3.2.4 Tool wear models

Tool wear has a great influence not only on the tool life but also on the quality of the final product in terms of dimensional accuracy and surface integrity. These aspects are even more relevant in machining of difficult-to-cut materials such as nickel alloys [57].

In Archard's tool wear model, present in DEFORM-2D/3D, the wear rate is a function of interface pressure ( $p$ ), relative velocity ( $v$ ), at the contact area, and tool hardness surface ( $H$ ) as given in:

$$W = \int K \frac{p^a v^b}{H^c} dt \quad 3.14$$

where  $a, b$  and  $c$  are experimental calibrated constants. This model is generally better suited for discrete processes such as cold or hot forging. In these cases, abrasive wear is the dominant wear mode.

DEFORM-2D/3D can use Usui's tool wear model to compute tool wear, which is used only with non-isothermal run as it requires interface temperature calculations. This model is generally better for continuous processes such as metal cutting, where diffusion is a major contributor to wear. In Usui's tool wear model, the wear rate is a function of interface pressure ( $p$ ), relative velocity ( $V$ ) and absolute temperature ( $T$ ) at the contact surface as given in:

$$W = \int apV e^{-b/T} dt \quad 3.15$$

Takeyama and Murata's model considers abrasive as well as diffusive wear mechanisms for predicting the tool flank wear. This model comprises two expressions, one for the mechanical abrasive wear ( $W_a$ ) which is related to the cutting velocity and machining length ( $L$ ) and abrasive wear resistance ( $\sigma_a$ ) of the tool and the second part for the thermal diffusive wear

( $W_r$ ) which is related to the tool-workpiece interface temperature ( $T$ ) and contact time ( $t_k$ ) [93].

$$W = W_a(L, \sigma_a) + W_r(T, t_k) \quad 3.16$$

Attanasio et al. [94] proposed a coupled abrasive and diffusive model for calculating the total wear rate by combining Takeyama and Murata's and Usui's models, where  $T_{act}$  is the activation temperature of the diffusive phenomenon and before reaching it the wear is dominated by abrasive wear.  $D(T)$  is defined as a third order polynomial function of the temperature ( $T$ ), while  $a$  and  $b$  are constants.

$$T \leq T_{act} \rightarrow \frac{dW}{dt} = a \cdot p \cdot V \cdot e^{-\frac{b}{T}} dt \quad 3.17$$

$$T > T_{act} \rightarrow \frac{dW}{dt} = a \cdot p \cdot V \cdot e^{-\frac{b}{T}} + D(T)e^{-\frac{b}{RT}} dt \quad 3.18$$

In Akazawa model [95], the total wear rate is determined from separate expressions for abrasion and diffusion. The first part of the model specifies wear rate due to abrasion and the second part specifies wear rate due to diffusion. The wear rate due to abrasion was related to the sliding velocity ( $V$ ) of the work material passing over the tool face and the relative hardness of work,  $H_w$ , and tool,  $H_t$ . The relative hardness between these two plays the key role in the amount of abrasive wear and should be given as function of temperature. The diffusive wear rate in Akazawa model was related to sliding velocity ( $V$ ) of workpiece material passing over the interface and the tool-workpiece interface temperature while  $c_1, c_2, c_3$  are empirical constants.

$$\frac{dW}{dt} = c_1 \cdot V \cdot \frac{H_w}{H_t} + c_2 \cdot V \cdot e^{-\frac{c_3}{T}} dt \quad 3.19$$

# Chapter 4

## Experimental procedure

### 4.1 Introduction

This section focuses on the experimental details of this dissertation, which consisted of the machinability assessment of Inconel 718 (in two distinct heat treated conditions) using two different CBN cutting inserts. The machining tests involved longitudinal cylindrical turning of rods with data acquisition of cutting load and tool wear analysis. Two different materials were analysed for the sake of comprehensiveness of this study and to understand the influence that different metallurgical conditions (promoted by the distinct heat treatments) have on the tool wear of CBN cutting tools. This allowed to understand if the mechanical strength and hardening IN718 is directly related to wear. Given the distinct mechanical strength of each Inconel 718 alloy, expected mechanical properties for each alloy are shown at Table 4.1, compression tests were performed enabling their characterization with will be further employed in the modelling and calibration of their material behaviour. Alloy 1 was subjected to a solution and aging heat treatments, while alloy 2 undergone only through solution heat treatment. The details of these heat treatments are displayed in Figure 4.1.

*Table 4.1- Expected mechanical properties of IN718 alloys.*

|                        | Alloy 1 <sup>[1]</sup> | Alloy 2 <sup>[2]</sup> |
|------------------------|------------------------|------------------------|
| Yield strength (MPa)   | 1164                   | ~762                   |
| Tensile strength (MPa) | 1411                   | ~870                   |
| Elongation (%)         | 24.3                   | ~42.5                  |

[1] Alloy 1 datasheet, appendix A; [2] Granta Edupack, 2021

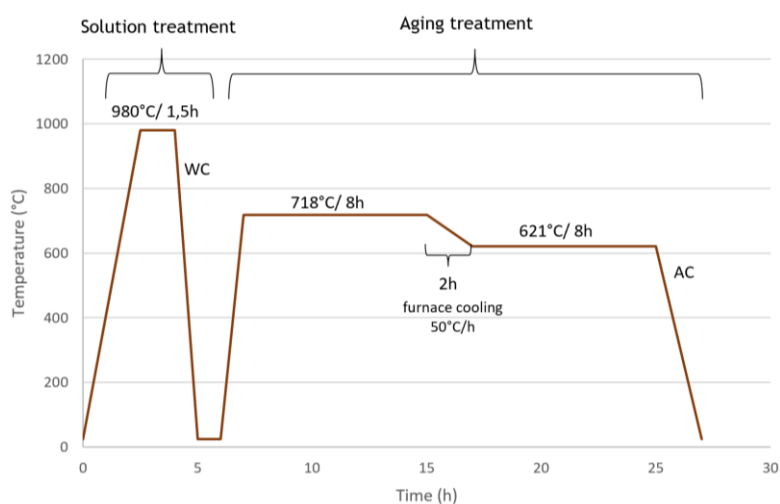


Figure 4.1 - Heat treatment stages of IN 718.

## 4.2 Material characterization tests

### 4.2.1 Chemical composition

The IN718 alloy was supplied in the form of a rod with a length of 500mm. The chemical composition was evaluated by arc/spark optical emission spectrometry (OES) at INEGI's metallographic laboratory using a spark emission spectroscopy, the *SPECTROMAXx* metal analyser equipment. This evaluation enabled the comparison/verification of the material standards for each alloying element. In Table 4.2 is displayed the minimum and maximum quantities of each Inconel 718 alloying element, according to ASTM B637 standard.

Table 4.2 - Chemical composition of Inconel 718 (wt %) according to ASTM B637.

| Element | Ni    | Fe        | Cr    | Nb   | Mo   | Ti   | Al   | Mn   | Si   | Co   |
|---------|-------|-----------|-------|------|------|------|------|------|------|------|
| Min     | 50.00 | remainder | 17.00 | 4.75 | 2.80 | 0.65 | 0.20 | ---  | ---  | ---  |
| Max     | 55.00 | ---       | 21.00 | 5.50 | 3.30 | 1.15 | 0.80 | 0.35 | 0.35 | 1.00 |

### 4.2.2 Microstructure analyses

Samples were submitted to microscopic examination after oxalic acid dihydrate etching which was used to highlight microstructural features in the samples. Firstly, samples were polished and then observed through a metallurgical microscope PMG3, from OLYMPUS, at INEGI's metallographic laboratory.

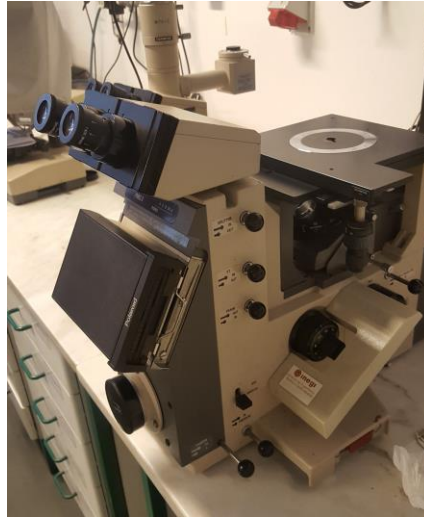


Figure 4.2 - Optical microscope OLYMPUS PMG3 [96].

#### 4.2.3 Hardness

Hardness measurements were conducted for both alloys according to ISO 6508 at INEGI's metallographic laboratory using a hardness tester *Emco M4U-075*, see Figure 4.3. Three repetitions were performed on each sample. Alloy 1 is expected to have the highest hardness of the two alloys given that it was submitted to aging heat treatment.

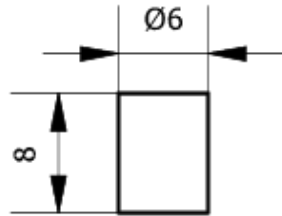


Figure 4.3 - EMCO Test M4U-075 hardness measurement machine.

#### 4.2.4 Uniaxial compression tests

Uniaxial compression tests are typically employed in order to obtain the stress-strain material response within relatively high levels of strain, which is quite relevant given the need to portray material behaviour under extreme deformation levels. Compression tests in quasi-static conditions at room temperature were performed. Given the high mechanical strength of

the alloys, small specimens ( $\varnothing 6 \times 8$  mm cylinders, as illustrated in Figure 4.4-a)) were machined in order to make cylindrical test specimens shown in Figure 4.4-b). Test specimens are recommended to be in the form of solid circular cylinders, with an appropriate height-to-diameter ratio in order to avoid buckling which may happen for slender specimens.



a)



b)

Figure 4.4 -a) specimens dimensions; b) specimens before compression.

These cylindrical test specimens were placed in a compression electromechanical testing machine (INSTRON 5900R) with force and displacement being acquired by a load cell connected to a computer. Five tests were conducted at a quasi-static speed of 1mm/min and the stopping criteria was a maximum displacement of 4.5 mm.

Test specimens were placed in the testing machine between two tungsten carbide parallel plates, which were lubricated using a thin film of graphite grease. The compression tests were made according to the following procedure:

- Specimens top and bottom polishing to reduce friction;
- Initial specimen diameter and height measurements;
- Placing the compression test specimen on the compression system;
- Compression test and data acquisition.

### 4.3 Turning tests

On this section the details of turning tests will be described including a brief description of the assessed turning inserts, experimental setup and test matrix. Given that the main goal of these turning tests is to evaluate both the IN718 machinability and tool performance, measurement of turning forces, tool wear and cutting inserts analysis through SEM /EDS were performed.

### 4.3.1 Turning inserts

Cutting tools can significantly influence a given machining operation. In this research work, two cutting tools were selected within Palbit's wide range of turning inserts. The chosen cutting inserts, grade PBY603 and PBY602, had 50% of CBN content (low-content CBN inserts, as revised in section 2.2.1) and were coated through PVD (physical vapor deposition) with a TiCN/AlTiN/TiN compound. Both inserts had the same negative  $80^\circ$  rhombic shape cutting insert and a honed edge preparation of 0.020mm of radius which was measured (for thorough control of cutting conditions) using the *Brucker Alicona* apparatus based on 3D optical measurement technology (at Palbit S.A.), as shown in figure Figure 4.5. Full tool edge measurement report is displayed in Appendix B.

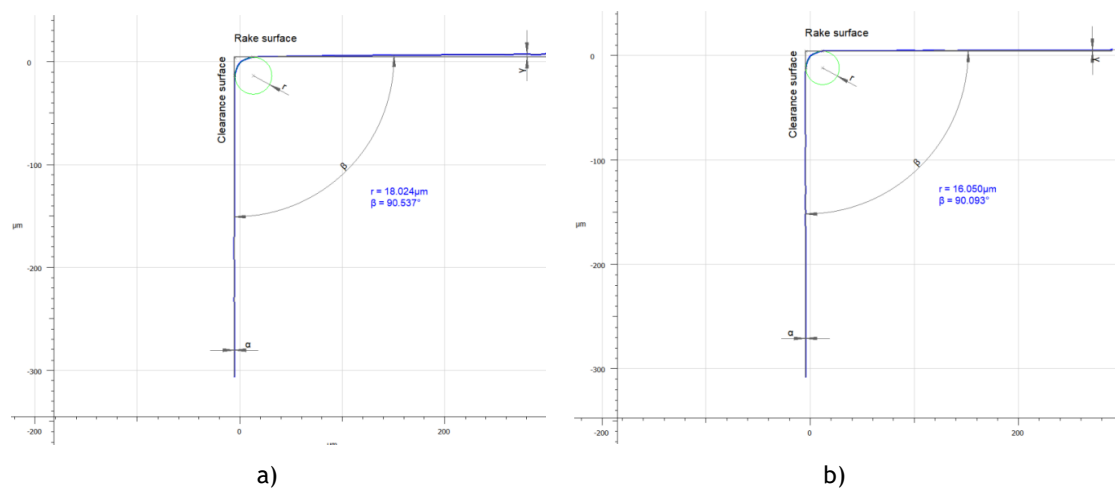


Figure 4.5 - Edge radius measurement: a) tool 603; b) tool 602.

These tools have a CBN tip brazed directly to the host carbide insert. Due to availability and operational reasons, the brazed tip geometry differs depending on the insert grade: PBY603 insert has a standard tip while PBY602 insert has a larger CBN mass that runs from top to bottom instead of just a small tip, highlighted in Figure 4.6. This innovative tip has a brazing contact area increased by around 150% and it is expected to tolerate higher temperatures and reduce the risk of edge chipping or braze damage. Nevertheless, the parametric geometry of the tool is the same in both configurations.

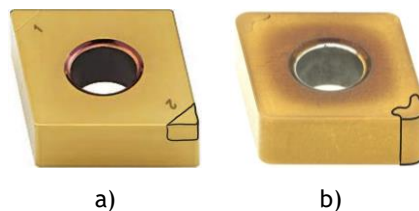


Figure 4.6 - Brazed tip geometry: a) PBY603; b) PBY602.

Both inserts have a medium grain size but their ceramic binders are different: grade PBY603 having a titanium carbide (TiC) whereas PBY602 a titanium nitride (TiN). These grades are recommended for continuously and lightly interrupted cutting of hardened steel, finishing abrasive high strength cast irons and can also be used to machine heat-resistant superalloys. Through the practical results section these two cutting inserts grades, PBY603 and PBY602, will be referred as 603 and 602, respectively. Cutting inserts geometrical features are displayed in Figure 4.7.

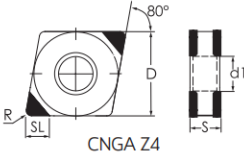
|  |       |        |                 | Dimensions (mm) |      |      |      |      |
|-----------------------------------------------------------------------------------|-------|--------|-----------------|-----------------|------|------|------|------|
| Grade                                                                             | % CBN | Binder | ISO Reference   | D               | S    | R    | d1   | SL   |
| <b>PBY603</b>                                                                     | 50    | TiC    | CNGA 120408- Z4 | 12.70           | 4.76 | 0.80 | 5.16 | 2.40 |
| <b>PBY602</b>                                                                     | 50    | TiN    | CNGA 120412- Z4 | 12.70           | 4.76 | 1.20 | 5.16 | 2.00 |

Figure 4.7 - Inserts grade PBY603 and PBY602 technical data.

#### 4.3.2 Experimental setup

The longitudinal cylindrical tests provide a precise comparison to real life machining operations. The turning specimens ( $\varnothing 50 \times 120$ ) were tested on a INTEGREX i-200ST multi-tasking machine from MAZAK at Palbit SA. Load measurement during cutting was accomplished through a piezoelectric dynamometer (Kistler 9129A) and a multi-channel charge amplifier (Kistler 5070A), which converted electric signals (pC) from the dynamometer to proportional tension (V) signals. The signal from the charge amplifier was then collected by a data acquisition system (Kistler 5697A) and Kistler *Dynoware* software which allowed signal conversion and data collection. Besides cutting forces acquisition, tool flank wear measurements and image collection of rake and flank face were made with a *DinoLite* digital microscope. The schematic representation of the experimental setup is shown in Figure 4.8. SEM images were taken and a spectroscopy analysis was also made. The SEM / EDS exam was performed using a high resolution (Schottky) Environmental Scanning Electron Microscope with X-Ray Microanalysis and Electron Backscattered Diffraction analysis: FEI Quanta 400 FEG ESEM / EDAX Genesis X4M.

Figure 4.8-a) shows a schematic representation of the tool holder and cutting angles which is clamped to the dynamometer. An ISO DCLNL 2525M 12 tool holder with a cutting edge angle of  $95^\circ$ , radial rake angle of  $-6.5^\circ$  and an axial rake angle of  $-6.5^\circ$  suitable for ISO CNGA inserts was used in turning experiments. The tool holder was installed in a dynamometer which measured force at sampling rate of 1000Hz in 3 three components,  $F_x$ ,  $F_y$  and  $F_z$  which corresponded to the passive force, cutting force and feed force, respectively. Lubrication is

guided into the rake face and cutting edge through internal holes on this tool holder at a pressure of 3.7 MPa.

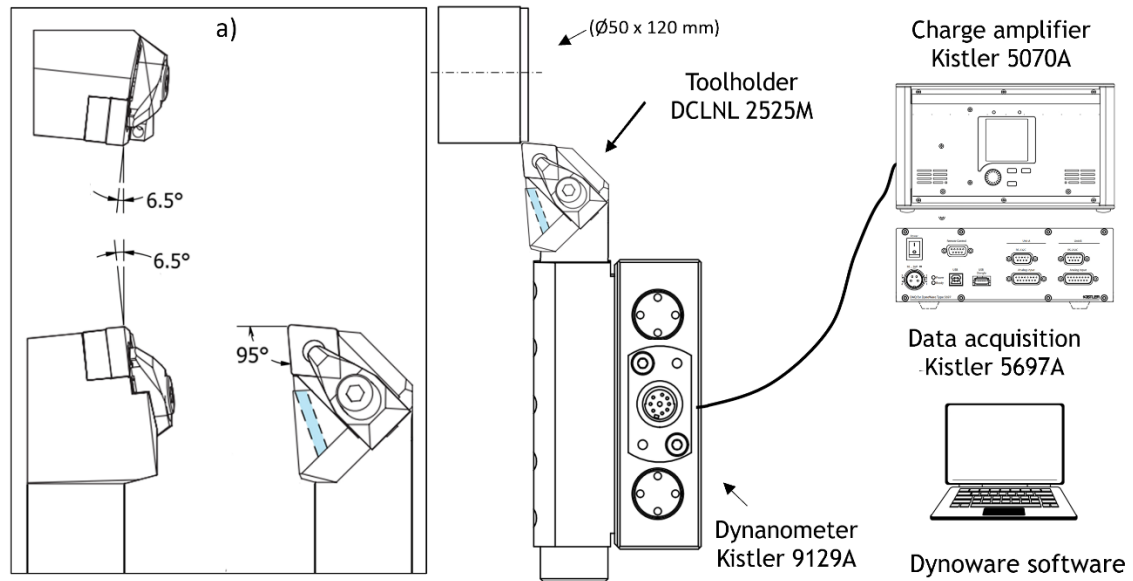


Figure 4.8 - Experimental setup diagram: a) detailed view of tool holder angles.

Running each experimental test on the same starting condition is highly crucial, so in order to homogenize surface conditions in each cylindrical specimen cut from the initial rod, a preliminary turning and facing operation was performed with cemented carbide tools. The turning operation goal was to eliminate an outer layer that may have small surface defects and dimensional inaccuracy, thus achieving a precise specimen diameter of 50mm. Additionally, the facing operation resulted in a smoother tool entrance surface on each pass. In Figure 4.9 the before and after pictures of this initial operation are shown.

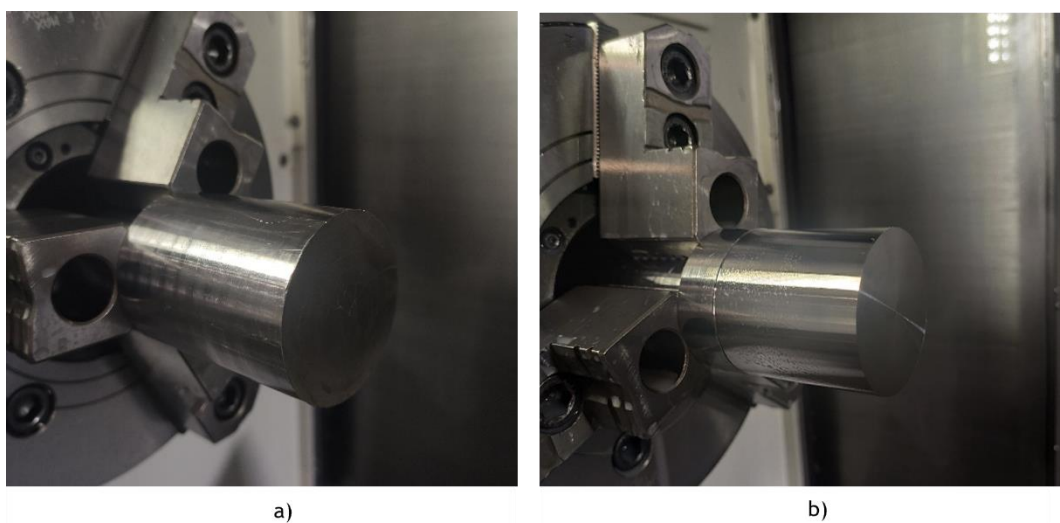


Figure 4.9 - Before (a) and after (b) preliminary turning and facing operations.

The specimens had a free length of 55 mm where successive turning passes were made. All turning tests were performed on the experimental setup schematized on Figure 4.8 according to the following procedure:

1. Place turning insert on tool holder;
2. Zero data acquisition system with the lathe is fully stopped;
3. Start turning test while acquiring data;
4. Stop test, tool inspection and flank wear measurement with digital microscope;
5. Sample of produced chip collection;
6. Repeat steps 1 to 4 until a flank wear of 0.2mm is reached or 5 minutes of machining time have passed.

A summary of the configuration of tested cutting parameters is presented in Table 4.3. According to literature, experimental tests usually vary cutting speed ( $v_c$ ) from 150 to 400 m/s, so five cutting speed levels within this range were selected. A feed ( $f$ ) of 0.1 and 0.2 mm/rev and a cutting depth ( $a_p$ ) of 0.15 mm were selected for the experimental runs. This combination of cutting conditions results in a matrix of 10 tests for each tool grade summing up 20 different experimental runs for alloy 1. Alloy 2 experiments will follow the same matrix although only insert 603 will be tested on this material, meaning a total of 10 different experimental runs for that alloy. A virgin tool was used for each cutting parameter tested. Complete turning tests matrix can be found on Appendix C. After this test matrix was completed further tests were performed towards a better comparison of the two inserts.

*Table 4.3 - Summary of turning test cutting parameters.*

| Exp. Number | $a_p$ [mm] | $f$ [mm/rev] | $v_c$ [m/min] |
|-------------|------------|--------------|---------------|
| 1           | 0.15       | 0.1          | 150           |
| 2           |            |              | 200           |
| 3           |            |              | 250           |
| 4           |            |              | 300           |
| 5           |            |              | 350           |
| 6           | 0.15       | 0.2          | 150           |
| 7           |            |              | 200           |
| 8           |            |              | 250           |
| 9           |            |              | 300           |
| 10          |            |              | 350           |

Literature reviewed pointed out that the use of TiN and TiC binders provided greater wear resistance to PCBN tools due to its superior heat resistant and chemical stability, so this was further investigated by employing a second test matrix, displayed in Table 4.4, allowing to compare insert 603 (TiC binder) and insert 602 (TiN binder). Tests were performed, on alloy 1,

with insert 602 and 603 with constant cutting speed, feed and depth of cut of 250 m/min, 0.1 mm/rev and 0.15 mm, respectively. Due to the limited amount of insert 602, tests were performed only with insert 603 for alloy 2 with the same conditions above mentioned. This cutting operation was repeated three times, with a virgin tool for each time, and every test had a cutting time of approximately 1.5 min and then VB was measured, SEM images were taken, and a spectroscopy analysis was also made. This allowed the comparison of insert 602 with 603 for alloy 1, and the machinability of alloy 1 and alloy 2 using insert 603.

*Table 4.4-Secondary test matrix.*

| $a_p$ [mm] | $f$ [mm/rev] | $v_c$ [m/min] | Insert | Alloy | Repetition |
|------------|--------------|---------------|--------|-------|------------|
| 0.15       | 0.1          | 250           | 603    | 1     | 3x         |
|            |              |               | 602    | 1     | 3x         |
|            |              |               | 603    | 2     | 3x         |

# Chapter 5

## Results and discussion

### 5.1 Introduction

This section focuses on presenting the results of the previously described material characterization and experimental turning tests. The experimental setup installed on the lathe allowed for load acquisition and tool wear measurement.

### 5.2 Material characterization tests

#### 5.2.1 Chemical composition

The chemical composition analysis enabled the comparison with material standards and verified that both alloys chemical composition is within the range established by the standard.

*Table 5.1 - Chemical composition (wt %) of alloy 1 and alloy 2.*

| Element | Ni    | Fe    | Cr    | Nb   | Mo   | Ti   | Al    | W     | Si    | Co    |
|---------|-------|-------|-------|------|------|------|-------|-------|-------|-------|
| Alloy 1 | 52.70 | 19.06 | 18.43 | 4.73 | 3.00 | 1.02 | 0.541 | 0.114 | 0.114 | 0.109 |
| Alloy 2 | 53.20 | 18.58 | 18.39 | 4.67 | 3.00 | 1.03 | 0.524 | 0.103 | 0.090 | 0.200 |
| Min     | 50.00 | rem.  | 17.00 | 4.75 | 2.80 | 0.65 | 0.20  | ---   | ---   | ---   |
| Max     | 55.00 | ---   | 21.00 | 5.50 | 3.30 | 1.15 | 0.80  | 0.35  | 0.35  | 1.00  |

### 5.2.2 Microstructure analysis

Oxalic acid chemical etching enabled the visualisation of different phases and grain structures as shown in Figure 5.1 and Figure 5.2. Even though no highly significant differences can be found, extremely fine precipitates along the matrix are expected in the aged IN718, which are responsible for the notorious hardness improvement [97].

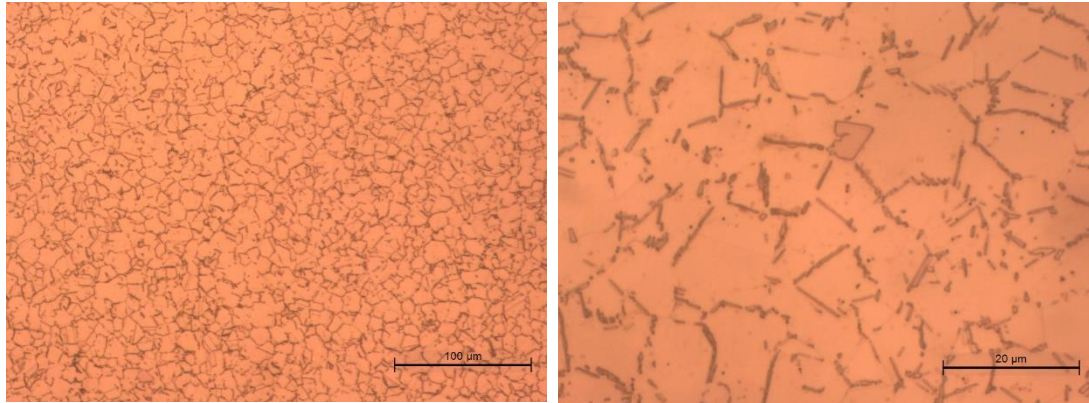


Figure 5.1 - Optical microscopy images of the microstructure (chemically etched) of alloy 1.

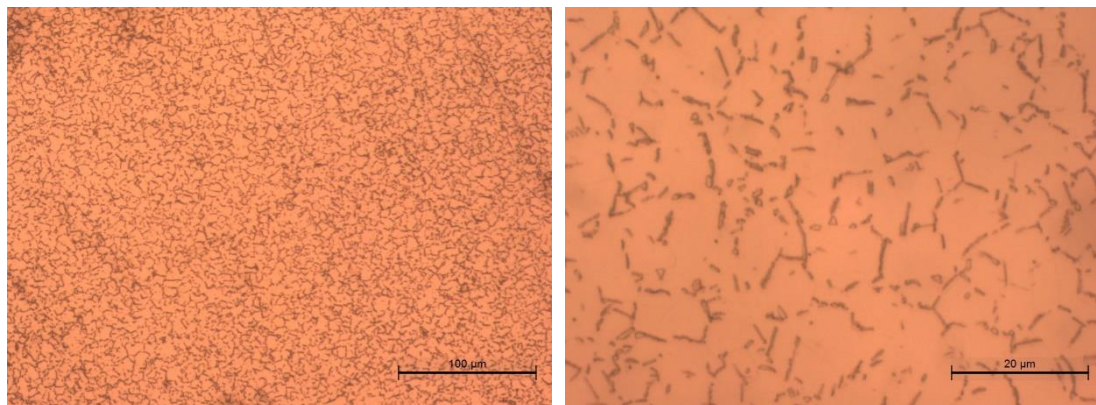


Figure 5.2 - Optical microscopy images of the microstructure (chemically etched) of alloy 2.

### 5.2.3 Hardness

Hardness measurements confirmed the much higher hardness (>double) of the aged IN718 (alloy 1), when compared to the annealed condition. Table 5.2 shows the measured values for both materials. As will be further analysed in Section 5.2.4, these results are consistent with the mechanical strength obtained from compression testing.

Table 5.2 - Hardness (HRC) of supplied alloys.

|         | #1   | #2   | #3   | Average |
|---------|------|------|------|---------|
| Alloy 1 | 44.0 | 44.2 | 44.0 | 44.1    |
| Alloy 2 | 20.0 | 20.5 | 19.0 | 19.8    |

#### 5.2.4 Compression testing

Specimens were placed in the testing machine between two tungsten carbide parallel plates as shown in Figure 5.3 a). After testing, all the specimens exhibited round lateral edges and cracks at the external surface, as seen in Figure 5.3 c). If ideal frictionless conditions had taken place during the test no round lateral edges were visible as the specimen would experience a homogenous deformation.

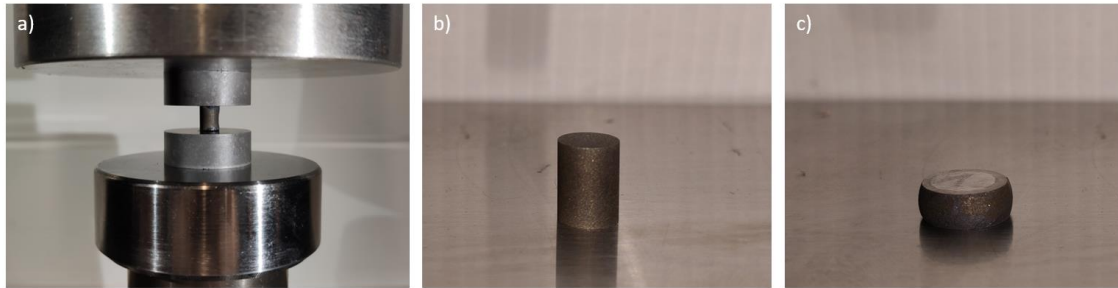


Figure 5.3 - a) Test specimen inside compression system; b) test specimen before compression; c) test specimen after compression.

At Figure 5.4-a) and Figure 5.5-a) are shown the force-displacement curves before data treatment, of each alloy, which had an excellent repeatability on the specimens from the first material. Figure 5.4-b) and Figure 5.5-b) display true stress-strain curves obtained for the tested specimens, although it is important to note that the machine stiffness correction was also performed.

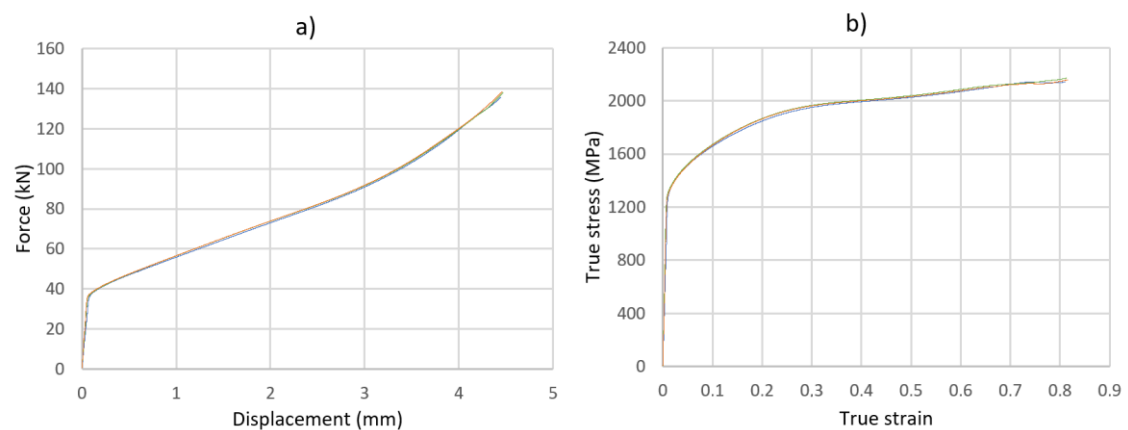


Figure 5.4 - Alloy 1 compression test results: a) force-displacement curves; b) true stress-strain curves.

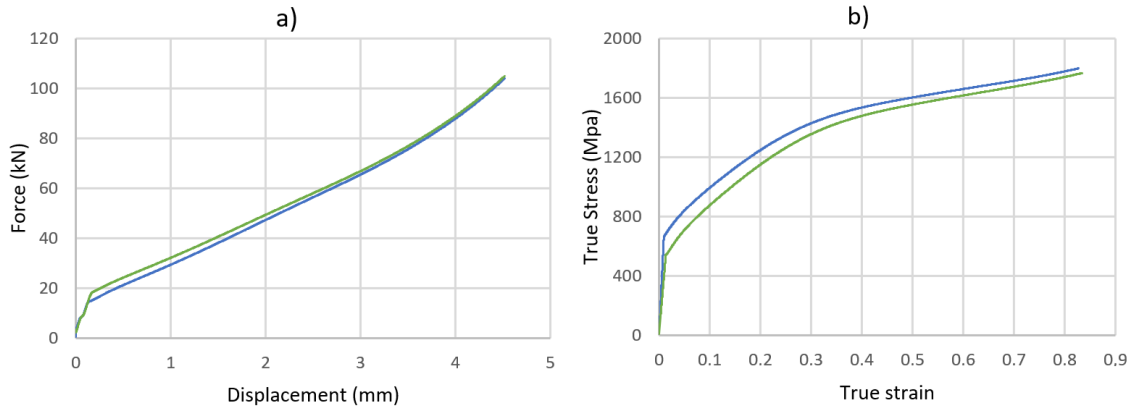


Figure 5.5 - Alloy 2 compression test results: a) force-displacement curves; b) true stress-strain curves

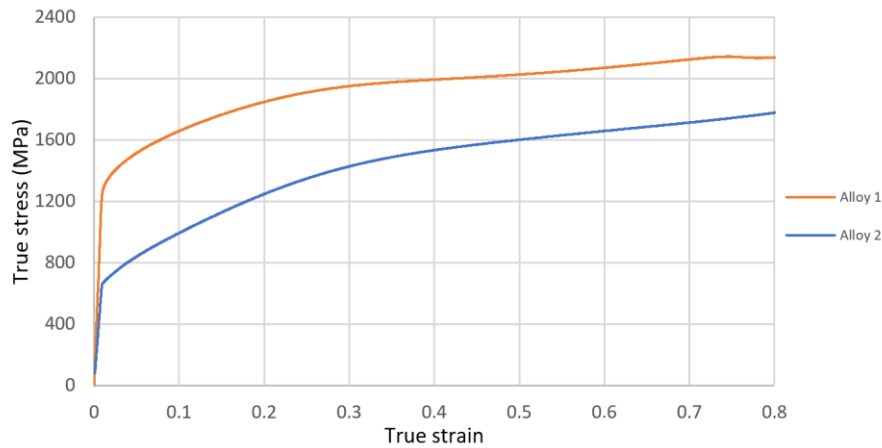


Figure 5.6 - Comparison between true stress-strain curves.

Figure 5.6 enables the comparison of the compression behaviour the two considered alloys. As expected, the alloy 1 (age-treated) presents a much higher yield strength. In accordance with hardness results, alloy 2 (annealed) has approximatively half of the yield strength of alloy 1. Also, interesting to note is their distinct work-hardening behaviours. Alloy 2 presents a notoriously higher work hardening, meaning that for higher strains its flow stress tends to come closer to alloy 1. This may be an important fact to take into consideration, given the typically high strains of metal cutting, indicating that the cutting loads of alloy 1 and 2 may be close.

The expected mechanical properties of the alloys indicate a smaller elongation (24.3%) of alloy 1, when compared to alloy 2 (42.5%). This data, obtained by quasi-static tensile testing at room temperatures, illustrates the typical strength-ductility ratio of metallic materials.

A limitation of the conducted testing procedure is associated to the friction effect for higher strains. Also, as previously mentioned, the occurrence of small cracks on the barrelling surfaces of the specimens indicate fracture signals, which limit the usage of the identified high-strain

data for modelling purposes. As will be further shown (in Section 6.2), material behaviour calibration was carefully performed.

### 5.3 Turning results and discussion

#### 5.3.1 Cutting forces

Figure 5.7-b) shows the as-recorded cutting force data. Given that the available cutting length of the workpiece was of 55 mm, 3 (in this case) sequential cuts (using the same parameters) were performed. Figure 5.7-a) presents a single passage, where distinct stages can be noticed. On the first stage (I) force noise is coming from the lath since the spindle is already rotating but the cutting tool is motionless whereas on the second zone (II) the cutting tool starts its movement to enter the workpiece and start cutting. This second stage is characterized by a suddenly increase in forces which stabilize less than half a second later into the cutting stage itself (III). This third zone corresponds to valid results that can be analysed. The last stage (IV) is characterized by a peak in force possibly due to inertial effects and occasional chip tangling and winding around the workpiece.

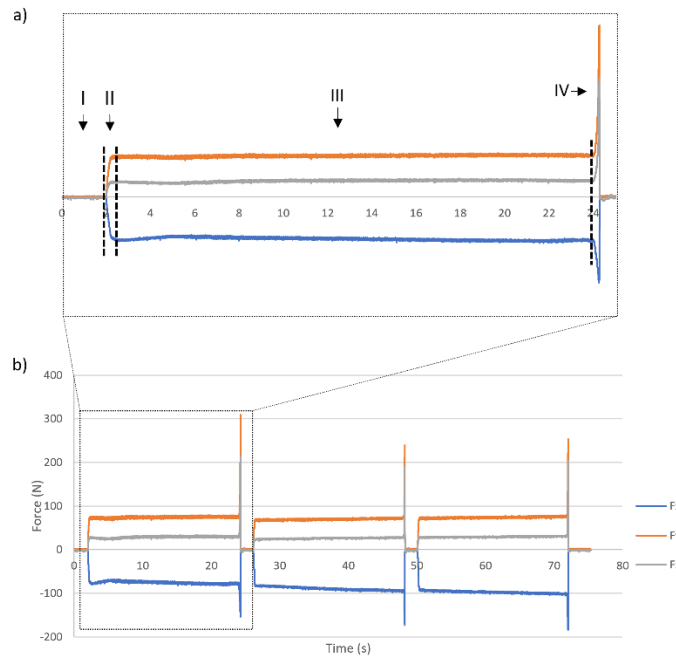


Figure 5.7 - Load spectrum of the Inconel 718 turning operation with cutting tool 603,  $v_c=200\text{m/min}$ ,  $f=0.10\text{ mm/rev}$  and  $a_p=0.15\text{ mm}$ .

After processing, where region III data was the only one considered for each pass, subsequent results are presented in Figure 5.8 and Figure 5.9. Regarding loads all three force components are exhibited, for each combination of cutting parameters. Considering the

temporal length of cutting tests and the great amount of data originated from these experiments it was chosen to additionally show the minimum and maximum force values as well the average values, with the goal of giving a clear vision of force evolution during turning tests. In addition to the results above mentioned, forces on the first cutting pass (i.e., initial forces) will also be displayed since these have less tool wear effect and will be used later for calculating specific cutting pressures and comparison with the simulated ones.

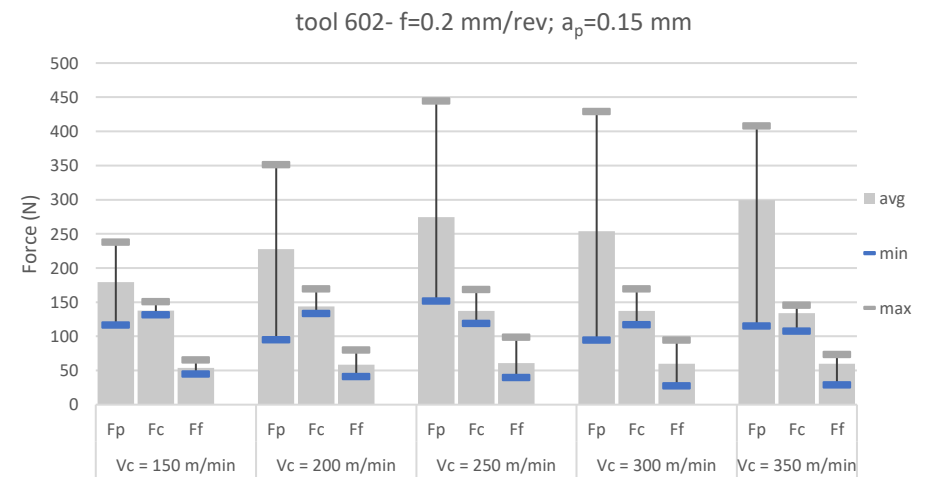
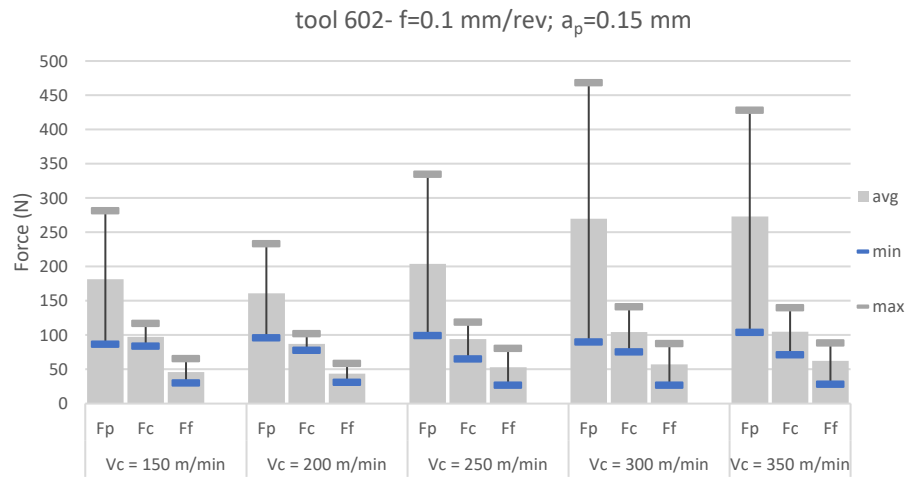
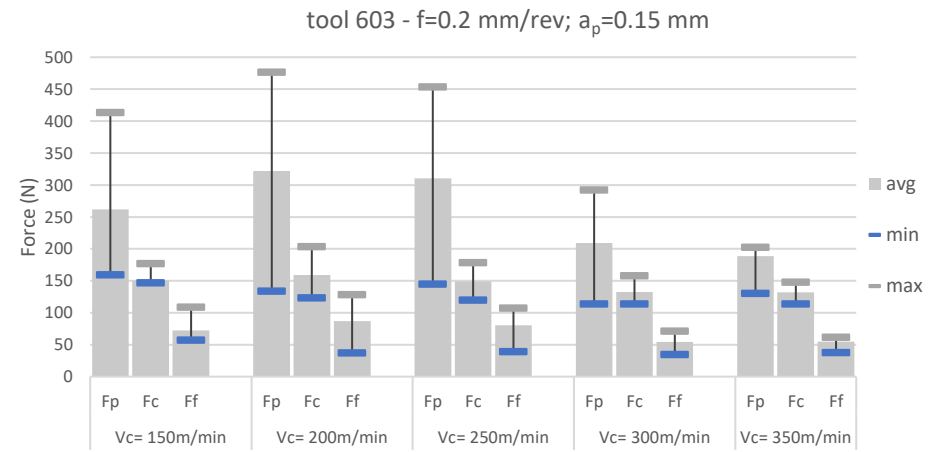
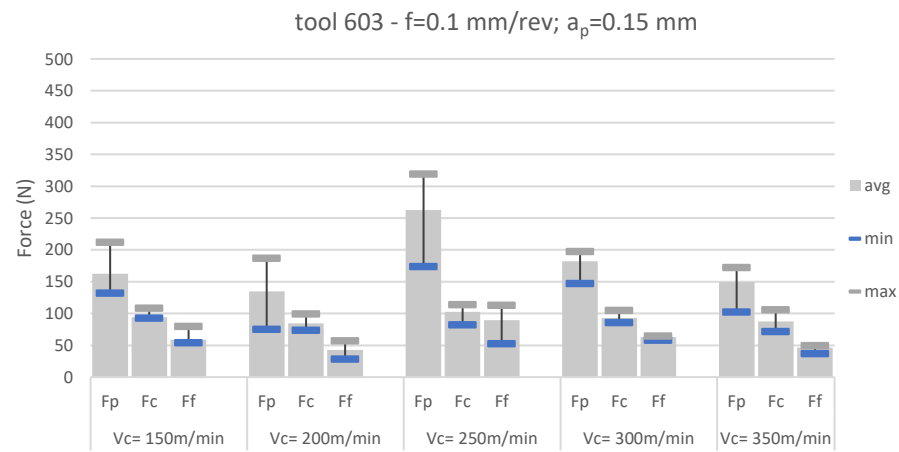


Figure 5.8 - Cutting loads results from various tests on Inconel 718 - alloy 1.

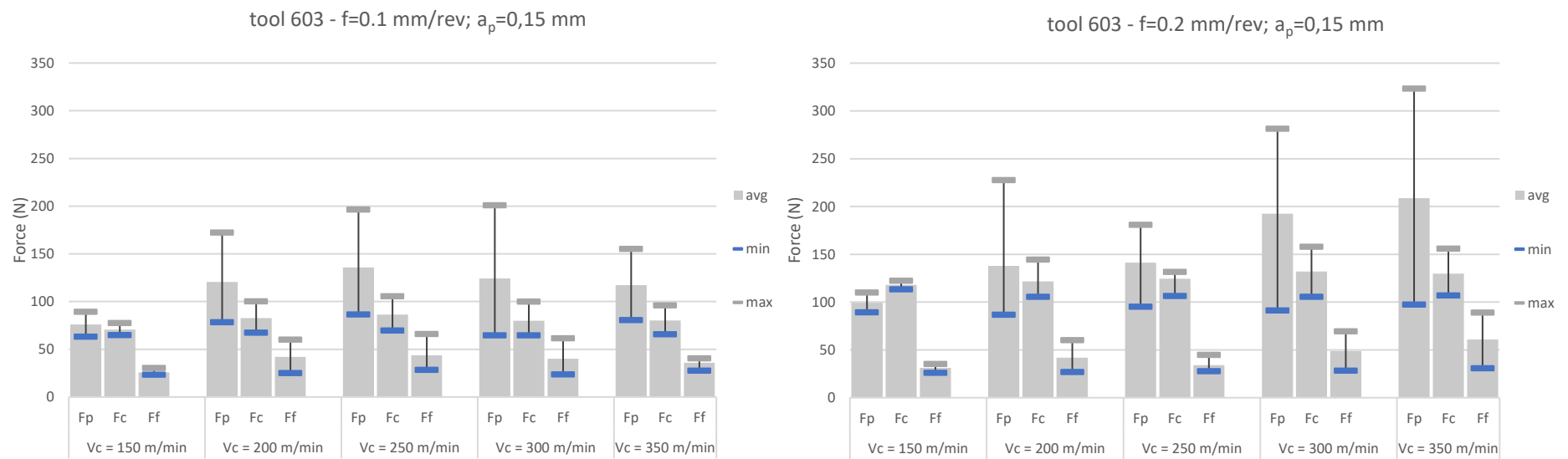


Figure 5.9 - Cutting loads results from various tests on Inconel 718 - alloy 2.

Figure 5.8 and Figure 5.9 display the results from the turning tests involving alloy 1 and 2, respectively. These figures allow to perceive force evolution during the experimental tests. The initial force values, which are minimum due to insignificant tool wear, are represented by *min* while *max* value symbolizes the last pass force values which are maximum due to tool degradation. Average force values over the entire test are represented by *avg*.

Overall, passive force component ( $F_p$ ) achieved the highest values followed by the cutting force ( $F_c$ ) and feed force ( $F_f$ ) in descending order, which is consistent with literature review, as usually when the depth of cut is smaller than the nose radius of the tool, passive or radial component of tool forces is found most dominant [19, 20, 24, 32, 98]. Moreover, passive force had significant evolution over time amounting to often triple and even quadruple the initial (virgin tool) value, when reaching at the end of tool life. Monitoring the evolution of this force can give relevant information about tool wear evolution. The aforementioned force appears to be highly sensitive to the evolution of tool wear and degradation of tool edge surface which is a tendency also observed in literature [19, 32, 99]. Also, the passive force seems to be associated to the ploughing force which is caused by the flow of material ploughed by the clearance face of the tool due to the elastic deformation of the workpiece material under the clearance surface [32].

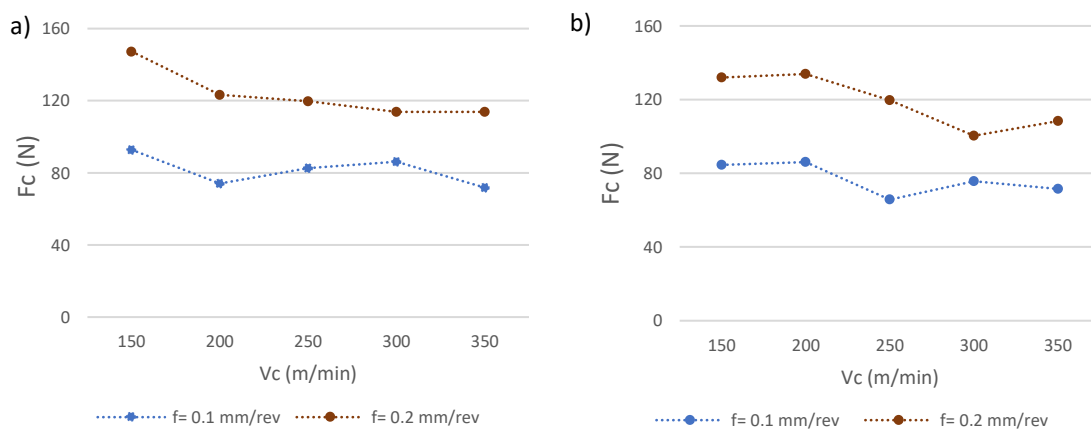


Figure 5.10 - Measured initial cutting forces ( $F_c$ ) for alloy 1: a) tool 603; b) tool 602.

Figure 5.10 shows the cutting forces obtained on the first pass on alloy 1, for each tool and feed. As expected, the force is higher when the feed is higher for both tools and there is no significant difference on cutting forces between insert 603 and 602 given that the measured values of force oscillate around 120 N when machining with a feed of 0.2 mm/rev and 80 N with a feed of 0.1 mm/rev, for alloy 1.

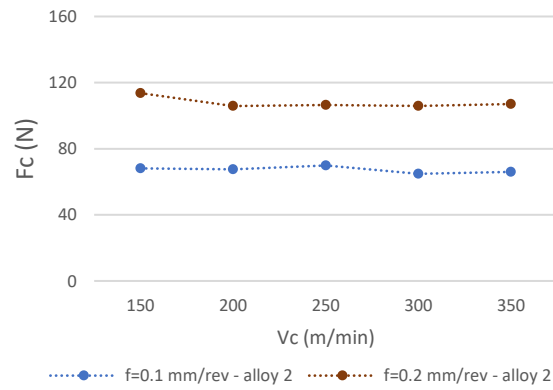


Figure 5.11 - Measured initial cutting forces ( $F_c$ ): tool 603, alloy 2.

When machining the softer material, i.e., alloy 2, cutting force values shown at Figure 5.11, oscillated around 105 N for a feed of 0.2 mm/rev and 70 N for a feed of 0.1 mm/rev. Again, maintaining depth of cut and increasing feed results in higher chip cross sectional area along with higher cutting forces. Regarding alloy 1 varying the feed from 0.1 mm/rev to 0.2 mm/rev when cutting with 603 inserts resulted in average increase of 52.1% in cutting forces while in the same conditions an increase of 55.5% was observed when machining the same alloy with 602 inserts. No relevant change in cutting forces was found when machining the later alloy with inserts 603 and 602, as expected since its cutting edge geometry is the same despite the larger nose radius on the 602 insert. Alloy 2 revealed less variation on the cutting force given that varying the feed from 0.1 mm/rev to 0.2 mm/rev increased cutting forces by an average 37.5% against 52.1% observed on alloy 1 when testing the same insert type (tool 603). This may indicate that this alloy is less sensitive to the hardening/softening compromise, promoted by the high strain rates and temperatures, typical of metal cutting.

Figure 5.12 shows the experimental correlation of the passive force,  $F_p$ , and feed force,  $F_f$ , with the cutting force,  $F_c$  for both alloy 1 and 2 using 603 inserts. Despite the differences in feed and passive forces, both forces experience the same behaviour when subjected to increasing cutting forces. Passive force, on both materials, had a perceptible increase when cutting forces increased whereas the feed force also increased but in a more discreet way.

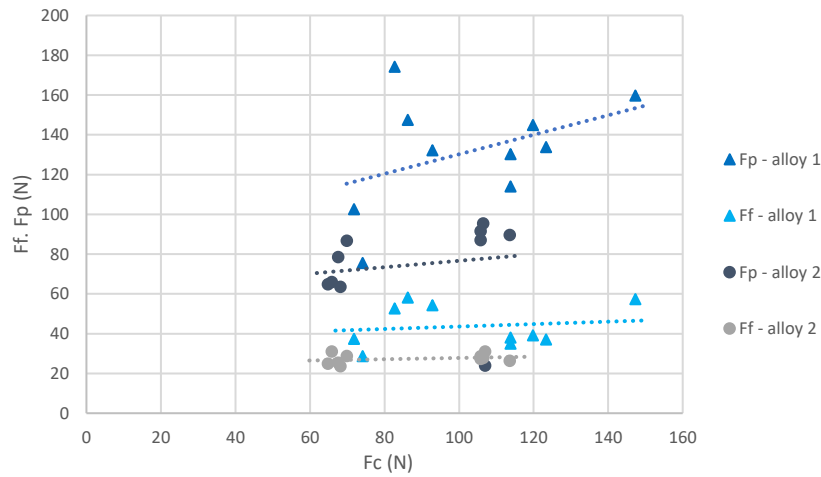


Figure 5.12 - Experimental correlation of the thrust force,  $F_p$ , and feed force,  $F_f$ , with the cutting force,  $F_c$  for both alloy 1 and 2 using 603 inserts.

Figure 5.13 displays a comparison between the cutting forces obtained for the two machined alloys with insert 603 at a constant depth of cut of 0.15 mm. When compared to alloy 1, alloy 2 obtained, on average, 16.8% and 12.3% lower cutting forces for a feed of 0.1 and 0.2 mm/rev, respectively. During compression testing alloy 2 demonstrated about half of the yield strength of alloy 1, although to the considerably higher work hardening of alloy 2, the difference in flow stress ended up on approximately 20% for a strain of 0.8, thus explaining the comparable (~ 16% difference) cutting forces of alloy 1 and 2 for the same operative conditions.

Given that metal cutting is a process characterized by intense plastic deformation, high strain rates and temperatures, it is though that the variation of stress at higher strains, between the two materials, seemed to give a better approximation of cutting forces differences than by judging only for the differences in the yield strength.

Cutting forces proved to have a slightly decreasing tendency when increasing cutting speed, as the cutting speed increase leads to more energy involved on the process and lower heat diffusion, therefore increasing temperature resulting in thermal softening of the workpiece material.

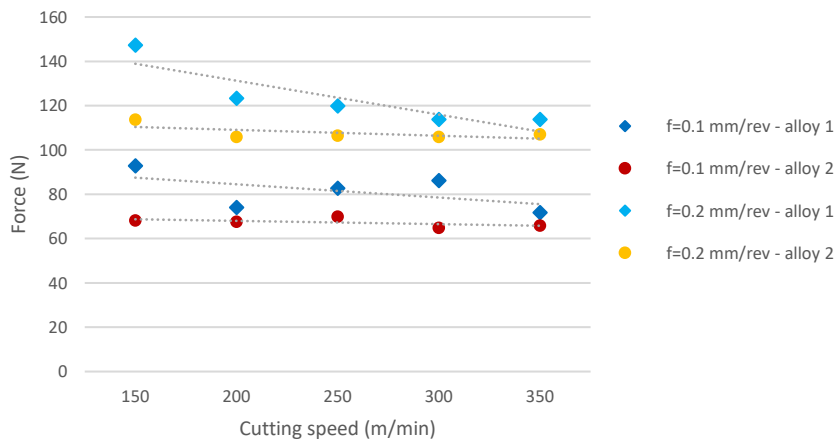


Figure 5.13 - Comparison between cutting forces for the two machined alloys with insert 603 at a constant  $a_p$  0.15mm.

### 5.3.2 Specific cutting pressure

Specific cutting pressure,  $K_c$ , is a parameter that can be used to evaluate the material machinability and can be used to estimate the cutting force. Specific cutting pressure can be defined as the ratio between the main cutting force  $F_c$  and cross-section area of an undeformed chip,  $A$ . The cross-section area of undeformed chip can be calculated through equation 5.1:

$$A = a_p \cdot f \quad 5.1$$

And the specific cutting pressure,  $K_c$ , can be calculated using equation 5.2:

$$K_c = \frac{F_c}{A} \quad 5.2$$

Turning tests only focused on two different chip cross-sectional area with the highest values of cutting pressure being achieved for the lowest feed which corresponded to the lower chip section, explained by the size effect in metal cutting. Typically,  $K_c$  exponentially increases for smaller chip section, while stabilizing when increasing chip section which is a phenomenon associated with size effects in metal cutting, as observed by other authors [32, 100, 101]. The occurrence of defects in metals, such as grain boundaries or missing atoms, is generally acknowledged and the chance of encountering those stress-reducing defects increases for bigger sizes of removed material [101]. Also explaining the size effect, is the occurrence of ploughing for increasingly smaller feed rates. When the uncut chip thickness becomes smaller, or similar, to the tool edge radius cutting loads do not decrease proportionally due to the considerable relative contribution of workpiece deformation (compression), leading to higher  $K_c$  values.  $K_c$  values between 4000 - 5500 N/mm<sup>2</sup> and between 3500 - 4500 N/mm<sup>2</sup> were obtained when machining alloy 1 and alloy 2, respectively, which are typical values for Inconel 718 turning processes with negative rake angles, inducing high values of specific cutting forces.

Figure 5.14 displays the average  $K_c$  values obtained for each combination of tool and material, plus the  $K_c$  value obtained by Cantero et al. [32] when turning Inconel 718, with similar hardness to alloy 1, at a cutting speed of 300 m/min using Kennametal grade KB5625 PCBN insert, which has medium-CBN content and ceramic binder, with a similar edge preparation to the tested tool on this work.

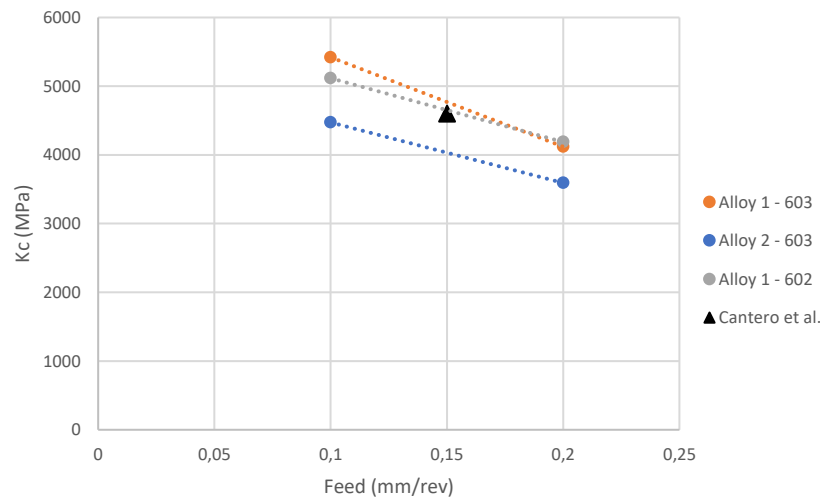


Figure 5.14 - Average  $K_c$  values obtained for each combination of tool and material.

Figure 5.15 shows specific cutting pressure for each experimental run. Lower feed values led to higher  $K_c$  as explained before. This figure allows to understand that values have significantly less scatter when machining alloy 2.

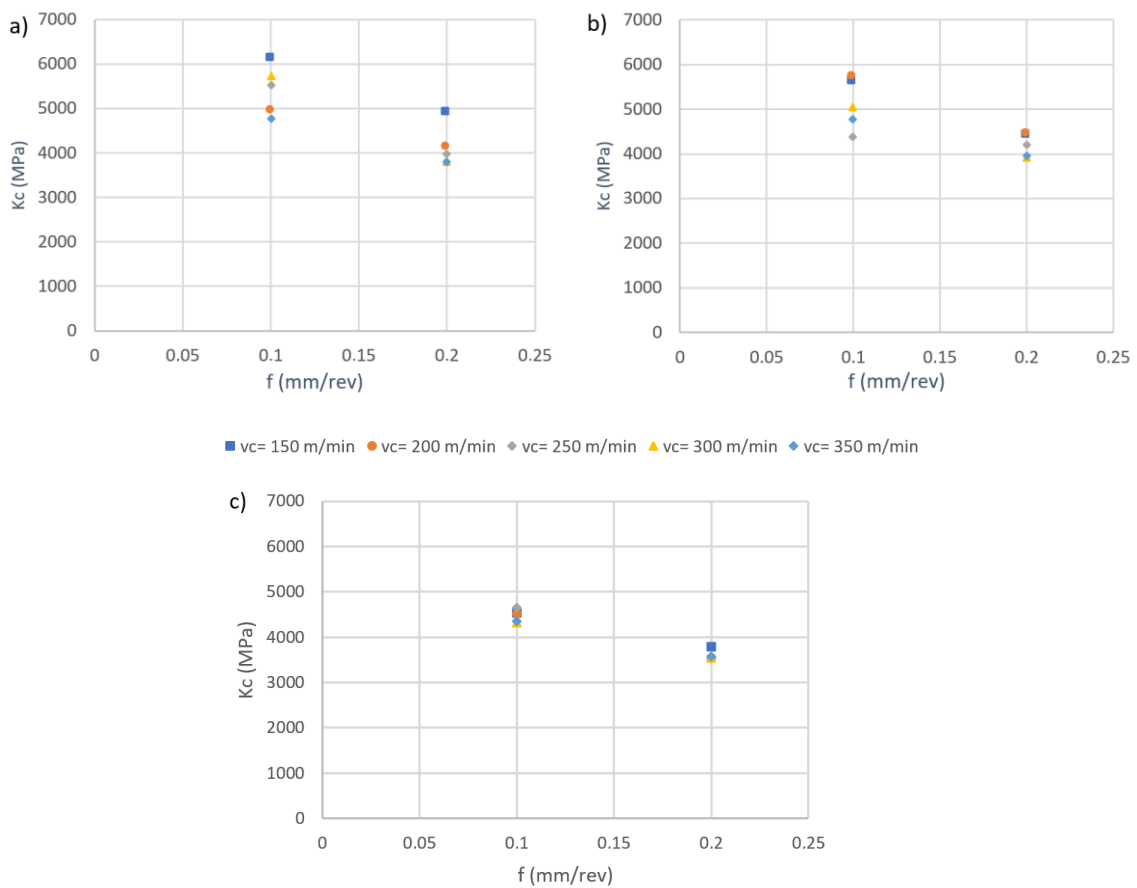


Figure 5.15 -Specific cutting pressure: a) tool 603, alloy 1; b) tool 602, alloy 1; c) tool 603, alloy 2.

### 5.3.3 Tool wear

Tool wear is an inevitable, gradual and complex phenomenon affecting workpiece surface accuracy and integrity and contributing to the cost of the machining process. It occurs due to geometrical damage, frictional force and temperature rise at the tool-workpiece interface region. Studying the influence of cutting parameters and its effect on tool wear allows to optimize the process achieving both better results on the final product and on the economical side of the operation.

In order to establish tool flank wear progression depending on machining time, wear data was acquired approximately every 30 to 60 seconds of machining time. To do so the test was stopped and flank wear ( $VB_{max}$  and  $VB_{notch}$ ) was measured according to ISO 3685.  $VB_{max}$  will just be referred to as VB for simplicity. This data is then computed into a graph where the ratio of VB and cutting time represents tool flank wear rate ( $TW_f$ ) in mm/s as presented in Figure 5.16.

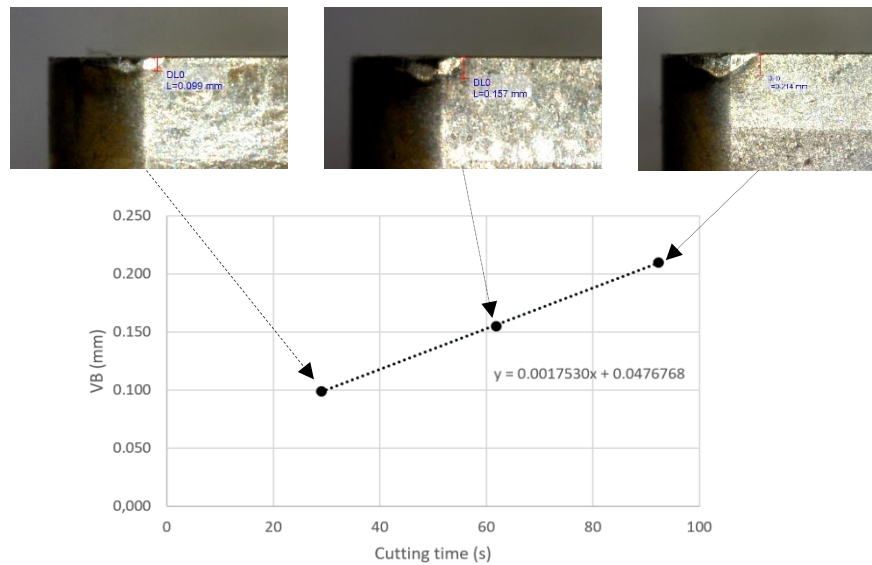


Figure 5.16- Tool wear for  $V_c=300$  m/min;  $f=0.2$  mm/rev;  $a_p=0.15$  mm; insert 603.

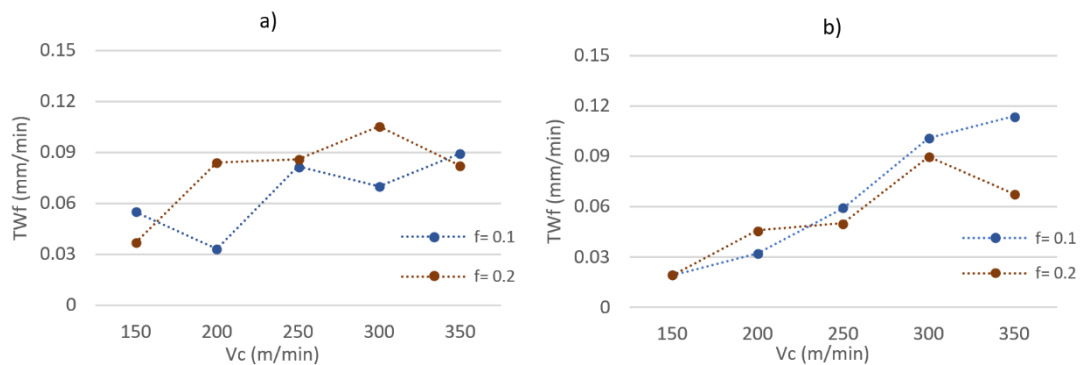


Figure 5.17- Calculated  $TW_f$  for each test on alloy 1: a) tool 603; b) tool 602.

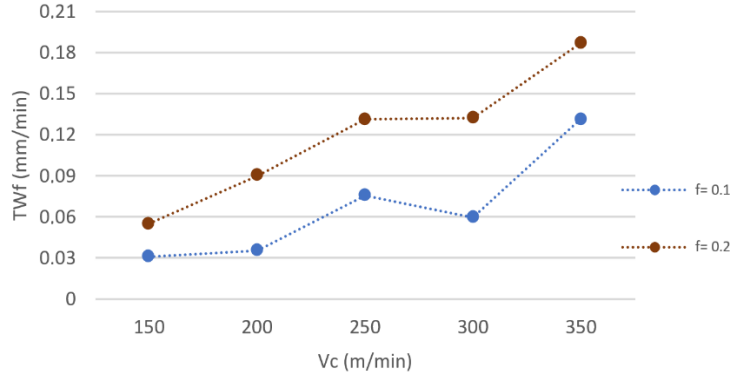


Figure 5.18 - Calculated  $TW_f$  for each test on alloy 2 with tool 603.

All tools experienced noticeable crater wear on the rake face and flank wear due to abrasion on the flank face. In the majority of experimental runs, increased cutting speed improved the stability of the cut. Thus, it is noticeable that within cutting speeds between 250 m/min and 350 m/min wear rate tends to a steadier rate when machining alloy 1 with insert 603. However, when machining the same alloy with tool 602 this is not observed since the tool flank wear rate kept increasing with increasing cutting speed. Brittle fracture was not easily identified due to workpiece material adhesion to the cutting edge, will be further presented (in Figure 5.29).

Figure 5.19 shows two distinguishable wear patterns often found in the current experimental campaign. At lower cutting speeds, i.e.,  $v_c$  between 150-200 m/min, flank wear is extremely irregular with length variations on the flank itself, in addition to the formation of build-up edge and notching. At higher cutting speeds, despite the rapidly wear of the tool, this phenomenon was less discernible.

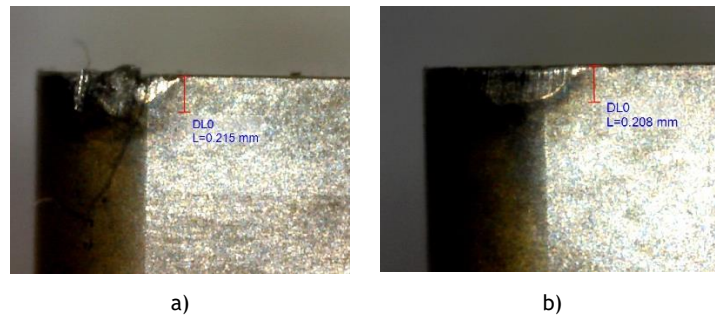


Figure 5.19 - Worn tools after cutting with constant  $a_p = 0.15$  mm: a)  $v_c = 200$  m/min,  $f = 0.2$  mm/rev; b)  $v_c = 350$  m/min,  $f = 0.2$  mm/rev.

Regarding the influence of the feed on flank wear on alloy 1, the results do not show a noticeable influence to the different levels of tested feed (0.1 and 0.2 mm/rev), which is supported by Cantero et al. [32] who found similar results when machining 44 HRC Inconel 718. Contrarily, alloy 2 flank wear results proved to be sensitive to feed parameter during turning since all conducted tests with a feed of 0.2 mm/rev present higher flank wear. Turning tests on alloy 2 consistently achieved higher tool flank wear rates higher than in alloy 1 despite the

later higher mechanical proprieties. Furthermore, when cutting alloy 2 at 250 and 300 m/min flank wear appeared to stabilize.

Figure 5.20 shows the expected tool life using a flank wear of 0.2mm as wear criterion. Regarding alloy 1, it was chosen to display average tool life of both feeds for each tool because no consistent difference was found on the flank wear for the two tested feeds (0.1 and 0.2 mm/rev). Contrary to this, when machining alloy 2 with tool 603, feed parameter revealed to have consistent impact on tool life therefore tool wear is shown for each tested feed on this alloy. It is also important to note that tool life at a cutting speed of 150 m/min was extrapolated and can hardly be achieved due to chipping and notching phenomenon which will be discussed later. Also important to remark that cutting speed greatly affects tool life on every combination of tool/material tested and interestingly tool life of all experimental runs converges to a plateau at 350 m/min. This could be justified by a change in the phenomenon leading the wear from a tribological type of wear (abrasion and adhesion) to a chemical wear (diffusion and oxidation). Within the selected range of tested parameters, cutting speeds between 250 and 350 m/min resulted in smaller notching, better cutting stability and chip control, despite low tool life.

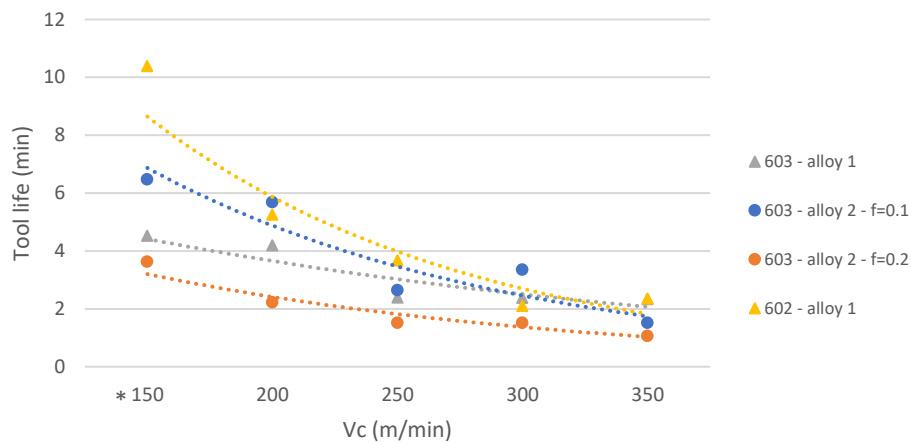


Figure 5.20 - Expected tool life using a flank wear of 0.2 mm as worn criterion.

Productivity cannot be assessed only by the geometric parameters of the operation, which allow to calculate the MRR, but also with regards to tool life. At Figure 5.21 is shown the removed material volume, in function of feed and cutting speed, for the maximum tool life allowing to evaluate tool performance particularly on an industrial level.

$$MRR = v_c \cdot f \cdot a_p \quad 5.3$$

Figure 5.21 allows to perceive two distinct conclusions: the highest machined volume was achieved by machining alloy 1, with a feed of 0.2 mm/rev given that the wear results of this alloy did not show a noticeable influence on the different levels of tested feed; apparently the

increase in feed on alloy 2 did not produce any noticeable difference on the productivity since it led to a shortened tool life, therefore which disabling the advantages of having an higher MRR.

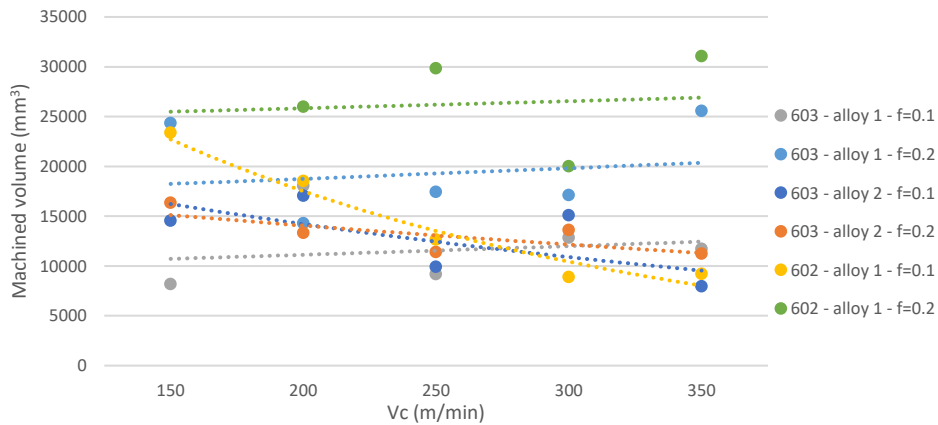


Figure 5.21 - Machined volume considering tool life.

Notch wear induced by chipping, contrarily to flank wear, reduces with an increase on cutting speed and becomes indistinguishable from flank wear at  $v_c = 250$  m/min which was also reported by several authors, for the same tool-workpiece material pairs [32, 102]. When machining the hardest material, i.e., alloy 1, notching and built-up edge were particularly intense at lower cutting speeds for both tested feeds with tool 603, as seen on Figure 5.23, whereas on 602 inserts for the same cutting conditions less notching occurred, probably due to its higher nose radius therefor achieving greater resistance to this phenomenon. Thus, this excessive notch wear at lower cutting speed led to an accelerated deterioration the cutting edge and its ability to maintain strength properties culminating either on (i) the premature failure of the tool or (ii) in the best-case flank wear ends up homogenizing and hiding the initial notching. Moreover, tool flank wear pattern becomes more homogenous when cutting speeds are higher, becoming the failure mode of most tools for  $v_c > 200$  m/min. Tool unexpected failure, besides increasing the frequency of tool change, may destroy the previously machined surface causing inherent impact on the economical side of the process.

Tool notching also occurred when machining alloy 2 with insert 603, at a cutting speed of 150 m/min, as seen on Figure 5.24, although less noticeable most likely due to the lower hardness of alloy 2. Tool failure due to notching at the depth of cut at cutting speeds within the range of 150-200 m/min and a reduction of notching as the cutting speed increases is also reported by various authors [22, 103]. This tool nose notching at the depth of cut is located by intersection between cutting edge and machined surface, as shown on Figure 5.22, being a common failure mode when machining nickel-based alloys. Notch formation results from a combination of aggressive conditions involved during machining process of Ni-based alloys: high temperature, elevated strength and strain hardening of the workpiece maintained at high temperature and the abrasive chips [104].

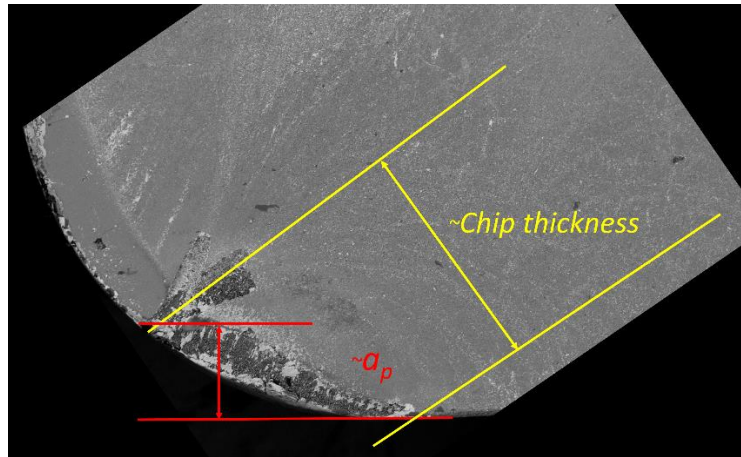
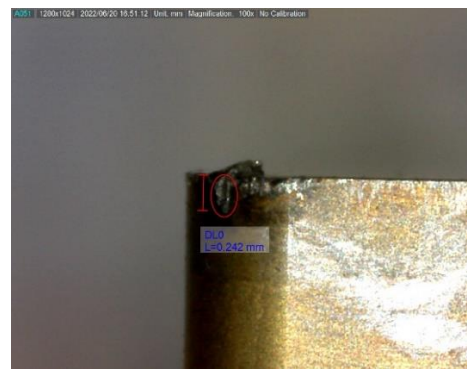


Figure 5.22 - Notching at the depth-of-cut.



a)



b)

Figure 5.23 - Flank surface of insert "603" exhibiting notching after machining alloy 1 at  $v_c=150$  m/min and  $a_p=0.15$  mm: a)  $f=0.1$  mm/rev after 105 seconds of cutting; b)  $f=0.2$  mm/rev after 65 seconds of cutting.



a)



b)

Figure 5.24 - Flank surface of insert "603" exhibiting notching after machining alloy 2 at  $v_c=150$  m/min and  $a_p=0.15$  mm: a)  $f=0.1$  mm/rev after 150 seconds of cutting; b)  $f=0.2$  mm/rev after 45 seconds of cutting.

Comparing tool wear of insert 602 with insert 603, on the previous turning experiments, seemed that the first one appeared to have a more homogenous and predictable flank wear. The flank wear rate ( $TW_f$ ) of insert 602 showed less variation than insert 603, for the two tested

feeds, except at a cutting speed of 350 m/min, so a further investigation and comparison of these two inserts was performed with results being shown on Section 5.3.4.

#### 5.3.4 Test results from the experimental campaign for wear comparison and assessment

Table 5.3 shows the measured flank wear (VB), after performing the Table 4.4 test matrix, confirming what was pointed during the results discussion of the first turning tests, where insert 602 outperformed insert 603 achieving less flank wear when machining alloy 1. Rake face images shown at Figure 5.25 also supported the initial premise of insert 603 tendencies to notch at the depth-of-cut line. TiN binder inserts outperformed TiC by almost 30%, a value in line with the 20% difference on the studies made by Bushlya et. al. [102] when machining Inconel 718 under following cutting conditions:  $v_c = 300$  m/min,  $f = 0.1$  mm/rev,  $a_p = 0.3$  mm, flood coolant. Curiously it is reported that the oxidation of TiN and TiC start at 700°C and 800°C, respectively, forming  $TiO_2$  [105]. With these experimental runs it was also possible to compare and confirm that machining alloy 2 with insert 603 results in higher tool flank wear, but less deeper grooves on the notching zone than alloy 1.

Table 5.3 - Flank wear after machining 1.5 min.

| Material | Insert | VB (mm) |       |       |         |
|----------|--------|---------|-------|-------|---------|
|          |        | #1      | #2    | #3    | Average |
| 1        | 603    | 0.099   | 0.082 | 0.085 | 0.089   |
| 1        | 602    | 0.089   | 0.061 | 0.058 | 0.069   |
| 2        | 603    | 0.114   | 0.102 | 0.099 | 0.105   |

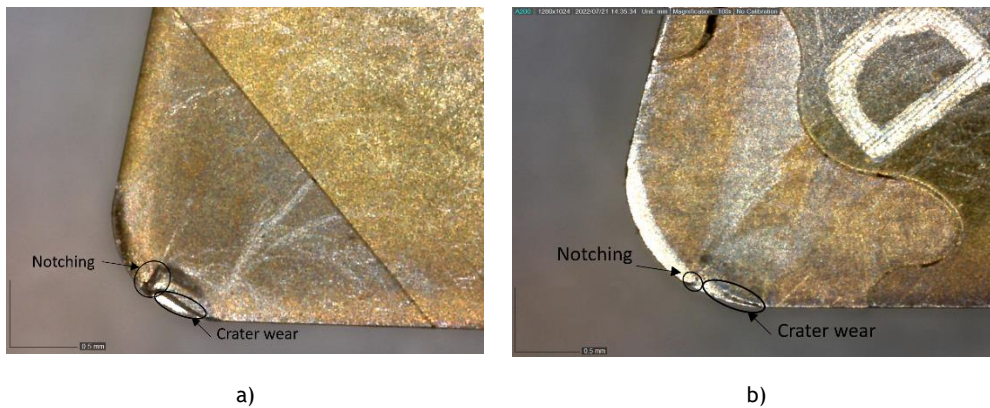


Figure 5.25 - Rake face after 1.5 min of machining time: a) insert 603, b) insert 602.

Electron backscatter diffraction (EBSD) imaging was used to further investigate and distinguish compositional changes in the tools tested. Different zones usually have different

light intensities which correspond to distinct chemical compositions. EDS analyses and SEM images allowed to identify compositional changes in the tool's surface such as build-up edge and recognize that as consequence of the abrasion in the tool-workpiece interface small portions of the workpiece tend to become attached to the tool while the coating removed. By knowing the composition of each zone, displayed in Appendix D, that appeared in BSED images a qualitative analysis was made to each of the six tools used.

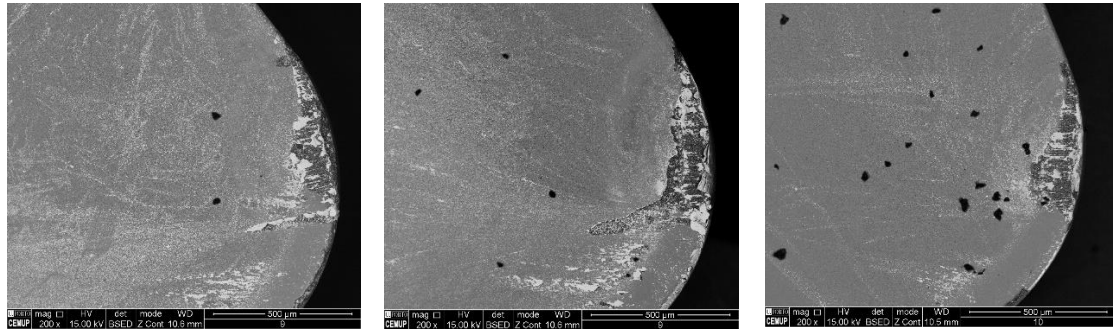


Figure 5.26 - SEM images of insert 603 rake face after 1.5 min of machining; alloy 2.

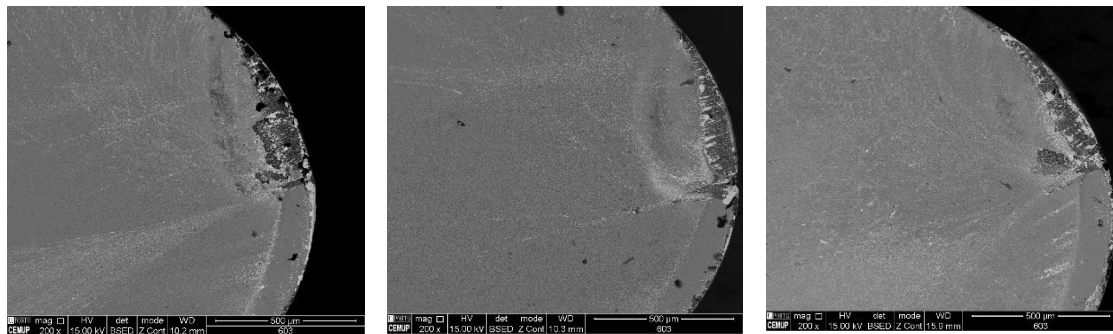


Figure 5.27 - SEM images of insert 603 rake face after 1.5 min of machining; alloy 1.

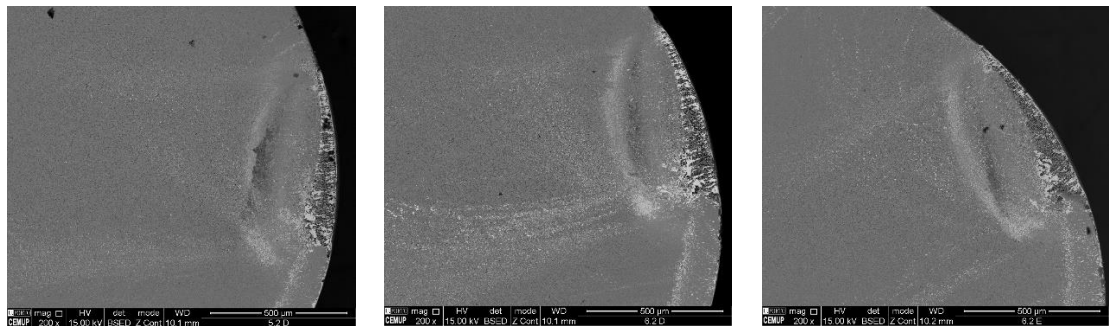


Figure 5.28 - SEM images of insert 602 rake face after 1.5 min of machining; alloy 1.

At Figure 5.26 and Figure 5.27 the SEM images of the three 603 inserts used to machine alloy 2 and alloy 1 are shown, respectively. The visible rake face wear pattern on Figure 5.26 and Figure 5.27 is similar, both presenting signals of workpiece material adhesion, particularly on the cutting edge, although it seems that alloy 2 developed a larger area of crater wear in addition to the higher flank wear (VB). This may be explained by the fact that alloy 2 not submitted to any aging treatment it was expected that this alloy has higher ductility than alloy

1. Heat treating nickel superalloys through aging enables a compromise between strength and ductility that can be customized by the duration and temperature of the aging cycle, since typically longer aging duration offers higher strength with reduced ductility [106, 107]. For this reason, alloy 2 with its improved ductility has less tendency to fracture in chip formation and the deformations are superior, possibly creating larger contact areas with the tool, resulting in larger crater wear. All tested inserts exhibited a curvilinear elongated branded zone were chip primarily exits rake face resulting both in a loss of tool coating due to the tool-chip interaction, diffusion and adhesion of workpiece elements. Regarding inserts 603 and 602, there was a notorious difference between them, visible on a prominent abrasion wear roughly in the same place on the three 603 inserts which was coincident with the notching present on the flank face seen in Figure 5.29. This excessive insert 603 notching tendency, when compared to insert 602, has been observed when carrying out the secondary experimental plan and was once again observed in this second smaller experimental plan. The bigger tool nose radius of tool 602 also contributes to its reducing chipping tendency.

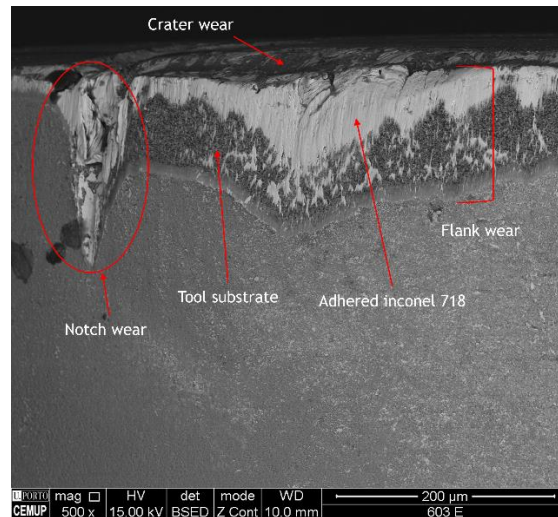


Figure 5.29 - SEM image of a worn 603 tool flank.

In addition to this, flank wear on 602 inserts was generally more homogeneous than in 603 inserts mainly due to the absence of notching. Moreover, SEM images made it possible to understand that the cutting edge on 603 inserts undergoes more workpiece adhesion than 602 inserts. While the workpiece material adheres to the tool, a new edge is created resulting in the loss of geometric and mechanical characteristics. This newly generated layer makes the cutting edge less sharp thus increasing forces in cutting particularly the passive or radial force.

Further investigating tool wear through SEM images and EDS analysis different tool zones were characterized in order to understand wear mechanisms such as abrasion, diffusion and adhesion and relate them with the different inserts. Three different zones are shown in Figure 5.30, Z1 EDS analysis reveals high quantities of titanium, aluminium and nitrogen which belongs to the tool coating layer while chemical elements of the machined alloy are not detected. Z2

is shown as a white smooth zone being characterised by high quantities of nickel, iron, chromium along with other elements present in the tool coating such as aluminium and carbon which indicate that this layer is resultant both from diffusion of coating elements and the alloy and adhesion of this new compound into the tool both on the rake face and on the cutting edge. Black spots as the one marked as Z9 are just contamination either from the lubricant used or due to hand handling.

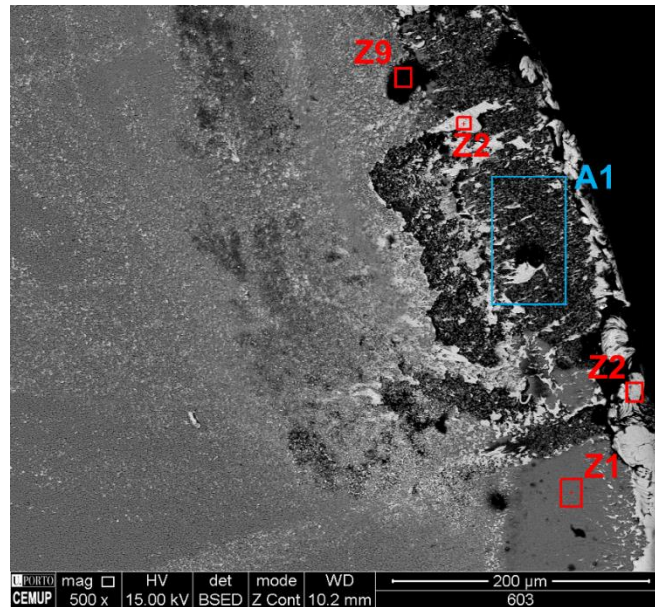


Figure 5.30 - SEM image of insert 603 rake.

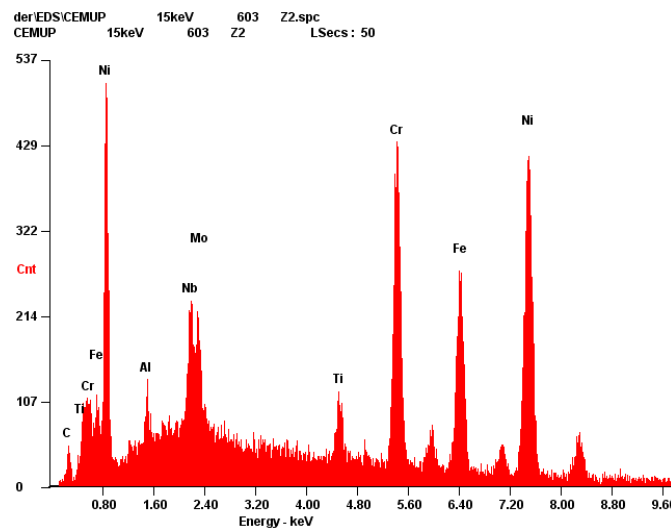


Figure 5.31 - EDS analysis of Z2.

Zooming from 500x to 5000x into the zone highlighted as A1 enables the analysis of an irregular surface shown in Figure 5.32. This irregular surface with up and down texture appears to be constituted by two different compounds. Z3, which corresponds to the texture peaks, main constituents are titanium and aluminium whereas a relative quantity of other components resulting from the diffusion of the alloy are also present. Even though the chemical composition of Z4 is quite similar to Z3, the presence of Boron which may be an indicator wear depth

(reaching the PCBN substrate of the tool). Brighter zones on Figure 5.32 show adhesion of the workpiece into the tool which was common on all samples seen through SEM.

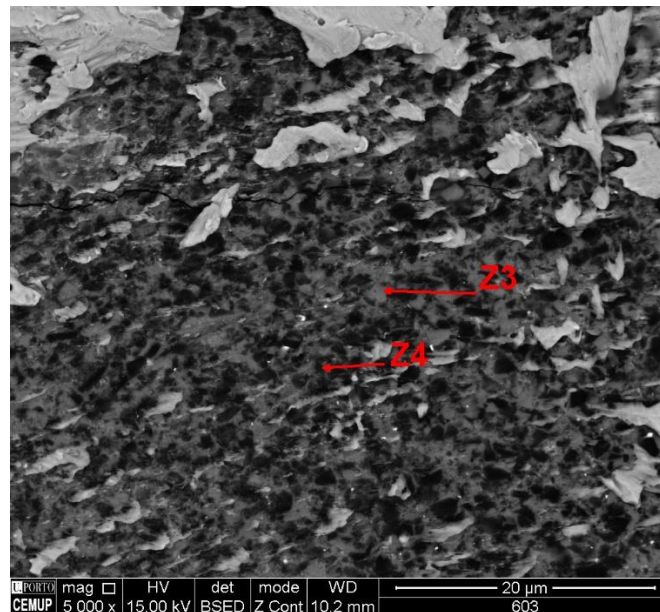


Figure 5.32 - Area A1 SEM image of insert 603.

A detailed image of the notching on 603 inserts is shown in Figure 5.33. Prominent tool wear in the form of notch wear seems to occur at the rake face location that coincides with the chip upper border. Abrasion in this place affects the cutting tool toughness leading to a newly formed surface on the tool with workpiece elements lowering mechanical and chemical strength which triggers both the adhesive and abrasive mechanisms in the contact area. Also, regarding in Figure 5.33 a) two more zones are identified as Z7 and Z8 which have titanium and aluminium as main constituents hence belonging to the tool coating.

Tool 602 inserts seem to have a geometric consistent wear pattern on the rake face and tool 603 inserts crater wear appears to be darker in images indicating the presence of deeper erosion consequently reaching the tool substrate. Both inserts suffered from grooves roughly on the same zone which seems to have a relation with cutting depth, as discussed on section 5.3.3, although in 603 inserts the cutting edge appeared to be more affected by chipping whereas in 602 inserts the cutting edge seemed to withstand its geometrical characteristics.

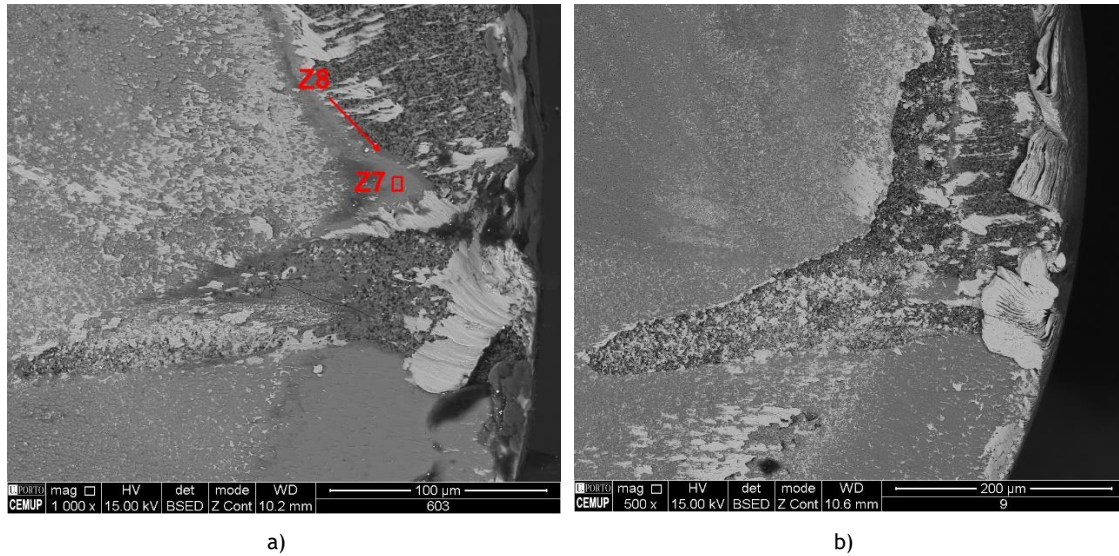


Figure 5.33 - Notching at depth of cut detail on insert 603: a) alloy 1, b) alloy 2.

Notch wear when turning Inconel 718, is reported not only on PCBN tools but also other ceramic tool such silicon nitride, SIALON or whisker-reinforced alumina [104, 108]. Figure 5.34-a) shows the wear of a silicon nitride tool after a cutting length of 50 m, where there is a noticeable increase of notch wear at cutting speeds of 150 m/min. Flank wear increases gradually with cutting speed. Figure 5.34-b) shows the average flank wear of a SIALON tool, after 30 seconds of machining. The wear modes changed when increasing the cutting speed from 150 to 310 m/min, as the highest cutting speed achieved minor notching on the sialon tool with increased flank wear, which is close to the findings made in this work regarding PCBN tools.

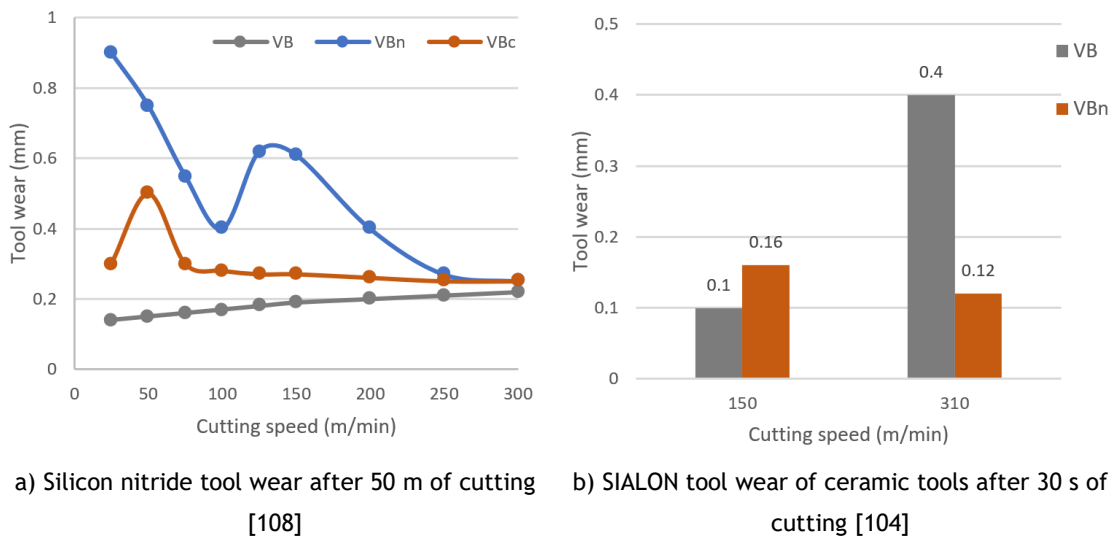


Figure 5.34 -Ceramic tool wear during Inconel 718 turning-

Additionally, the worn flank face was characterized by adhered workpiece material and notching when employing an alumina tool in a certain way similar to the worn patterns found on PCBN tools, at Figure 5.29. It was also noticed that silicon nitride, sialon or whisker-reinforced alumina tools generally achieved lower tool life than PCBN tools when machining Inconel high cutting speeds.

Carbide tools used in finishing turning of Inconel 718, both in wet and dry cutting conditions, also revealed similar wear mechanisms, especially significant notch wear due to high work hardening of the Ni alloy. Carbide tools were tested cutting speeds of 50 and 70 m/min, therefore achieving higher tool life than PCBN tools [109].

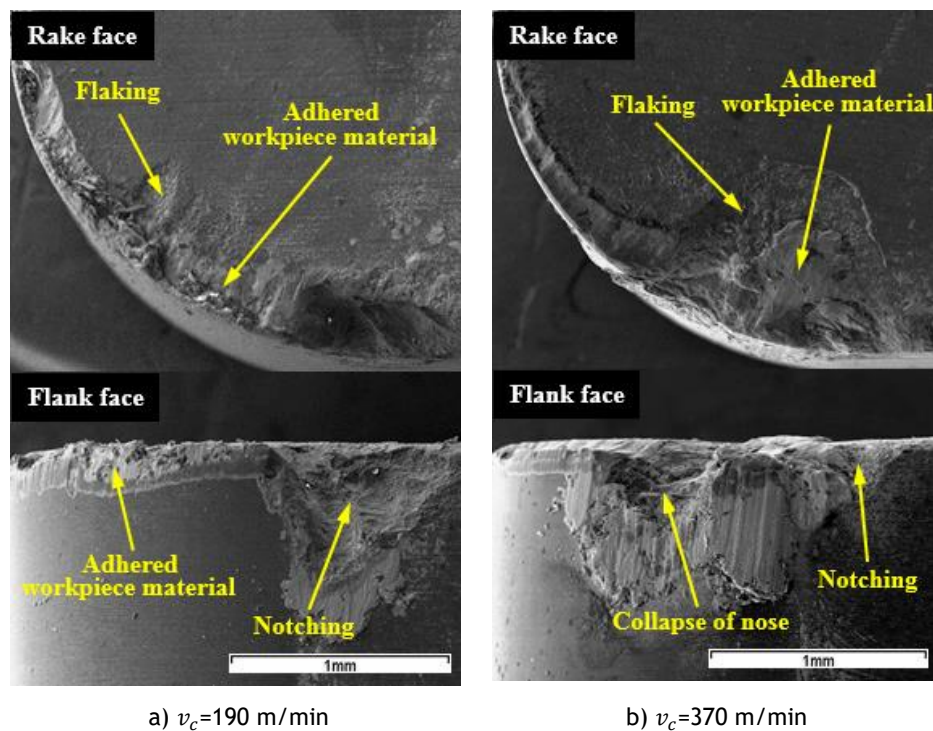


Figure 5.35 - SEM micrographs of wear morphologies of an alumina tool [104].

Inconel 718 proved to be a difficult to machine material even when using PCBN tools. At lower speeds, irregular cutting conditions, the widespread tool chipping and the lack of chip control might lead to too failure which is unacceptable in industrial applications. At higher cutting speeds ( $v_c \geq 200$  m/min) tool performance became more regular and predictable, although increasing material removal rates negatively affects tool wear rate. Both inserts went through various type of wear whit crater, flank and notching wear being the main ones. Insert 603 is more prone to develop notching than insert 602 and the latter proved to have consistently improved tool wear resistance due to its TiN binder superior diffusion resistance and its enhanced tool tip.

### 5.3.5 Chip analysis

Chip formation depends on the material being machined and the cutting conditions of the operation. It is often used as criteria to determine the machinability in continuous processes including turning. Samples of chips were collected after each test as shown in Figure 5.36 and Figure 5.37. Resultant chips from cutting at 250m/min and above were very similar and seem to be a mixture of tubular chips and washer-type helical chips according to ISO 3685. The lowest cutting speed, i.e., 150m/min, resulted on irregular shaped chips alternating between long ribbon and helical forms on the same chip. From a macroscopic point of view, both materials chips had a similar geometry.

Chip formation greatly changes under different conditions which is an associated problem with Inconel 718 turning. Lower cutting speeds lead to poor chip control due to its continuous ribbon-type morphology that can get entangled as shown in Figure 5.38 a). With the increase of cutting speed chips tend to be continuous with various segments: so-called serrated chips. The intensity of chip serration increases with cutting speed and the segments within the chips are eventually separated therefore producing the discontinuous chip [110].

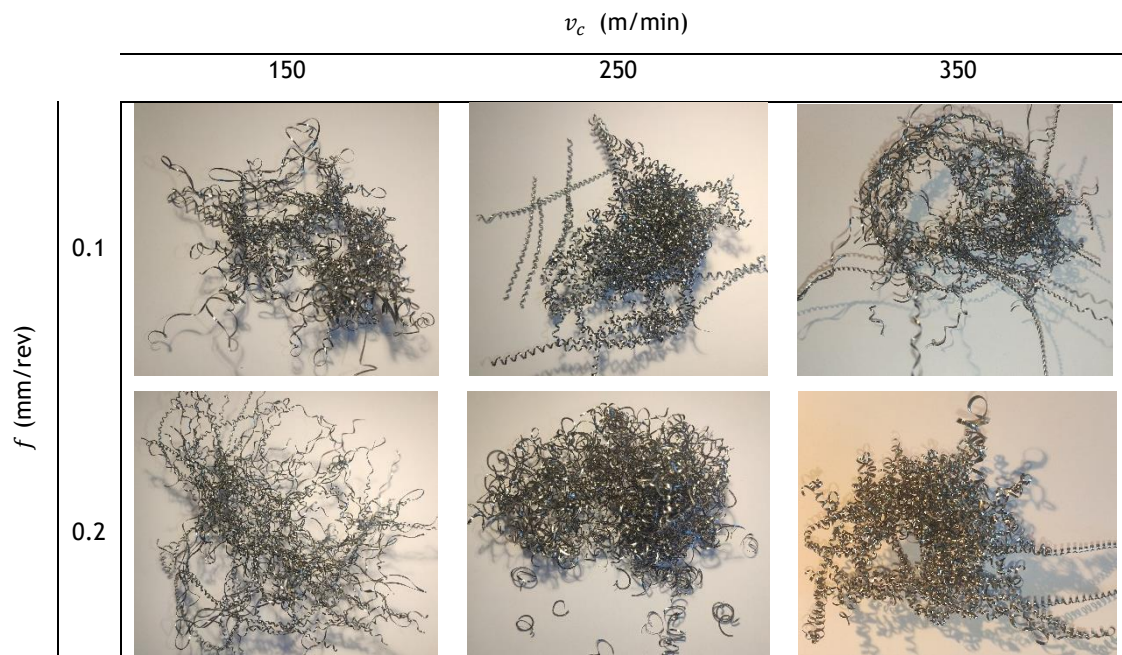


Figure 5.36 - Chip geometry obtained from alloy 1 turning tests with 0.15 mm of cutting depth.

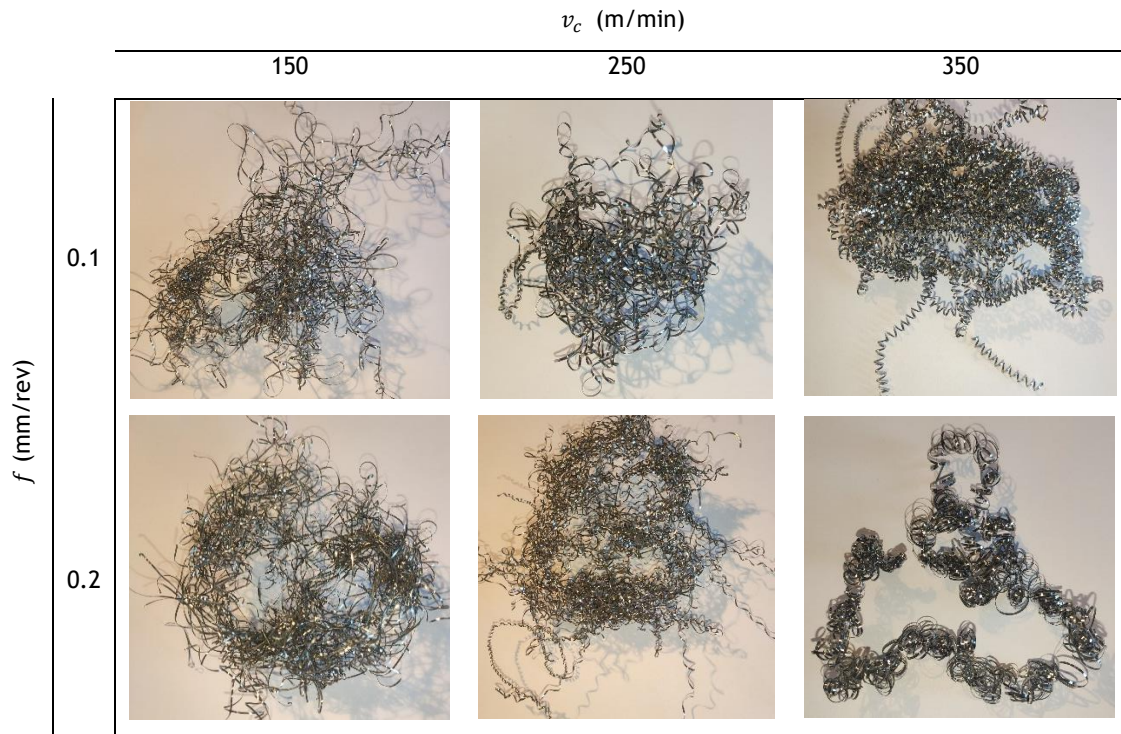


Figure 5.37 - Chip geometry obtained from alloy 2 turning tests with 0.15 mm of cutting depth.

Since there was no chip breaker on the inserts and due to the length of the carried out test, chip control was a difficulty that became notorious and may have had a negative impact on the showed tool wear results. Lower cutting speeds lead to unfavourable chip formation which had a tendency to be continuous and get tangled around the workpiece, as shown in Figure 5.38-a), consequently impacting the lubricant ability to dissipate heat. At higher cutting speeds the opposite occurred with chips turning out to be helical and discontinuous, as demonstrated in Figure 5.38-b). The use of high pressure coolant is reported to enhance chip breakability resulting in short and discontinuous chip while low pressure coolant application generally produced long and continuous chips, which occasionally led to entanglement problems [111].



Figure 5.38 - Chip formation: a) chips tangled around the workpiece; b) discontinuous chips.

The SEM observations of alloy 1 chips, shown at Figure 5.39 and Figure 5.40, allowed for the analysis of serrated chip formation. This type of formation is typical of hard-to-machine materials with significant hardness such as the considered nickel superalloy. The intensity of chip serration seems to increase with cutting speed since at high cutting speeds, intense shear deformation occurs, which due to the low conductivity (inability to dissipate heat) of IN718, promotes localized softening at the primary deformation zone that, allied to fracture phenomena, results in a cyclical chip geometry [110].

In serrated chip formation, each tooth formed is limited by two shearing planes and distance between the successive teeth is known as pitch of the serrated chips which was determined based on the average of ten measured distance between successive teeth. Pitch values obtained in Table 5.4 prove that pitch of serrated chip decreases, as the cutting speed increases thus increasing the chip segmentation frequency. Similar observations were made by Pawade and Joshi [112] and Lorentzon et al. [113].

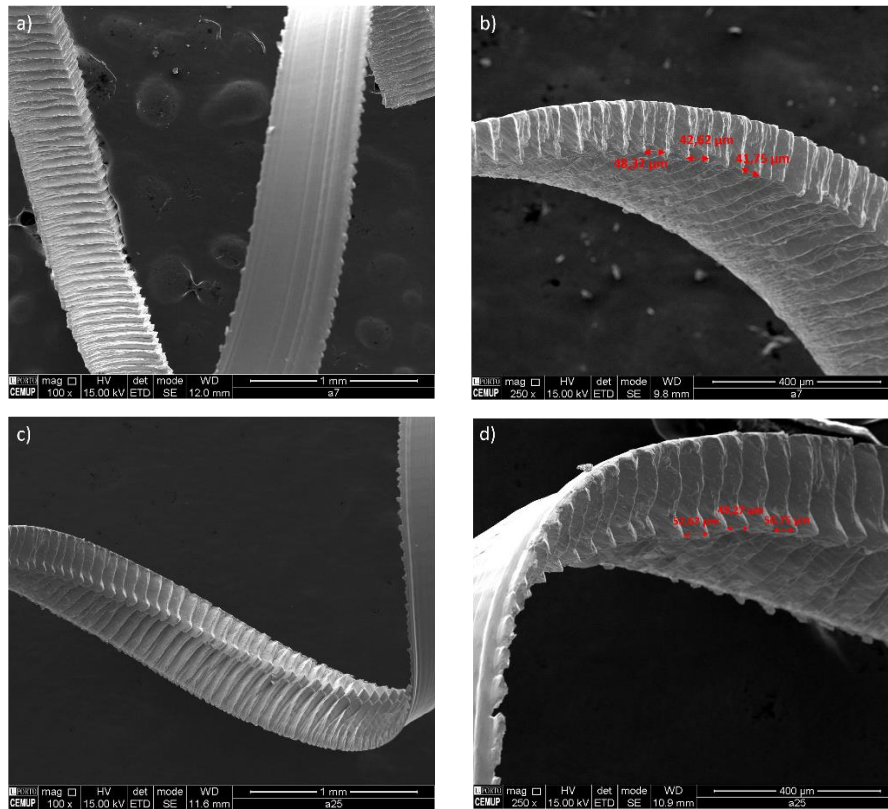


Figure 5.39 - SEM images of the chips obtained from machining with tool 603,  $v_c=150$  m/min,  $a_p=0.15$  mm: (a) and (b),  $f = 0.1$  mm/rev; (c) and (d),  $f = 0.2$  mm/rev.

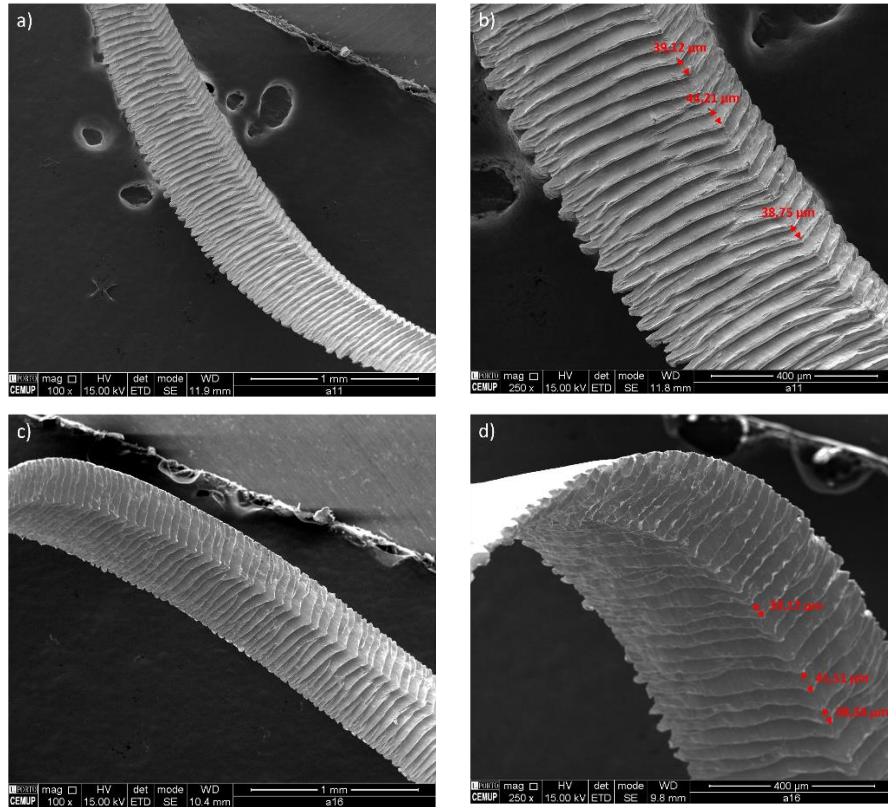


Figure 5.40- SEM images of the chips obtained from machining alloy 1 with tool 603,  $v_c=350$  m/min,  $a_p=0.15$  mm: (a) and (b),  $f = 0.1$  mm/rev; (c) and (d),  $f = 0.2$  mm/rev.

Table 5.4 - Average pitch values.

| $v_c$ (m/min) | $f$ (mm/rev) | Pitch ( $\mu$ m) |
|---------------|--------------|------------------|
| 150           | 0.1          | 52.07            |
|               | 0.2          | 53.70            |
| 350           | 0.1          | 38.21            |
|               | 0.2          | 41.58            |

Chip thickness ( $t_c$ ) increases for bigger feed, resulting in a larger of shear zone. It is a simple parameter used as a measure of the tool penetration depth and it is expected have higher values than the feed due to the plastic deformation. Figure 5.41 shows measured maximum chip thickness ( $\max t_c$ ) proving to be consistent with the feed used. It should be noted that these values aim to give a qualitative comparison of chip thickness since orthogonal cutting conditions were not tested.

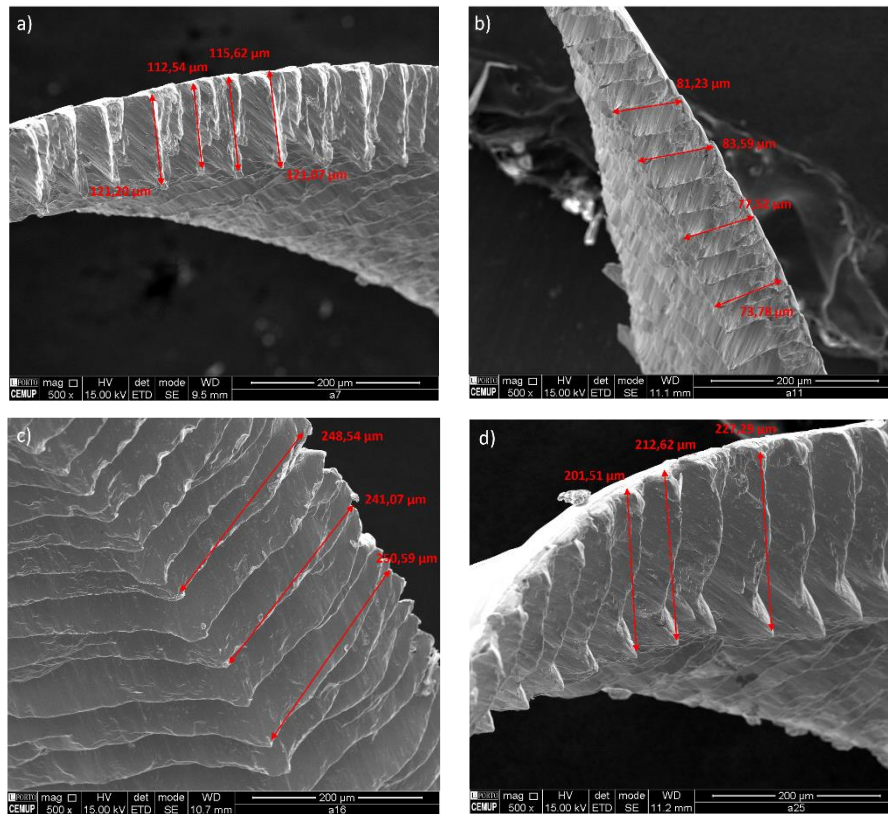


Figure 5.41 - Chip thickness analysis of alloy 1 at a constant  $a_p$  of 0.15 mm: a)  $v_c=150$  m/min,  $f = 0.1$  mm/rev; b)  $v_c=350$  m/min,  $f = 0.1$  mm/rev; c)  $v_c=350$  m/min,  $f = 0.2$  mm/rev; d)  $v_c=150$  m/min,  $f = 0.2$  mm/rev.

Table 5.5 - Average max  $t_c$  values.

| $v_c$ (m/min) | $f$ (mm/rev) | Max $t_c$ ( $\mu\text{m}$ ) |
|---------------|--------------|-----------------------------|
| 150           | 0.1          | 119.69                      |
|               | 0.2          | 216.30                      |
| 350           | 0.1          | 84.62                       |
|               | 0.2          | 249.70                      |

# Chapter 6

## FEM simulation with DEFORM™

### 6.1 Introduction

In this chapter results from numerical turning simulation of Inconel 718, using DEFORM™ 2D/3D, are presented. This chapter is divided into subsections, aimed to describe the steps of creating the numerical problem such as: tool and workpiece material and geometry characterization, mesh sensitivity analysis and ultimately the results. Forces and chip formation outputted from the simulation are then validated with experimental data obtained in Chapter 5.

DEFORM™ 3D/2D is one of the commercially available software's with specific modules capable of simulating various machining operations. This master thesis is focused on exploring DEFORM™ 3D/2D capacities involving cutting forces and tool wear simulation when machining Inconel 718 with PCBN tools. This material comes fully defined in the software's material library which is an advantage for the simulation achieving to save time and cut extra steps if the software's material constitutive model is similar to the real material. Still, the tool material proprieties had to be searched and defined according to literature and empirical data.

DEFORM™ software is divided into three main modules. First, the Pre-Processor, where is possible to build, characterize and join all the data regarding simulation. The pre-processor allows to make various operations such as creating geometric models and positioning objects, defining material models, meshing, definition of boundary conditions and generating the database file. The simulation module is meant to run the simulation. In the last module, the post-processor, is possible to display/analyse results graphically and extracting numerical data.

## 6.2 Workpiece material and geometry

DEFORM™ 2D/3D software has a built-in library with various materials from aluminium, copper, stainless steel, titanium and the studied superalloy Inconel 718. Workpiece and tool material as well as operational conditions (i.e. cutting parameters, tool geometry) were defined accordingly to the experimental setup. The workpiece material, Inconel 718, is already characterized in DEFORM™ material library although the flow stress constitutive model was replaced by a Johnson Cook equation calibrated based on the conducted compression test and literature.

Still, elastic properties (namely Young modulus and Poisson's ratio) and thermal properties (such as thermal conductivity, heat capacity and thermal expansion) were defined by the available library data for IN718. Both Young modulus and thermal expansion are also temperature dependent with opposite behaviour when increasing temperature: Young modulus declines and thermal expansion raises, as shown in Figure 6.1.

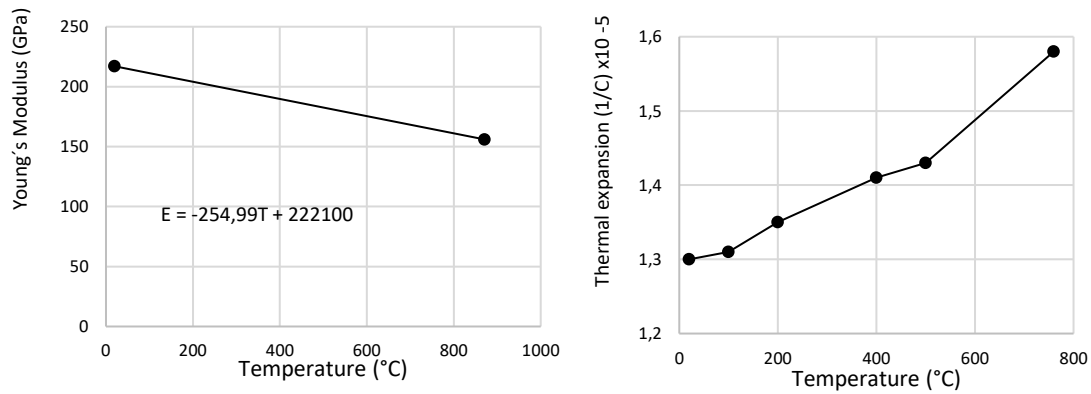


Figure 6.1 - IN718 temperature dependent Young's modulus and thermal expansion.

For most materials an increase of strain rate raises flow stress, and a temperature increase leads to decrease of flow stress. The flow stress of Inconel 718 is, by default, defined in a tabular form as a function strain, strain rate and temperature.

$$\bar{\sigma} = \bar{\sigma}(\bar{\epsilon}, \dot{\bar{\epsilon}}, T)$$

Since reviewed literature made use of Johnson-Cook (JC) constitutive model, equation 3.8, to model IN718 behaviour, an attempt to get closer to experimental results was made employing this constitutive model. Compression tests allowed identification of material behaviour and enabled the calibration of the first three parameters of this model ( $A$ ,  $B$  and  $n$ ). Given the very challenging task of conducting high temperature and strain rate tests, those effects were modelled according to literature data.  $C$  constant, which is related with strain-rate hardening, was determined by Pereira et al. [65] for aged IN718 using quasi-static and high strain rate compression testing. Regarding the thermal softening related constant,  $m$ , a decrease in the flow stress as a result of the temperature increase was observed at the different strain rates by Iturbe et al. [68]. The value used for this constant was 1.3 which was experimentally

determined by Uhlmann et al. [64] in orthogonal turning tests of Inconel 718. Chosen parameters for each alloy are presented in Table 6.1 and a comparison between experimental and this numerical approach at quasi-static stress-strain curve is plotted at Figure 6.2.

*Table 6.1 - JC equation parameters for each alloy.*

| Constant        | Alloy 1 | Alloy 2 |
|-----------------|---------|---------|
| $A$ [MPa]       | 1250    | 700     |
| $B$ [MPa]       | 1000    | 1050    |
| $n$             | 0,3     | 0,3     |
| $C$             | 0,0134  |         |
| $m$             | 1,3     |         |
| $T_{melt}$ [°C] | 1430    |         |

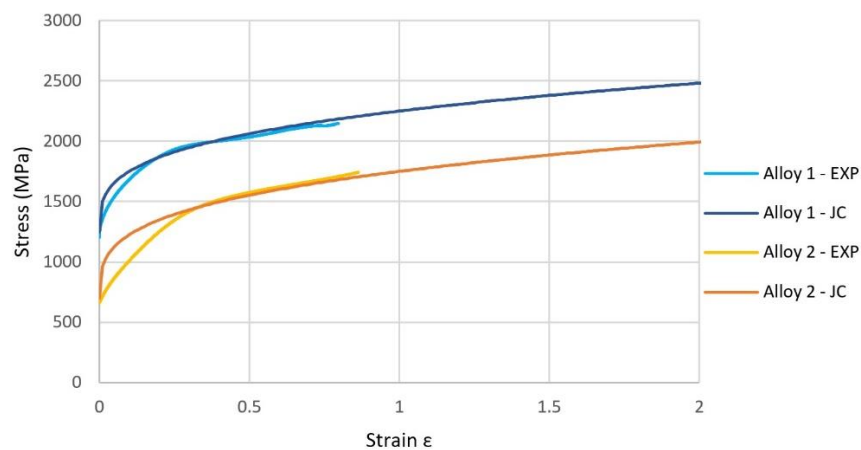


*Figure 6.2 - Comparison between experimental and Johnson-Cook flow stress-strain curves (quasi-static, room temperature).*

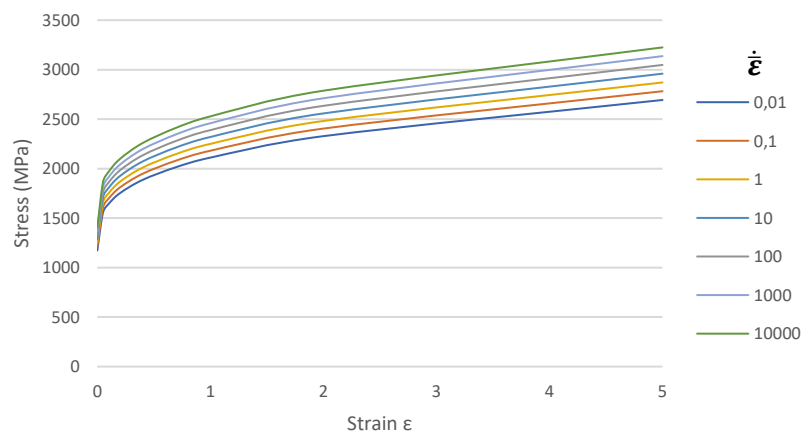


*Figure 6.3 - Stress- strain curves of IN718 for different strain rates at a fixed temperature (20°C).*

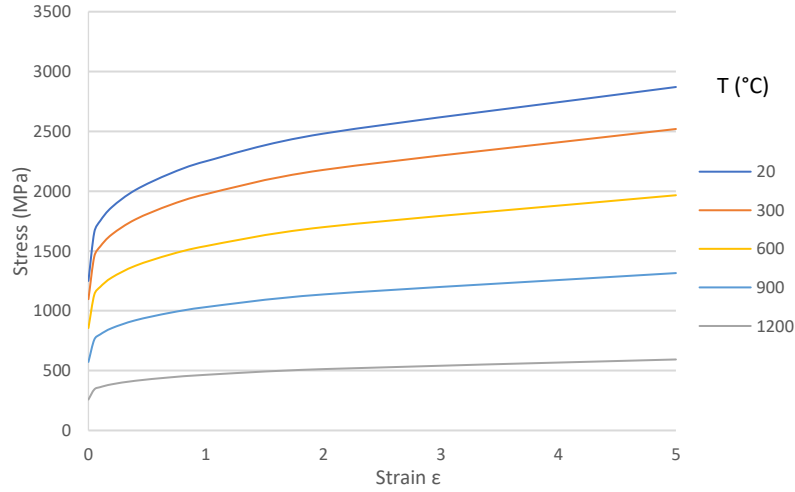


Figure 6.4 - Stress- strain curves of IN718 for different temperatures at a fixed strain rate ( $1s^{-1}$ ).

The strain rate hardening effect at fixed temperature ( $20^{\circ}C$ ), for alloy 1, is shown in Figure 6.3, while at Figure 6.4 is displayed the thermal softening effect at a fixed strain rate ( $1s^{-1}$ ). Alloy 2 undergoes the same strain rate hardening and thermal softening effects given that the proposed parameters for each alloy are the same. Although JC material model is the most widely used in metal cutting simulation it describes strain hardening as an increasing function that diverges to infinity, as shown, and does not consider strain-softening phenomena [68].

This model does not accurately represent flow stress at lower strain values. Still this limitation of the JC model does not noticeably affect the results given that cutting operations are dominated by intense deformations, which this model is able to represent in a more precise way. In DEFORM<sup>TM</sup>, Cockroft & Latham damage model is used to determine the fracture moment of the distorted material.

$$D = \int_0^{\varepsilon_f} \sigma_1 d\bar{\varepsilon} \quad 6.1$$

where  $\sigma_1$  is the maximum principal tensile stress,  $\bar{\varepsilon}$  the equivalent strain and  $\varepsilon_f$  is the equivalent strain at which fracture occurs. This model is based only in one constant to indicate the fracture properties of a material. This damage state variable ( $D$ ) is used to trigger fracture modelling using continuum damage softening, with a softening coefficient of 20%. The flow stress value for element stiffness calculation is reduced to a specified percentage (20%) of the flow stress calculated for the element. For alloy 1, the critical value of fracture energy density, was 500 MPa, the default value proposed by Deform, whereas for alloy 2, due to the lower strength of the alloy, a critical value of 300MPa was inversely calibrated.

The workpiece geometry definition and generation is straightforward process when simulating turning operations in DEFORM<sup>TM</sup>. A curved or simplified, with the latter being shown at Figure 6.5, workpiece geometry is automatically generated by the software according to the defined process parameters, feed rate and depth of cut. It is possible to choose the cutting length. The

analysis domain is a small portion of the complete turning operation due its complexity and long computational time.

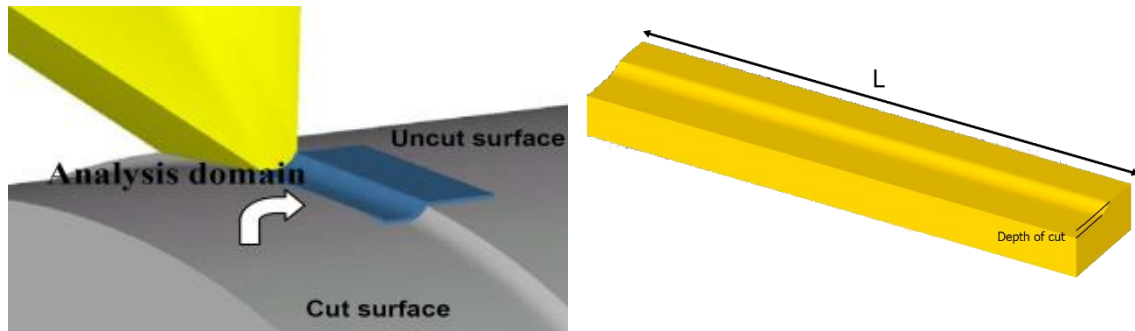


Figure 6.5 - Workpiece geometry for 3D simulation.

### 6.3 Tool material and geometry characterization

Contrary to the workpiece material, the tool material (i.e., PCBN) is not characterized in DEFORM™ library. To overcome this, research on scientific papers regarding PCBN characterization and simulation was conducted. Deform by default characterizes tool material according to five parameters: Young's modulus, Poisson ratio, thermal expansion coefficient, thermal conductivity, and heat capacity. With a focus on using the predefined models for predicting wear, Usui's model and Archard's model, hardness values should also be defined and entered using the Rockwell C hardness scale. Inconel 718 properties used during simulation are displayed on Table 6.2.

Table 6.2- PCBN properties compiled from different author's.

| Properties                                                             | PCBN (low CBN %)             |
|------------------------------------------------------------------------|------------------------------|
| Young ( $E$ ) (GPa)                                                    | 690 [114]                    |
| Poisson ( $\nu$ )                                                      | 0.2 [114]                    |
| Thermal expansion (K)                                                  | 4.7 e-6 [115]                |
| Thermal conductivity ( $\kappa$ )(W.m <sup>-1</sup> .K <sup>-1</sup> ) | 44 [116, 117]<br>35-55 [118] |
| Heat capacity (J.kg <sup>-1</sup> .C <sup>-1</sup> )                   | 750 [116]                    |
| Hardness (HV)                                                          | 5000 [115]                   |

The tool insert selected was CNGA 120408 according to ISO standard, so its geometry was imported in STL form, which generated from any CAD system, to DEFORM™. Tool geometry was defined according to the dimensions displayed at Section 4.3.1. In an attempt to optimize the simulation only the tool tip was designed so it could have the same number of elements in a

smaller area resulting in a high-density mesh discussed on the next subsection. The tool geometry modelled and used in turning simulation is shown at Figure 6.6. Besides the tool material and geometry also the tool holder, which gives the cutting angles to the insert, had to be defined. Deform also includes various tool holder types but it was chosen to import the tool with the cutting angles given by the DCLNL tool holder.

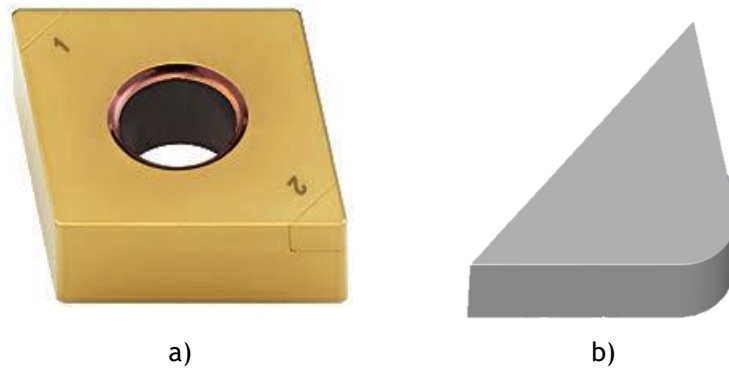


*Figure 6.6 - Insert geometry: a) tool used in experimental tests and b) 3D tool model used in simulation.*

#### 6.4 Mesh sensitivity analysis

Element size may considerably influence the accuracy of finite element results, the convergence of the problem and computational time. Fine mesh generally improves the accuracy of results, but it increases the computational time required to do the simulation while coarse mesh leads to inconsistent results and convergence problems during simulation process although requiring less time to complete the simulation due to a smaller number of elements.

After having both the workpiece and tool materials and geometry defined, meshing both the tool and workpiece as well as defining other process parameters such as environment temperature, environment convection coefficient friction, heat transfer coefficient was performed. These values were set according to the software default solution for turning operations.

Element size in the tool was smaller near the cutting edge in order to improve the geometrical accuracy of the numerical model and avoid geometrical vertices in the contact zone that would create singularities, which often result in peak values. It was found that tool mesh has a direct impact on the cutting edge geometry due to the tool geometry being replaced by mesh polygons. These 0.02 mm cutting edge radius were meshed by smaller elements concentrated only on the contact areas of the tool with sizes between 0.004 and 0.006 mm as shown in Figure 6.7.

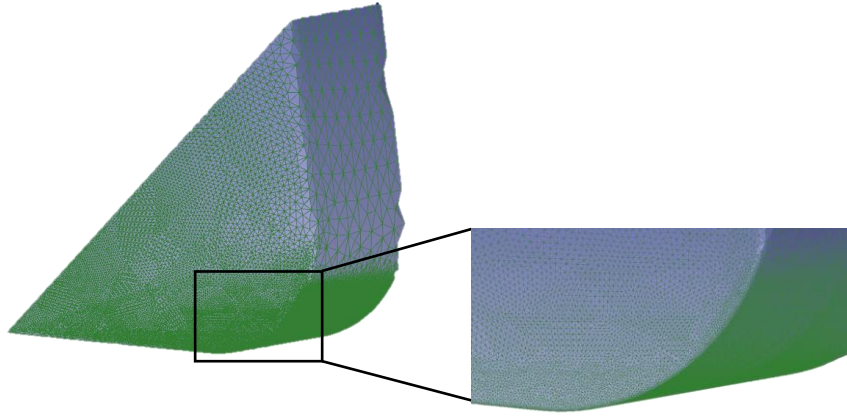


Figure 6.7 -Detail view of high-density mesh near the cutting edge

It was also noticed that tool mesh has insignificant influence on cutting forces when compared to workpiece mesh given that an increase of 400% on tool mesh elements resulted on a difference of 2% in cutting forces and an increase of 75% on workpiece mesh elements changed cutting forces by 4.8%. This is explained by the fact that the workpiece is defined as having a plastic behaviour whereas cutting tool is a rigid body that does not deform. Mesh element number, mainly in the workpiece, heavily impacts simulation time so it is important to understand its effect on the results. To make study this topic three different simulations were made, and resultant force ( $R$ ) convergence was analysed. Resultant force is calculated according to equation 6.2.

$$R = \sqrt{F_c^2 + F_f^2 + F_p^2} \quad 6.2$$

Tool and workpiece format, tool mesh and cutting parameters were constant so only workpiece tool mesh was varied during this mesh sensitivity analysis. Cutting speed of 200 m/min, feed rate of 0.2 mm/rev and a depth of cut of 0.15 mm were select to this convergence analysis. For all runs a cutting length of 1.5mm was considered at a environment temperature of 20°C and an environment convection coefficient of 0.02 N/s/mm/°C. Tool mesh is represented at Figure 6.7 having 138880 nodes, summing up 663600 elements. Concerning the tool-workpiece it was chosen Coulomb friction law with a coefficient of 0.8. Workpiece- tool and workpiece-workpiece heat transfer was set to 45 N/s/mm/°C, which is the default DEFORM<sup>TM</sup> value. A summary of the mesh sensitivity simulation parameters is displayed on Table 6.3.

Table 6.3 - Summary of simulation parameters used in 3D mesh sensitivity analysis.

|                      |                                    |                        |              |
|----------------------|------------------------------------|------------------------|--------------|
| Process              | Cutting speed, $v_c$               | 200 m/min              |              |
|                      | Feed rate, $f$                     | 0.2 mm/rev             |              |
|                      | Depth of cut, $a_p$                | 0.15 mm                |              |
|                      | Cutting length                     | 1.5 mm                 |              |
|                      | Environment temperature            | 20°C                   |              |
|                      | Environment convection coefficient | 0.02 N/s/mm/°C         |              |
| Tool parameters      | Material                           | Alloy 1                |              |
|                      | Mesh                               | Elements number        | 663600       |
|                      |                                    | Nodes number           | 138880       |
|                      |                                    | Size ratio             | 4            |
| Workpiece parameters | Material                           | Alloy 1                |              |
|                      | Mesh                               | Table 6.4              |              |
| Contact              | Friction                           | Tool-Workpiece         | Shear 0.8    |
|                      |                                    | Workpiece-Workpiece    | Coulomb 0.3  |
|                      | Heat transfer coefficient          | Tool-Workpiece         | 45 N/s/mm/°C |
|                      |                                    | Workpiece-Workpiece    |              |
| Numeric              | Simulation type                    | Lagrangian incremental |              |
|                      | Iteration method                   | Direct iteration       |              |

Table 6.4 - Workpiece mesh sensitivity analysis results

| # | Workpiece mesh elements | Minimum element size (mm) | Simulation time (h) | Resultant Force (N) | Change (%) |
|---|-------------------------|---------------------------|---------------------|---------------------|------------|
| 1 | 7230                    | 0.06                      | 1.5                 | 162.62              | -----      |
| 2 | 19882                   | 0.05                      | 2.5                 | 154.81              | -4.8       |
| 3 | 30978                   | 0.04                      | 3.75                | 152.50              | -1.49      |
| 4 | 64682                   | 0.03                      | 6.2                 | 152.02              | -0.31      |

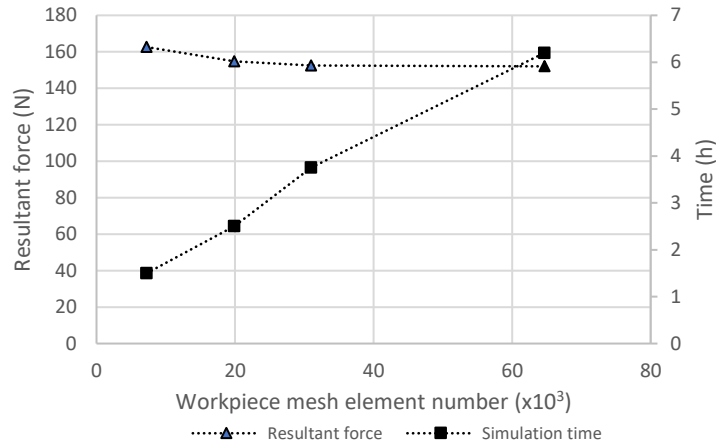


Figure 6.8 -Resultant force and simulation time in function of workpieces mesh

After this brief mesh sensitivity analysis, given that simulation time increased from less than 2 to slightly above 6 hours while the resultant force decreased 6.5% it was concluded that workpiece mesh would have limited influence on the results not being a major concern. For reference Lotfi et al. [62], when estimating the wear of ceramic and coated carbide tools in turning of Inconel 625, used a workpiece mesh with a minimum element size of 0.03mm. This mesh seems to offer results that won't change much even with a finer mesh, although it is important to note that this simulation took 6.75 hours to simulate a cutting length of 1.5mm.

## 6.5 Results and discussion

Cutting simulations were performed using a transient analysis based on the Lagrangian formulation. The workpiece remains stationary while the tool moves against it, deforming the workpiece mesh. This formulation along with a chip separation criterion enables chip formation. DEFORM<sup>TM</sup> uses an implicit formulation hence the time step size has no influence on the stability of the solution.

For each material, simulations were made at a constant depth of cut, varying the cutting speed from 150 to 350 m/min and the feed from 0.1 to 0.2 mm/rev, the same cutting parameters experimentally tested. Tool mesh, environment convection coefficient, friction and heat transfer parameters were set according to Table 6.3. Simulating a cutting length of 1.5 mm was sufficient for forces to reach a steadier state and at the same time allowing to save computational time as shown in Figure 6.9. Initially, forces rise quickly in what is known as the transient chip formation zone until reaching a steady state chip formation zone where forces tend to fluctuate around a stable plateau due to remeshing steps on the workpieces mesh. For the subsequent analysis, the average forces for each simulation were calculated from the steady state zone.

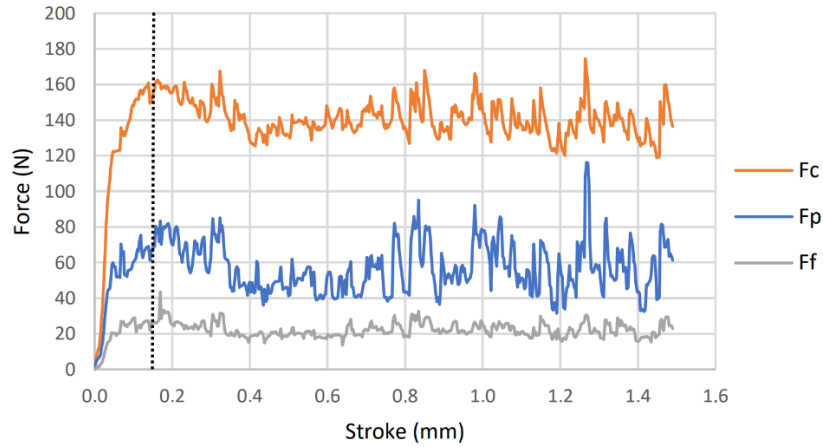


Figure 6.9 - Load spectrum for the numerical simulation.

Figure 6.10 shows the average results of alloy 1, per each cutting speed, for both 0.1 and 0.2 mm/rev feeds. An increase in feed rate results in an increase in the cutting force for both alloys, as was expected and verified in the experimental runs. Furthermore, with the increase on cutting speed, cutting force has a slight decreasing tendency, phenomenon that also happened on the experimental tests. Despite this, the main difference from experimental data and FEM simulation is on the passive force ( $F_p$ ) which was higher than the cutting force ( $F_c$ ) with this trend being verified both on experimental and literature. Several reasons may have contributed to the highly underestimation of passive force: the workpiece material being defined has having and plastic behaviour instead of elasto-plastic; invariable friction model and coefficient through all the chip-tool interface; size effects which are not replicated in the simulation due the element size on tool-chip interface, possibly needing more refined discretization on the workpiece mesh; difficulties to represent stress below the tool radius.

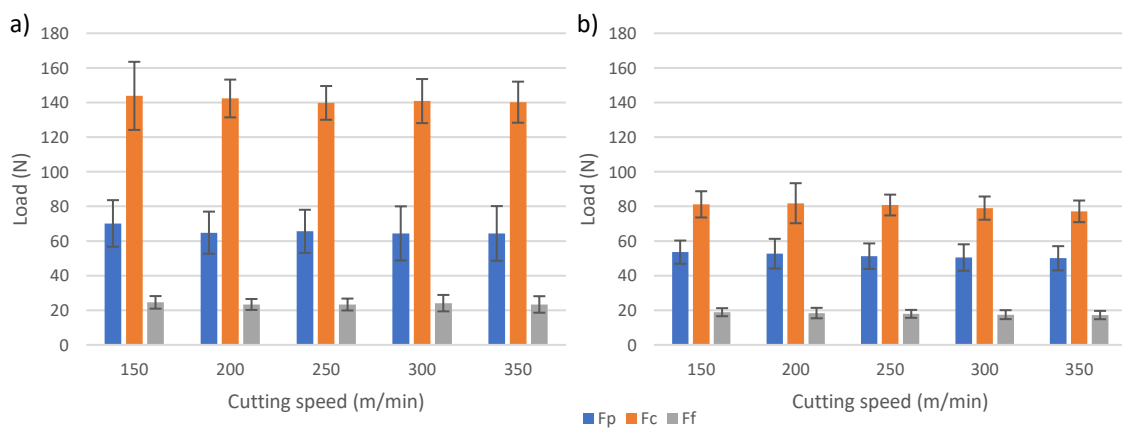


Figure 6.10 - Average cutting loads for alloy 1 turning simulation at constant  $a_p = 0.15\text{mm}$ : a)  $f = 0.2\text{ mm/rev}$ , b)  $f = 0.1\text{ mm/rev}$ .

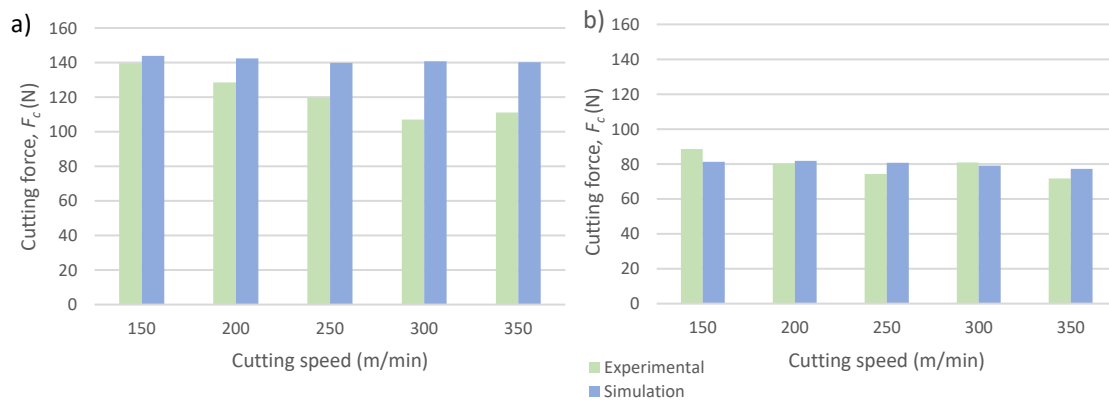


Figure 6.11 -  $F_c$  comparison between experimental and simulation for alloy 1 at constant  $a_p = 0.15$  mm: a)  $f = 0.2$  mm/rev, b)  $f = 0.1$  mm/rev.

Even though that for this three-dimensional simulation, material characterization was limited, when comparing with experimental results, alloy 1 obtained an average relative error smaller than 6% and 18% for feeds 0.1 and 0.2 mm/rev, respectively. It was also notable that the proposed constitutive material law for alloy 1 did not accurately represent the real effects of thermal softening and/or strain rate hardening. This is particularly noticeable in Figure 6.11 a), where the decrease on experimental cutting forces is not accompanied by the simulated cutting forces. Despite presenting some deviation from the experimental, the built model for alloy 1 is able to reasonably estimate the principal cutting force particularly at lower cutting speeds where strain rates and temperatures are lower.

Concerning alloy 2, an average relative error smaller of 7% and 14% was obtained for feeds 0.1 and 0.2 mm/rev, respectively. Again, passive force was highly underestimated.

All simulations resulted in higher cutting forces than the experimental ones suggesting that the model could be calibrated based on experimental cutting tests to achieve closer results. Despite the initial overestimation in cutting forces, at the lowest cutting speed, the proposed Johnson-Cook model seems to represent the real effects of thermal softening and/or strain rate hardening of alloy 2, which are less noticeable on the later alloy than in alloy 1. So, the proposed flow stress model for alloy 1 represents the cutting forces, at the lowest speed, with a negligible error of 4N, but then fails to compensate for the thermal softening and strain rate at higher speeds. On alloy 2, despite the overestimation of cutting forces, the equation seems to represent the thermal softening and/or strain rate hard close to the experimental behaviour of the alloy.

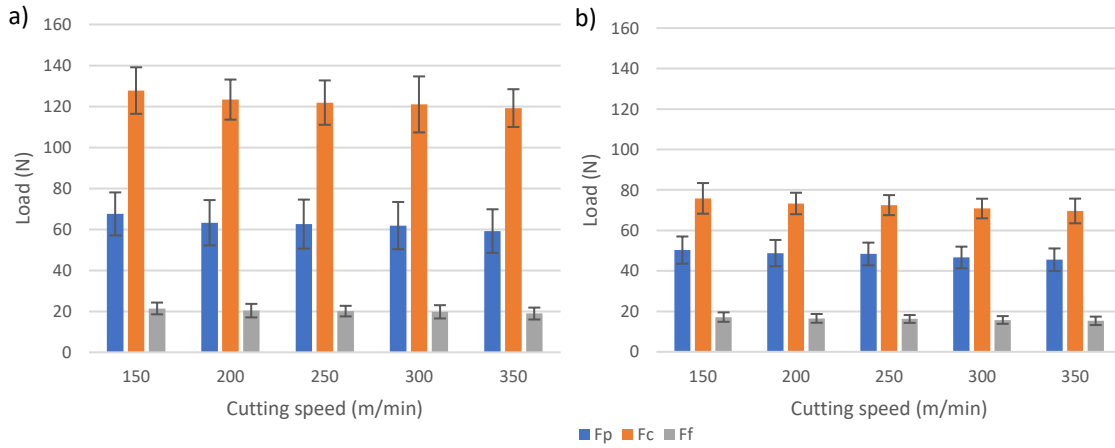


Figure 6.12 - Average cutting loads for alloy 2 turning simulation at constant  $a_p = 0.15\text{mm}$ : a)  $f = 0.2\text{ mm/rev}$ , b)  $f = 0.1\text{ mm/rev}$ .

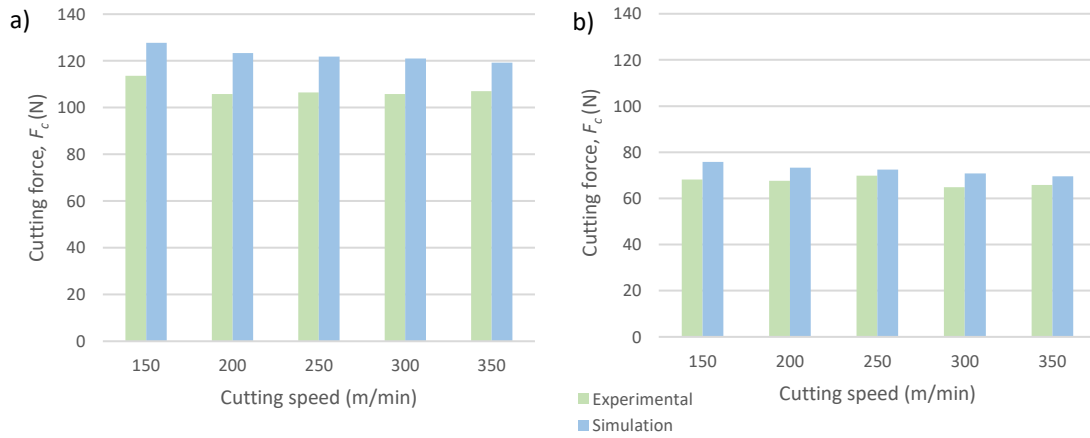


Figure 6.13 -  $F_c$  comparison between experimental and simulation for alloy 2 at constant  $a_p = 0.15\text{mm}$ : a)  $f = 0.2\text{ mm/rev}$ , b)  $f = 0.1\text{ mm/rev}$ .

## 6.6 Chip analysis

Both materials obtained serrated chips due to the presence of a damage model in the simulation. Stress distribution is on Figure 6.14 and Figure 6.15, showing that intense plastic deformation stresses are focused in the primary shear zone. Stress concentration is also visible on the secondary deformation zone due the friction between the chip and tool especially on the 2D simulation. Alloy 1 achieved higher stress values than alloy 2, due to its increased strength. 3D simulations resulted always in higher stresses and temperatures due to the two angles made by the tool which make the chip curl into a spiral.

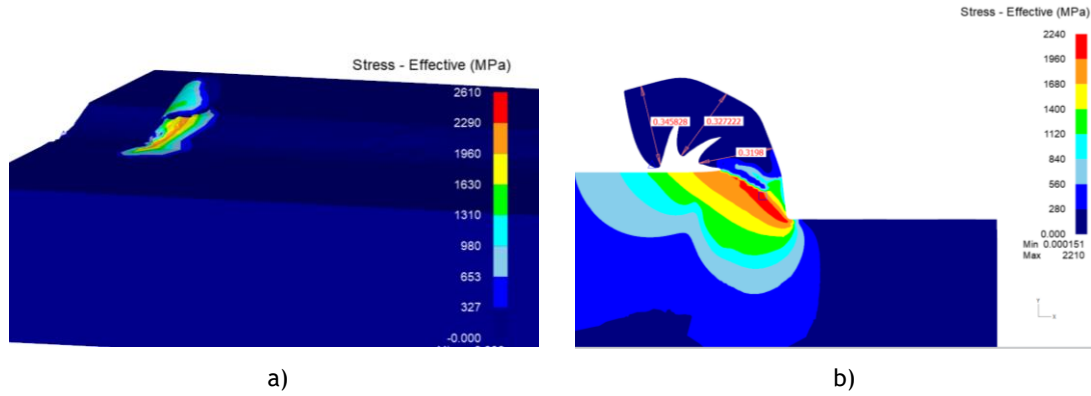


Figure 6.14 - Chip stress distribution for alloy 1, at  $v_c = 200\text{m/min}$ ,  $f = 0.2\text{ mm}$ .  $a_p = 0.15\text{mm}$ : a) 3D, b) 2D.

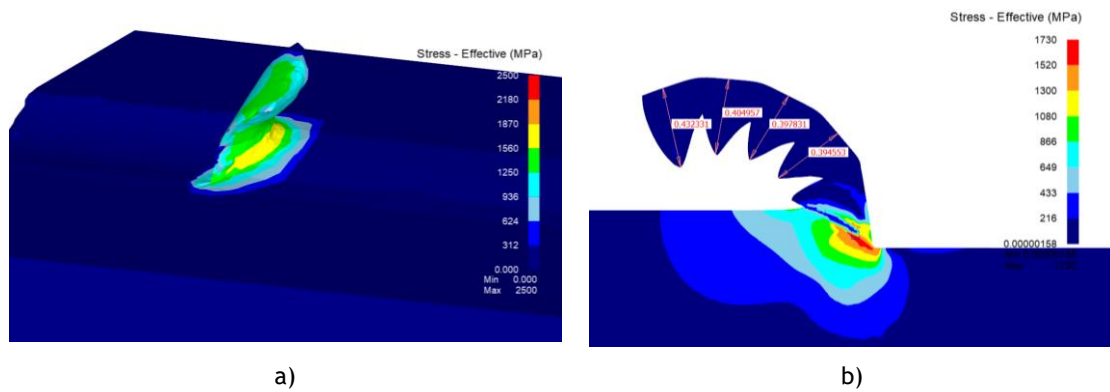
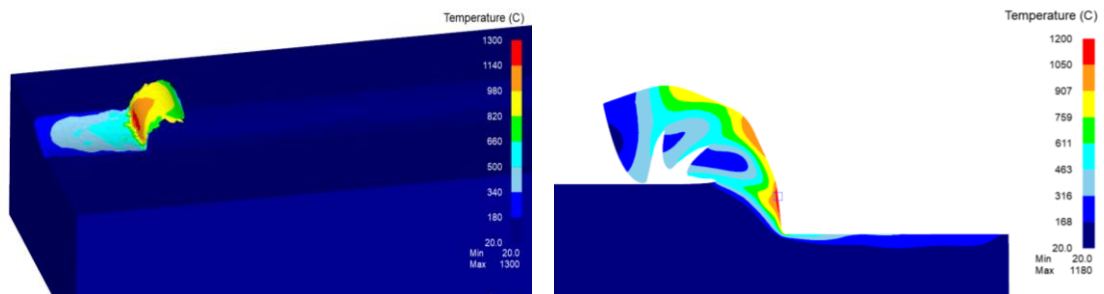
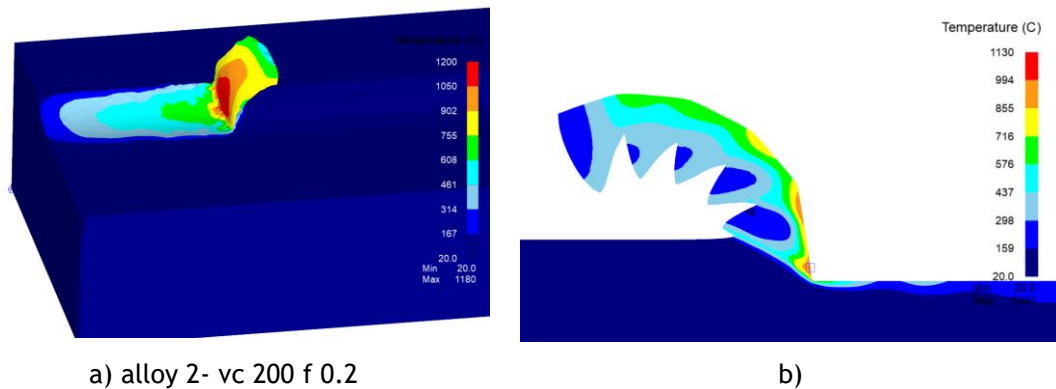


Figure 6.15 - Chip stress distribution for alloy 2, at  $v_c = 200\text{m/min}$ ,  $f = 0.2\text{ mm}$ .  $a_p = 0.15\text{mm}$ : a) 3D, b) 2D.

Regarding temperature distribution, the zone with the maximum temperature is located at the bottom of the chip, which is related to the zone where the maximum plastic deformation is achieved and there is friction between cutting edge and chip. Temperature decreases when increasing the distance to this point. Alloy 1 achieved maximum temperatures of  $1300^\circ\text{C}$  and  $1180^\circ\text{C}$  for the 3D and 2D simulations, respectively. Regarding alloy 2, maximum temperatures of  $1180^\circ\text{C}$  and  $1040^\circ\text{C}$  were obtained for the 3D and 2D simulations, respectively, which seem values well correlated with experimental obtained values [108, 119]. Given that alloy 1 had higher strength, thus attaining higher cutting forces during the cutting simulation, resulting in more energy involved and its subsequent higher generation of heat.



a) b)  
Figure 6.16 - Chip temperature distribution for alloy 1, at  $v_c = 200\text{m/min}$ ,  $f = 0.2\text{ mm}$ .  $a_p = 0.15\text{mm}$ : a) 3D, b) 2D.



a) alloy 2-  $v_c$  200  $f$  0.2 b)  
Figure 6.17 - Chip temperature distribution for alloy 2, at  $v_c = 200\text{m/min}$ ,  $f = 0.2\text{ mm}$ .  $a_p = 0.15\text{mm}$ : a) 3D, b) 2D.

## 6.7 Tool wear

DEFORM<sup>TM</sup> software tool wear module comes with two predefined models to calculate tool wear. These two models, represented on Section 3.2.4 by equations 3.14 and 3.15, have interface pressure and sliding velocity between tool and workpiece as input for the tool wear to be calculated.

Further analysing interface pressure and sliding velocity, it was possible to see that these are present only on the rake face, where exiting chip interferes with the rake face of the turning tool. Given that these two parameters are an input for the tool wear calculation, as expected no tool flank wear is simulated. This could be caused by unrepresentative elastic model which could not modulate the elastic return of the material after being cut and friction that is also not correctly set for this zone.

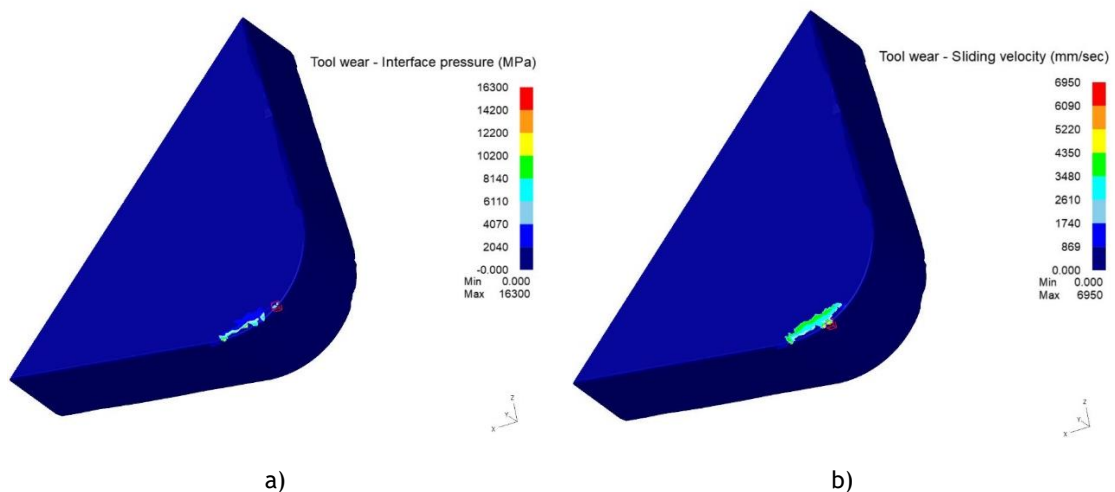


Figure 6.18 - Tool interface pressure (a) and sliding velocity (b).

Despite not being possible to replicate wear on the flank face, the area of tool-chip interface, where crater wear is located, seems to be reasonably reproduced on the simulation. From a macroscopic point of view, the morphology of the wear zone appears to correlate well with the crater zone created during experiments. Both on the experimental and simulation the worn area starts larger close to the depth of cut line, becoming gradually finer until reaching the flank face of the tool. Figure 6.19 and Figure 6.20 show the similarities between the experimental and simulated crater wear at a feed of 0.1mm/rev and 0.2 mm/rev, respectively. As expected with an increase in feed resulted in a larger wear area, with the cutting edge suffering from the larger wear. The wear depth values were not calibrated due to the inherent limitation of not being possible to predict flank wear.

Figure 6.21 compares the simulated wear pattern with a SEM image of the rake face, allowing to verify a close correlation in the wear area morphology and dimensions.

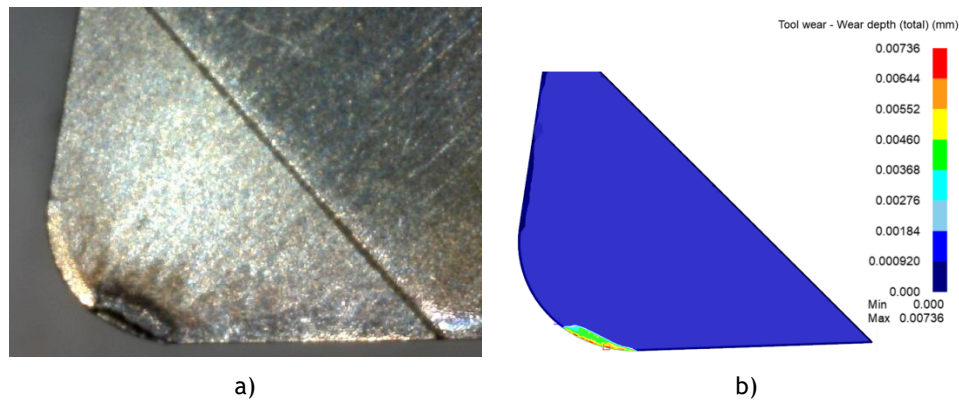


Figure 6.19 - Crater wear on the rake face at a feed of 0.1mm/rev: a) experimental, b) simulation.

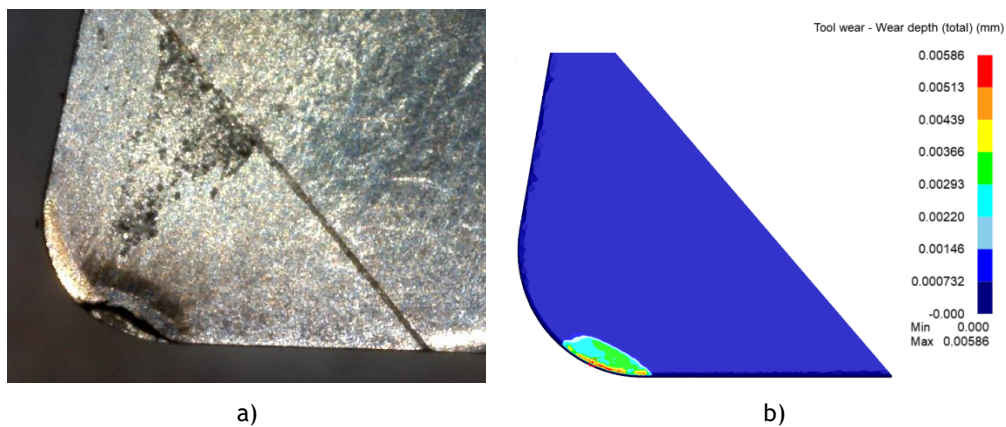


Figure 6.20 - Crater wear on the rake face at a feed of 0.2mm/rev: a) experimental, b) simulation.

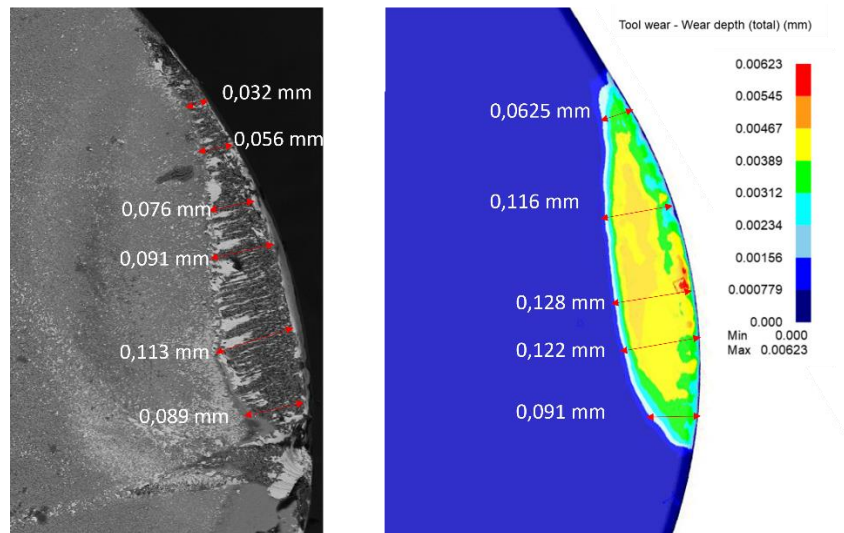


Figure 6.21 - Comparison of crater SEM image and simulated wear profile.

# Chapter 7

## Conclusions and future work

### 7.1 Conclusions

In this section, the obtained conclusions from the experimental procedures are presented, as well as preliminary conclusions derived from the 2D/3D metal cutting simulations with DEFORM™.

#### 7.1.1 *Hard turning Inconel 718 with PCBN tools*

- In terms of cutting forces, there is a clear dependence between the obtained values and the adopted cutting parameters. The main cutting force increases for higher feed rates and decreases for higher cutting speeds.
- Inconel 718 heat treatments and therefore mechanical properties influence wear modes and tool life. While material hardness has greater impact on the notching phenomena, the lower strength material achieved higher flank wear probably due to its higher ductility and adhesion to the workpiece.
- With increasing cutting speed, it seems that the dominant wear mode changes from mechanical abrasion to chemical diffusion thus decreasing the influence of mechanical properties on tool life.
- Low content PCBN tools are suitable to machine Inconel 718 at high cutting speeds ( $250 < v_c < 350$  m/min) and low depth of cut (0.15 mm). At lower cutting speeds ( $150 < v_c < 200$  m/min) notching and chipping are the main cause of wear causing instability on the cutting operation and lead to unpredictable tool failure. At high cutting speeds adhesion and diffusion of Inconel 718 into the tool surface deteriorate the cutting edge geometry and toughness.

- TiN binder seemed to improve the tool resistance when machining this superalloy, yet more experiments should be done.
- Lower cutting speeds and the lack of chip breaker resulted in poor chip control at low cutting speeds, there was a tendency of chips to tangled around the workpiece. Increasing cutting speed was favourable to the appearance of chip segmentation.
- Of all forces involved in the turning operation, passive force was the greatest, which is typical when the depth of cut is smaller than the nose radius of the tool, and showed a close evolution with the increase on tool wear.

### 7.1.2 FEM simulation of Inconel 718 hard turning

- Cutting forces obtained from the proposed numerical models correlated well with the experimental values, with an average relative error lower than 10% and 11% for alloy 1 and for alloy 2, respectively.
- The need for accurate mechanical and tribological characterization is highlighted by the lack of predictive power of the numerical model with regards to passive and feed forces.
- Inverse material characterization through compression tests revealed as a simple and effective method, despite the constraints of not knowing the material behaviour at high strain-rates and high temperatures.
- The numerical model was able to accurately predict tool-chip interface pressure and sliding velocity, which is illustrated by the tool wear variable distribution on the tool's rake face.

## 7.2 Future work

- Further studies on the characteristics of surface integrity, such as microhardness, surface roughness and residual stresses of the workpiece after machining and possibly adding other cutting parameters and variables such as cooling.
- Comparison of cutting forces, tool wear, chips formation between the same material produced by conventional and additive methods, which allows for producing complex geometries and has gained significant interest in aerospace, energy, automotive and medical industries.

- Experimentally testing higher parameters ( $v_c$ ,  $f$ ,  $a_p$ ) in turning operations to understand it's effect on cutting integrity and tool wear and enable the establishment of predictive process data in terms of cutting forces, tool wear and specific cutting pressure.
- Flow stress characterization of the Inconel 718 under high strain rates and temperatures, and thermal and elastic characterization over a wide range of temperatures, in order to build an accurate material constitutive model that simulates the material behaviour.
- Development and simulation of a more realistic material model for the Inconel alloy that accounts, for example, for material recrystallization and microstructural effects.
- Creation and development of subroutine capable of updating the tool geometry with experimental calibration.
- Investigate the economical side of high-speed machining superalloys with PCBN tools and comparison with other tool materials (e.g. cemented carbide).
- Flank wear may be possible to simulate with updating geometry after reaching the thermomechanical steady state followed by calculation of the tool wear for each node. After these two steps a new worn tool geometry is defined and tool geometry and mesh can be updated.

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# Appendix A

## Alloy 1 technical sheet

VDM Metals GmbH  
on behalf of VDM Metals International GmbH

Inspection certificate 232215/0  
DIN EN 10204/01.05 3.1

Order No. 588376  
Purchase Order No. VDMJ-7497

VDM Metals

Page: 1 / 2  
Printed: 14. JAN 2022

VDM Metals Japan K.K. for  
Osaka Stainless  
1-4-2 Kasumigaseki, Chiyoda-ku  
J -100-0013 Tokyo

VDM  
Trademark  
VDM® Alloy 718  
NICROFER 5219 NB  
2.4668

Product  
Bar, round, hot rolled, solution ann. / age hardened, peeled

Specification  
Osaka Specification Rev. 17 26.05.2021  
ASTM B 637-18  
ASME BPVC.II.B-2017 SB-637  
AMS 5663 N  
GE C50TF13-S19 only analysis  
GE B 50TF15 S34 only analysis

Material  
Alloy 718  
UNS N07718  
UNS N07718  
UNS N07718  
2.4668  
2.4668

| Item | Pcs | Weight [kg] | Dimension [mm] | Cast   | Lot       | Delivery No. |
|------|-----|-------------|----------------|--------|-----------|--------------|
| 1    | 9   | 715         | 55,00 Ø x 4000 | 421723 | 105196012 | 8682055026   |

Analysis (weight %)

| Cast   | country of manufacturer | country of melt |
|--------|-------------------------|-----------------|
| 421723 | Germany                 | Germany         |

GFAAS=graphite furnace AAS analysed corresponding to ASTM E1184-21, ASTM E1834-18  
ICP=inductive coupled plasma analysed corresponding to ASTM E1479-16, ASTM E2594-20  
LE=combustion analysis analysed corresponding to ASTM E1019-18  
OE=optical emission analysis analysed corresponding to ASTM E1086-14, ASTM E3047-16  
RF=X-ray fluorescence spectroscopy analysed corresponding to ASTM E572-21, ASTM E1085-16, ASTM E1621-21, ASTM E2465-19  
Osaka Specification Rev. 17 26.05.2021; ASTM B 637-18; ASME BPVC.II.B-2017 SB-637; AMS 5663 N; GE C50TF13-S19 only analysis; GE B 50TF15 S34 only analysis

| analysis |             |          | C        | S         | Cr       | Ni            | Mn       | Si      | Mo       | Ti       | Nb            | Cu             | Fe     |
|----------|-------------|----------|----------|-----------|----------|---------------|----------|---------|----------|----------|---------------|----------------|--------|
| Cast     | Melting Pr. |          |          |           |          |               |          |         |          |          |               |                |        |
| 421723   | VIM/VAR     | top Meth | 0,03 LE  | <0,001 LE | 18,55 RF | 52,50 RF      | 0,04 RF  | 0,06 RF | 3,04 RF  | 0,94 RF  | 5,31 RF       | 0,03 RF        | R18,67 |
| Cast     | Melting Pr. |          | P        | Al        | Mg       | Pb            | Ca       | Co      | B        | Ta       | Se            | Bi             |        |
| 421723   | VIM/VAR     | top Meth | 0,007 OE | 0,57 RF   | 0,002 OE | <0,0002 GFAAS | 0,001 OE | 0,15 RF | 0,004 OE | 0,01 ICP | <0,0003 GFAAS | <0,00003 GFAAS |        |

| Sample Condition             |             | Tensile Test                                                                                       |       |       |       |       |       |       |         |                |                | Hardness Test         |  |
|------------------------------|-------------|----------------------------------------------------------------------------------------------------|-------|-------|-------|-------|-------|-------|---------|----------------|----------------|-----------------------|--|
| solution ann. / age hardened |             | 1 ASTM E8/E8M - 21 (acc) / longitudinal specimen<br>2 ASTM E 21 - 20 (acc) / longitudinal specimen |       |       |       |       |       |       |         |                |                | 1 ASTM E10 - 18 (acc) |  |
|                              |             | Temp Yield0.2% Yield1.0% Tensile Elongation                                                        |       |       |       |       |       |       |         |                |                |                       |  |
| Lot                          | Sample No.  | [°C]                                                                                               | [MPa] | [MPa] | [MPa] | A [%] | A [%] | A [%] | RoA [%] | HBW 10/3000/ A |                |                       |  |
| 105196012                    | 103T001-A01 | 2                                                                                                  | 649   | 982   | 1155  | 4D    | 36,1  |       | 69,0    |                |                |                       |  |
| 105196012                    | 103T001-A01 | 1                                                                                                  | RT    | 1169  | 1444  | 4D    | 21,7  |       | 40      | 1              | 428 1/2 radius |                       |  |

We herewith certify, that the material is in conformance with the above mentioned specifications

Mark of the Inspector

\* 232215-O-E \*

E-Mail uenal.uecuencue@vdm-metals.com

Authorized inspection representative

Date of release: 14.01.2022

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Daniel Apfalter Zemp, Frank Moritz, Rolf Schencking  
Commercial register: Iserlohn local court, 45327  
Company domicile: Werdohl

# Appendix B

## Edge measurements

Tool 602

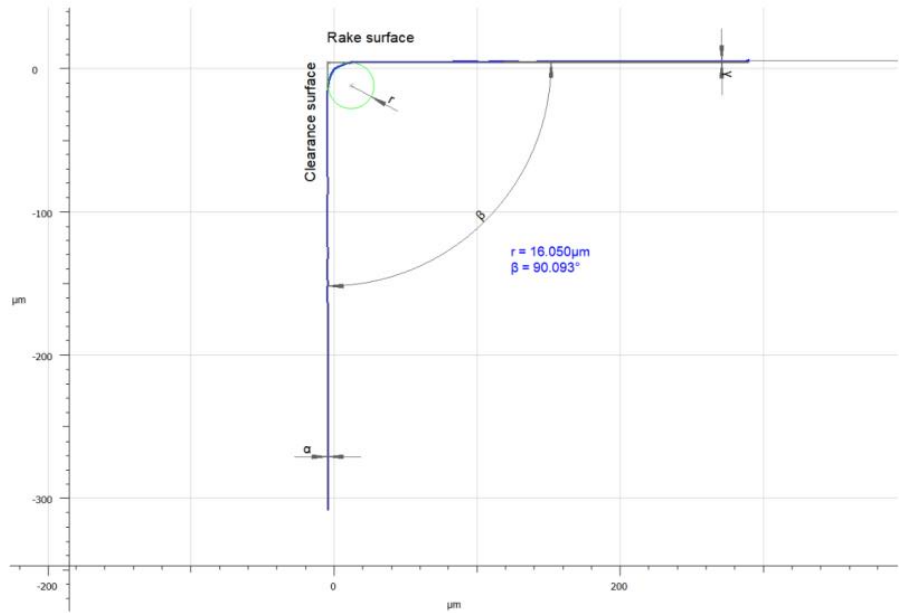
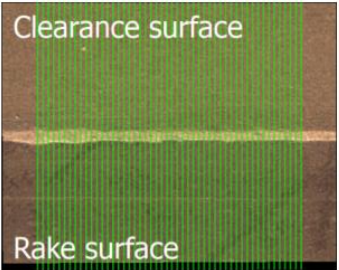
Alicona Imaging GmbH  
Dr.-Auner Strasse 21a  
A-8074 Raaba/Graz

alicona

### EdgeMasterModule Measurement Report

Date of Measurement: 06/07/2022 15:38:04 Operator: producao  
Edge Profile Type: Negative Bevel  
Reference Type: PCBN-ISO-POS

| Name  | Value      | Unit | Status | Nom.   | Lower   | Unit | Upper   | Unit | Description                                             |
|-------|------------|------|--------|--------|---------|------|---------|------|---------------------------------------------------------|
| r     | 16.050     | µm   | OK     | 15.000 | -8.500  | µm   | 38.500  | µm   | Mean radius of mean edge                                |
| by1   | -          |      | n.a.   | 0.000  | -10.000 | µm   | 10.000  | µm   | True negative bevel length w.r.t. tangent-line crossing |
| by1   | -          |      | n.a.   | 0.000  | -10.000 | µm   | 10.000  | µm   | True negative bevel length w.r.t. tangent point         |
| γb    | -          |      | n.a.   | 0.000  | 11.000  | °    | 1.000   | °    | Angle of negative bevel                                 |
| β     | 90.093     | °    | OK     | 0.000  | -11.000 | °    | 11.000  | °    | Clearance angle                                         |
| α     | 90.093     | °    | OK     | 80.000 | -10.500 | °    | 170.500 | °    | Wedge angle                                             |
| γ     | -0.162     | °    | OK     | 24.000 | -2.000  | °    | 50.000  | °    | Rake angle                                              |
| φ     | 853.774e-9 |      | OK     | 0.000  | -2.000  |      | 2.000   |      | Symmetry angle                                          |
| SRa   | 16.278     | µm   | NOK    | 0.000  | -10.000 | µm   | 10.000  | µm   | Dist. apex to end of clearance roundness                |
| SRV   | 16.832     | µm   | NOK    | 0.000  | -10.000 | µm   | 10.000  | µm   | Dist. apex to end of rake roundness                     |
| K     | 1.034      |      | NOK    | 0.000  | -0.100  |      | 0.100   |      | Symmetry of cutting edge                                |
| Δr    | 6.409      | µm   | NOK    | 0.000  | -5.000  | µm   | 5.000   | µm   | Min. dist. of edge to apex                              |
| WΔr   | 13.096     | µm   | OK     | 80.000 | -70.000 | µm   | 230.000 | µm   | Edge width                                              |
| Eoq   | 0.170      | µm   | OK     | 0.000  | 0.000   | µm   | 1.000   | µm   | Form deviation of circle (RMS)                          |
| Ftype |            |      | OK     |        |         |      |         |      | Estimated Curvature                                     |



Measurement performed by Alicona EdgeMasterModule, 06/07/2022 15:38:04

Tool 603

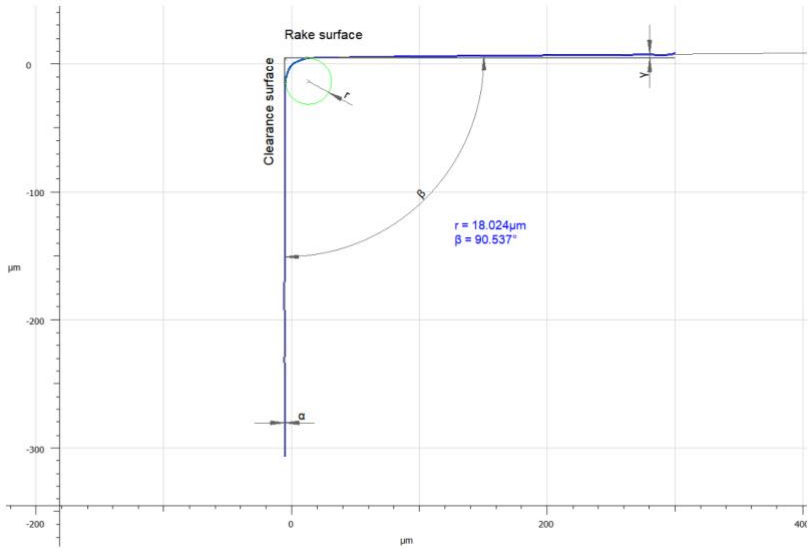
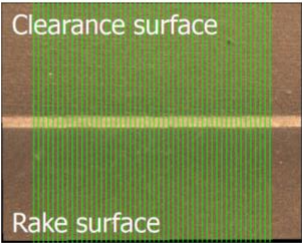
Alicona Imaging GmbH  
Dr.-Auner Strasse 21a  
A-8074 Raaba/Graz

aliconona

EdgeMasterModule Measurement Report

Date of Measurement: 06/07/2022 15:34:25 Operator: producao  
Edge Profile Type: Negative Bevel  
Reference Type: PCBN-ISO-POS

| Name  | Value  | Unit | Status | Nom.   | Lower   | Upper   | Unit | Description                                             |
|-------|--------|------|--------|--------|---------|---------|------|---------------------------------------------------------|
| r     | 18.024 | µm   | OK     | 15.000 | -8.500  | 36.500  | µm   | Mean radius of mean edge                                |
| py1   | -      |      | n.a.   | 0.000  | -10.000 | 10.000  | µm   | True negative bevel length w.r.t. tangent-line crossing |
| py    | -      |      | n.a.   | 0.000  | -10.000 | 10.000  | µm   | True negative bevel length w.r.t. tangent point         |
| pb    | -      |      | n.a.   | 0.000  | -1.000  | 1.000   | µm   | Angle of negative bevel                                 |
| α     | -0.029 | °    | OK     | 0.000  | -11.000 | 11.000  | °    | Clearance angle                                         |
| β     | 90.537 | °    | OK     | 80.000 | -10.500 | 170.500 | °    | Wedge angle                                             |
| γ     | -0.508 | °    | OK     | 24.000 | -2.000  | 30.000  | °    | Rake angle                                              |
| φ     | 0.000  | °    | OK     | 0.000  | -2.000  | 2.000   | °    | Symmetry angle                                          |
| Sα    | 18.796 | µm   | NOK    | 0.000  | -10.000 | 10.000  | µm   | Dist. apex to end of clearance roundness                |
| Sγ    | 18.911 | µm   | NOK    | 0.000  | -10.000 | 10.000  | µm   | Dist. apex to end of rake roundness                     |
| K     | 1.006  | NOK  | NOK    | 0.000  | -0.100  | 0.100   |      | Symmetry of cutting edge                                |
| Δr    | 6.964  | µm   | NOK    | 0.000  | -5.000  | 5.000   | µm   | Min. dist. of edge to apex                              |
| WΔr   | 14.505 | µm   | OK     | 80.000 | -70.000 | 230.000 | µm   | Edge width                                              |
| Eci   | 0.167  | µm   | OK     | 0.000  | 0.000   | 1.000   | µm   | Form deviation of circle (RMS)                          |
| Ftype |        |      | OK     |        |         |         |      | Estimated Curvature                                     |



Measurement performed by Alicona EdgeMasterModule, 06/07/2022 15:34:25

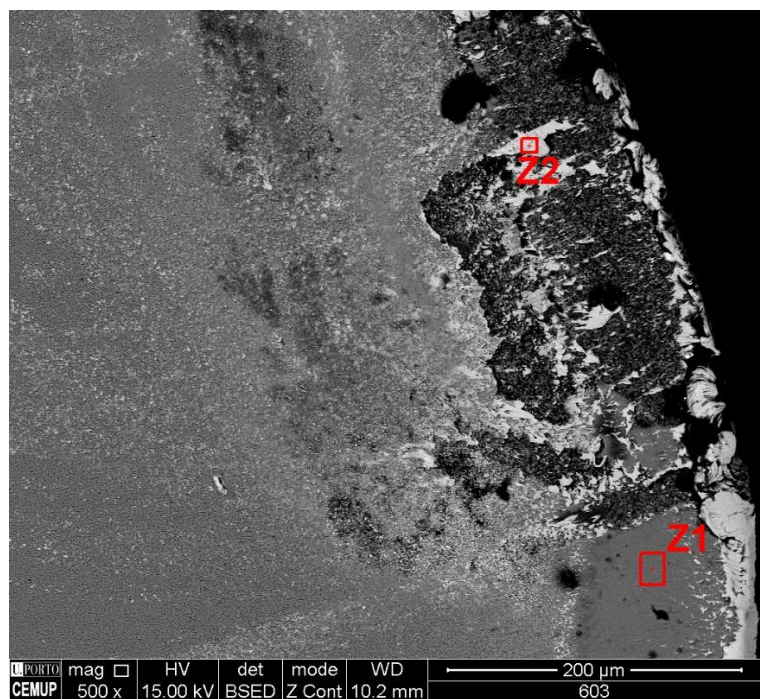
## Appendix C

### Test matrix

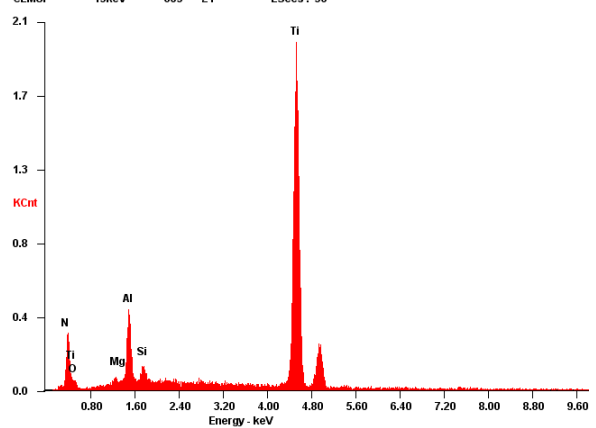
| Exp. Number | $a_p$ [mm] | $f$ [mm/rev] | $v_c$ [m/min] | Tool grade | Alloy |
|-------------|------------|--------------|---------------|------------|-------|
| 1           | 0.15       | 0.1          | 150           | PBY 603    | 1     |
| 2           |            |              | 200           | PBY 603    | 1     |
| 3           |            |              | 250           | PBY 603    | 1     |
| 4           |            |              | 300           | PBY 603    | 1     |
| 5           |            |              | 350           | PBY 603    | 1     |
| 6           |            | 0.2          | 150           | PBY 603    | 1     |
| 7           |            |              | 200           | PBY 603    | 1     |
| 8           |            |              | 250           | PBY 603    | 1     |
| 9           |            |              | 300           | PBY 603    | 1     |
| 10          |            |              | 350           | PBY 603    | 1     |
| 11          |            | 0.1          | 150           | PBY 602    | 1     |
| 12          |            |              | 200           | PBY 602    | 1     |
| 13          |            |              | 250           | PBY 602    | 1     |
| 14          |            |              | 300           | PBY 602    | 1     |
| 15          |            |              | 350           | PBY 602    | 1     |
| 16          |            | 0.2          | 150           | PBY 602    | 1     |
| 17          |            |              | 200           | PBY 602    | 1     |
| 18          |            |              | 250           | PBY 602    | 1     |
| 19          |            |              | 300           | PBY 602    | 1     |
| 20          |            |              | 350           | PBY 602    | 1     |
| 21          |            | 0.1          | 150           | PBY 603    | 2     |
| 22          |            |              | 200           | PBY 603    | 2     |
| 23          |            |              | 250           | PBY 603    | 2     |
| 24          |            |              | 300           | PBY 603    | 2     |
| 25          |            |              | 350           | PBY 603    | 2     |
| 26          |            | 0.2          | 150           | PBY 603    | 2     |
| 27          |            |              | 200           | PBY 603    | 2     |
| 28          |            |              | 250           | PBY 603    | 2     |
| 29          |            |              | 300           | PBY 603    | 2     |
| 30          |            |              | 350           | PBY 603    | 2     |

## **Appendix D**

### **Energy-dispersive X-ray spectroscopy**



derEDS/CEMUP  
CEMUP 15keV 603 Z1 Z1.spc LSecs: 50



derEDS/CEMUP  
CEMUP 15keV 603 Z2 Z2.spc LSecs: 50

