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**Machinability analysis of VAT 32[®] nickel based superalloy using commercial and
experimental milling inserts**

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Análise da usinabilidade da superliga de níquel VAT 32[®] utilizando insertos comerciais e experimentais para fresamento

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Orientador: Prof. Dr. Manoel Cléber de Sampaio Alves

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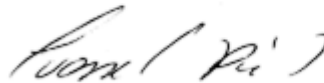
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This work is dedicated to my family.

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“Science knows no country, because knowledge belongs to humanity, and is the torch which illuminates the world.”

Louis Pasteur

ABSTRACT

Over the past decades, the superalloy metallurgy industry has made possible many innovations with high impact to the metal-mechanic industry. However, currently, these industries have to cope with both the technical and commercial challenges of new rigid environmental regulations. In this scenario, due to a more restrict series of environmental requirements, a new nickel intermediate superalloy designated VAT 32[®] was developed for application in automotive high performance valves. The VAT 32[®] superalloy presents high wear and high temperatures resistance and lower production costs if compared to traditionally applied superalloys. However, due to its chemical composition and microstructure, serious difficulties are observed in its machining process, making it very difficult to machine and limiting its application. Therefore, in order to study the machinability of the VAT 32[®] new superalloy considering the milling process, the present research work evaluated the alloy's machinability by applying experimental alumina-based ceramic cutting tools ($\text{Al}_2\text{O}_3\text{-MgO}$) developed by the research group of the Materials and Technology Department of the São Paulo State University (UNESP), in comparison to TiAlN-TiN PVD-coated commercial carbide tools. The machining process output variables analyzed were power consumption, vibration, acoustic emission, resulting surface quality (roughness R_a , R_t and R_z), tools wear, chip formation and the specific cutting pressure (K_{sm}). To evaluate the main effects in machining it was applied the analysis of variance (ANOVA) and normality tests conducted according the design of experiments of Full-Factorial methodology. The dry finishing machining by milling was executed to the cutting speeds of 60, 80 e 100 m/min for the carbide inserts and to 700, 800 and 900 m/min to the ceramic inserts (HSM). Results obtained reveal that it was possible to accomplish the VAT 32[®] superalloy machining through milling within standard surface quality ranges, to both cutting tools applied. The alumina-based ceramic inserts allowed satisfactory roughness results (R_a 0.734 μm) associated to similar wear per cutting length results $V_b \cdot 1000/L_c$ (0.015) in comparison to the coated carbide inserts. The $\text{Al}_2\text{O}_3\text{-MgO}$ inserts are recommended for machining the VAT 32[®] at speeds of 900 m/min and low feed of 0.05 mm/t due to its high chemical stability and hardness, allowing the production of shear type chips. The coated carbide tools presented a superior performance to machine the VAT 32[®] by milling, being the best roughness (R_a 0.608 μm), flank wear V_b (0.125 mm) and $V_b \cdot 1000/L_c$ (0.010) results found to the cutting speed of 60m/min and feed of 0.10mm/t, that generate segmented chips with loose arc form, excellent for good handling and disposal.

KEYWORDS: Machining. Milling. Nickel superalloy. Alumina-based tool. Coated carbide inserts. HSM.

RESUMO

Nas últimas duas décadas a indústria metalúrgica de fabricação de superligas tem possibilitado diversas inovações de alto impacto na indústria metal mecânica. Entretanto, atualmente, essas indústrias tem tido que lidar com os vários desafios técnicos e comerciais impostos pelas atuais rígidas regulações de normas ambientais. Portanto, com o objetivo de satisfazer uma nova série de normas ambientais mais restritiva, a nova superliga de níquel intermediária designada VAT 32[®] foi desenvolvida para a aplicação em válvulas automotivas de alta performance. A superliga VAT 32[®] apresenta alta resistência ao desgaste à altas temperaturas aliada a custos de produção mais baixos se comparados às superligas aplicadas tradicionalmente. No entanto, devido à sua composição química e microestrutura, sérias dificuldades são observadas durante o processo de usinagem, diminuindo sua usinabilidade e limitando sua aplicação. Portanto, com o objetivo de estudar a usinabilidade desta nova superliga VAT 32[®] pelo processo de fresamento, o presente trabalho de pesquisa avaliou a aplicação de ferramentas de corte cerâmicas experimentais compostas de alumina dopada com óxido de magnésio ($\text{Al}_2\text{O}_3\text{-MgO}$), desenvolvidas pelo grupo de pesquisa do Departamento de Materiais e Tecnologia da UNESP, em comparação com ferramentas de corte comerciais de metal duro revestidas com TiAlN-TiN pelo método PVD. As variáveis de saída do processo de usinagem analisadas foram: a potência consumida, vibração, emissão acústica, qualidade da superfície resultante (rugosidade R_a , R_t e R_z), desgaste e avarias da ferramenta de corte, mecanismos de formação dos cavacos e a pressão específica de corte média (K_{sm}). Para avaliar os principais efeitos na usinagem, foi aplicada a análise de variância (ANOVA) e testes de normalidade, conduzidos de acordo com o delineamento de experimentos pela metodologia fatorial completo. O fresamento foi realizado sem lubrificação e com aplicação de velocidades de corte de 60, 80 e 100 m/min para as ferramentas de metal duro e 700, 800 e 900 m/min para as ferramentas cerâmicas (HSM). Os resultados obtidos revelam que foi possível realizar com sucesso a usinagem por fresamento da superliga VAT 32[®] com rugosidade dentro das faixas de qualidade superficial padrão para as duas ferramentas de corte aplicadas. As pastilhas experimentais de cerâmica possibilitaram obtenção de baixa rugosidade média (0.734 μm) associada a um desgaste específico $V_b \cdot 1000/L_c$ (0.015) semelhante ao obtido em comparação às pastilhas de metal duro revestidas (0.010). As pastilhas $\text{Al}_2\text{O}_3\text{-MgO}$ podem ser recomendadas para a usinagem do VAT 32[®] em velocidades de 900 m/min e baixo avanço de 0,05 mm/dente devido à sua alta estabilidade química e dureza, com produção de cavacos de cisalhamento. As ferramentas de metal duro revestido

apresentaram alto desempenho aliado à baixa rugosidade média ($0.608 \mu\text{m}$) e desgaste de flanco V_b (0.125 mm) para a velocidade de corte de 60m/min e avanço de $0,10\text{mm/dente}$ com produção de cavacos segmentados com forma de arco solto que facilitam seu manuseio e descarte.

PALAVRAS-CHAVE: Usinagem. Fresamento à seco. Superliga de níquel. Ferramenta de alumina. Metal duro revestido. HSM.

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LIST OF ABBREVIATIONS

ABNT	Associação Brasileira de Normas Técnicas
ANOM	Analysis of means
ANOVA	Analysis of variance
AISI	American Iron and Steel Institute
ASM	American Society of Metals
ASTM	American Society for Testing and Materials
BCT	Body-centered tetragonal
BUE	Built up edge
CBN	Cubic Boron Nitride
CVD	Chemical Vapour Deposition
DIN	Deutsches Institut für Normung
DOC	Depth of cut
EDS	Energy-dispersive X-ray spectroscopy
FCC	Face cubic centrate
FFD	Full factorial design
HRC	Hardness Rockwell C
HSM	High Speed Machine
HV	Hardness Vickers
ISO	International Organization for Standardization
MRR	Material removal rates
NBR	Norma Brasileira Registrada
OM	Optic Microscopy
PVD	Physical Vapour Deposition
SEM	Scanning Electron Microscope
XRD	X-Ray Diffraction

LIST OF SYMBOLS

A	Amperes
A_c	Cutting area
AC	Alternate current
a_e	Radial depth of cut
AE	Acoustic emission
Al	Aluminum
Al_2O_3	Alumina
A_m	Mean cutting section area
a_p	Cutting depth
b	Cutting width
Co	Cobalt
C_s	Cutting speed
DC	Continuous current
D_{cap}	Max. cutting diameter at a specific depth (a_p)
D_i	Insert diameter
f	Feed
f_z	Feed per tooth
Fe	Iron
F_c	Cutting force
F_{cm}	Mean cutting force
h	Chip thickness
h_{ex}	Maximum chip thickness
h_m	Average chip thickness
K_s	Specific cutting pressure
K_{sm}	Mean cutting pressure
MgO	Magnesium oxide
N	Nitrogen
Ni	Nickel
P_c	Power consumption
R_a	Roughness average (centre line average)
R_t	Maximum height of the profile
R_z	Average maximum height of the profile
Ti	Titanium
TiN	Titanium nitride
u	Specific cutting energy
V	Volts
V_b	Flank wear
v_c	Cutting speed
W	Watts
γ'	Gamma prime phase

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1 INTRODUCTION

Nickel based superalloys are high-engineered materials that have a wide range of consolidated applications in marine, automotive and aeronautical industries. Currently applied in gas turbines engines, nickel based superalloys are now also used in rocket engines, space vehicles, nuclear reactors, submarines, experimental aircrafts, petrochemical equipment, steam power plants and several other high temperature applications (THELLAPUTTA; CHANDRA; RAO, 2017). However, for the past few decades the need of introducing environmental requirements into design and development of these materials became a vital issue, even considering highly applicable and well consolidated alloys. The metallurgic industry was forced to search for alternatives and apply changes to adequate the material's properties to the new working conditions generated by the environmental regulations impositions and changes, which caused the increase of mechanical stresses, operation temperatures, corrosion and wear during operation.

In order to attend to a more restrict series of environmental regulations (i.g. EURO V and VI) to materials applied for the manufacture of engine components, FARINA et al (2013) developed a new nickel intermediate superalloy for application in automotive high performance valves, designated as VAT 32[®]. The new developed superalloy present an alternative for substitution to the traditionally applied superalloy UNS N07751, showing several advantages combined with similar to better properties than the UNS N07751 alloy, including an important economic-environmental advantage marked by the reduction of nickel content in the total chemical composition.

The VAT 32[®] superalloy is a high wear resistant nickel based superalloy characterized by a high nickel-chromium austenitic matrix with dispersion of γ' and γ'' phases with a high volumetric fraction of NbC carbides, that allow the high wear resistance properties (FARINA; LIBERTO; BARBOSA, 2013b). However, the alloy's machining process face serious difficulties, due to the presence of these high-hardened NbC carbides (2500 HV), elements that increase resistance to high temperatures, but that also make the superalloy very abrasive leading to a significant increase in the wear of cutting tools during the machining process.

It is known that nickel based superalloys are generally difficult to machine materials because of their toughness, high heat resistance and high operating temperatures, hardness and chemical property to react with tool materials, low thermal conductivity and creep resistance (THELLAPUTTA; CHANDRA; RAO, 2017). Although all of these properties are necessary to design requirements, they generate a greater challenge to the manufacturing area

due to the inevitable high temperatures and stresses generated during machining. The high mechanical and thermal loads also cause high wear rate in cutting tools. The high temperature favor the solution wear mechanism and plastic deformation of the cutting edge of carbide tools, reducing tool life. However, the use of ceramic as a cutting material can be explored to machine nickel based superalloys, since ceramics are more chemically stable and retain hardness even at higher temperatures ($> 800\text{ }^{\circ}\text{C}$) when machining difficult-to-cut materials. The additional advantage of ceramic tools is the possibility to apply high speed machine (HSM), increasing the material removal rate, where the cutting speed can be three to ten times higher than carbide tools, which contributes consequently to higher productivity (ARUNA; DHANALAKSHIMI, MOHAN, 2010). Machining, being a major operation to the industry, needs to be improved in order to reduce the throughput time and an alternative is the use of ceramic tools (GRGURAŠ; KERN; PUŠAVEC, 2019).

Therefore, to increase productivity, as an alternative to the application of commercial carbide tools, this work presents the application analysis of ceramic cutting tools to machine the VAT 32[®] superalloy. The ceramic cutting tools are alumina-based experimental inserts developed by the Machining study group at the Materials and Technology department of São Paulo State University (UNESP) in Guaratinguetá Campus, that have presented good performance results in previews researches during the machining of other materials (CALLISAYA; ALVES, 2019; DE PAULA et al., 2019; SOUSA et al., 2019).

The work also focus in the milling process analysis, since milling remains as the most common manufacturing method of nickel-based superalloys parts (ARUNACHALAM; MANNAN, 2000). The study of VAT 32[®] considering specifically the milling process aims the beginning of understanding the behavior of these recent developed material during this process, favoring commercial applications beyond the automotive industry.

Pleta et al. (2015) highlight that the demand for nickel-based superalloys is increasing, especially considering the growth of the aircraft and gas turbine markets. Therefore, the study of nickel based superalloys is more than relevant (GUO; LI; JAWAHIR, 2009; M'SAOUBI; JOHANSSON; ANDERSSON, 2013). Thus the imminent necessity to study a cost-effective method to manufacture high quality components and the justification to analyze the machinability of these alloys.

The content of this research work covers the following items. Initially, the Chapter 2 state the study's main objective and detail each specific objective to achieve the research aim. Chapter 3 contains a review of the relevant literature summarizing existing studies regarding the specific research topic, in order to state the overall theoretic framework of the study and

highlight the main gaps. The applied methods and materials are described in Chapter 4, after which the results are presented and discussed in Chapter 5. Finally, Chapter 6 outlines the main conclusions and identify both limitations to the study and recommendations for further research.

1.1 SCOPE OF THE RESEARCH

This research work aims to study the machinability of the recently developed VAT 32[®] superalloy through the milling machining process applying commercial and experimental cutting tools, in order to analyze not only the material machinability but also the cutting tools performance and applicability to the process. The process output variables that were analyzed in this work are: power consumption, vibration, acoustic emission, resulting surface quality (roughness), tools wear, chip formation and the specific cutting pressure.

A detailed characterization analysis of both material and tools was done before and after the machining tests. Before the experimental phase, the superalloy characterization was made by means of chemical composition analysis, microstructure, micro and nano-hardness. The experimental cutting tools were characterized by mechanical and physical properties (e.g Young modulus, fracture toughness, micro-hardness, apparent density and microstructure).

After the machining tests, an extensive statistical treatment was applied to all output variables of the process, including the analysis of variance (ANOVA) and normality tests. The statistical analysis was conducted conform establish design of experiments (DOE) of Full-Factorial design methodology. The statistical treatment allowed the data's main effect analysis and the estimation of tendencies.

1.2 JUSTIFICATION OF THE RESEARCH

This work represents a unique approach to the broad topic of superalloys machining by focusing on the machinability determination of a new developed superalloy using not only commercial carbide tools but also experimental ceramic cutting tools. The research aim highlight the work's innovation aspect by investigating the introduction of new ceramic materials (in terms of chemical composition and density) as cutting tools to machine the VAT 32[®] superalloy, which machinability is still little known. The study focused on the machinability of this material will directly contribute to the current industrial scenario, where

there is a scarcity of works on machining of nickel-based superalloys, as pointed out by Davoodi and Eskandari (2015) and Molaiekiya, Aramesh and Veldhuis (2020).

Furthermore, understanding the new material's behavior in the specific machining process of milling is important, since most published work on the machining of nickel-based high temperature alloys using ceramic inserts are in turning, whilst milling has received little attention (ARUNACHALAM; MANNAN, 2000) although it is a common operation in the industry. Besides, the choice to study the milling process will also favor other applications to the new alloy than only in automotive industry.

The ceramic cutting tools have been showing great potential in the manufacturing sector (SINGH et al., 2018), as among the various available ceramic tools, the Alumina-based ceramics are widely applicable due to its excellent stability and oxidation resistance. However, even several studies are available on wear behavior, there still exists deficiency in a comprehensive analysis of the dominating wear mechanisms (SINGH; GHOSH; ARAVINDAN, 2020). Therefore, it is important to study the different tool wear mechanisms for the enhanced understanding of the limitations to the application of this ceramic material as cutting tool.

Moreover, there is another important justification of this research, which is the application of dry machining in the studied milling process. Several studies are giving priority to dry-machining application in manufacturing industries (SHALABY; VELDHUIS, 2019). Considering the increasing regulatory attention to the environmental and health impacts of industrial activities have been compelling manufacturers to reduce the use of cutting fluids (YOON et al., 2015). The costs of coolant use and disposal are significant (DUDZINSKI et al., 2004). Devillez, et al. (2004) demonstrated that dry machining of Inconel[®] can lead to a potentially acceptable surface quality.

The results of this research may also be beneficial to contribute to the VAT 32[®] consolidation in the market, as determining the best conditions to machine by milling with both commercial carbide and experimental alumina-based tools. This analysis can lead to the reduction of processing costs of VAT 32[®] parts and at the same time to significant scientific contribution to national technology, since currently in Brazil, the ceramic tools used are mostly imported, a fact that limits their use.

1.3 RESEARCH QUESTIONS AND HYPOTHESIS

Due to the complexity of machining analysis of newly developed materials, and since the work evaluates not only the superalloy but also the analysis of experimental cutting tools, the research work has multiple secondary research questions that answer the overall research problem. All secondary questions are connected and focused around two main points regarding the machined material (VAT 32[®]), and the cutting tools (experimental and commercial), therefore, the two main research questions are:

- What is the machinability response of the VAT 32[®] superalloy in the milling process?
- Are the experimental alumina-based ceramic cutting tools applicable to machine a nickel-based superalloy?

Each main research question rule an investigation work that can be described in terms of secondary research questions that aim to find the answer to a determined hypothesis. The secondary research questions regarding the superalloy study are detailed in Table 1, and considering the cutting tools are shown in Table 2.

Table 1 – Research questions regarding the machined material.

Research question	Hypothesis
How significant is the influence of input variables (cutting speed, feed, cutting depth) in the output variables (power consumption, acoustic emission, vibration, roughness, tool's wear)? (Considering each type of cutting tool isolated).	The cutting parameters will have strong influence on the output variables. Applied feed rate may have stronger impact in the output variables due to the milling cutting process. Machining parameters will have different influence using commercial and experimental tools.
What was the final surface quality?	Roughness results will be within standard amplitudes to both tools.
Is it possible to establish tendencies of output variables behavior?	Some output variables will be more significant than others.
Which are the most suitable conditions to machine the VAT 32 [®] superalloy by milling using both commercial and experimental tools?	Higher cutting speeds will favor the ceramic tools application.

Source: Author.

Table 2 – Research questions regarding the cutting tools.

Research question	Hypothesis
Does the experimental ceramic tools presented the necessary and essential requirements to be characterized as cutting tools? (Considering mechanical properties and chemical stability)	The experimental tools composition will guarantee the mechanical properties of toughness, hot hardness, abrasion and wear resistance. The chemical stability will not allow the formation of oxide composites and specific wear mechanisms such as diffusional wear.
What is the performance of the experimental tools in comparison to the commercial tools? (Considering wear, damage and output variables).	The experimental ceramic cutting tools will allow more productivity, with close performance to commercial tools considering power consumption and acoustic emission. Wear will have different mechanisms.
What was the tool's life considering both types of tools? Which are the observed main types of wear mechanisms? How is the tools integrity after tests?	Commercial tools life and integrity will support its future application in an industrial context of VAT 32 [®] machining. Experimental tools life and integrity will provide reliable data to continue tests with a short variation of machining parameters. Types of wear will help to understand further changes in chemical composition.
Does the tool's ceramic composition have a specific effect on the wear occurrence? What are the main causes of the wear/damage?	The ceramic composition will have a positive effect considering wear. Mechanical properties will have high impact in wear formation.
Is the final surface quality obtained with the commercial tools satisfactory? What is the impact on the surface quality of applying this ceramic composition as cutting tool?	The use of TiAlN-TiN coated carbide tools will guarantee roughness results within the standard values. The ceramic composition of experimental tools will affect the roughness results.

Source: Author.

2 OBJECTIVES

2.1 MAIN OBJECTIVE

The main objective of this work is to study the machinability of the recently developed VAT 32[®] nickel-based superalloy in order to provide knowledge regarding its behavior during the milling process and establish the best conditions to execute the machining process.

In addition, the work also investigated the application feasibility of ceramic experimental inserts in comparison to commercial inserts to successfully accomplish the milling process within standard quality results ranges.

2.2 SPECIFIC OBJECTIVES

2.2.1 VAT 32[®] Machinability analysis

- To analyze the influence of the input variables of the process (i.e., cutting speed “ v_c ”, feed “ f ”) in the output variables of the process (i.e., power consumption “ P_c ”, acoustic emission “AE”, vibration, tools wear, chips and surface quality).
- To establish and describe the best conditions applied to machine the alloy using both commercial and experimental inserts.
- To determine the best cutting parameters to execute the machining of the VAT 32[®] alloy.

2.2.2 Experimental inserts feasibility analysis

- To verify the applicability of the experimental ceramic-based inserts composed by aluminum oxide doped with magnesium oxide (Al_2O_3 -MgO), in the milling of the nickel-based superalloy VAT 32[®]. The applicability considers the tool’s final performance, surface quality, and results of P_c , EA and vibration.
- To analyze the resulting performance of the experimental and commercial inserts. The performance considers the analysis of observed wear, damages and tools integrity.
- To compare the performance of the experimental inserts to the commercial inserts composed by cemented carbide with (Ti, Al)N-TiN coating.

3 LITERATURE REVIEW

3.1 SUPERALLOYS

Superalloys are face-centered cubic (fcc, austenitic) structured alloys that can be classified by chemical composition into three groups: the Fe-Ni superalloys, the Ni-based superalloys and the Co-based super alloys (ASM, 2000), as shown in Table 3.

Table 3 – Superalloys main chemical composition.

Fe-Ni Superalloys										
Element	Ni	Fe	Ti	Al	Mo	Co	Cr	Nb	W	C
Mass %	9-44	29-67	0.3	0.3-1	0-3	0-20	0-25	0-5	0-2.5	<0.35
Nickel based Superalloys										
Element	Ni	Fe	Ti	Al	Mo	Co	Cr	Nb	W	C
Mass %	37-79,5	50-70	0-5	0-6	0-28	0-20	5-22	0-5.1	0-15	<0.30
Cobalt based Superalloys										
Element	Co	Ni	Ti	Al	Mo	Fe	Cr	Nb	W	C
Mass %	20-62	0-35	0-3	0-0.2	0-10	0-21	19-30	0-4	0-15	0-1

Source: Adapted from ASM (2000).

The austenitic fcc matrix of superalloys have extended solubility for some alloying additions, excellent ductility, and favorable characteristics for precipitation of uniquely effective strengthening phases to iron-nickel and nickel-based superalloys. According to Silva and Mei (2006), superalloys are among the most complex metallurgy materials, which in general are constituted by fcc matrix phase γ and secondary phases, including carbides. The secondary phases are the carbides MC, $M_{23}C_6$, M_6C , and M_7C_3 (rare) in all superalloy types; the fcc ordered $Ni_3(Al,Ti)$ γ' phase, γ'' bct (body-centered tetragonal) ordered Ni_3Nb , η hexagonal ordered Ni_3Ti , and δ orthorhombic Ni_3Nb intermetallic compounds only to nickel and iron-nickel-based superalloys (ASM, 2000).

The remarkable mechanical properties, especially when working at high temperatures, arise due to precipitation hardening and solid solution hardening. Most important strengthening precipitate phases are γ' and γ'' . Where the main function of carbides is to stabilize the grain boundaries against excessive shear.

Superalloys are also designed to provide high mechanical strength and high resistance to corrosion and oxidation at high temperatures, combining good resistance to fatigue and creep, with ductility and rigidity (CHOUDHURY; EL-BARADIE, 1998), being generally applied for use in temperatures above 540 °C (1000 °F). The properties can be controlled by

adjustments in chemical composition and by processing (including heat treatment), that can lead to excellent elevated-temperature strengths to finished products. These alloys have been used in cast, rolled, extruded, forged, and powder-processed forms. Sheet, bar, plate, tubing, shafts, airfoils, disks, and pressure vessels (cases) are some of the shapes that have been produced through many machining processes (ASM, 2000). These metals have been used in aircraft, industrial, and marine gas turbines; nuclear reactors; aircraft skins; spacecraft structures; petrochemical production; orthopedic and dental prostheses; and environmental protection applications. Although developed for high-temperature use, some are used at cryogenic temperatures and others at body temperature.

Superalloys are the materials which have made much of our very-high-temperature engineering technology possible. One of the start points to superalloys development could be the wide limitation of strength capabilities found in previously materials during the last second and third decades of the 20th century such as the stainless steels, the manufacturing industry needed very stronger and more corrosion resistant materials for high temperature applications (SIMS, 1984). According THELLAPUTTA et al 2017, the World War II armaments rush boosted the super alloy industry, with the adoption of a cobalt alloy (Vitallium, also known as Haynes Stellite31) used in industry to satisfy high temperature strength requirements of aerospace industry mostly in manufacturing of aircraft engines. Applications continue to expand, but at lower rates than in previous decades. Aerospace usage remains the predominant application on a volume basis.

Optimal material selection for high-temperature applications requires a understanding of the mechanical requirements at the temperature of operation including upset conditions and mechanical degradation due to high-temperature corrosive attack (AGARWAL, 2004). These specific mechanical properties requirements are: high-temperature strength, stress rupture strength, creep strength, fatigue, thermal stability, thermal shock and Toughness.

The properties requirements will vary and are different for various industries, but the important mechanical properties in the development and characterization of super alloys are: creep resistance, resistance to thermal and mechanical fatigue, structural stability, and resistance to corrosion and hot oxidation (Neto, 2009).

3.1.1 Nickel based superalloys

The addition of nickel content ensure and increase the superalloy's thermal stability (BEHERA; SAHOO, 2020) if compared to Co-based superalloys. According Ding et al. (2020)

if nickel is introduced in the chemical composition, the mechanical and thermal properties of the alloys are improved. Furthermore, Ni-based superalloys have useful resistance to a wide variety of corrosive environments, typically encountered in various industrial processes, such as in chemical processing, petrochemical processing, aerospace engineering, power generation and energy conversion and thermal processing (SHEA, 2005).

Nickel based superalloys are also extensively used in automotive industry and nuclear reactors (BEHERA; SAHOO, 2020), where wear takes place. Fact that highlight the importance to investigate techniques to improve the wear resistance of Ni-based superalloys.

Iron-nickel-base superalloys have densities of approximately 7.9 to 8.3 g/cm³ and nickel-base superalloys, approximately 7.8 to 8.9 g/cm³ (ASM, 2000). Density is an important property for nickel superalloys, since reducing the density of the jet turbine component leads to an increase in centrifugal stresses, reducing the component's life (MARQUES, 2007). Thermal conductivity of pure nickel is on the order of 0.089 (W/mm²)/(°C/mm), higher than pure iron 0.072 (W/mm²)/(°C/mm). The thermal conductivity of the Ni-based superalloy is 10% of the value of pure Ni, due to the addition of many alloy elements at high levels (MARQUES, 2007). However, the ideal would be to obtain Ni-based superalloys with greater thermal conductivity, which would be important to dissipate heat, thus reducing temperature gradients and thermal stresses that lead to the tendency to fail due to thermal fatigue.

Nickel is extracted from two types of deposits which are sulfide and laterite ores. Nickel demand has been increased mainly because of high consumption in China, Europe, Japan, America, and South Korea. Stronger trends are observed for BRIC countries as well. Therefore growing market demand of these super alloys is driving manufacturing sector to explore options for higher material removal rates or change of chemical composition of alloys (PERVAIZ et al., 2014).

The development of nickel-base superalloys has, almost entirely, have been motivated by the requirement to improve the efficiency, reliability and operating life of gas turbines (CAHN; EVANS; MCLEAN, 1995). Nickel based alloys were first used for manufacturing of turbine blades in the early 1940s due to their excellent oxidation resistance and creep rupture strength which were remarkably improved by the addition of small amounts of aluminum and titanium (THELLAPUTTA, 2017 apud EZUGWU, 1999)¹. The unique set of properties required in nickel-based superalloys is obtained by having an fcc matrix which is hardened by

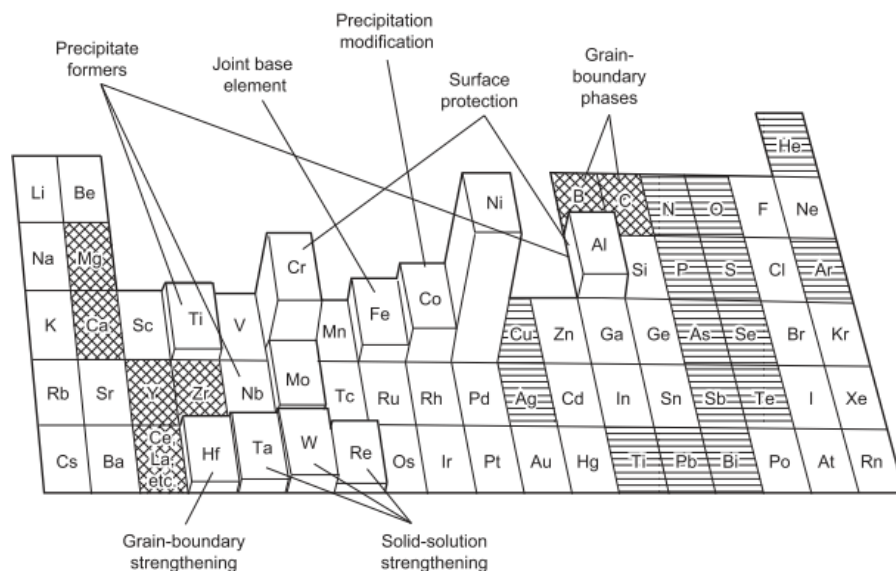
¹ THELLAPUTTA, G. R.; CHANDRA, P. S.; RAO, C. S. P. Machinability of nickel based superalloys: a review. **Materials Today:Proceedings**, Netherlands, v. 4, n. 2, p. 3712–3721, part A, 2017 apud EZUGWU, E. O.; WANG, Z.M.; MACHADO, A. R. The machinability of nickel-based alloys: a review. **Journal of Materials Processing Technology**, Netherlands, v. 86, n. 1-3, p. 1–16, 1999.

solutes and precipitates. The precipitates in are primarily $\text{Ni}_3(\text{AlTiNb})$ type intermetallic compounds and carbides and are of suitable structure, shape, size and distribution so as to give the desired properties and to resist microstructural changes at high temperatures. According (GOBBI, 2013), the Nickel-based superalloys have high concentration of alloying elements (up to about 50% by weight) to provide strength, creep resistance, fatigue endurance, and corrosion resistance at high temperature.

3.1.1.1 The role of alloying elements in the design of nickel based superalloys

The constituents of nickel-base superalloys have been classified into solid solution formers, precipitate formers, carbide formers and surface stabilizers (JENA; CHATURVEDI, 1984). Thus it is important to know the characteristics of solutes and alloying elements to fully understand each element role in the superalloy's final chemical composition that will have influence in its properties. Figure 1 shows the alloying elements and their effects in Ni-based superalloys, the height of the element locks indicates the amount that may be present; beneficial trace elements are marked with cross hatching and harmful trace elements are marked with horizontal line hatching.

Figure 1 – Alloying elements used in nickel-base superalloys.



Source: Adapted from ASM (2000).

Iron and manganese enter a solid solution in the austenitic matrix, promoting an increase in mechanical strength and creep (SAWFORD ET AL, 2008; EZUGWU ET AL, 1999). Iron is a lower cost element in relation to binding elements (TANCRET ET AL, 2003).

The nickel stabilizes the austenitic matrix and promotes the formation of phase (γ') which increases resistance to high temperature (SAWFORD ET AL, 2008; EZUGWU ET AL, 1999). Optimum nickel content for maximum oxidation resistance is 40 to 50% (JENA; CHATURVEDI, 1984).

The aluminum increases the high temperature resistance of the alloys by combining nickel precipitating the intermetallic phase gamma prime (γ'). Another important function of aluminum is to increase the resistance to oxidation at high temperatures through the formation of Al_2O_3 during heating (EZUGWU et al, 1999). However, the aluminum levels should be restricted, since very high amounts of this element can lead to deterioration in strength and hot workability due to loss of ductility (BARBOSA et al, 2009).

Chromium is used to provide resistance to corrosion and oxidation at high temperatures. The presence of chromium in the alloys results in the formation of an oxide layer which reduces further oxidation and hot corrosion. For a good protective layer against oxidation is required about 20% Cr (JENA; CHATURVEDI, 1984). Chrome levels above 25% threaten the stability of the microstructure due to the tendency to form the fragile sigma phase which deteriorates ductility (BARBOSA et al., 2009; TANCRET et al., 2003).

When added to the alloy, the titanium and niobium preferentially combine with carbon, given the high chemical affinity of these elements leading to the carbides formation. The content of titanium and niobium not combined with carbon combines with nickel to form the intermetallic phases γ' and γ'' . Add more niobium lead to the precipitation of primary NbC carbides (PATEL et al., 2001) that have greater hot hardness than titanium carbides. However, the titanium and niobium content cannot be excessively high, as it would promote the formation of coarse intermetallic, damaging the mechanical properties of the alloy in terms of strength and ductility, in addition to increasing the cost of the alloy (BARBOSA et al, 2009). Carbon is added to increase grain contour strength by the formation of secondary phases (carbides) (XU et al., 2011; CHEN et al., 2002; BAE et al., 2001). Carbides are important to provide mechanical strength, control grain size. The volume of carbides is determined by the content of carbon. In this way, the carbon content is used as a controller of the volume of particles formed and is preferably below 0.4% (BARBOSA et al, 2009).

3.1.1.2 VAT 32[®] Superalloy properties and applications

The VAT 32[®] is classified as a nickel-iron based alloy, developed by Villares Metals through thermodynamics modeling to project a new nickel intermediate alloy with better wear resistance than the UNS N07751 alloy, common applied in automotive high performance valves. The UNS N07751 (Inconel 751[®]) superalloy present high hot resistance to mechanical strength, oxidation and creep combined with microstructural stability to corrosive environments, being applied not only to high performance internal combustion engines, but also in aircraft, marine vehicles, nuclear reactors, submarines, and steam power plants (ZHU et al., 2013). However, the UNS N07751 alloy has severe disadvantages that restrict its applicability, such as low wear resistance combined to high manufacturing costs due to its high nickel content.

In this context, the VAT 32[®] superalloy came to the market to present an alternative to the use of UNS N07751 alloy in the most varied applications, since it has a lower content of nickel in its composition and according to Farina et al. (2013) presents better to equivalent properties than the UNS N07751 alloy. The new developed superalloy VAT 32[®] is based on a high nickel chromium austenitic matrix with dispersion of γ' and γ'' (Ni₃Nb) phases (FARINA; LIBERTO; BARBOSA, 2013a), its chemical composition is presented in Table 4.

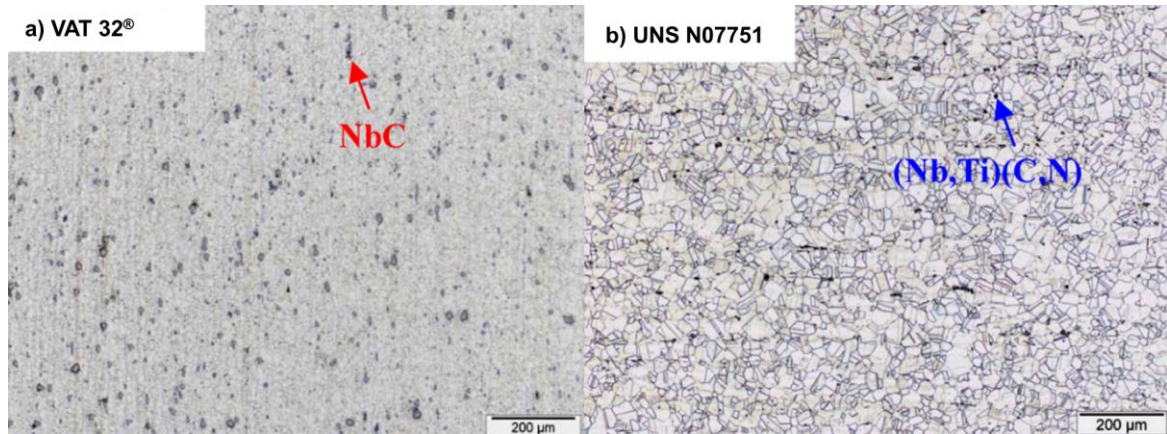
Table 4 – VAT 32[®] and UNS N07751 alloys nominal chemical composition in weight percent.

Alloy	C	Si	Mn	Ni	Nb	Al	Ti	Cr	Fe
VAT 32[®]	0.30	0.20	0.30	32	3.90	1.80	2.0	15.50	44
UNS N07751	0.02	0.20	0.30	72.48	1.0	1.20	2.30	15.5	7.0

Source: Farina; Liberto; Barbosa (2013b).

Considering the comparison between VAT 32[®] and UNS N07751 alloy composition, it is evident the expressive reduction of nickel content. The nickel reduction lead to a high economical advantage of this alloy application, combined to sustainability gains, since the nickel is a non-renewable resource. Figure 2 presents the microstructure of both alloys.

Figure 2 – Optical micrographs of a) VAT 32[®]; b) UNS N07751 (Inconel 751[®]).

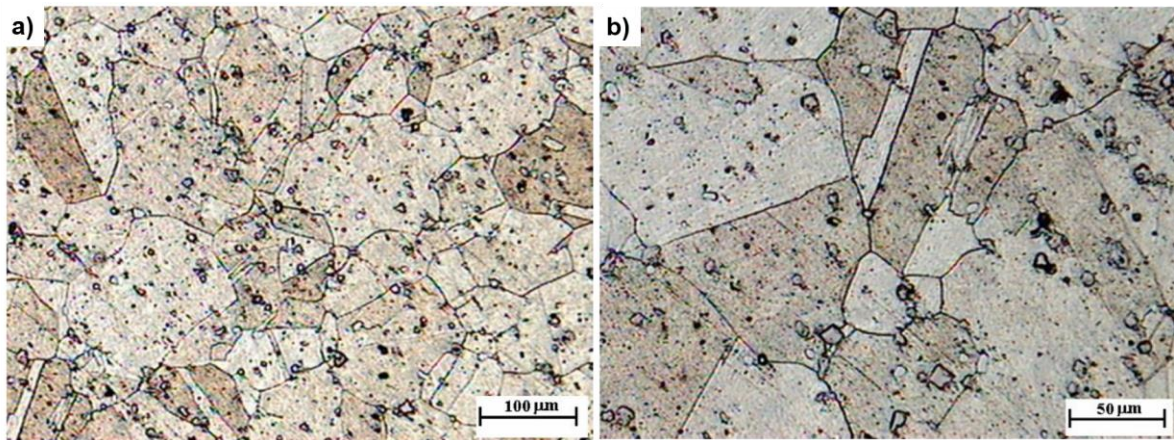


Source: Farina; Liberto; Barbosa (2013b).

The VAT 32[®] is hardened by precipitation of the γ' phase. Due to the reduction in the total content of nickel, the niobium was increased to improve the mechanical resistance of the matrix by promoting the precipitation of a fine dispersion of the γ' ($\text{Ni}_3(\text{Al,Ti})$) phase and γ'' (Ni_3Nb) intermetallic phase during the aging heat treatments. The high addition of niobium also cause the precipitation of primary eutectic carbides of the NbC form, as can be seen in Figure 3. The high volumetric fraction of NbC carbide of VAT 32[®] alloy improves the wear resistance of the alloy, acting as a barrier to the abrasive wear of the matrix. The carbides also act as nuclei sites for the nucleation and propagation of the cracks, collaborating to the maintenance of similar fatigue resistance response if compared to UNS N07751 alloy.

Farina et al. (2013) determined the volumetric fraction of carbides after solution annealing and aging heat treatments, and concluded that the VAT 32[®] alloy presents higher volumetric fraction of carbides, having about 2.5% of NbC carbides, if compared with the UNS N07751 alloy that present about 0.25% of NbC carbides. The formation of these hard particles (carbides of niobium and titanium) generate high abrasion resistance properties resulting of the increase in carbon content coupled with niobium addition (BONHIN et al., 2019).

Figure 3 – Metallographic characterization by optical microscopy of VAT 32[®] superalloy showing large presence of carbides, Etching: Kalling's reagent. Magnification: a)100x b)200x.



Source: Gobbi (2013).

The decrease of titanium content favor the precipitation of MC type carbides (NbC) that present higher hardness than the titanium carbides. The good balanced addition of titanium and aluminum assure a sufficient volumetric fraction of γ' phase, in order to provide a high hot mechanical resistance, as well as a large hot workability range which allows the industrial processing of these alloy.

Currently the main demands of industries are always associated with the reduction of raw material costs associated with improvement or, at least, the maintenance of materials properties. The VAT 32[®] superalloy combines both reduction of raw materials costs with improvement of mechanical properties.

The reduction of total nickel content in almost 50% in weight percentage, lead to an expressive economic advantage, since the consumption of nickel have been increasing since 2010 due to the grown in demand for higher purity nickel (LME, 2020) increasing the official settlement nickel price (US\$/Tonne) in trades on the London Metal Exchange.

Nonetheless, the VAT 32[®] also allows a reduction in four stages of the production process when compared to the UNS N007751 alloy reducing even more the alloy's total production costs.

In a performance comparison study developed by Farina et al. (2013) considering alloys in creep and rupture tests, hot tensile test, hot rotating bending fatigue tests, Charpy “V” notch impact tests, abrasive wear tests, hot hardness test, oxidation and hot workability tests, the VAT 32[®] has, in the properties tested, performance equivalent or superior in relation to the alloy UNS N007751. Moreover, if the resistance to abrasion is compared, the performance of

VAT 32[®] is even superior, and can be associated with a high hardness property between 700 °C and 800 °C.

Moreover, the application of superalloys continue to expand in several industries. Even with other materials being studied as alternatives to the use of nickel superalloys such as chromium alloys, higher melting metals and refractory ceramics, until now, these materials have not found a better combination of properties required for high temperature than that currently obtained with nickel superalloys, fact that corroborates with a wide possibilities to application of the new VAT 32[®] alloy. According (THELLAPUTTA; CHANDRA; RAO, 2017) the aerospace application remains the predominant application of superalloys on a volume basis. The specific application in aeronautical and aerospace industry requires high resistance to abrasion properties, as the new superalloy presents.

However, the precipitation of carbides, such as NbC formed in VAT 32[®], in 10 times the volumetric fraction of carbides than in VAT 751[®] alloy, turns the new superalloy a hard machining material. The precipitation of carbides increases mechanical resistance of superalloys in high temperatures, but it also increases the wear of tools during machining processes (KONDO et al., 2018). Due to the increasing importance of the quality of products and processes, with the growing demand of superalloys in metal-mechanic industry, and the visible problems in their machining, the search for solutions to optimize the machining process is an important topic to be studied.

3.2 MACHINING OF SUPERALLOYS: CHARACTERISTICS AND CHALLENGES

According to Sarikaya et al. (2015), the machining of superalloys and advanced engineering materials is more difficult than the processing of conventional steel, defining these materials as difficult to cut or machine. Donachie (2002) affirms that the machining of superalloys differs from carbon steels machining by having a higher cost, mainly due to the use of low cutting speeds, from 5 to 10% of those used in the steels. Furthermore, it is not just high costs and the difficulty in removing the material when working with superalloys, as the surface conditions of the parts after machining play an important role in their mechanical properties, especially under cyclical conditions.

Generally, nickel-based high temperature alloys are difficult to machine because of the very same characteristics that make them good high temperature materials (ARUNACHALAM; MANNAN, 2000). Superalloys have many properties that end up increasing the total machining costs, among them are the maintenance of mechanical

resistance at high temperatures, stage where steels are usually more malleable; high dynamic shear strength and presence of hard carbides in the microstructure, which make the superalloys abrasive (DONACHIE AND DONACHIE, 2002). During machining the superalloys also suffer a hardening process and promote the formation of long chips that are harmful to the process and operator. Bushlya et al. (2012) and Thellaputta et al. (2017) complement with another property, the chemical affinity of superalloys with the materials of the cutting tools. It generates greater efforts and temperatures during machining, favoring the degradation of tools, which makes the machining of super alloys even more difficult.

According Trent (1984 apud HASSUI; MORAES, 2005)² reinforces the claim that the temperature at the chip-tool interface increases with the increase of the cutting speed and this specific parameter constitutes the practical limit for the machining of materials with a high melting point, such as superalloys.

Therefore, the big challenge of research on superalloys is to find precise machining conditions, exploring different cutting speeds, feeds and depths to assure best output responses. The use of cutting fluids in different strategies is also studied, such as use in abundance, optimized use and the use of minimal amount of fluid (MQL). Finding suitable materials for cutting tools is another focus in machining research involving superalloys. Nevertheless, there is a scarcity of works on machining of nickel-based superalloys, as pointed out by Davoodi and Eskandari (2015), even with their importance for the industry.

3.2.1 Machining of nickel-based superalloys

The machining of nickel-based superalloys presents a significant challenge into the attempts of machining operations improvement (RAHMAN, et al. 1997; BEHERA et al., 2020). The combination of high shear stress due to their high strength in addition to the high frictional stress due to their sticking nature induces high cutting forces. It is known that the normal stresses on the tool face are almost twice as high for machining nickel alloys as that of steel at the same cutting conditions (CHOUDHURY and EL-BARADIE, 1998; RICHARDS AND ASPINWALL., 1989; DUDZINSKI, et al., 2004; LI, et al., 2014; EZUGWU, et al., 1999).

² HASSUI, A.; RODRIGUES, M. A. **Análise dos desgastes de ferramentas de metal duro revestidas no fresamento da liga a base de níquel – Inconel 625.** Escola Politécnica da USP, Departamento de Engenharia Mecatrônica e de Sistemas Mecânicos, PMR/POLI/USP, 2005 apud TRENT, E. M. **Metal cutting.** 2. ed. London: Butterworths, 1984. 242 p.

The other characteristic of nickel-based superalloys is the large volume of precipitates in their austenitic matrix, which causes work hardening during cutting, contributing to machining difficulties (EZEGWU et al., 2003).

During machining, some of the high-nickel alloys work harden rapidly, generate high heat during cutting, may weld to the cutting tool surface, and offer high resistance to metals removal due to their high shear strength in comparison to stainless steels and/or carbon steels.

According Evans et al, (2013), the following points should be kept in mind when machining nickel alloys:

- Machine should have sufficient power and be rigid. The workpiece and cutting tool should be held rigid without any chatter. Vibration should not be present during machining operation.
- Tools should be sharp at all times and should be changed as the need arises. A 0.015-inch wear land is considered a “dull tool.” Use positive rake angle tools for most machining operations. Negative rake angle tools can be used for intermittent cuts and heavy stock removal.
- Use heavy constant feed to maintain positive cutting action, that is, the tool should be constantly engaged with low cutting speed and higher feed rate. If feed slows and the tool dwells in the cut, work hardening will occur, tool life will lessen and close tolerances will be difficult to achieve.
- Lubrication is desirable. Water-based cutting oils are recommended to avoid overheating of the cutting tools. However, operations such as threading, tapping, or drilling require sulfonated or chlorinated lubricants. However, all traces of these fluids must be removed prior to any heat treatment or high-temperature service.

Nickel superalloys are readily machinable by the conventional methods. Tungsten carbide and recently ceramic-tipped tools have been successfully used for machining these alloys (AGARWAL, 2004).

According to Ezugwu et al. (2003), the main difficulties encountered in machining nickel superalloys can be summarized as:

- Most of the material's resistance is maintained during machining due to its high heat resistance;
- Hardening occurs quickly due to the efforts applied to the material during machining, contributing to the notch wear on the tool, especially at the height of depth of cut, increasing cutting efforts;
- The existence of hard abrasive carbides on superalloys microstructure leads to excessive abrasive wear that can favor tool premature failure/damage;

- High diffusion rates in the contact region of tool-specimen due to high temperatures presence in the cutting region. Choudhury and El-Baradie (1998) observed temperature results around 1000°C when cutting nickel-based superalloys;
- Low thermal conductivity. This characteristic impairs the tools performance since the heat generated in the machining process will not be extracted in the conventional way by the chip or the refrigerant, if it is used in the process;
- The easy weldability of workpiece material at the tool edge, forming a built-up edge (BUE), compromising the surface integrity of the workpiece, as well as the cutting tool.

3.2.1.1 Milling of nickel based superalloys

As turning, milling, drilling and grinding are common operations carried out on superalloys, milling stands out as the major operation carried out in the manufacture of jet engine mounts and blades for the compressor of jet engines, while turning is the predominant machining operation in the manufacture of disks for gas turbines (ARUNACHALAM; MANNAN, 2000). Aerospace structural applications require end milling and drilling operations onto superalloys (PERVAIZ et al., 2014).

Although the manufacturing challenges persist in all process to machine nickel based superalloys, milling remains as the most common manufacturing method (ARUNACHALAM et al., 2000). In fact, to date most research on the machining of nickel-based high temperature alloys has been directed towards turning, while the milling process has received little attention which may be due to the complexity of the process (ARUNACHALAM; MANNAN, 2000).

A significant amount of heat is generated in milling due to the rubbing process, as well as the friction between the test specimen and the tool (SIVASAKTHIVEL et al., 2010). According Trent (2000), the machining of Ni-based superalloys presents severe problems of economic and technical order, mostly due to the excessive heat generated during cutting.

During the milling process of Ni-based superalloys, this heat generation is further intensified by the low thermal diffusivity that characterize the material, therefore increasing the problems encountered in milling (Shaw, 2005). Despite the low thermal diffusivity, the workpiece still increases in temperature, and the hardness increases with the temperature (LIAO et al., 2008). The rapid work hardening of the material results from the austenitic matrix and the microstructural alterations of the machined surface where excessive strain takes place. The strain increases the stress on the tool tip, leading to high tool wear and increasing difficulty to make sequential cuts (ULUTAN et al., 2011; AXINTE et al., 2006).

Due to the increase in demand for nickel based superalloys, many researchers have been trying to develop models to predict the behavior of milling these materials (PLETA; ULUTAN; MEARS, 2015). Milling itself is difficult to model, due to the multi-tooth interrupted chipping, non-uniform chip loading and the variation of the cutting force direction (ZHANG et al., 2009). Henderson et al. (2010) affirms that the empirical updates that milling models incorporate to the application of end-milling process of superalloys can be synthesized to the conclusion that the increase in the average cutting forces in time can be attributed to tool wear and that cutting speed had a significant effect on overall tool wear and force trends. These trends were related to the chip formation mechanisms. For milling, the resultant cutting forces also increased with increasing axial depth of cut and feed rate (PLETA; ULUTAN; MEARS, 2015).

Of the various types of tool wear that occur in milling, notching is of great importance when dealing with nickel-based superalloys, as this type of tool wear causes catastrophic or instantaneous tool failure. The dominant factors in the manifestation of notch wear are the welding and adhesion of the workpiece material onto the cutting tool which causes removal of the tool coating and the tool substrate (LI et al., 2002). Researchers also found that built up edge (BUE) is formed by high pressure and chemical affinity of the tool (KRAIN et al., 2007).

Notch wear manifests itself as pitting in its early stages. Through multiple tool rotation cycles, the pitting is worsened and initiates localized chipping, in turn leading to notch wear (JAWAID et al., 2001). With the formation of BUE and changes in the tool geometry, the friction at the cutting edge of the tool increases, leading to an increase in cutting temperature.

This further weakens the bond between the tool coating and the tool substrate material leading to high amounts of wear (JAWAID et al., 2001). The tool's fragments can sometimes be dislodged as the BUE breaks off, acting as a mechanism of wear. Other researchers have identified pitting transforming into notch wear when milling, and that it occurs on both the flank and rake faces of the tool near the depth of cut line (SHARMAN et al., 2001; KRAIN et al., 2007; KASIM et al., 2013).

Milling being an interrupted cutting process, tools with high fracture toughness are always preferred. Carbides have the highest fracture toughness among all the tool materials currently used for machining nickel-based high temperature alloys. But their major drawback is the lower hot hardness, which does not permit them to be used at high speeds. So as long as the material removal rate is not a major criteria, carbides are the most economical tool materials for milling nickel-based high temperature alloys (ARUNACHALAM; MANNAN, 2000).

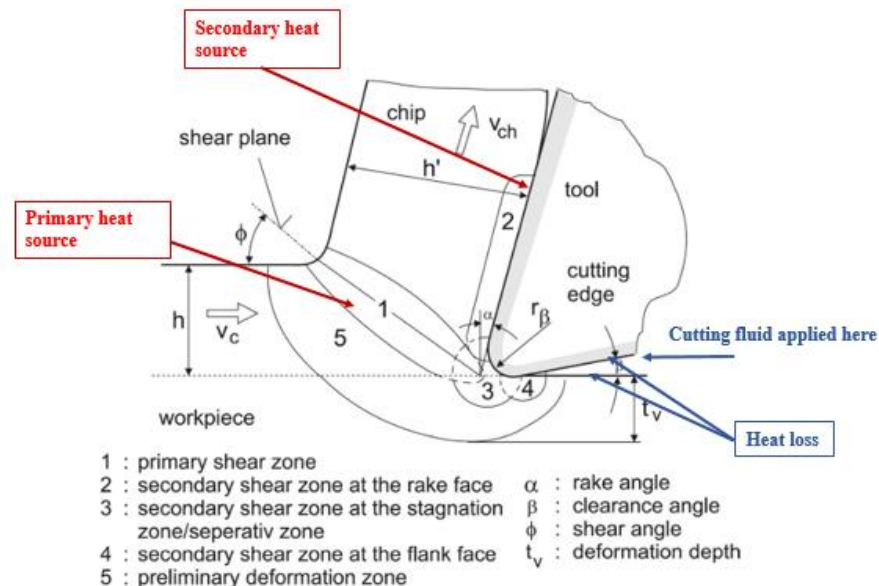
3.2.2 Challenges in machining of nickel-based superalloys

Poor machinability of nickel-based superalloys has been reported due to their inherent properties such as high chemical reactivity and low thermal conductivity result in poor machinability (RIBEIRO et al., 2003). Main cause of all machining complexities is its low heat conductivity that results in poor heat dissipation at tool, chip, and workpiece interface. Presence of high temperature in cutting zone results in poor tool life and accelerated abrasion, adhesion, and diffusion wear mechanisms. Important findings related to the complications in machining nickel-based alloys are listed as under.

3.2.2.1 Poor heat dissipation

Temperature in the cutting zone is a critical parameter that directly influences cutting forces, tool life, tool wear rate, and surface integrity of workpiece. The plastic deformation at shear zone, friction between chip and tool surface, and friction between tool and workpiece are major sources of heat production in machining phase as shown in Fig. 4.

Figure 4 – Sources of heat generation in machining.



Source: Adapted from Pervaiz et al. (2014); Rodríguez, Carbonell, Jonsén (2020).

Trent and Wright (2000) revealed that 99% of the work is converted into heat that caused high temperature in cutting tool and workpiece surface. Temperature on tool face

changes with change in cutting speed and exposure time (OOSTHUIZENA et al., 2010). Longer time duration and higher cutting speed results in higher cutting temperature in the cutting zone (ZHANG et al., 2009). Combination of high cutting temperature, high heat capacity, and low thermal conductivity of titanium results in poor heat dissipation during the cutting process. As most of the heat stays at the cutting edge because of low thermal conductivity it produces high thermal stresses at the cutting edge. Combination of high thermal stresses and chemical affinity of nickel superalloys facilitate tool failure through diffusion and adhesion wear mechanisms. It has been reported that approximately 80% of the heat generated during machining of Inconel 718 is transferred to the cutting tool due to low thermal conductivity of workpiece and fast flowing chip removal cannot take heat away from the cutting zone (PERVAIZ et al., 2014).

3.2.2.2 High hot hardness and rapid strain hardening

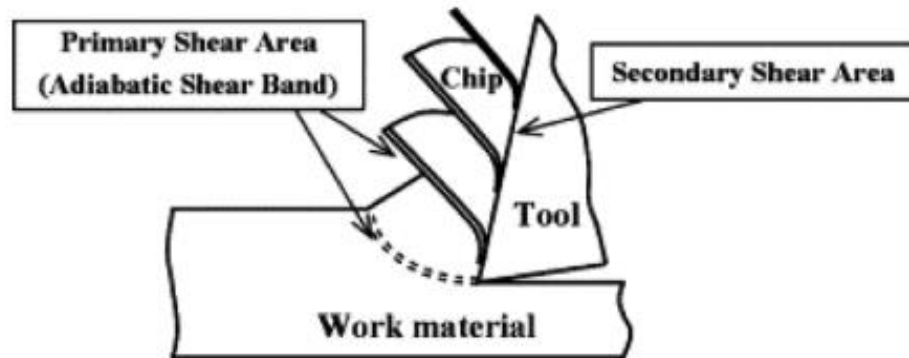
Nickel-based superalloys exhibit high strength at elevated temperatures. Although cutting temperature increases during cutting operation but these alloys maintain their strength that results in rapid deterioration of cutting tool material and shorter tool life. Nickel alloys also show work hardening behavior that result in excessive wear rate during machining.

Working with high depth of cut is not possible because of their high strength at elevated temperatures. Due to extraordinary hot hardness of nickel-based alloys high cutting forces and heat are generated.

3.2.2.3 Segmented chip formation

Nickel-based alloys maintain strength at elevated temperatures that makes plastic deformation very difficult during machining. Adequate plastic deformation is required to facilitate the chip formation mechanism. For any specific material, selection of cutting speed decides if the chip will be continuous, discontinuous, or segmented (PERVAIZ et al., 2014). For all conventional materials chip morphology changes from continuous to discontinuous as cutting speed increases. It has been reported that for nickel alloys segmented chips are formed at all levels of cutting speed. In segmented chip formation, material deforms plastically ahead of the tool. Figure 5 shows schematic illustration of segmented chip formation.

Figure 5 – Schematic of segmented chip formation.



Source: Adapted from Rhim (2006).

The fracture occurs in the form of shear band when certain strain level is reached in the cutting process. The chips formed under these conditions are segmented in shape (MATTHEW and GERRY, 2008). The phenomenon of cyclic chip formation generates variable forces during machining phase (SHIVPURI et al., 2002). Rhim et al (2006) and Settee et al., (2010) affirmed that cyclic nature of cutting forces are generated due to serrated chip formation and low Young modulus which results in excessive chatter on cutting tool.

3.2.2.4 Self-induced chatter

Chatter is another important point in machining of nickel-based superalloys (SETTE, DINIZ, PEDERIVA, 2010). The cutting force produced during machining operation can cause elastic strain in machine tool structure. Due to this strain, cutting tool and workpiece engagement is disturbed. Regenerative effect is also produced due to the overlapping of cutting tool passes. Chattering causes inaccuracies in finishing operations. Chattering also limits the material removal rate (MRR) during machining operations.

Currently, the aerospace industry is focusing to achieve higher MRRs to increase total production rate. Due to the chattering problem, the machine tool has to work under region specified by its dynamic stability. Bad surface finish, immense noise, excessive tool wear, low production rate, machine tool fracture, increase in scrap, increase in energy, and high cost are some other drawbacks introduced by chattering effect (QUINTANA and CIURANA, 2011).

Ni-based alloys have high yield point and low plasticity which gives it good elastic properties. Davim (2010) reports that during machining phase cutting tool bounces back like a spring because of high elasticity of the superalloy matrix. This bounce back action reduces

clearance angle on flank face which facilitates chatter during the machining process. Cyclic nature of force produced due to the formation of segmented chips is another reason of excessive chatter.

3.2.2.5 High stresses at the cutting interface

Heat-affected zones are formed very close to the cutting edge due to machining operation. The heat-affected zone is very small in case of machining nickel-based alloys (KOMANDURI, 1983). Less contact area between tool and material causes high magnitude of mechanical stresses in the near vicinity of the cutting edge.

High hot hardness of these alloys at elevated temperature is another reason of generating high cutting forces and stress levels at tool tip. The heat generation is conducted into the cutting tool causing much higher level of stresses than the value obtain in case if machining steel. The higher value of heat generation represents severe plastic deformation at shear plane and severe contact conditions at the rake face of the tool resulting in higher cutting pressures.

3.2.2.6 High chemical reactivity

Nickel-based superalloys, have very chemical reactivity to some tool materials (THELLAPUTTA; CHANDRA; RAO, 2017). Due to high chemical reactivity, chips tend to weld at tool tip and cutting edge which results in crater wear, catastrophic tool failure, and severe edge chipping. High tendency of built-up edge (BUE) formation is present due to high chemical reactivity of these alloys. As increase in cutting speed results in increasing cutting temperature at the cutting interface, it is extremely difficult to machine nickel superalloys at higher material removal rates. With the recent developments in the field of cutting tool materials, many difficult to cut materials such as stainless steel, harden steels, and tool steels can be machined at higher material removal rates with satisfactory machining performance. However, the majority of advanced cutting tool materials still suffer from the high chemical affinity and do not perform well at higher cutting speeds (PERVAIZ et al., 2014).

3.3 MACHINABILITY OF SUPERALLOYS: DETERMINATION METHODS AND CONSIDERATIONS

The machinability is a complex function of many variables involved in the cutting process. Figure 6 shows the factors which govern the material's machinability.

Figure 6 – Factors affecting machinability

MACHINE PARAMETERS	CUTTING TOOL PARAMETERS	CUTTING CONDITIONS	WORKPIECE PARAMETERS
• Capacity of a machine tool • Power • Torque • Precision • Dynamic characteristics • Rigidity of machine • Compliance • Back lash stability	• Type of tool • Single edge • Multiple edges • Material of the tool • HSS, Carbide, CBN, PCBN, Diamond, Ceramic • Geometry of the tool • Tool angles • Radius • Edge preparation • Engagement of tool • Continuous or intermittent	• Feed rate • Cutting speed • Depth of cut • Environment	• Chemical Composition • Tensile strength • Hardness • Microstructure • Rigidity of workpiece • Shape of workpiece

Source: Adapted from Groover (2010); Kopac and Bahor (1999); Tash (2006).

According Diniz et al., (2013), the machinability can be defined as the degree of difficulty in machining a given material. Assessment of machinability can be based on several parameters like tool life/tool wear, cutting conditions, workpiece/tool material, power, and thrust forces generated during machining, chip formation, cutting temperature, etc. For practical considerations, machinability is judged by using tool life/tool wear, cutting forces, and surface roughness-based criteria (PERVAIZ et al., 2014; SOARES, 2013). Weingaertner et al. (1994) specifies that the four most considered machinability of metals criteria are: chip formation, tool life, surface quality and cutting forces.

In this aspect, machinability has a strong influence on productivity, final cost of production and serves as a parameter to reinforce the need for concern not only with materials with superior mechanical, physical and chemical properties, but also with the behavior of these materials when submitted to some type of manufacturing process.

Machining parameters like depth of cut, cutting speed, and feed rate play key role toward machining performance of workpiece and cutting tool material. Variation in cutting conditions controls tool life, cutting temperature, surface roughness, chattering, etc.(PERVAIZ et al., 2014). In addition to the ease with which machining has been performed, tool life and surface integrity of machined surface are also important functional characteristics.

According to Ezugwu et al. (1998), the factors that govern the machinability of nickel alloys include tool life, limited material removal rate, cutting forces and power consumed, surface finish and integrity of machined components, chip shape and high strength/hardness ratio. The most important being the tool life and the superficial quality of the machined parts. Notch wear, primarily in the region of the machining depth, is the dominant failure mode due to the hardened layer of material, adhesion between chip and tool and friction wear. Flank wear and chipping are other determining factors in tool life caused by wear by diffusion, wear by abrasion, and wear by friction and fatigue due to the thermal and mechanical load on the tools.

The machinability is also affected by tool geometry, square or round tools will perform better than rhomboid shaped inserts to machine Ni-based superalloys (KONDO et al., 2018).

The cutting environment also contributes significantly toward the ease provided in machining. Machinability varies under dry cutting than with lubricant. The type of lubricant and way of its application also play role in machinability variation. Mechanical, thermal, physical, and electrical properties of workpiece material also contribute toward machining performance (KOPAC and BAHOR (1999); TASH et al., (2006)). For example, machinability of ductile material is different from brittle material. Similarly coarse microstructure behaves different in machining than the fine microstructure (PERVAIZ et al., 2014).

There are several methods for measuring the machinability index of a material, the most traditional applied method is the long-term test (TAKENOUCHI, 2011). In this method, the analyzed material and a standard material are tested until the end of a determined criteria such as tool life, certain tool wear, with different cutting speeds (DINIZ et al, 2013). However, long term tests have been replaced to less expensive methods of testing that can summarize the materials machinability according to specific criteria.

3.3.1 Short time test for evaluation of alloy's machinability

For many companies, due to increseally large costs with material and time, the control of the machinability of materials is not feasible through long-term tests. Long-term tests cause high disposal of resources and demand time allocation leading to unavailability of operating machines and interruption of processes. The precise surveillance and control of long term tests is far from industries reality, these tests cannot be engaged in the production lines for checking daily machinability level of materials.

Therefore, industries adopted tests that provide results of optimal machining conditions in a short time and with little material expense (FERRARESI, 1982), so called short-term tests.

Considering the importance of machinability testing methods based in tool wear criteria and due to the fact that long-term tests are very expensive, several types of short-term tests methods have been proposed and tested. Many short-time tests are based on tool wear, which can be performed under normal or forced machining conditions. There are also, short tests based on other criteria to determine material's machinability, such as: Surface finish, chip characteristics, cutting temperature, productivity, cutting forces and dimensional analysis. Within each type of short-term test based on a criterion, there are machinability test methods that consider a specific variable, which contributes to the assertiveness of the method employed (i.e. power consumption, roughness analysis, wear, chip formation, etc).

3.3.1.1 Power Consumption and cutting forces

Power and cutting force-based criterion is used when rigidity of machine tool is critical (PERVAIZ et al., 2014). In this case cutting forces or power consumption are monitored closely to meet the rigidity requirement of machine tool. The criterion provides an effective way to suppress chatter and vibration-related problems. The analysis of machining forces as a short-term machining test criterion, allows the comparison of different materials, tools and cutting fluids in the various machining operations. The determination of the force component according to the cutting direction, that is, the cutting force, is the main responsible for the machining power (FERRARESI, 1982). The study of power consumption plays a major role in the energy consumed by using determined machine tool, a fact that helps to obtain necessary data for projects and impacts the choice of machine tools and their accessories. The power consumption of the equipment can also be directly associated with the level of material removal from a given part (GONÇALVES et al., 2010). According to Souza (2004), the study of machining power and strength is important to ensure the integrity of the machine-tool-workpiece system, since they influence the deflections in the tool and part, affecting the final dimensions of the machined component, being also responsible for the vibration phenomena.

In addition, the control of power consumption during machining processes allow the evaluation of cutting conditions that represent less energy demand, allowing the possibility of cost and energy reduction. Reducing energy usage is an essential consideration in sustainable manufacturing. In the past, metal cutting operations have been mainly optimized based on

economic and technological considerations without the environmental dimension. It is essential to improve production rate and cutting quality while simultaneously mitigating the effect of manufacture on the environment (YAN; LI, 2013).

It is known that machining forces are higher when machining superalloys than commercially pure iron. The contact area on the tool finish surface is very large, with a small shear angle, generally producing very thick chips (TRENT; WRIGHT, 2000). According to Marques (2015), the cutting forces tend to decrease as the cutting speed increases, as the chip-tool contact area becomes smaller and the chip thinner. However, for all cutting speeds, forces are relatively high for machining nickel superalloys, promoting high tool wear rates. Alauddin, Baradie and Hashmi (1996) studied the machinability of the Inconel[®] 718 through end milling, optimizing cutting parameters through measurements of the machining force components during the process. The results show that machining forces increase almost exponentially as the feed speed increases and it can also be seen that they were higher for low cutting speeds. Machining forces increased almost linearly with increasing depth of cut or decreasing of cutting speeds.

3.3.1.2 Surface Integrity (Roughness)

Surface roughness-based criterion is used when high surface finish is critically required for functionality of the part. At certain cutting conditions, lower value of surface roughness represents higher machinability rating under this criterion (PERVAIZ et al., 2014).

According to Machado et al. (2015), the condition of a machined surface is the result of a process that involves plastic deformations, rupture, deformation and elastic recovery, heat generation, vibration, residual stresses and chemical reactions. Thus, all of these factors can have different effects on the surface integrity and therefore, correspond to distinct machinability levels. The surface integrity involves the study and control of surface roughness or topography, surface hardness, variations in microhardness and metallurgical variations of the surface. In machining factors as cutting parameters, tool material and geometry, metallurgic characteristics and use of fluids can directly affect the roughness results.

The roughness criterion is very important especially considering Ni-based superalloys due to its main application in industry. According to Ulutan and Ozel (2011), nickel superalloys represent a significant portion of the metal in structural components and aircraft engines. When these critical structural components in the aerospace industry are manufactured with the aim of achieving high levels of reliability, surface integrity becomes

one of the most important parameters used to assess the finish quality of machined surfaces.

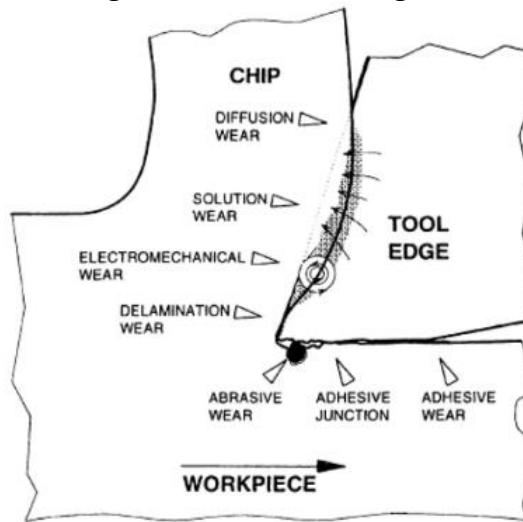
Considering Ni-based superalloys, the diverse surface alterations that occur due to high efforts during machining (i.e. residual stresses, dimensional errors, hardness gradient), can result in distortions negatively affecting the mechanical properties and the corrosion resistance of produced parts. These distortions directly compromise the performance during application. Therefore, extreme caution is necessary to ensure the surface integrity of the part during machining. The heat generation and the plastic deformation induced during machining affect the machined surface. The heat generated generally alters the microstructure of the alloy and induces residual stresses. Residual stresses are also produced by plastic deformation without heat. Heat and deformation generate microstructural changes and cracks, as well as variations in microhardness of the subsurface (EZUGWU and TANG, 1995). Residual stresses have consequences on mechanical behavior, especially about the fatigue life of the parts. Residual stresses are also responsible for the phenomenon of dimensional instability of parts, which can lead to difficulties during assembly (DUDZINSKI et al., 2004).

3.3.1.3 Tool Wear

Tool wear is an important machinability criteria (BEHERA; SAHOO, 2020). Tool life-based criterion has been accepted as the most important machinability criterion in the manufacturing sector. Out of other cutting parameters, cutting speed has shown direct influence on tool life (PERVAIZ et al., 2014). According to the criterion, higher machinability rating represents that material can sustain higher cutting speeds to attain certain level of tool life.

Different types of wear mechanisms are induced due to the interaction between cutting tool and workpiece materials. Figure 7 shows different wear regions present in the metal cutting process.

Figure 7 – Tool wears regions.



Source: Adapt from Pervaiz et al. (2014).

Huang and Liang (2004) grouped tool wear mechanisms into five categories, mentioned as abrasion, adhesion, diffusion, fatigue, and tribo-chemical wear. Studies related to tool wear assessment showed that combination of different wear mechanisms is responsible for tool failure.

El-Bestawi et al. (1993) pointed out that adhesive wear is the main reason of flank wear propagation when milling nickel based superalloys using reinforced ceramic tools. In high speed machining of Inconel 718, higher magnitude of cutting forces and cutting temperatures soften upper layer of workpiece material. The softening of workpiece material facilitates adhesion wear and reduces tool life (DEVILLEZ et al., 2007).

Abrasive wear mechanism is experienced when hard inclusions in the workpiece or tool material passed through the cutting zone. The rubbing action of these inclusions forms abrasive wear on the tool surface (HUANG and LIANG, 2004). It has been revealed in literature that abrasion is a dominant wear mechanism that appears in combination with adhesion (PERVAIZ et al., 2014). Diffusion wear mechanism starts at high cutting temperature, when particles from tool material are diffused into the chip material. Diffusion wear weakens the crystal structure of tool resulting in poor tool life (ZHUN; ZHANG; DING, 2013). As higher cutting forces and cutting temperature are involved in the machining nickel-based superalloys, it supports diffusion wear mechanism. Previous work has shown that cobalt element in carbide tools can easily be diffused into the chip material when machining Inconel 718. Ezugwu et al. (1998) also revealed revealed similar behavior of ceramic tools when machining Inconel 718.

Tribo-chemical wear mechanism are result of combined action of mechanical and thermal processes happening at the cutting interface between cutting tool, workpiece material, and cutting environment. Oxidation wear is the most common type of tribo-chemical wear. Literature supports that different tool materials react with atmospheric oxygen and affect tool life. It is observed that Aluminum (Al) elements in the carbide tool have high chemical affinity toward oxygen. In coated carbide tools oxidation tool wear is reported after coating delamination (ZHUN; ZHANG; DING, 2013). Fatigue wear mechanism is also another commonly observed wear mechanism found specially when machining nickel-based alloys. Fatigue wear causes micro-cracks to be formed due to the rubbing action of roughness profiles against each other.

Arunachalam and Mannan (2000) explain that the notch wear, constant observed in nickel-based superalloys machining, is due to this work hardening; these alloys maintain a major part of strength during machining which adds to the difficulty. In addition, the cutting forces and temperature at the cutting zone are extremely high due to the high shear stresses developed and the low thermal conductivity. This, coupled with the reactivity of nickel-based high temperature alloys with the tool material, leads to galling and welding of the chips on the work piece surface (ARUNACHALAM; MANNAN, 2000). All these characteristics of these alloys contribute to low material removal rates and short tool life resulting in huge machining costs.

3.3.1.4 Vibration

The vibration analysis during machining helps on the understanding of a material's machinability. Alves et al. (2009) reports that through analysis of vibrations is possible to accurately detect the moment of the occurrence of tool damage, burning in parts, failure of lubrication, etc. As a particularity, the vibrations analysis make possible to identify irregularities or malfunctions in operating machines components related to electrical problems, problems with components such as belts, gears and bearings, clearances, eccentricity, lack of rigidity, unbalances etc.

Metal cutting processes can entail three different types of mechanical vibrations that arise due to the lack of dynamic stiffness of one or several elements of the system composed by the machine tool, the tool holder, the cutting tool and the workpiece material (QUINTANA; CIURANA, 2011). These three types of vibrations are free vibrations, forced vibrations and self-excited vibrations. Free vibrations occur when the mechanical system is displaced from

its equilibrium and is allowed to vibrate freely. In a metal removal operation, free vibrations appear, for example, as a result of an incorrect tool path definition that leads to a collision between the cutting tool and the workpiece. Forced vibrations appear due to external harmonic excitations. The principal source of forced vibrations in milling processes is when the cutting edge enters and exits the workpiece. However, forced vibrations are also associated, for example, with unbalanced bearings or cutting tools, or it can be transmitted by other machine tools through the workshop floor. Self-excited vibrations extract energy to start and grow from the interaction between the cutting tool and the workpiece during the machining process. This type of vibration brings the system to instability and is the most undesirable and the least controllable.

The vibrations during machining diminish tool life, generate unacceptable surface finishes on the parts and reduce productivity. Nowadays, authors still refer to vibrations as a limiting factor, one of the most important machining challenges and, of course, an aspect to be improved (QUINTANA; CIURANA, 2011). Free and forced vibrations can be avoided, reduced or eliminated when the cause of the vibration is identified.

Researchers generally discuss about detecting, identifying, avoiding, preventing, reducing, controlling, or suppressing vibrations. According to Kalpakjian and Schmid (2010), the vibrations are proportional to the cutting forces, width, depth and the nature of the material. Some methods try ensure a stable machining process by selecting cutting parameter combinations to determined studied material. Indeed, to study the vibration profile as response of a material's difficulty to cut can provide important data to understand the material's machinability response, and contribute to ensure more stable machining processes.

3.3.1.5 Acoustic Emission

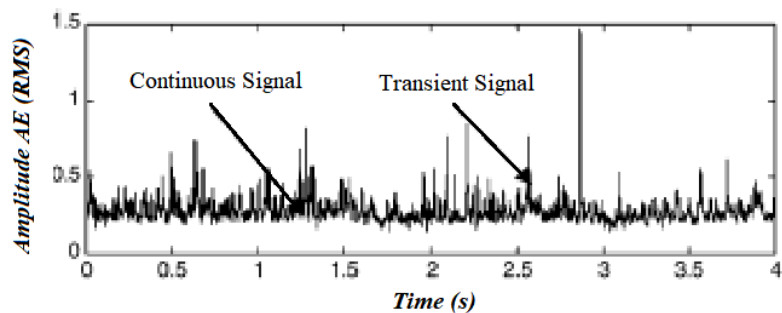
The acoustic emission (AE) is caused to many sources such as plastic and elastic deformations, both of the workpiece and of the cutting tool, friction, fracture of the workpiece, wear and break of the tool (HARA, 1999). Among the indirect methods for detecting tool's wear, the AE is the most effective, as the frequency range is higher than environmental noise and machine vibrations, since the analysis does not interfere with the cutting operation (SOUZA, 2018). The analysis of AE during machining can help to detect and correlate wear, damages and other phenomena that can occur during machining processes, helping to identify the material's machinability response.

Euzébio (2012) exposes the understanding of AE values as elastic tension waves due to

the rapid release of energy in the deformation of a material subject to an external stress. These signals can be detected by a piezoelectric sensor, which transforms displacement into electrical signals. Signals can be continuous or with peaks, where peak signals occur due breaks, cracks, and impacts and are identified by the sudden increase in signal strength.

In machining, the continuous signal is characterized by plastic deformations of ductile materials, while the transient signal is characteristic of the propagation of cracks and chip impacts (Figure 8).

Figure 8 – Characterization of an AE signal



Source: Adapted from Maia (2009).

According to Hassui (2002), what makes the acoustic emission interesting in the machining monitoring are the frequency limits that determine the phenomenon, high frequencies make the AE signal insensitive to the noise present during the process, such as bearings, vibrations, tension peaks or machine components influence.

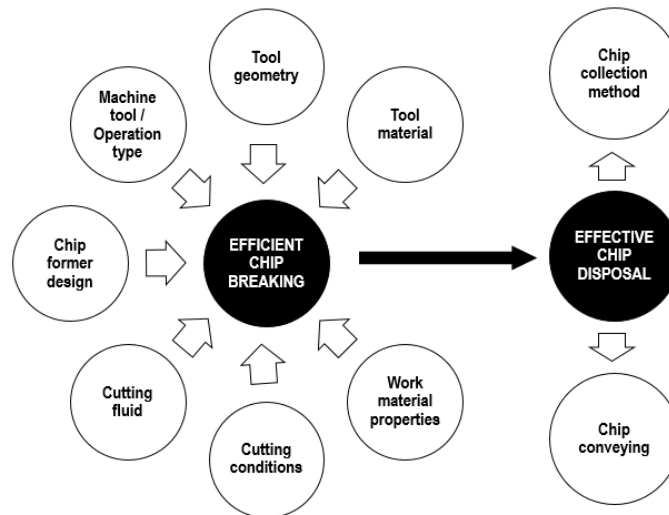
3.3.1.6 Chip Formation

The chip formation has influence on several factors related to machining, specially to the surface integrity, but also to tool wear, cutting efforts, heat produced during machining and penetration of lubricating fluid (DINIZ; MARCONDES; COPPINI, 2013), where the micro- and macro-morphology of generated chips can reveal signs of difficulties encountered in the cutting process that occurred during machining.

Chip control is an essential aspect of automated machining, where the basic elements of chip control are: efficient breaking and effective removal of chips. Figure 9 examples the factors with high influence on chip breaking, denoting the complex nature of the chip

breaking process. Greater understanding of these influencing factors and their interactions is essential to achieve efficient chip breaking and hence chip control.

Figure 9 – Most influencing factors on chip breaking.



Source: Adapted from Jawahir (2014).

The study of chips can be done by classification in different types and forms through observation and analysis of mechanisms of formation. In literature, the classification by type can be related to the characteristics of machined material, for ductile materials the originated chip is classified as continuous and to fragile materials is observed the rupture chip, which is broken into small pieces (discontinuous).

According to Machado (2015), the resulting chips generated in metal cutting can be classified as continuous, discontinuous or segmented. In general, continuous chips are observed in the machining of ductile materials as discontinuous chips come from hardened and fragile materials. However, according to Ferraresi (1982), the most common type classification of chips is that mentioned in both German and American literature (SCHWERD, 1956; SIBEL, 1955 apud DA SILVA, 2008)³ and consists of at least three possibilities: continuous chips, shear chips and rupture chips. In addition, Machado and Da Silva (2004), present a classification in the following types: continuous chip, partially continuous chip (shear chip), discontinuous (rupture chip) and segmented chip.

As regarding the form, the standard ABNT NBR ISO 3685 (2017) classifies the different chips forms (Figure 10). According to Machado et al. (2015), the machined material is the

³ SCHWERD, F. **Spanend werkzeugmaschinen**. Berlin: Springer, 1956. 543p. apud SIBEL, E.; LUDWIG, N. **Handbusch der werkstoffprüfung**. 2nd. ed. Berlin: Springer, 1955. 754p.

factor that most influences the form (shape) and the type of chips. Any of the chip's types can be produced in the different shapes shown in Figure 10, however, discontinuous chips can only be classified as fragmented. Regarding the cutting parameters, the feed has more influence in chip type and form, followed by the cutting depth.

Figure 10 – Chips forms produced in machining.

Table G.1 — Chip forms							
1 Ribbon chips ¹⁾	2 Tubular chips ¹⁾	3 Spiral chips	4 Washer-type helical chips ¹⁾	5 Conical helical chips ¹⁾	6 Arc chips ²⁾	7 Elemental chips	8 Needle chips
1.1 Long 	2.1 Long 	3.1 Flat 	4.1 Long 	5.1 Long 	6.1 Connected 		
1.2 Short 	2.2 Short 	3.2 Conical 	4.2 Short 	5.2 Short 	6.2 Loose 		
1.3 Snarled 	2.3 Snarled 		4.3 Snarled 	5.3 Snarled 			

Source: Adapted from ISO (2017).

Considering superalloys, the high temperature resistant materials have lower thermal conductivity, leading to higher temperatures during chip formation and heat concentration in the cutting region. In consequence, controlling chip formation and breaking is more difficult (CHOUDHURY and EL-BARADIE, 1998). The heat generated during the machining of superalloys tend to favor the adhesion of work material to the rake face of the tool, near the cutting edge, due to the increase of friction causing the chip welding. Much of this material is carried away with the chip, sometimes taking portions of the tool rake face with it, which reduces the life of the cutting tool. Some left portions that are not carried off with the chip generate a rough surface. Since the chip welding has a considerable and adverse effect on tool life, power consumption and surface finish, every attempt must be made to prevent its occurrence.

Gao et al. (2011) investigated the chip formation during the machining of the Inconel 718[®] applying cutting speeds of 20, 30, 40, 50, 60, 70, 80, 90 and 100 m/min, feed of 0.2 mm/rot and depth of cut of 2 mm. The results showed that to cutting speed of 20 and 30

m/min, it was generated continuous ribbon chips with no zone of concentration of shear stress. When the cutting speed is greater than 40 m/min, the chip was segmented with a serrated type.

3.3.1.7 Specific Cutting Pressure “Ks”

The specific cutting energy is one of the most important physical quantities derived from the phenomenology of machining, along with other parameters such as strength, cutting temperature, machining time, tool wear (RODRIGUES, 2005). During machining, the total energy per time or the cutting power can be determined by directly multiplying the cutting force “ F_c ” by the cutting speed “ v_c ” (Equation 1). However, as many parameters have a direct influence in the value of the consumed energy, it is necessary to normalize it by the rate of material removed from the workpiece (Equation 2) by calculating the cutting area “ A_c ”, where “ u ” is the specific cutting energy. The area is the product of the cutting or chip thickness “ h ”, and the cutting width “ b ” and the cutting speed “ v_c ”, according to Equation 3.

$$P_c [W] = F_c [N] * v_c [m/min] \quad (1)$$

$$u = F_c / A_c \quad (2)$$

$$A_c = h * b \quad (3)$$

Similarly, the specific cutting pressure “ K_s ” is defined as the ratio between the cutting force and the area of the cutting section (MACHADO et al., 2015). It can be understood as the effective energy consumed to remove a volume unit from the material of the piece (SALMON, 1992). The specific cutting pressure is considered a good index of material machinability and allows to understand the whole cutting process (POLONI; TURCHETTA, 2004).

Among the various formulations presented by several researchers to determine the K_s , the expression of the specific cutting pressure for a general case is given by Equation 4, as suggested by Kienzle (KIENZLE, 1952) to the calculation of cutting force “ F_c ”.

$$K_s = F_c / A_c \quad (4)$$

The specific cutting pressure determination allows not only the understanding of the machining process but also provides an estimation of the material’s strength σ during the cut,

therefore can be considered a way to evaluate the material's machinability. The K_s considers also the measurement of cutting force produced during a material cutting operation, which is a standard method of assessing the machinability of a material (ALAUDDIN, 1993).

The specific cutting pressure is influenced by several characteristic parameters of the machining processes. The three main factors of influence are the workpiece material, cutting parameters and the applied cutting tool (RIGATTI, 2010). To the machined material, its chemical composition and properties vary the specific cutting energy. Materials with high hardness have also higher specific cutting pressure.

The cutting tool material and geometry also lead to variation in the specific cutting pressure (CORRÊA et al., 2015). The chemical affinity of the tool material with the workpiece material can act by modifying the cutting section area. Where if there is a stable and strong adhesion zone, the machining force can be increased, increasing the " K_s ". If the tendency is to reduce friction at the interface, the contact area can be reduced, decreasing the machining force and the corresponding " K_s ".

Considering the cutting parameters applied, for the cutting depth, studies point to small proportional variations in specific cutting energy when the cutting depth is changed. The greater the cutting depth, the lower the specific cutting energy (ERSOY, 2004). The feed and depth of cut factors when increased lead to higher machining force results, increasing the specific cutting pressure in a direct proportion, almost linear.

3.4 TOOL MATERIALS USED IN SUPERALLOYS MACHINING

The cutting tool material has been nominated as the most basic factor that governs machinability (PERVAIZ et al., 2014). A machining process cannot be conducted efficiently if appropriate cutting tool material is not selected, even though all other governing factors are carefully monitored. The cutting tool selection and their machining performance evaluation has always been a big challenge to manufacturers. One cannot achieve good machinability rating without considering appropriate tooling (material and geometry) requirements.

Smith (2008) affirmed that cutting tool materials should exhibit the characteristics of hot hardness, thermal shock resistance, low chemical affinity, oxidation resistance, and toughness to perform effective and efficient cutting with excellent tool life. These characteristics with their functions are listed in Table 5. A correct balance of these characteristics can assure the metal cutting performance economically and efficiently.

Table 5 – Characteristics of a cutting tool material required to machine nickel-based superalloys.

Properties	Function
Hot hardness	It is required to maintain sharp and stable cutting edge at elevated temperatures.
Resistance to thermal shock	It is required to resist the effects introduced by cyclic heating and cooling during machining phase.
Less chemical affinity	Chemical affinity between tool and workpiece is discouraged due to the formation of built-up edge.
Oxidation resistance	It is required to resist accelerated wear rate at elevated temperature.
Toughness	It is required to withstand high cutting forces and mechanical shocks. Otherwise edge chipping is observed.

Source: Pervaiz et al. (2014).

The tool life when machining nickel-based superalloys is short compared to those obtained when machining common carbon steels at the same cutting speeds, increasing production costs. The tools used in the machining of superalloys must meet the following aspects: Excellent resistance to the main wear mechanisms, high mechanical resistance, maintain hardness and toughness at high temperatures, good resistance to thermal shock, high thermal conductivity and sufficient chemical stability at high temperatures (SIMS; HAGEL, 1972 apud EZUGWU; WANG; MACHADO, 1999)⁴.

In most cases, the main parameters considered for improve the machining process performance of nickel-based superalloys are: material selection and tool geometry, machining method, cutting speed, feed, and depth of cut (SOARES, 2013). With these parameters well controlled, an adequate tool life can be achieved during machining. The tool geometry affects the tool-chip contact area, resulting stresses and therefore, the machinability. The geometry of a cutting tool such as cutting tool nose radius, rake, and clearance angles play an important role toward the generation of the cutting forces and stress formation at the cutting edge (PERVAIZ et al., 2014).

Carbide and high-speed steel tools have been widely used for machining nickel-based superalloys (FILHO, 2018). About 80% of the indexable carbide inserts to machine superalloys are coated inserts (ARUNACHALAM; MANNAN, 2000). However, a saturation

⁴ SIMS, C. T.; HAGEL, W. C. **The superalloys**. 3rd ed. New York: Wiley-Interscience, 1972. 614p. apud EZUGWU, E. O.; WANG, Z. M.; MACHADO, A. R. The machinability of nickel-based alloys: a review. **Journal of Materials Processing Technology**. Amsterdam, v. 86, n. 1-3, p.1-16, 1999.

point has almost been reached in improving the performance of carbides. They are slowly giving way to other, newer materials such as cermets, ceramics and CBN. Attempts have been made to use polycrystalline cubic boron nitride (PCBN) tools for machining nickel-based superalloys (SHALABY; VELDHUIS, 2019). However, the high sensibility to abrasive wear and the chemical reaction of CBN with some alloying elements (Fe, Cr, Ni, Ti, etc.) at high cutting speeds or temperatures limits tool life (TANAKA, et al., 2016; KHANA et al., 2012; BUSHLYA, et al., 2012).

3.4.1 Cemented carbide cutting tools to machine nickel-based superalloys

Carbides are the most widely used tool materials to date for any machining application, mainly because of their toughness and resistance to thermal shock (ARUNACHALAM; MANNAN, 2000). The carbide tools are still largely used for machining nickel-based superalloys in a speed range of 10-40 m/min (SHALABY; VELDHUIS, 2019). Above these cutting speeds, carbide tools failed due to thermal softening of the cobalt binder and subsequent plastic deformation of the cutting tool edge (CHOUDHURY and EL-BARADIE, 1998; EZUGWU, et al., 2008). Dosbaeva, et al., (2010) adds that the use of coated carbide tools to machine direct age-hardened Inconel results in a short tool life.

With the introduction of coatings such as TiN, TiC, TiCN and Al_2O_3 , the hot hardness and wear resistance of the carbides has been improved, enabling them to be used at higher speeds than uncoated carbides (ARUNACHALAM; MANNAN, 2000). Among the diverse existing coatings, the titanium and aluminum based (TiAlN), has wide use in dry machining processes, whether by turning or milling. Carbides with TiAlN coating have greater resistance to oxidation, in addition to increased hardness, greater chemical stability and lower thermal conductivity (DINIZ; MARCONDES; COPPINI, 2013). The titanium nitride coating (TiN) reduce the tendency of adhesion, and therefore the BUE formation, due to its high abrasion resistance and lower coefficient of friction. The PVD deposited TiAlN has a chemical stability superior to that offered by TiN and TiCN coatings. The layer thickness obtained in the PVD deposition (up to 5 μm), is less than that usually obtained with the CVD (from 5 to 20 μm), which gives a sharper cutting edge (HASSUI; RODRIGUES, 2005).

Generally, coatings are performed to improve resistance toward abrasion, adhesion, diffusion, oxidation wear mechanisms, lower coefficient of friction. Coatings also improve lubricity of cutting tool which results in better mechanical and chemical wear resistance and low cutting temperature (PERVAIZ et al., 2014). To assure these improvements, cutting tool

materials are coated with different coating materials in single, multiple, and nanolayers. In multilayer coating, bond strength should be high in between first layer and substrate. The outermost layer offers high wear resistance. Intermediate layers are multipurpose coatings to improve strength and cutting performance. CVD coatings are deposited at higher temperature of 700°C whereas PVD coated are performed at temperature below 500°C, fact that results in better bonding between substrate and coating to CVD tools (PERVAIZ et al., 2014). However, due to difference in thermal expansion coefficient between substrate and coating material, residual stresses are formed on hard coating. Transverse cracks are formed on coating material to relieve residual stresses, these cracks may cause catastrophic fracture in intermittent cutting process.

Different studies on the machinability of superalloys have been conducted. Yeo (1994) studied the performance of CVD and PVD coated cemented carbides tools, which indicated that the usable speeds and feeds are notably low with coated cemented carbides if compared to other tools materials. The best performance observed was at a cutting speed of 30 m/min and a feed rate of 0.1 mm/rev, with CVD coated tools performing better than PVD coated tools. At 50 m/min both coated cemented carbides tools performed unsatisfactorily.

Teo (1995) studied the influence of tool geometry on the tool life of coated cemented carbides. Both PVD coated and CVD coated inserts were tested at different cutting speeds and feeds. The results show that with an increase in the side cutting edge angle (SCEA) from 5° to 15° and then to 45°, there is a significant increase in tool life, but the surface finish is compromised. TiN PVD coated carbides perform better than the multi Al₂O₃ CVD coated carbides. The optimum cutting condition was observed with 45° SCEA, 30m/min cutting speed and 0.2 mm/rev feed rate. Tee (1997) investigated the effect of different chip breaker series on tool life for coated cemented carbides. The results showed that chip breakers do not have much effect on the tool life.

Arunachalan and Mannan (2000) list the main conclusions and considerations in using carbide cutting tools to machine Ni-based superalloys:

- Work hardening can be consider as the major problem encountered in machining Ni-based superalloys.
- Cutting speed range of 15-30m/min can be used for carbide and coated carbides can be used from 10 to 50m/min. Feed ranges of 0.18-0.25 mm/rev provide the longest tool life (ZLATIN and CHIRSTOPHER, 1975)
- Flank wear and notching are the most dominant damage modes.

- Cutting conditions largely depend upon the hardness of the alloys. The best way to machine the age hardenable alloys, is to machine almost to size in the unaged condition, age harden and then finish to size (METALS HANDBOOK, 1989).

Even with several studies available on wear behaviour of the PVD as well as CVD coated cutting tools during continuous cutting operations, there still exists deficiency in a comprehensive analysis of the dominating wear mechanisms in intermittent processes (SINGH; GHOSH; ARAVINDAN, 2020). Therefore, it is important to study the different tool wear mechanisms for the enhanced understanding of the limitations and applications of cutting tools materials. Since, the deterioration of the cutting tool during the machining operation not only affects the surface integrity of the machined component but also hampers its intended application as a component (SINGH; GHOSH; ARAVINDAN, 2020).

3.4.1.1 Use of carbide cutting tools in the milling of nickel based superalloys

This section summarizes previews investigations on milling of nickel-based high temperature superalloys using carbide tools specifically applied to the milling process.

Li et al. (2006) conducted end milling operation on Inconel 718 using TiCN/ Al₂O₃/TiN coated carbide inserts. The experimentation was performed under dry condition using cutting speed range of 30–45m/min. It has been observed that flank wear controlled the tool life of coated carbides. Propagation of flank wear was found to be the main reason of increase in mean peak cutting force. Zhang et al. (2012) executed dry end milling experiments on Inconel 718. The study was conducted at cutting speed of 55m/min using TiN/TiAlN coated carbide inserts. The study revealed that flank wear and chipping fracture are the dominant failure modes.

Kim et al. (2000) performed tests to differentiate the machining performance between TiN and TiAlN coatings. It was observed that TiAlN has higher hardness than TiN coating. TiN showed lower friction coefficient with respect to TiAlN coating but higher friction coefficient was noticed at higher sliding speeds. The study concluded as TiAlN coating better than TiN for high speed applications. These results holds validity to use PVD coated carbides.

Teo (1997) carried out face milling tests on Inconel 718 using uncoated and TiN coated carbide tools. The results conclude that TiN-coated carbides give the maximum tool life when compared to all other tool materials tested. The maximum tool life was obtained at a cutting speed of 20 m/min. At cutting speeds higher than 20 m/min, the tool life deteriorated rapidly. Carbide tools cannot be used to machine nickel-based alloys at high speed since they cannot

withstand the conditions of extreme high temperature and stress in the cutting zone (EZUGWU et al., 1999).

Koksal et al (1998) studied the wear mechanisms of PVD-TiN and CVD-TiCN + Al₂O₃ coated cemented carbides when face milling Inconel 718. Applied cutting speeds of 50-100 m/min, feed rates of 0.08 and 0.12 mm/tooth and a depth of cut of 2 mm were used for the tests under wet cutting conditions. Results show that CVD coated tools perform much better than PVD coated tools. Also it was found that coatings have no significant effect under the cutting conditions used in the tests. The dominant mode of tool failure is chipping, flaking and plastic deformation at the cutting edge.

Balazinski (1995) studied the effect of varying the feed on the tool life during face milling Inconel 600. The M40 carbide grade was used at cutting speeds of 22.6 m/min and feed per tooth was varied from 0.1 to 0.25mm. The results indicate that oscillating (non constant) feed during machining increases the tool life by at least 30% depending on whether the same inserts are used after wear measurements or a new insert is used. The most influential factors on tool life are the amplitude and duration of each feed variation step.

Elbaradie et al. (1995) carried out tool life testing when end milling Inconel 718. Results show that there is a significant difference in tool life between up cut and down cut end milling. Tool life in down cut end milling is greater than in up cut end milling. Also full immersion end milling increases the tool life compared to half immersion.

From all the above research works the following conclusions could be arrived:

- Climb milling or down milling is the preferred technique as it reduces the effect of work hardening. Also it makes the set up rigid and diminishes chatter.
- Cutting speeds of 20-30 m/min and feeds of 0.10-0.15 mm/tooth give the best performance for most nickel-based superalloys.
- Coated carbides can be used at higher speeds (50 m/min).
- In general, CVD coated tools perform better than PVD coated tools.
- Chipping is the dominant type of tool failure for un-coated carbides; although flank wear is also a major contributing factor leading to tool failure. For coated carbides in addition to chipping, flaking and plastic deformation at the cutting edge are also dominant modes of tool failure.

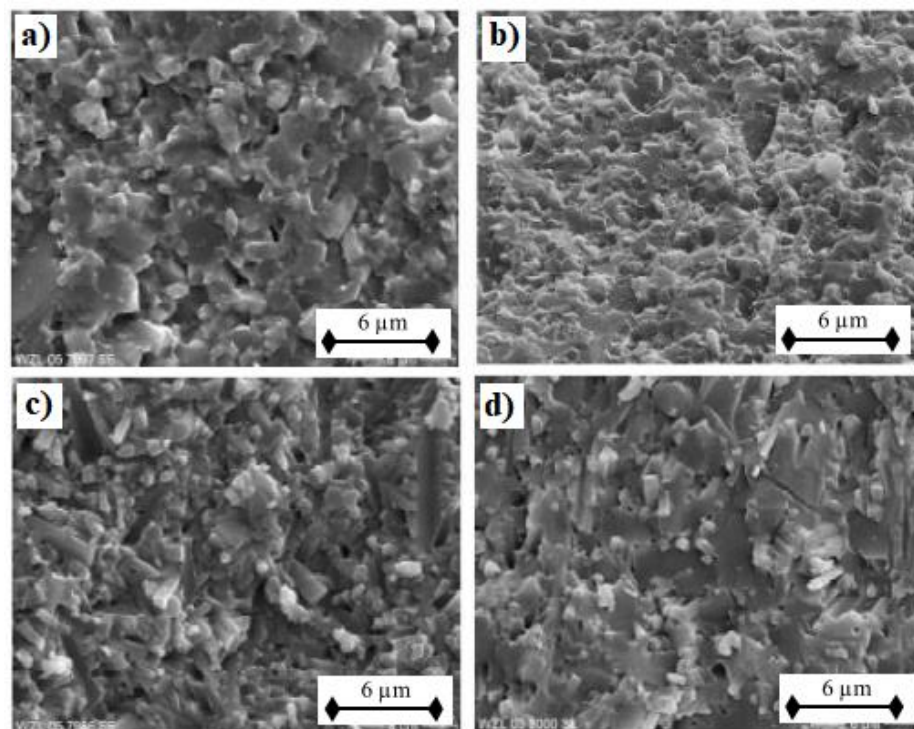
In conclusion, the milling process being an interrupted cutting process demands the application of tools with high fracture toughness. Carbides have the highest fracture toughness among all the tool materials currently used for machining nickel-based high temperature alloys. But their major drawback is the lower hot hardness, which does not permit

them to be used at high speeds. So as long as the material removal rate is not a major criteria, carbides are the most economical tool materials for machining nickel-based high temperature superalloys.

3.4.2 Ceramic cutting tools to machine Ni-based superalloys

The costs of machining nickel-based superalloys are very high (SOARES, 2013). The metal removal rates are limited by the choice of cutting tool materials that frequently cannot withstand the temperatures and stresses generated. In consequence, much effort has been observed since 1980s decade to employ ceramic tools in machining, and therefore, to increase the operations efficiency (TRENT and WRIGHT, 2000). Ceramic materials such as mixed alumina ($\text{Al}_2\text{O}_3 + \text{TiC}$), SiAlON (Si_3N_4) and whisker reinforced alumina ($\text{Al}_2\text{O}_3 + \text{SiC-whisker}$) have been used in cutting tools to machine nickel-based superalloys (EZUGWU, WANG e MACHADO, 1999). Figure 11 shows SEM images of different the ceramic materials used as cutting tools, the usual composition and properties are described in Table 6.

Figure 11 – SEM images of different ceramics cutting tools; a) Alumina; b) Mixed ceramic; c) SiAlON; d) Whisker reinforced alumina.



Source: Adapted from Soares (2013).

Table 6 – Different ceramic tools main properties.

Properties	Tools materials					
	Tungsten carbide (K10)	Alumina	Mixed alumina	Whisker reinforced alumina	Sialon	Cubic Boron Nitrite
Typical composition (vol. %)	94%WC+ 6% Co (wt %)	90-95%Al ₂ O ₃ + 5-10%ZrO ₂	Al ₂ O ₃ +30% (TiC or TiN) + 5-10% ZrO ₂	75%Al ₂ O ₃ + 25%SiC	77%Si ₃ N ₄ + 13%Al ₂ O ₃ + 10%Y ₂ O ₃	50-90% CBN +50-10% TiN/TiC
Grain size (µm)	1–2	1–2	1–2	-	1	1–3
Density (g/cm³)	14.8	3.9 – 4.0	4.2 – 4.3	3.7	3.2	3.1 (solid CBN)
Hardness (HV) at 20°C	1700	1700	1900	2000	1600	3000 – 4500
Hardness (HV) at 1000°C	400	650	800	-	900	1800
Fracture toughness K_{1C} (MNm^{-3/2})	10	1.9	2	8	6	10 (solid CBN)
Young's modulus (kN/mm²)	630	380	420	390	300	680 (solid CBN)
Thermal conductivity (W/m°C)	100	8 – 10	12 – 18	32	23	100 (solid CBN)
Coefficient of thermal expansion (x 10⁻⁶/°C)	5 – 6	8.5	8	-	3.2	5

Source: Adapted from Richards; Asspinwall (1989).

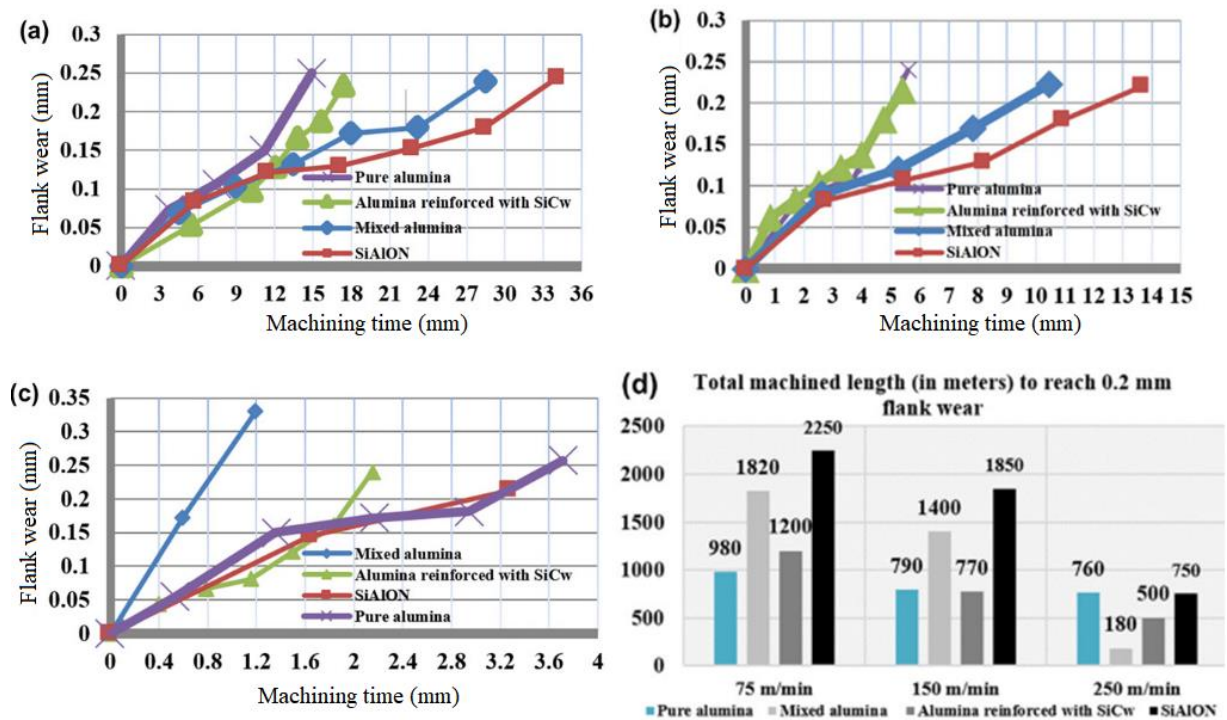
Ceramic tools high melting point, high hot hardness, and low chemical affinity properties make them suitable for HSM applications. The cutting speed is three to ten times higher as at carbide tools, which contributes to a higher material removal rate (MRR) and consequently higher productivity (GRGURAŠ; KERN; PUŠAVEC, 2019). Considering the machining of nickel-based superalloys performed by ceramic tools, it is possible to achieve metal removal rates of four times greater than that of carbide tools (SHALABY; VELDHUIS, 2019). Another advantage of HSM is the possibility of chip control. Characteristically tough continuous streams are produced when machining at low speeds; however, as the cutting speed increases above 120 m/min small segmented chips are produced, which generally helps chip removal.

Another property of ceramic tools is better oxidation resistance when compared to cemented carbides due to its high hot hardness and less chemical affinity (PERVAIZ et al., 2014). However, ceramic tools are very sensitive to mechanical and thermal shocks. Dry cutting is usually recommended when using ceramic tools to avoid thermal shocks to the cutting tool edge (Lima, et al. 2017). Moreover, dry machine has diverse economic-sustainability advantages, since the application of fluid also causes a reduction in the contact with the tool, which increases tensions at the edge of the tools, leading to reduced life.

Excessive edge chipping and high notch wear rate have been reported as a major cause of ceramic tool failure (PERVAIZ et al., 2014; RICHARDS; ASPINWALL, 1989). Notch wear is very sensitive to depth of cut parameter. Adhesion, attrition, and diffusion were also reported as general wear mechanisms present in ceramic tools. When machining nickel alloys ceramic tools and cemented carbide tools form special groove at the line of depth of cut that converts into the notch wear. The brittle nature of some ceramics often makes them susceptible to notching by attrition wear mechanisms, whereas prevention or minimization of this problem would yield further improvements in nickel alloy machining. Notching can also result from employing too low a cutting speed; indeed ceramic tool wear at high cutting speeds is often not as high as may be expected from lower speed tool life tests (RICHARDS; ASPINWALL, 1989). This is partly due to the more favorable heat flow and workpiece softening at higher speeds, which tends to transfer more heat into the chip than the tool. This is particularly noticeable in nickel alloys where the chips are commonly at 1000°C or above.

Ceramic tools show good machinability characteristics when machining nickel superalloys (PERVAIZ et al., 2014). Shalaby and Veldhuis (2019), investigated the tribological performance of different ceramic tools at different cutting speeds in machining of Inconel 100. The results showed that the pure alumina ($\text{Al}_2\text{O}_3 + \text{ZrO}_2$) ceramic tool outperformed the tools with mixed alumina ceramic and alumina matrix reinforced with SiCw, and its tool life was equal to SiAlON to maximum cutting speed applied (Figure 12-c). Tool performance of the pure alumina ceramic with the addition of ZrO_2 improves with an increase in cutting speed, giving the same tool life as SiAlON at 250 m/min.

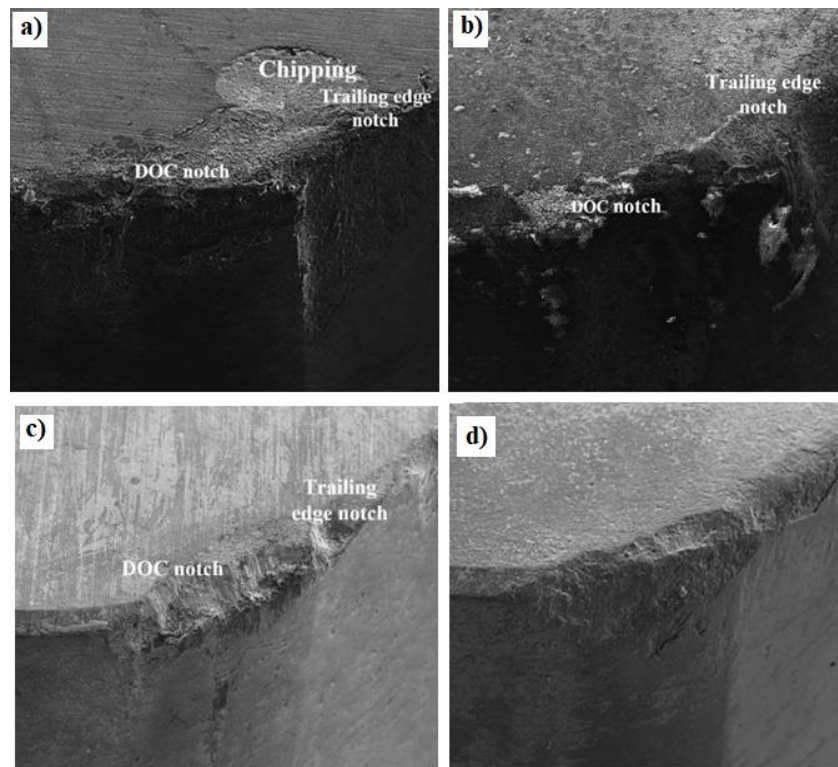
Figure 12 – Tool life curves of different ceramic tools at different cutting speeds in machining of Inconel 100. a) $v = 75$ m/min; b) $v = 150$ m/min; c) $v = 250$ m/min.



Source: Shalaby; Veldhuis (2019).

The authors also stated that the increase in tool performance of the pure alumina ceramic in proportion to cutting speed can be attributed to the thermal barrier properties of ZrO_2 tribolayers induced at a high cutting speed (temperature). Figure 13 highlight the main types of wear observed in the cutting tools after machining.

Figure 13 – SEM micrographs of a) mixed alumina; b) pure alumina with the addition of ZrO_2 ; c) alumina matrix reinforced with SiCw; d) SiAlON.



Source: Adapted from Shalaby; Veldhuis (2019).

3.4.2.1 Alumina cutting tools: characteristics and perspective for improvements

One of the many categories of ceramic tool materials is the alumina-based tools. This category can be divided in two main types of compositions: based in pure oxides ($\text{Al}_2\text{O}_3 + \text{ZrO}_2$) and based in mixed oxides (TiB_2 , TiC , TiN mixed in Al_2O_3). Pure alumina tools are composed by fine sintered grains of Al_2O_3 with the addition of lower content (up to 10%) of oxide zirconium (ZrO_2). Other oxides can also be added, such as magnesium oxide, chromium oxide, titanium and nickel. The MgO has the function of inhibit the growth of grains, the chromium oxide, titanium and nickel, to increase the mechanical strength, and the ZrO_2 increase the fracture toughness. The mixed ceramics contain, in addition to alumina, 20 to 30% of titanium carbide (TiC) and small amounts of titanium nitride (TiN).

According to Trent and Wright (2000), the refractory oxides used to made alumina-based tools were among the many substances of high hardness and melting point investigated as potential materials for cutting tools. Pinheiro (2018) reported that Al_2O_3 with fine particle size (less than $5\text{ }\mu\text{m}$) and high relative density, that is, containing less than 2% porosity have been shown good performance results in application as cutting tools. Other advantage in using

alumina-based tools is the high availability and low costs of basic raw material (PINHEIRO, 2018). However, the tool processing is expensive, increasing the final price if compared to carbide tools.

Alumina-based cutting tools can be formed into single point tools by cold pressing and subsequent pressureless sintering (RICHARDS; ASPINWALL, 1989). Fine-grained powder is pressed under high pressure and bounded at temperatures between 1200-1800 °C (GRGURAŠ; KERN; PUŠAVEC, 2019). Properties of the ceramic tools depend of the composition, the density of the structure, size and distribution of the grain. Alumina being an oxide material characteristically possess a high level of chemical stability which makes the cutting tools inert in most machining environments. The greater chemical stability than carbides and nitrides supports better performance in high temperature applications. In contrast, worse thermal and mechanical shock resistance is observed if compared to tungsten carbide tools (RICHARDS; ASPINWALL, 1989). Even with superior hot hardness, the room temperature hardness of alumina-based tools is in the same range as that of carbide tools, in the range of 1550–1700 HV.

Ceramic cutting tools have shown great potential in the manufacturing sector. Alumina-based ceramics are widely used in aerospace, manufacturing and automobilist industries due to its excellent stability, oxidation resistance, low density, low thermal coefficient, high strength at elevated temperature and less wear (SINGH et al., 2018). However, low toughness and high brittleness have constantly restricted the use of alumina in tools applications.

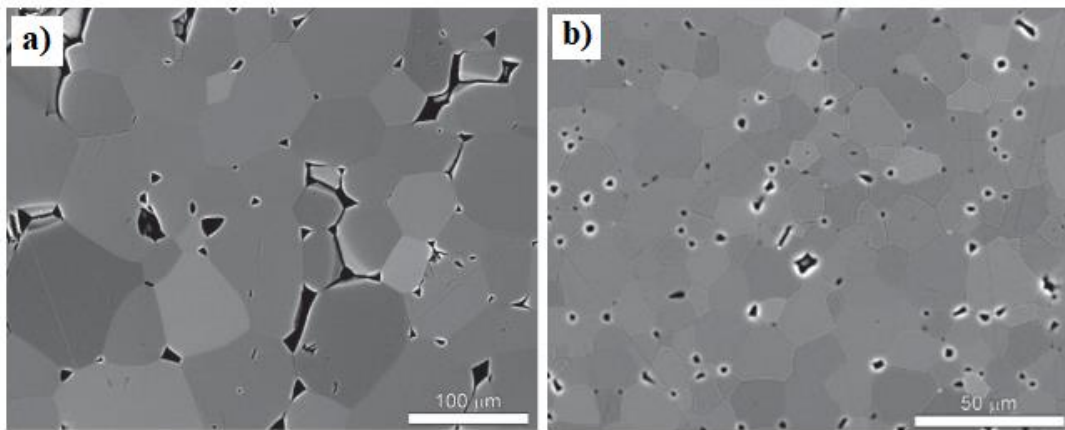
The key in improvement of alumina-based tools is that of alloying oxides to the alpha alumina in order to establish better balance of properties. Among others, the magnesium oxide have been investigated by several researchers. The MgO mainly acts as a sintering aid and inhibitor of discontinuous grain growth, promoting densification during sintering and allowing fine grain size (PINHEIRO, 2018). Berry and Harmer (1986) investigated the effect of MgO as a solid-solution additive on the Al_2O_3 microstructure development through sintering. The MgO was found to increase the densification rate during sintering by a factor of 3 through a raising of the diffusion rate. Magnesia also increased the grain growth rate during sintering by a factor of 2.5. The grain size dependence of the densification rate indicated control primarily by grain boundary diffusion. The authors concluded that the role of MgO in the sintering of alumina was attributed mainly to its ability to lower the grain-boundary mobility by a solid solution mechanism.

Several studies have demonstrated that the most important role of MgO doping is to reduce grain-boundary mobility in Al_2O_3 . Greskovich and Brewer (2004) highlight that the

important attributes of the MgO additive are to prevent discontinuous grain growth in Al_2O_3 and allow pores to reside on the grain boundaries for long periods of time during the sintering process, until they are eliminated by mechanisms of grain-boundary and/or volume diffusion. The authors explain that the solubility limits of MgO in Al_2O_3 at temperatures of between 1700°C to 1880°C were very low, of 75 and 175 ppm, respectively. The small MgO solubility was understood by the high enthalpy (326 kJ/mol) of solution (GRESKOVICH; BREWER, 2004).

Akiva, Katsman and Kaplan (2014) observed the reduction of the effective grain boundary mobility for undoped alumina $2.7 \times 10^{-15} \text{ m}^2/\text{s}$ to $1.5 \times 10^{-15} \text{ m}^2/\text{s}$ to doping with 23 ppm MgO. Figure 14 shows the microstructure of for undoped alumina and doped with MgO.

Figure 14 – Backscattered electron SEM micrographs of the microstructure of: a) undoped alumina annealed at 1650°C for 60 h; b) MgO-doped alumina annealed at 1600°C for 40 h.



Source: Adapted from Akiva; Katsman; Kaplan (2014).

Singh et al., (2018) evaluated the machinability and development of MgO doped zirconia-toughened alumina (ZTA) ceramic inserts, with the application of different weight percentages of MgO. The results showed a maximum value of flank wear of 0.29 mm, and improvement of surface roughness for medium to high speeds. The investigation concluded that the insert with the composition of 0.6 wt% MgO-ZTA presented maximum values of both hardness, fracture toughness and flexural strength, (i.e. hardness 17.04 GPa, fracture toughness of $5.09 \text{ MPa m}^{1/2}$) and can be used for medium to high-speed machining of AISI 4340 steel. The authors also highlight the importance of adding MgO in ZTA ceramics. Previous work by Greskovich and Anthony (2004) regarding solubility of magnesia in polycrystalline alumina showed that the solubility is restricted to nearly 75 ppm MgO at $1,720^\circ\text{C}$ and 175 ppm MgO at $1,880^\circ\text{C}$. It has been concluded by Rittidech et al., (2006) that

there is a significant increase in the hardness of Al_2O_3 when a small amount of MgO is doped in Al_2O_3 . Azhar et al. (2011) also carried out a study with different particle size of MgO to illustrate its effect on microstructure, mechanical properties and wear performance of ZTA. It has also been found that particle size of MgO greatly affects the hardness and wear resistant property of the ceramic cutting insert.

Although several researches has shown the superiority of ceramic tools in the machining of nickel-based high temperature alloys, machine shops are yet to implement the same (ARUNACHALAM; MANNAN, 2000). Noaker (1993) affirms that the two major inhibitors to the wide use of ceramic inserts are: many users are comfortable with machining using carbides, and the innumerable grades of ceramic tools which make tool selection a very complicated task.

Sing et al (2018) pointed out the constant replacement of conventional machining tool systems due to new technologies and the advent of newer materials, which would lead to increase productivity allowing to attend to a high demand balanced with low costs of production. Is a fact that alumina-based cutting tools represent a feasible path to improve cutting systems, thus the alloying of different oxides percentages the most likely way to achieve these improvements.

3.4.2.2 Use of ceramic cutting tools in milling of superalloys

Most published work on the machining of nickel-based high temperature alloys using ceramic inserts are in turning (ARUNACHALAM; MANNAN, 2000), whilst milling has received little attention (ELBCSTAWI, 1995; TEO 1997; BREUER, 1997) although it is a common operation in the aerospace industry (ELBCSTAWI et al, 1993). Literature reports that ceramic tools are not recommended for low speeds or intermittent cutting processes. The main complications are their brittleness, low thermal characteristics and the tendency to chipping. These difficulties make them generally unsuitable for intermittent cutting processes, such as milling. However, some studies successfully applied ceramic tools in milling of superalloys. Elbcstawi (1993) observed that cutting speeds of 700 m/min when end milling Inconel 718 using SiC_w , resulting in high material removal rate.

The inherent machining process complexity and tools in the application of ceramic cutting tool is milling of Ni-based superalloys highlight the importance of investigating the application of different set of parameters, compositions and tools geometries. Furthermore,

there are basic considerations that can be followed to enhance the strengths and minimize the weaknesses of ceramic tools, even considering intermittent process:

- In general, the most effective shape for ceramic inserts is a round (RICHARDS; ASPINWALL, 1989). The strength supported by round geometry reduce the possibility of chatter, and if used the correct depth of cut range, a round tool with its high SCEA most effectively thins out the chips, thus minimizing DOC notching.
- Ceramic inserts are often thicker than their carbide counterparts to provide a stronger geometry. It is good practice to use a chip breaker between the top clamp and the insert to eliminate point loading and the possibility of fracture. A clamp-on chip breaker is also necessary since ceramic inserts generally have no formed-in chip breaker grooves to avoid weakening of the cutting edge.
- Edge preparation of the insert important. In general, honing the cutting edge and/or adding a negative rake chamfer reduces the likelihood of catastrophic failure by ensuring that the cutting edge is in compression, thus increasing the resistance to crack initiation or propagation.
- Workpiece edges should be chamfered to avoid sudden entry or exit of the tool; high cutting speeds and low feed rates should be used at the onset, the feed rate being increased once the tool is properly engaged.
- Heavy interrupted cutting should be avoided due to sensitivity of impact operations.

4 MATERIAL AND METHODS

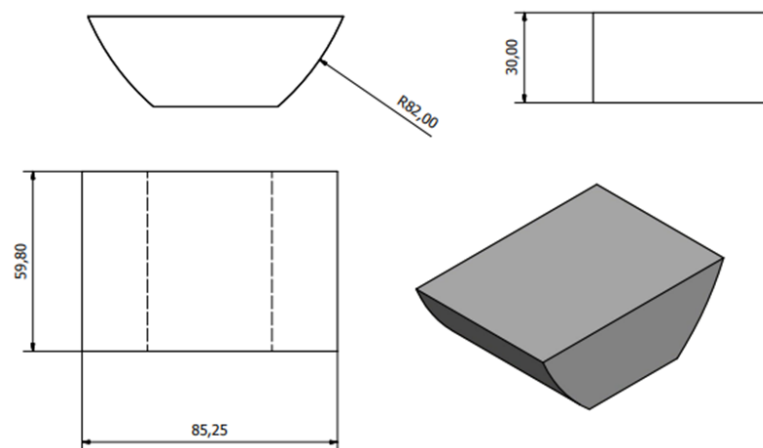
This section describes the main characteristics of the studied material and cutting tools and presents the methodological approach, methods of data collection, and data analysis applied to this research work. To assure the reliability of obtained experimental data all applied methods were oriented by ISO/ABNT standard regulations.

4.1 MATERIAL

4.1.1 Test specimen

To perform the machining tests, two test specimens made of VAT 32[®] superalloy were used separately, to the application of the ceramic and carbide tools. The test specimens (workpiece) dimension was 59x85x30 mm (Figure 15) before the beginning of the testing phase. The workpiece was submitted to machining tests as provided, without any application of further heat treatments that were not included in the alloy's fabrication process. The VAT 32[®] billet was provided by the Villares Metals enterprise.

Figure 15 – Schematic sketch of the machining test specimen



Source: Author.

4.1.1.1 Characterization methods to the VAT 32[®] material

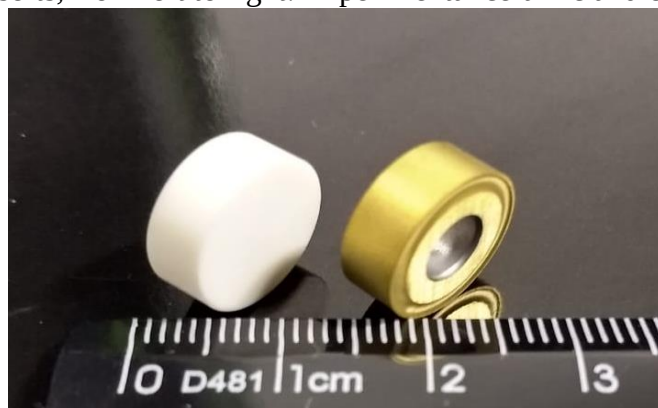
The superalloy characterization was made by means of chemical composition analysis, microstructure, micro and nano-hardness analysis. The preparation of samples for

metallographic characterization by optical microscopy and Scanning Electron Microscopy followed the usual metallography standards. To cut the samples it was used a diamond wafering blade (6" x 0.20" x 1/2") with diamond grain size 140/170 adjusted to the precision saw model IsoMet 1000 brand Buehler. The samples were mounted using a hot compression thermosetting phenolic resin. Grinding was performed using a series of water-cooled SiC papers of varying grit sizes (120, 240, 320, 400, and 600 grit), in a semiautomatic grinding machine. The sample was rotated 45 – 90° between papers so that the grinding direction was not constant. Polishing was done with diamond paste in 6, 3 and 1 µm cloths. The etchant used was waterless Kalling's reagent (number 2) composed by 5g CuCl₂, 100 ml HCl and 100 ml ethanol. Due to the alloy's excellent corrosion resistance, the etchant was soaked in cotton and applied swabbing in the sample surface. To obtain the SEM and OM images it was used scanning electron microscope (SEM) (Zeiss, model EVO LS15, Germany) and Inverted Metallurgical Microscope (Nikon, Epiphot-200, Japan). The hardness analysis was made using the Microindentation Tester (Wilson, model 401 MVD, USA), according the NBR NM ISO 6507-1:2008.

4.2 CUTTING TOOLS

The work evaluated the performance of two different types of cutting tools applied to the VAT 32[®] superalloy machining: commercial coated carbide inserts and experimental alumina-based ceramic inserts (Figure 16). The Seco tools enterprise supplied the commercial inserts and the experimental inserts were developed in laboratory by the Machining study group at the Materials and Technology department of the São Paulo State University (UNESP), Guaratinguetá Campus.

Figure 16 – Studied inserts, from left to right: Experimental ceramic and commercial insert.

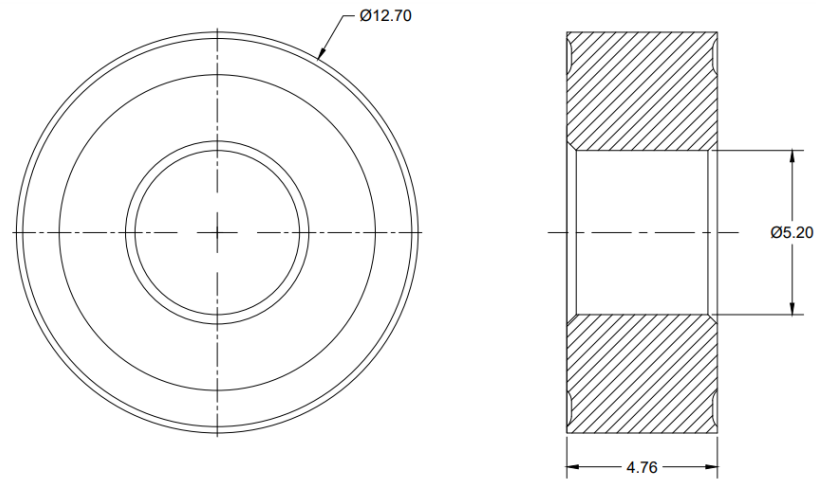


Source: Author.

4.2.1 Commercial TiAlN-TiN coated carbide inserts

The commercial inserts are composed of a body of cemented carbide and a wear-resistant coating with two layers. Figure 17 presents the commercial inserts dimensions.

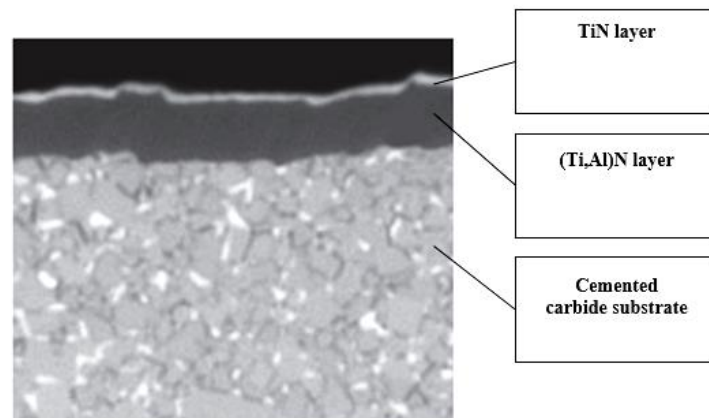
Figure 17 – Commercial coated carbide inserts.



Source: Author.

The coating is composed of titanium aluminum nitride (Ti,Al)N layer followed by a second titanium nitride (TiN) layer. Both layers were deposited by the Physical Vapor Deposition process (PVD) and are classified with a code-key TS2500 for the supplier. The TS2500 coating is designed to handle interrupted cuts, tough cast skin, and high stress due to its relatively hard micrograin grade. According to the company, it is ideal for roughing and semi-finishing applications in superalloys.

Figure 18 – Commercial carbide inserts coating layers.



Source: Adapted from Seco (2020).

The inserts code-key is RNMG120400-MR4, following the ISO 1832:2012 standard for the designation of indexable inserts for cutting tools. Table 7 describe each key letter specification.

Table 7 - Commercial coated carbide inserts Code key description.

Key designation	Key letter	Insert Description	Image
Shape	R	Round shape	
Side clearance angle	N	0° angle	
Tolerance	M	± 0,13 mm (thickness) ± 0,08 mm (diameter)	
Type	G	Type G	
Cutting edge length	12	12mm diameter	
Thickness	04	4,76 mm	
Insert with corner chamfer/nose radius	M	Sharp	
Internal designation	MR4	Machining conditions	-

Source: Adapted from Seco (2020).

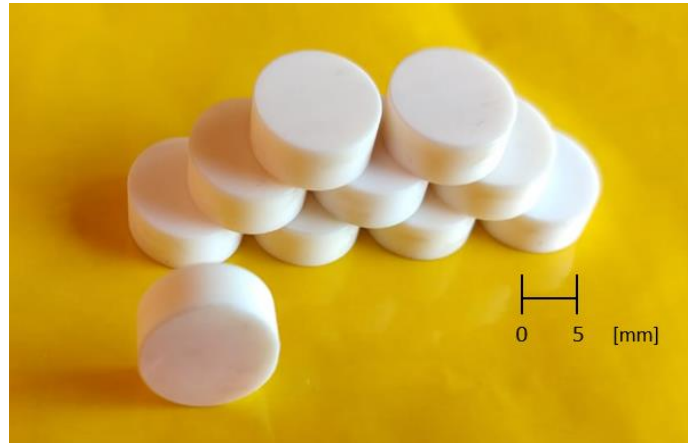
To the carbide inserts fixation it was used a modular milling cutter system, with a holder code SECO-EPB-E3476 5820 1260, according the DIN 69871 standard; and a milling cutter code R220.26-0050-RN1204.6A. In milling, SECO tools enterprise uses product specific designation systems, there is no ISO system available for the milling cutters.

4.2.2 Experimental Al₂O₃- MgO ceramic inserts

The experimental ceramic inserts are composed by aluminum oxide doped with magnesium oxide (Figure 19). The inserts were rectified according to ISO 1832:2012 in the following dimensions: Ø 12.76 × 4.76 mm, 0.2 mm x 20° chamfer, as shown in Figure 20. The inserts code-key is RNMN1204M0TN, Table 8 describe each key letter specification of the code-key. A modular milling cutter system, with a tool holder code SECO-EPB-E3476 5820 1260 and a milling cutter code R220.26-0050-RN1204.6A was used to the cutting tools

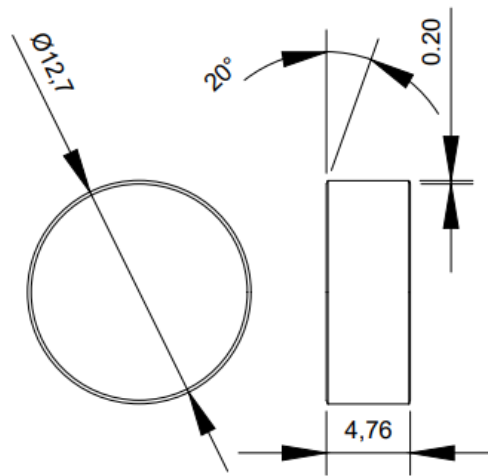
fixation during the machining tests. The cutter is from Seco tools specific division for ceramic inserts. The tests were performed using three inserts fixed in the tool holder.

Figure 19 – Experimental Al_2O_3 - MgO ceramic inserts.



Source: Author.

Figure 20 – Experimental Al_2O_3 - MgO ceramic inserts dimensions.



Source: Author.

Table 8 – Experimental Al_2O_3 - MgO ceramic inserts Code key description

Key designation	Key letter	Insert Description	Image
Shape	R	Round shape	
Side clearance angle	N	0° angle	
Tolerance	M	$s \pm 0.13$ mm (thickness) $d \pm 0.08$ mm (diameter)	
Type	N	Type N	
Cutting edge length	12	12mm diameter	
Thickness	04	S=4.76 mm	
Insert with corner chamfer/nose radius	M0	Round insert	
Cutting edge designation	T	Geometry of cutting edge	
Direction of cutting	N	Neutral (R- and L-rotated)	-

Source: Adapted from Seco (2020).

The experimental cutting tools are high density ceramic inserts composed of 99.75% of aluminum oxide (Al_2O_3) with the addition of 0.25% of magnesium oxide (MgO) in mass proportion. The characteristics of the used high-purity α -aluminum powder supplied by the Almatix Enterprise is in Table 9.

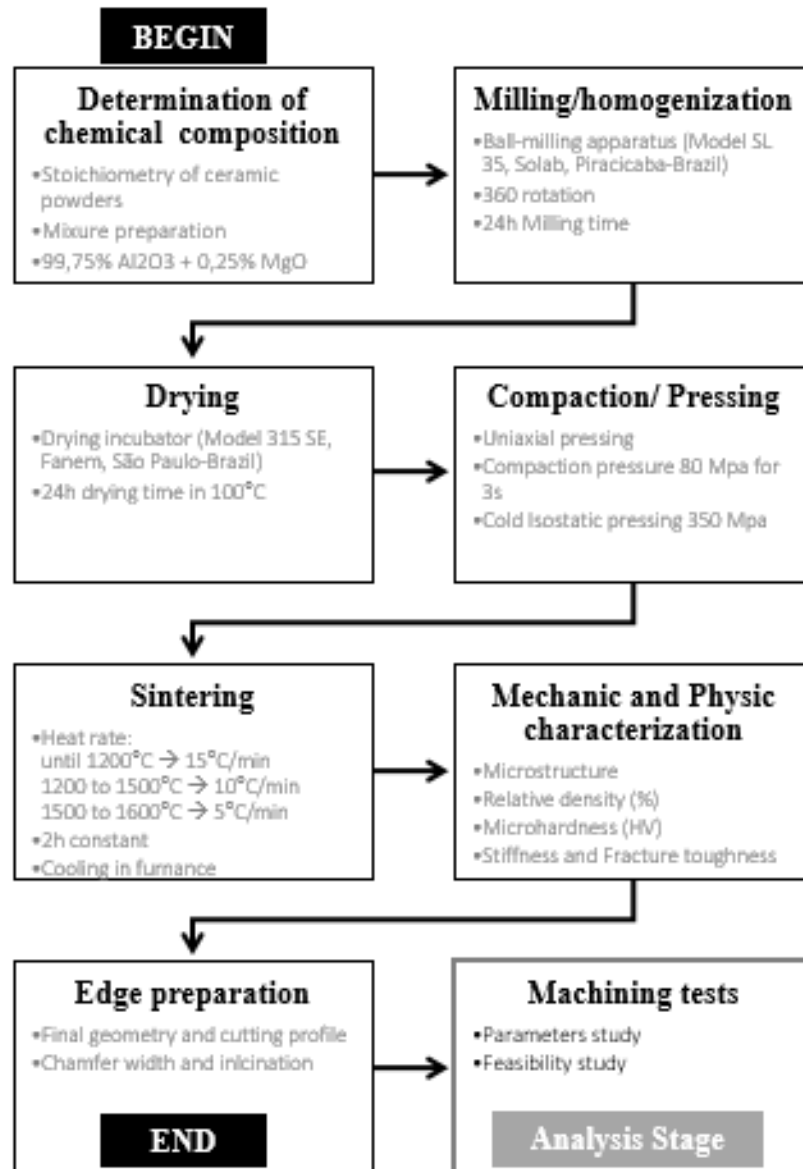
Table 9 – Alumina CT3000LS SG main characteristics description

Characteristic	Unit	Value
Na_2O	%	0.015
Fe_2O_3	%	0.0171
SiO_2	%	0.0161
MgO	%	0.0505
CaO	%	0.0140
Surface Area	m^2/g	8.28
D 50 grains	μm	0.42
D 90 grains	μm	1.9
Green Density	g/cm^3	2.25
Fired Density	g/cm^3	3.92
Shrinkage	%	17.0

Source: Author

The ceramic inserts were developed by the Machining study group at the Materials and Technology Department of the Sao Paulo State University (UNESP). The basic fabrication stages and main considerations are described in Figure 21, from beginning to end of the fabrication process. The last stage is destined to analysis during machining test.

Figure 21 – Experimental inserts fabrication stages and main consideration points.



Source: Author.

4.2.2.1 Characterization methods of experimental cutting tools

The ceramic cutting tools characterization was made by mechanical and physical properties. Density tests were performed through the Archimedes principle of the sintered

specimen through calculations based on Equation (5). The experimental density was correlated with the theoretical density evaluated according the rule of mixtures, following the Equation (6).

$$\text{Density} = \text{mass (g)} / \text{volume (cm}^3\text{)} \quad (5)$$

$$\text{Relative density} = \text{experimental density} / \text{theoretical density} * 100 \quad (6)$$

To measure the Young's Modulus of the ceramic material through the Impulse Excitation Technique, following the ASTM E1876 and correlated standards, it was used the Sonelastic® 2.8 dispositive with manual configuration of SA-BC support. The sample was positioned on a proper sample support and excited by an electromagnetic actuator. An acoustic sensor detected the acoustic response, which was processed by the Sonelastic® software that calculates the elastic modulus from the natural frequencies of vibration (resonance frequencies). The measurement was done in replicate to reduce experimental error.

The micrographs were collected using the SEM (Zeiss, model EVO LS15, Germany). After the grinding and polishing stages it was used the thermal etching method for detection of grain boundaries in 1400 – 1500°C for 10 min.

Another evaluation for mechanical properties was hardness test by using the Microindentation Tester (Wilson, model 401 MVD, USA). The test was conducted to obtain the reference value representing the hardness of the ceramic cutting tool following the ASTM C 1327-99. It was applied a 1kg load for 30s. To evaluate the fracture toughness the procedures followed the ASTM C 1421-99 standard.

4.3 METHODS OF DATA ACQUISITION

The machining experiments were performed on a 5 Axis CNC Machining Center (model DMU50ECO, DMG Ecoline, Germany) with power capacity of milling spindle 13/9 kW at the Machining study laboratory (LEU) of the Materials and Technology department of São Paulo State University (UNESP), Guaratinguetá Campus.

Figure 22 – CNC Machining Center DMG Ecoline, model DMU50ECO.



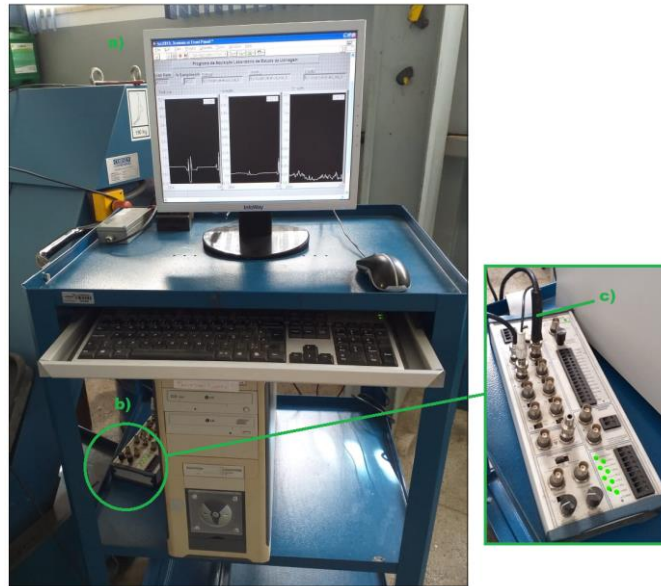
Source: Author.

The experiments were performed through a series of consecutive tests. Beginning by a preliminary test phase where were selected the best cutting parameters considering the supplier recommendation and previews studies of the ceramic tools. Then, the definitive testing phase was executed with selected parameters. The milling tests were conducted without any application of cutting fluids. To the acquisition of instant-data during the machining tests it was installed and assembled a data acquisition system adjusted to the machining center.

4.3.1 Data acquisition system

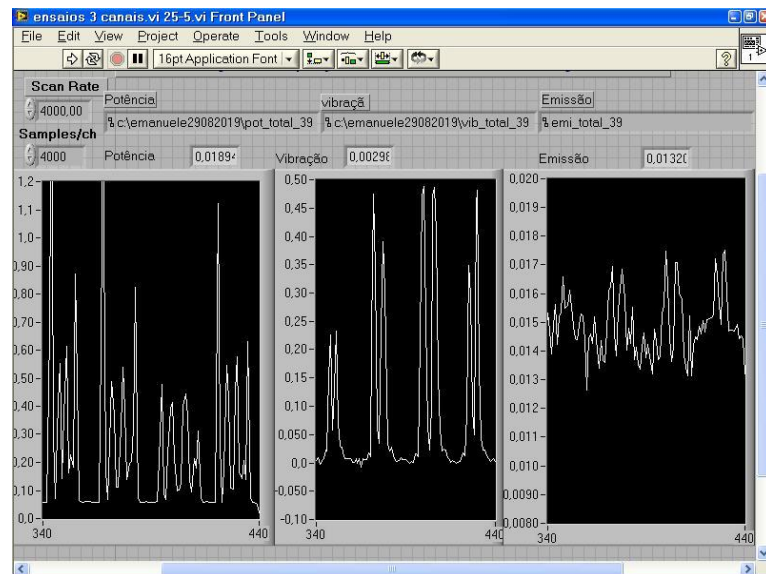
The data acquisition system was connected to the machining center allowing the real-time capture of data of cutting power, acoustic emission and vibration signals during the tests. The system (Figure 23) is composed of a shielded connector block (National Instruments, model BNC-2120, USA) cable coupled to the PCI (National Instruments, model NI 6220, USA) connected to a computer machine. A specific supervisory program was developed by the author using the National Instruments LabView[®] software, to obtain and record (in .txt format) any variation in the studied physical variables in an acquisition range of 4000 point/sec, any variation is converted into proportional electrical signals by the sensors and transducers. The program also allows the supervision of power, vibration and acoustic emission data through instant amplitude plot. The data entry of the sensors is done in voltage (V) units. Figure 24 exemplify the screen interface after the activation of the supervisory program during tests.

Figure 23 – Data acquisition system. a) Computer; b) BNC-2120 Connector block; c) Connection cables.



Source: Author.

Figure 24 – Screen of supervisory program to data supervision



Source: Author.

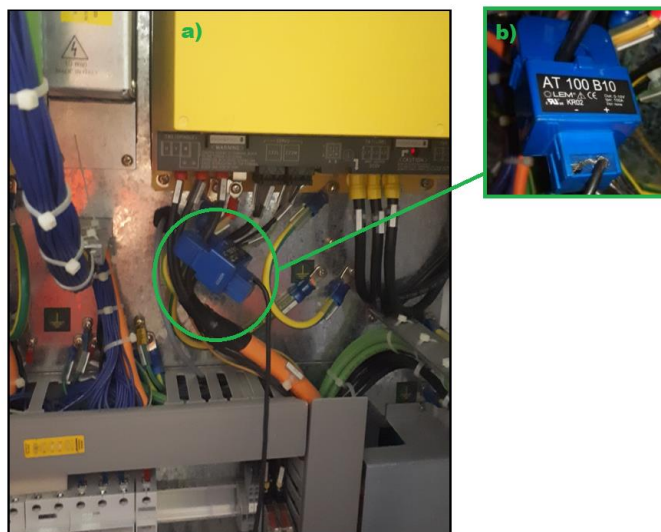
The data acquisition system also includes the power consumption, vibration and acoustic emission sensors.

4.3.1.1 Sensors

To obtain the power consumption during tests, it was used an AC Current Transducer AT-B10 (brand LEM, model AT100B10, China) connected to the machining center engine (Figure 25). Designed to the electronic measurement of AC waveform currents, the sensor measure the current signal of one engine phase and generates a proportional DC voltage output in a rage of 0 to 10 V, this signal allows to estimate the equivalent power consumption in Watts applying the equation (7) by replacing the value of voltage output divided by 10, since the sensor captures voltage amplitude in (0-10V) range, multiplying by 100 due to the transducer current measuring range of 100 (A), the value of the motor voltage (220 V), the motor power factor (0.92), and finally by $\sqrt{3}$ of three-phase motor.

$$\text{Power consumption [W]} = [(\text{voltage output})/10] * 100 * 220 * 0,92 * \sqrt{3} \quad (7)$$

Figure 25 – a) Disposition of power transducer in the machining center engine; b) Current Transducer AT100B10.



Source: Author.

The capture the vibration data it was used a basic vibration transmitter (VICROCONTROL, model TV-100, Brazil) with connector for frequency inverter (Connector IP 67, cable KMP AFS 1P - 24 AWG). Combining the action of a vibration sensor (Accelerometer) and a signal transmitter in the same housing, this unit was applied to detect vibrations during the tests, transmitting a proportional 4-20 mA signal directly to the computer. The vibration sensor has an output range of 25 mm/s in RMS. The values obtained in volts

were converted to speed values in mm/s applying to Equation 8, provided by the sensor manufacturer.

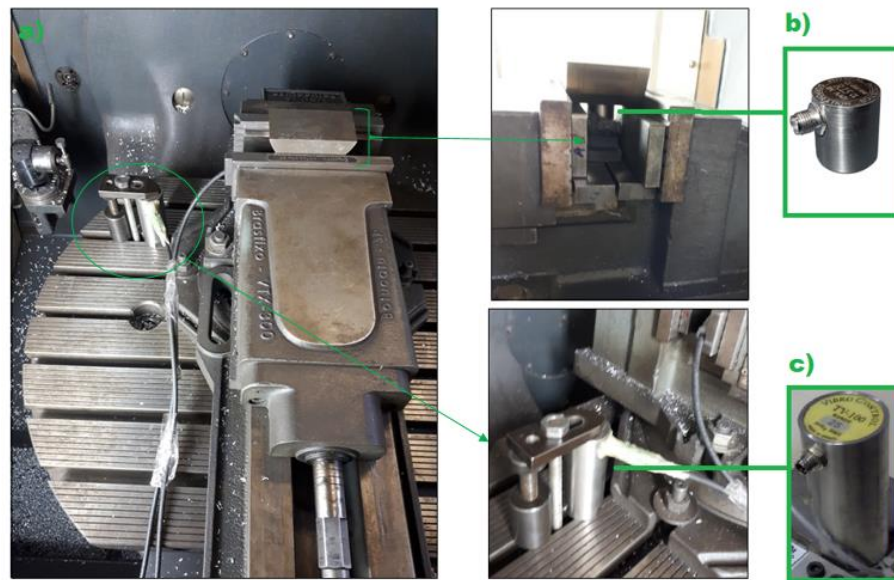
$$\text{Vibration [mm/s]} = [(\text{voltage output}) * 25] / 8 \quad (8)$$

To obtain the acoustic emission signals, it was used a narrow band resonant sensor (Physical Acoustic Corporation, model R15 α , USA) coupled to a pre-amplifier (Physical Acoustic Corporation, model 1272-1000, USA) with a RMS output to the connector block. As the sensor output is rectified in RMS (Root Mean Square with unit in volts), the emission value is equal to the voltage output signal obtained by the sensor (Equation 9).

$$\text{Acoustic Emission [RMS]} = \text{voltage output [Volts]} \quad (9)$$

The experimental disposition of the vibration and acoustic emission sensors and fixation of test specimen is presented in Figure 26a).

Figure 26 – a) Experimental disposition of sensors; b) AE sensor c) Vibration transmitter.



Source: Author.

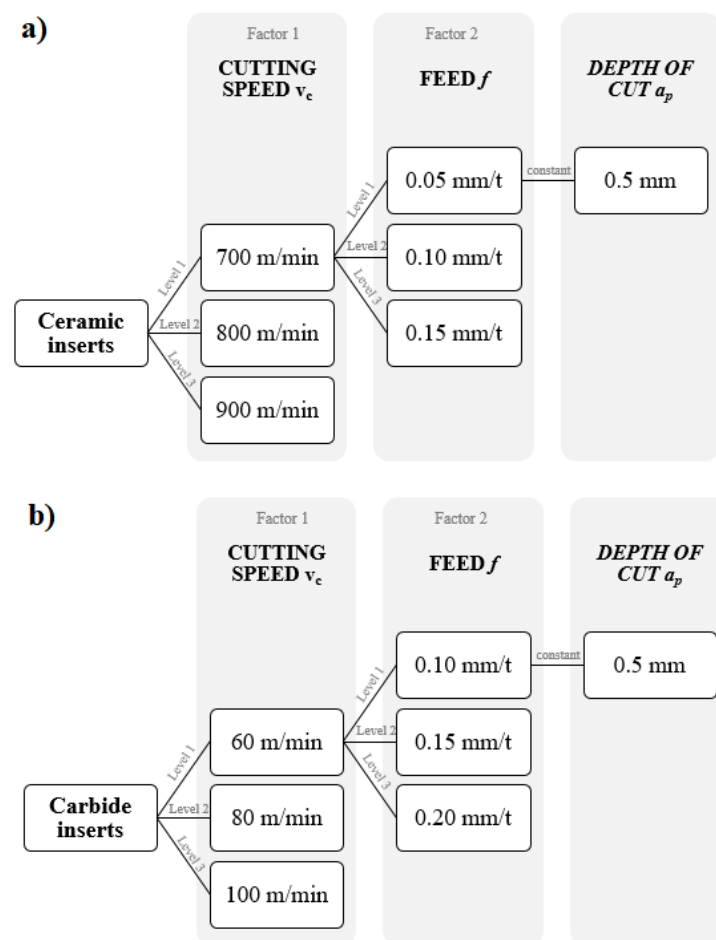
4.3.2 Testing methodology and design of experiments

The experimental design applied to the machining experiments was a 3-levels full factorial design (FFD), with 2 factors. Since the cutting speed ranges used to carbide and

ceramic tools are very different, the design was applied separately for each type of cutting tool (experimental and commercial) as shown in Figure 27.

The first factor is the applied cutting speed (v_c) with three levels: to the ceramic inserts (700; 800 and 900 m/min) and to the commercial inserts (60; 80 and 100 m/min). The second factor is the feed (f) again with three levels: to the ceramic inserts (0.05; 0.10; 0.15 mm/t) and to the commercial inserts (0.1; 0.15 and 0.20 mm/t). The depth of cut was maintained constant in 0.5 mm to both cutting tools.

Figure 27 – Schematic of FFD for a) ceramic inserts; b) carbide inserts



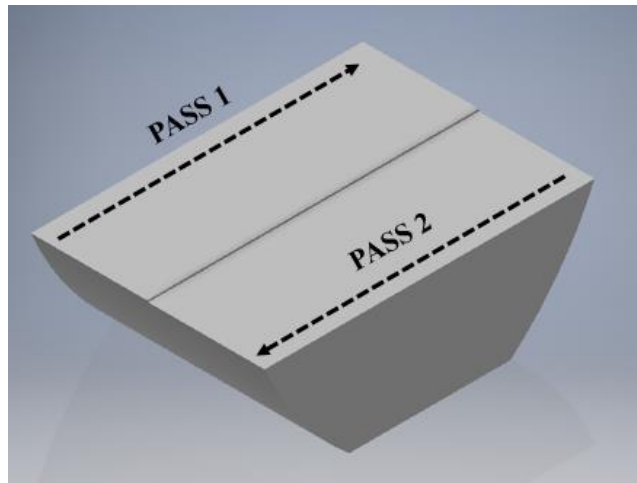
Source: Author.

The choice of applying a FFD instead of a fractional factorial design or a Plackett-Burman design (PBD) was due to the realization of preliminary tests that allowed the investigation and determination of cutting parameters specific ranges that indicate the possibility of better response in the output variables. In addition, the 3-levels FFD allowed the investigation of all possible effects of all the factors and their interactions on each response

variable, fact that would not be possible in other designs. In total, 9 experiments were conducted with two repetitions, totaling 18 experiments.

During the machining tests phase, each experiment consisted in two passes throughout the test specimen, as can be seen in Figure 28. On that basis, the machining process can be described by face concordant asymmetric milling.

Figure 28 – Schematic of experimental machining tests.



Source: Author.

4.4 METHODS OF DATA ANALYSIS

4.4.1 Data treatment

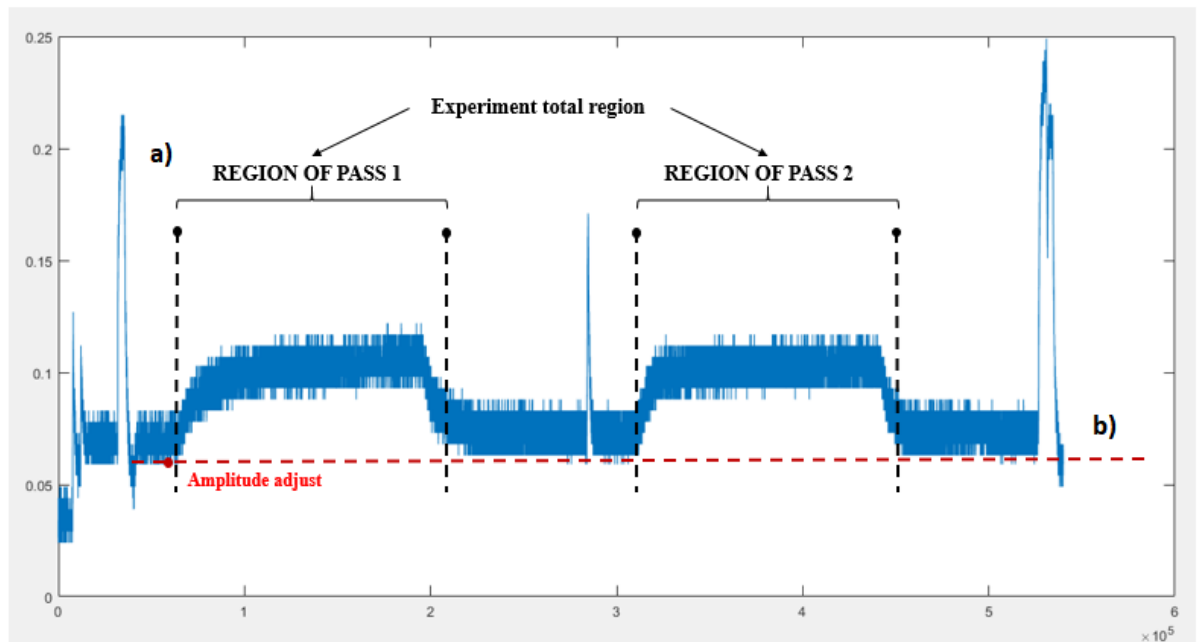
After the acquisition, the experimental data were processed using a program developed by the author in the MATLAB® R2015b software. The program include four steps of data treatment:

- i. Data adequacy: The data obtained using the LabView® were processed to adequate to the MATLAB® programming. It was necessary to substitute the commas (which separate the decimals in the text files generated by the LabView®) to points, to meet the standard programing of MATLAB®. Since the stored data were captured in an acquisition rate of 4000 points per second, the values were store in matrix dispositions. It was necessary to convert from matrix into single columns of data, to help the programming and equations the program.
- ii. Equations application: Since the sensors response was done in proportional voltage signals, corresponding to power, acoustic emission and vibration, it was necessary to

convert the data to standard units. The application of Equations 7, 8 and 9, respectively, to the signals in Watts (power), mm/s (vibration) and RMS (acoustic emission).

- iii. Determination of the test limits: In concordance of the power acquisition plot graph, the determination of begin and end of each experimental test was made separately by marking the two points that represent these stages in the graph, selecting the real region of contact tool-sample. Two points were marked for each test considering the first and second pass (Figure 29a). A third point was also marked to adjust the amplitude of data to the selected region (Figure 29b). This step is important to delimitate the area that will be estimate the maximum, minimum and mean of data.

Figure 29 – Example of a power graph plot; a) Selection of the experiment region for pass 1 and 2; b) Selection to adjust the power data amplitude.



Source: Author.

- iv. Mean results and graphs: After selection the experiment region, a distinct line graph is plotted for each variable response (power, EA and vibration). The calculation of all maximum, minimum and mean of the data is determined. In the study it was consider only the average of the points of maximum present in the experiment region, thereby to analyze the areas of more importance that could significantly be affected by the cutting parameters.

4.4.2 Statistical Analysis

After the data treatment, the obtained data was submitted to a statistical analysis according the design of experiments of each cutting tool. The analysis was done using the MINITAB17® software, with the application of different statistical techniques: the Two-way analysis of variance (ANOVA), analysis of means (ANOM), normality tests and multiple comparison tests.

The Analysis of Variance was consider to determine the influence of each independent variables (factors) on the dependent variables (responses), to specify the contribution of each factor in the final response and to estimate a regression equation that could explain the analyzed data. It was consider a significance level of 95% ($\alpha = 0.05$) to all statistical interactions. To verify the data normality it was applied the Anderson-Darling and the Kolmogorov-Smirnov tests. To the population of data that was found not in a normal distribution, different methods of data normalization were applied, such as Box-Cox transformation and logarithmic transformation. The multiple comparison tests of Tukey were applied to identify which group of data has statistically significant difference among the other data groups. Subsequently, the mean analysis (ANOM) was applied to determine the configuration of factors that result in the less variation in the process and better results. The statistic interest consider for all responses was “Less is better”.

To better understand the statistic relevant results the following plots were consider: individual value plot, normal probability plot of the residuals, Boxplot, histogram of residuals, residuals versus variables, main effects plot and interaction plots.

4.4.3 Surface quality analysis

The surface quality analysis was done considering the roughness analysis of the machined surfaces following the NBR ISO 4288 from 11/2008 of Geometrical product specifications (GPS) - Surface texture: Profile method - Rules and procedures for the assessment of surface texture. After each machining test it was performed the measurement of the Roughness average (R_a), Maximum height of the profile (R_t) and Average maximum height of the profile (R_z). The roughness measurement was made using a mobile roughness measuring instrument (Mahr, model MarSurf M 300, Germany) with a rounded cone diamond tip with 2 μm radius. The selected cut-off was 800 μm with 4mm length according the AISI NBR4287: 2002, with three replica measurement.

4.4.4 Cutting tools performance analysis (wear analysis)

The analysis of the wear and damages that occurred during tests was done by determining the type of wear, mechanisms of wear formation, measurement of flank wear (V_b) and identification of damages in the cutting tools surfaces. To evaluate the wear and obtain the damage images it was used a Manual Vision Measuring Machine (Quick Scope SERIES 359 model QS-L2010ZB, Mitutoyo®, USA) and a Stereomicroscope (Carl Zeiss, model Stemi 2000, Germany).

4.4.5 Chip analysis

The chips generated during machining were collected after each experiment. The classification was done according its type and form, following the recommendations of the ABNT NBR ISO 3685:2017 standard. The identification of type, form and analysis of mechanism of formation was done using the manual vision measuring machine (Quick Scope SERIES 359, model QS-L2010ZB, Mitutoyo®, USA) and the Stereo Microscope (Stemi 2000-C, Carl Zeiss Jena GmbH, Germany).

4.4.6 Specific cutting pressure analysis

With the aim of investigate the VAT 32® behavior during the machining tests, the specific cutting pressure was estimated along the cutting force and chip thickness, by employing Kienzle's model in Equation 10 (KIENZLE, 1952).

$$F_c \text{ [N]} = K_s \text{ [N/mm}^2\text{]} * A \text{ [mm}^2\text{]} \quad (10)$$

The specific cutting pressure was obtained for the workpiece material by considering the adaptations to the machining process by milling, thus calculating the mean cutting force (F_{cm}), mean cutting thickness (h_m) and mean cutting section area (A_m). To milling, the Kienzle's model allows us to calculate the mean specific pressure (K_{sm}) and cutting force for the mean chip thickness and depth of cut, as shown in equation (11).

$$F_{cm} \text{ [N]} = K_{sm} \text{ [N/mm}^2\text{]} * A_m \text{ [mm}^2\text{]} \quad (11)$$

To calculate the mean cutting force (F_{cm}) to each machining condition (i.e. cutting speed (v_c) and feed variation), it was used the Power consumption (P_c) data obtained by the sensor during the machining tests. The power consumption is related to the cutting force according the Equation 12.

$$P_c \text{ [W]} = (F_{cm} \text{ [N]} * v_c \text{ [m/min]}) / 60 \quad (12)$$

The mean cutting section area (A_m) is the result of the mean chip thickness (h_m) and the average width (b) (Equation 13).

$$A_m \text{ [mm}^2\text{]} = h_m \text{ [mm]} * b \text{ [mm]} \quad (13)$$

To estimate the mean cutting section area, it was necessary to calculate the mean chip thickness (h_m) as it is in equation 14. In milling, the chip thickness varies with the cut (Figure 30), from zero to maximum (concordant milling), changing chip thickness with feed, cutting depth, cutter diameter.

$$h_m = [(\sin \chi * 180 * a_e * f_z)] / [\pi * D_{cap} * \arcsin (a_e / D_{cap})] \quad (14)$$

Where:

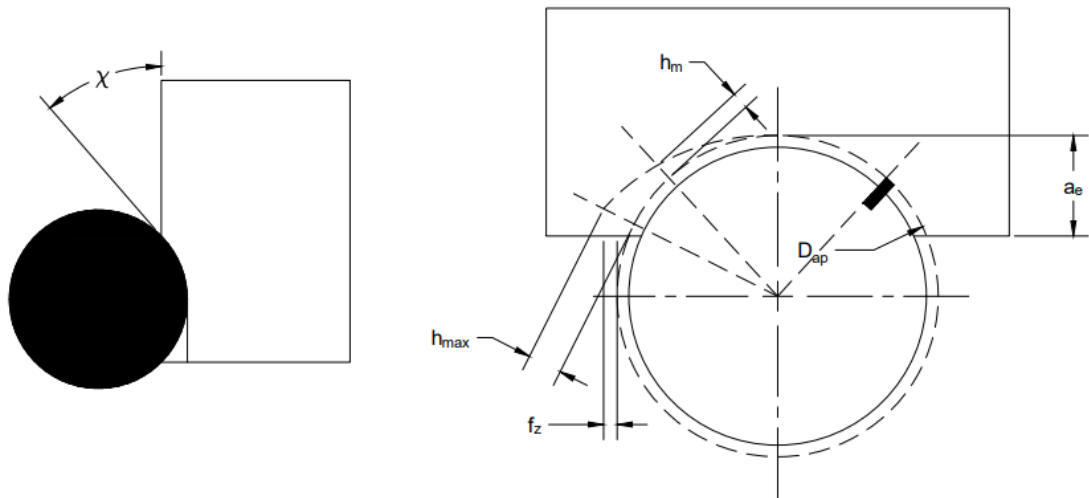
χ = Position angle

a_e = Radial depth of cut [mm]

f_z = Feed per tooth [mm/t]

D_{cap} = Cutting diameter at cutting depth (a_p)

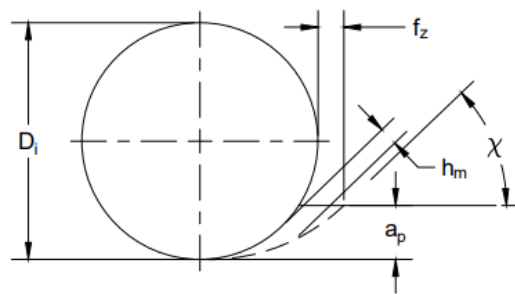
Figure 30 – Chip thickness variation to face milling operation with round inserts.



Source: Author.

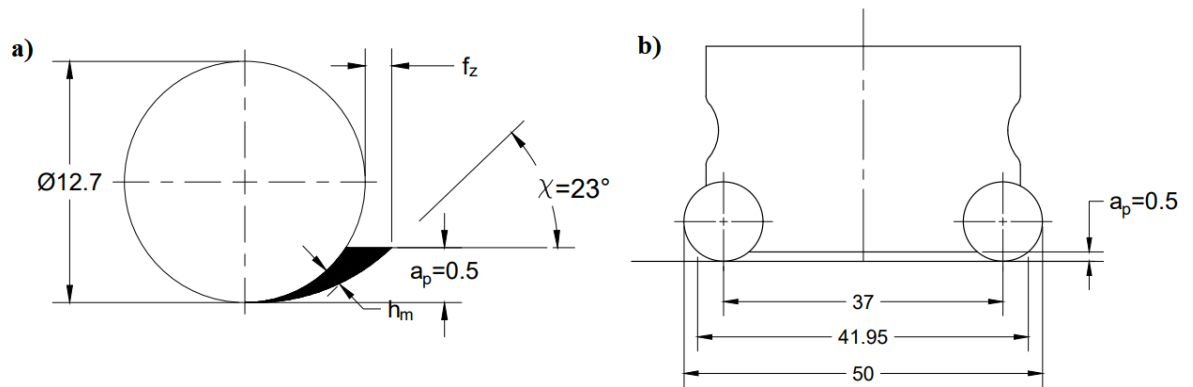
Since this work consider the application of round inserts to machine by milling (Figure 31), and the position angle changes during the cut, it was necessary to establish a criteria to the position angle determination. The maximum position angle ($\chi = 23^\circ$) was considered to both carbide and ceramic tools (Figure 32-a). The cutting diameter at the studied cutting depth ($a_p = 0.5\text{mm}$) is displayed in Figure 32-b)

Figure 31 – Chip thickness to round insert application.



Source: Author.

Figure 32 – a) Chip thickness to the carbide and ceramic tools application; b) Cutting diameters to the milling cutter.



Source: Author.

The average width (b) was estimated to the insert diameter (D_i) and the maximum position angle ($\chi = 23^\circ$) of the cutting inserts, according equation 15.

$$b_m [\text{mm}] = \pi * D_i * (\chi / 360) \quad (15)$$

The specific cutting pressure determination was done separately to the coated carbide and the experimental ceramic tools application to verify the implications of using the two different cutting tool materials to machine the VAT 32[®] alloy. The Kienzle equations were adjusted to the milling process conditions and the round inserts application.

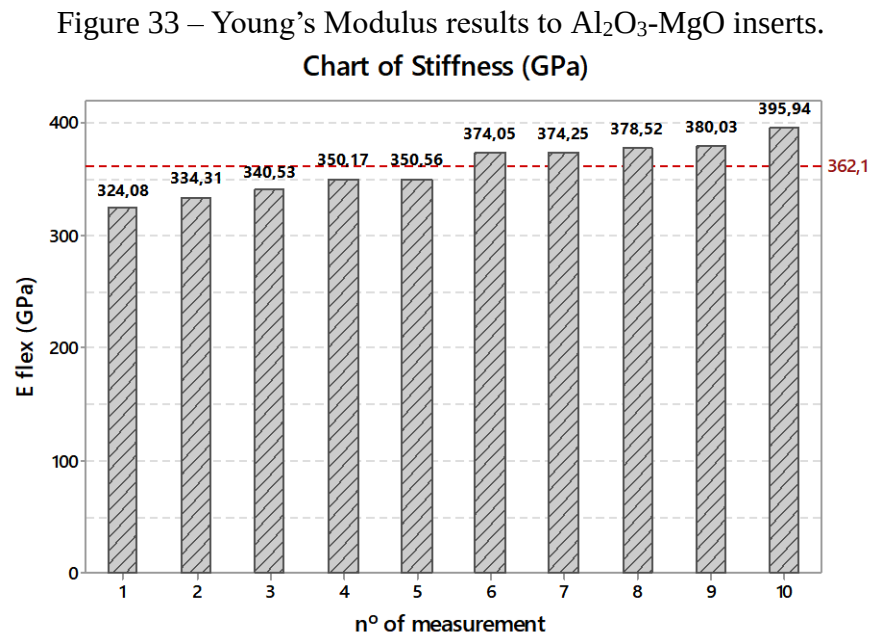
5 RESULTS AND DISCUSSION

In this section is presented the discussion of the results obtained by milling the VAT 32[®] superalloy using commercial (Ti,Al)N + TiN PVD coated carbide inserts and experimental Al₂O₃ + MgO ceramic inserts. The characterization of studied materials is also discussed.

5.1 TOOL AND MATERIAL CHARACTERIZATION

5.1.1 Experimental Al₂O₃-MgO ceramic tools

The measurement of the Young's Modulus of Al₂O₃-MgO inserts was obtained considering five consecutive measurements of two specimens, to reduce experimental error. The results were set maintaining standard voltage and time to the electromagnetic actuator refined to 30000 Hz frequency. The mean of measurements indicate a mean Young's modulus of 362.1 GPa to the tested material, with a Poisson's ratio of $\mu = 0.205$. The results of all measurements are shown in Figure 33.



Source: Author.

The Young's modulus value observed is consistent to the range of advanced ceramics, close of commercially available alumina (99.5%) with an elastic modulus of approximately 375 GPa. Supporting that the material possess high stiffness, measured by inspecting the

elasticity of the specimen. Fact that can be explained by the strong and directional bonding between constitutive atoms, which also lead to a high fusion temperature and thus a high thermal stability of the ceramic material. This high rigidity allows the ceramic inserts to be manufactured with much higher levels of precision regarding to size and shape, that together with high chemical stability and lightweight compared to most metals make them to be the best material choice for high-stress and high-temperature cutting conditions. The high stiffness also favor HSM conditions, and reduce flank wear rate in comparison to carbide tools.

The hardness results support the high value of stiffness found. With obtained micro-hardness of approximately 1928.4 HV or 18.91 GPa, the 0.25% MgO doped inserts present higher hardness result than the use of other dopants such as ZrO_2 , Y_2O_3 and lower hardness if compared to the use of chromium oxide, for example. Table 10 present a comparison between the experimental composition and hardness results of other compositions using dopants in alumina-based cutting tools.

Table 10 – Hardness comparison for different compositions of Alumina-based inserts.

Composition	Hardness (GPa)
99.75% Al_2O_3 + 0.25% MgO	18.91
Pure Al_2O_3	19
99% Al_2O_3 + 1% Cr_2O_3	21.50
81.5% Al_2O_3 + 18.5% 3Y- ZrO_2	16.22
95% Al_2O_3 + 5% Y_2O_3	12.10
99.4% Al_2O_3 + 0.6% MgO-ZTA	17.04

Source: Author's own and adaptation of Callisaya; Alves (2019), Souza (2013), Souza (2005); Singh et al. (2018).

The hardness value obtained for the Al_2O_3 -MgO inserts is within the average range found in manufacturers of alumina-based ceramic cutting tools (SANDVIK, 2012). To the specific application of MgO as dopant, the results are in accordance to previews studies of Al_2O_3 doped with MgO that presented a hardness range from 14 to 18 GPa (SOUSA, 2020 apud BARSOUM, 2013)⁵. It is also possible to notice an increase in hardness to the addition of MgO, as stated by Rittidech et al., (2006).

⁵ SOUSA, T. A. **Usinagem de ferro fundido vermicular com ferramenta de corte à base de alumina magnésio**. 2020. 143 p. Thesis (PhD in Mechanical Engineering) – School of Engineering, Sao Paulo State University (UNESP), 2020 apud BARSOUM, M. W. **Fundamentals of ceramics**. In: MC GRAW, H. (Ed.). IOP institute of physics publishing Bristol. 2nd ed. Philadelphia: 2003.

To obtain the material relative density, first the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic specimens were weighed, in order to verify the loss of mass occurred during sintering, to compare with the weight before the process. After weighing, the specific mass of the samples was evaluated, using the immersion method proposed by Archimedes. The results of the specific mass were correlated with the theoretical specific mass of the material, evaluated through the mixtures rule, being obtained then, the relative density of the samples. Results are displayed in Table 11.

Table 11 – Results to the sinter specimens of $\text{Al}_2\text{O}_3\text{-MgO}$

Loss of mass (%)	1.4 ± 0.1
Linear retraction (%)	20.41 ± 0.16
Relative Density (%)	98.52 ± 0.15

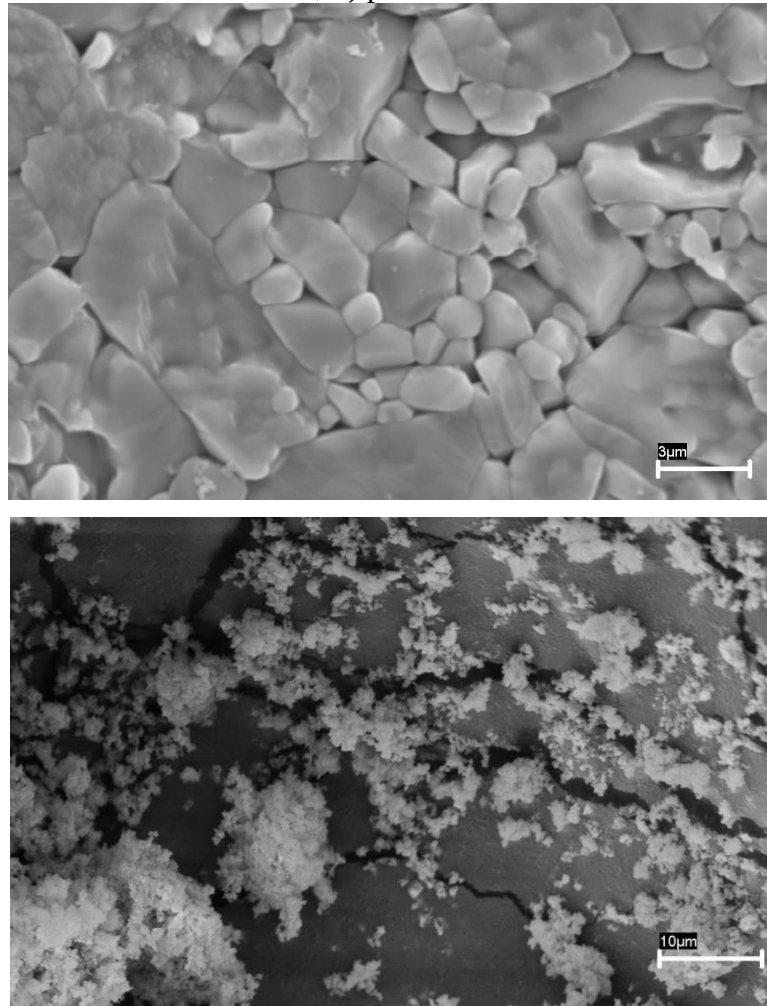
Source: Author

Considering the sintering process of the ceramic inserts, the $\text{Al}_2\text{O}_3\text{-MgO}$ specimens presented a high relative density of 98.52%. This high density is a result of the specific characteristics of the pressing and sintering processes applied to the inserts fabrication that resulted in high densification and low porosity. The result also indicates that for the applied sintering conditions (heating rates, landing temperature and sintering temperature) the use of magnesium oxide as additive was successful by enabling high densification rate.

As regarding the low loss of mass result of 1.4% it is possible to affirm that sintering conditions and specifications were effective and are well adjusted to the inserts fabrication process.

The microstructure of the $\text{Al}_2\text{O}_3\text{-MgO}$ inserts is presented in Figure 34-a). The image was obtained from a fracture surface of the insert. It is possible to observe the compact microstructure, with the presence of some intra-granular pores. The grains are predominantly equiaxed with heterogeneous grain size distribution. The observed morphology indicates that MgO was effective promoting densification during sintering, and inhibiting the discontinuous growth of grains, by reduce grain-boundary mobility in Al_2O_3 . Such efficiency suggests high MgO solubility at applied sintering temperatures. It is also possible to verify larger alumina grains that can occur since the grain growth of alumina is directly proportional to the sintering time (landing temperature), the longer the time the larger the grains. In the SEM image of the 99.75% Al_2O_3 + 0.25% MgO powder mixture (Figure 34-b) is possible to identify several aggregates that may have contributed to the irregular growing regions of the alumina grains, leading to the formation of larger grains in the sintered final form.

Figure 34 – SEM micrographs of the 99.75% Al_2O_3 + 0.25% MgO : a) insert microstructure; b) powder mixture.



Source: Author.

The characterization results indicate that the Al_2O_3 - MgO inserts with defined composition of 99.75% Al_2O_3 + 0.25% MgO are suitable to be applied as cutting tools presenting the necessary mechanical properties for the manufacture and tribological application of cutting tools. The results assure high hardness at high temperatures, low porosity, abrasive wear and oxidation resistance and chemical stability.

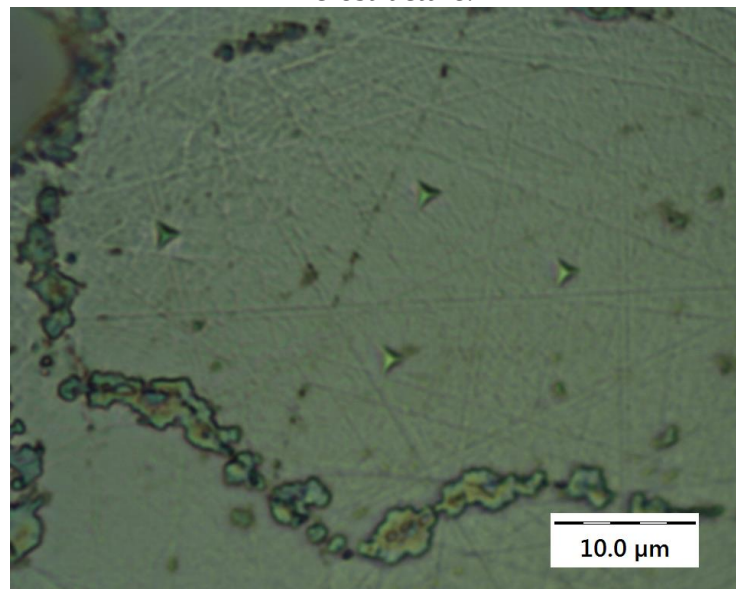
5.1.2 VAT 32®

The micro-hardness results obtained for the VAT 32® test specimen indicated a mean hardness of approximately 375.4 HV. The hardness result was expected, according to preview analysis by Farina et al. (2013a), where the VAT 32® presented hardness of 375 HV at a

temperature range of 250°C to 750°C. The result also indicate a higher hardness in comparison to the Inconel 751[®] that usually presents 352 HV at same conditions.

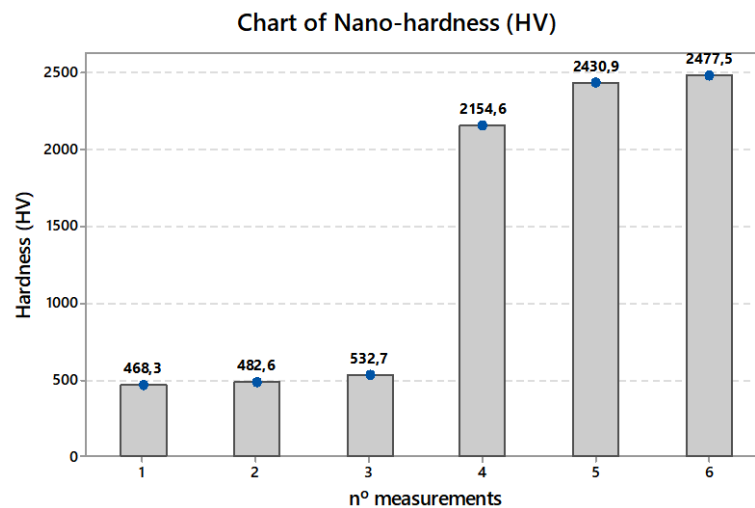
However, as the material is composed by very distinct phases, a more specific nano-hardness analysis was made. A sequence of indentations were made to define the hardness value of the matrix and the high hardness carbides. Nine indentations were made in different regions of the superalloy's microstructure, Figure 35 shows the indentations in the matrix region. Measurements 1 to 3 are located in the matrix region and 4 to 6 in the precipitation of carbides region, results are displayed in Figure 36.

Figure 35 – Determination of hardness by indentation in the different phases of the VAT 32[®] microstructure.



Source: Author.

Figure 36 – Nano-hardness results to different phase regions of VAT 32[®] superalloy.



Source: Author.

The hardness results were consistent to each analyzed region. The matrix region presented mean hardness of 494.53 HV while the carbides region present a mean of 2344.3HV. The lower hardness results found are consistent to the austenitic matrix hardness of nickel-based superalloys found in literature. The matrix is responsible for the good ductility, good impact resistance, high and low cycle fatigue resistance and thermal fatigue properties of the superalloy. The higher hardness values found are compatible with the precipitation of primary carbides type MC, in this case due to the high niobium addition with carbon, that control the formation of NbC. These carbides present high hardness which provide high abrasion resistance to the alloy. However, the presence of carbides also increase the difficult in machining processes, favoring tool damage and chipping of the cutting edge.

5.2 STATISTICAL ANALYSIS OF THE PROCESS

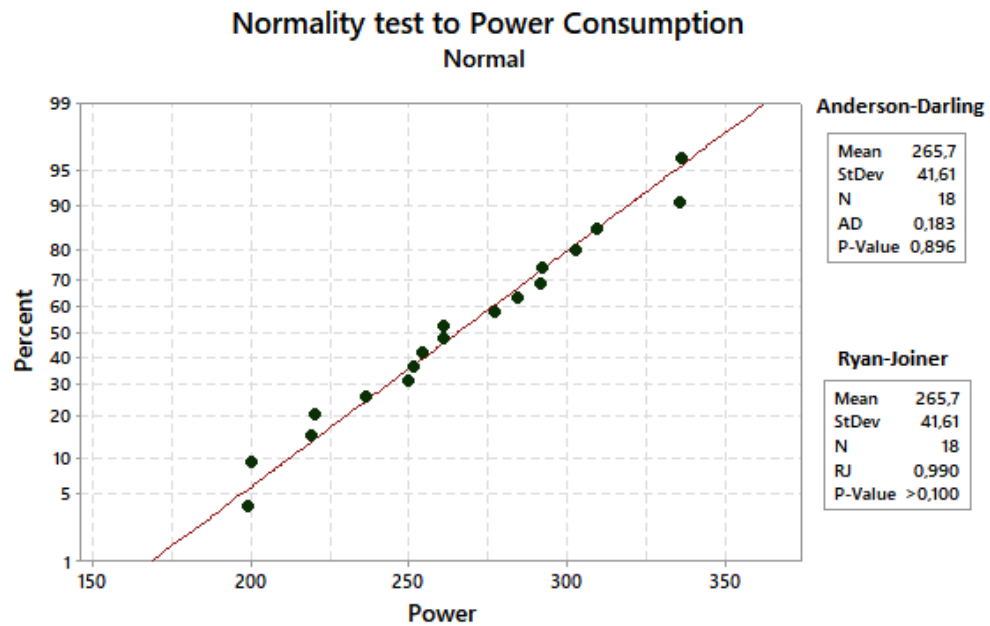
5.2.1 Application of the commercial TiAlN-TiN coated carbide tools

In this section, the statistical analysis of the output variables of the milling machining process is presented and discussed, considering the use of the TiAlN-TiN PVD coated carbide inserts. The output variables discussed are power consumption, vibration, acoustic emission, roughness (R_a , R_t and R_z) and wear.

5.2.1.1 Power Consumption

At first, the Anderson-Darling normality test was applied to the power consumption data obtained during the machining experiments. The Anderson-Darling normality test compared the ECDF (empirical cumulative distribution function) of the power data with the distribution expected if the data were normal. The obtained P-value of 0.896 was greater than the level of significance of 5% (0.05), what indicates that to a 95% confidence interval, the data obtained can be considered as part of a normal population. To ensure the normality tendency it was applied the Ryan-Joiner normality test that revealed a correlation coefficient of 0.990, supporting high normality distribution tendency of results. The Ryan-Joiner test assesses the strength of the correlation between the power data and the normal scores of the obtained data, as the coefficient is close to 1, strong normality tendency is verified. Figure 37 shows the normality results to both tests applied.

Figure 37 – Normality distribution analysis of Power consumption using carbide tools.



Source: Author.

Since the normality of results was proven, the analysis of variance was applied to the Power consumption data. ANOVA results are displayed in Table 12.

Table 12 – ANOVA to power consumption results using carbide tools

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed " v_c " (m/min)	2	22386.3	76.06%	22386.3	11193.1	52.22	0.000
Feed " f " (mm/t)	2	4258.6	14.47%	4258.6	2129.3	9.93	0.002
Error	13	2786.7	9.47%	2786.7	214.4		
Lack-of-fit	4	835.6	2.84%	835.6	208.9	0.96	0.472
Pure Error	9	1951.1	6.63%	1951.1	216.8		
Total	17	29431.5	100.00%				
						R-Sq = 90.53%	R-Sq (adj) =87.62%

Source: Author.

The analysis of variance indicated that the cutting speed and the feed factors were significant to a 95% confidence level ($\alpha=5\%$). That means, that the cutting speed and feed had significant influence the power consumption during the machining. Both P-values of 0.000 and 0.002 are below the set significance level of 5%.

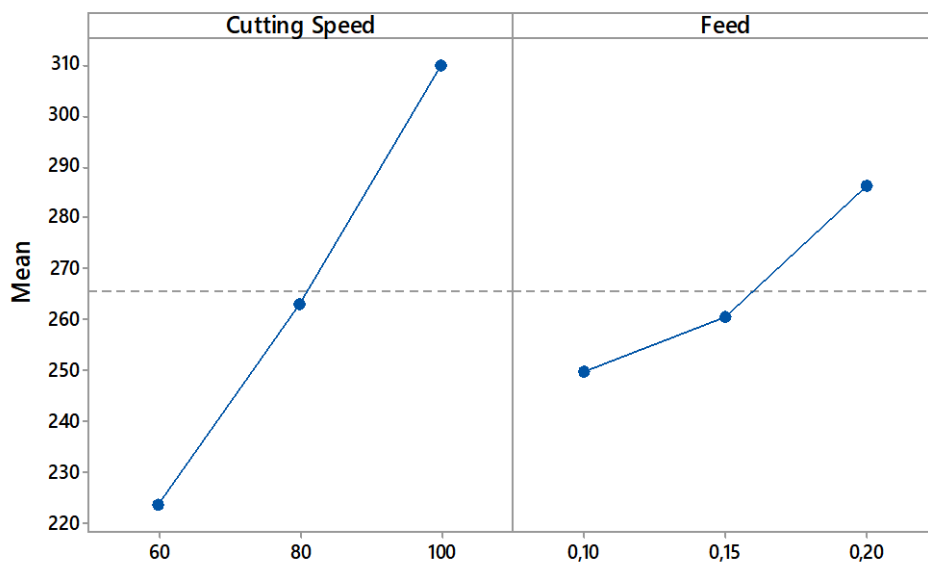
Moreover, it is possible to affirm that between the two parameters, the speed factor had greater influence in the power results, if compared to the feed factor. The F-value of 52.22 denotes a strong relevance of v_c in the power, since the F-value estimate the correlation of the variation between the power means to the variation within all power data. Therefore, the

cutting speed also exerts greater contribution, of almost 77% to all power data, while the feed have a contribution of approximately 15%, close to the error contribution of 9.47%.

To evaluate the variation within the factors, the Main Effects plot exhibit the tendency of influence of the levels into the power results (Figure 38), this analysis is also known as ANOM (Analysis of means). The center line in the main effects plot represents the obtained average power value of 227.56 W. As was stated in the ANOVA table, there is a strong dependence of cutting speeds levels. It is observed a constant increase in the power with the increase of applied cutting speed. The application of higher cutting speeds (100m/min) lead to an increase of 100 W in power. However, the contour plot demonstrate that the majority of power data is located in the mean area correspondent to the v_c of 80m/min level (Figure 39). The thickness of contour regions decrease to the level's extremes of 60m/min and 100m/min.

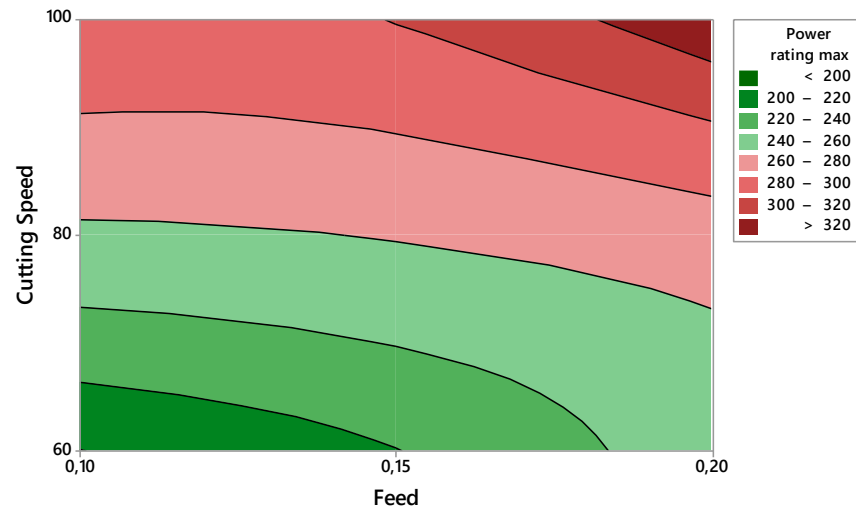
To the feed factor, there is the same increase tendency in power results, but with a lower variation of 40W between the lowest and highest feed. The increase in the power results can be explained due to the increase in the feed generates an increase the cutting area of the primary and secondary shear planes, increasing the cutting force and consequently the power.

Figure 38 – Main Effects Plot of Power Consumption using carbide tools.



Source: Author.

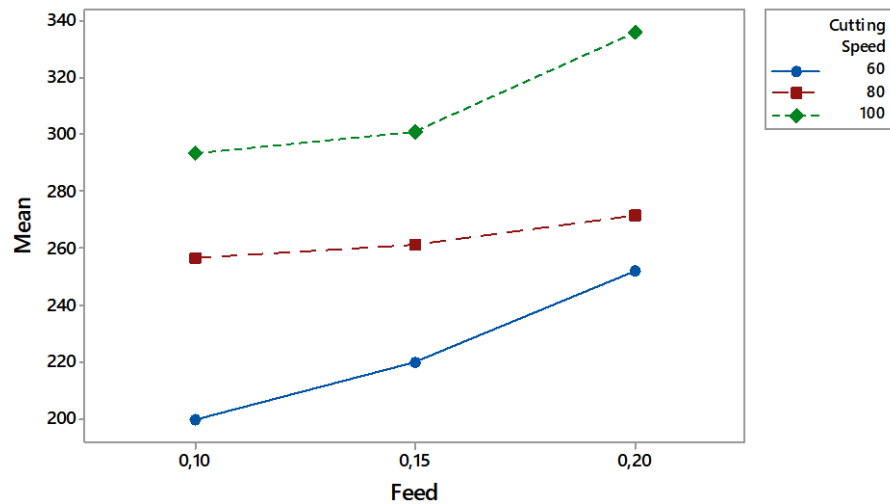
Figure 39 – Contour Plot of Power Consumption using carbide tools.



Source: Author.

The interaction between the factors can be evaluated by the interaction plot (Figure 40). As the lines with the different machining conditions are almost parallels, it can be affirmed that the interaction between the two factors is weak. However, to the 60 and 80 m/min speeds is possible to notice a tendency of interaction between v_c and f by extrapolation.

Figure 40 – Interaction Plot of Power Consumption using carbide tools.

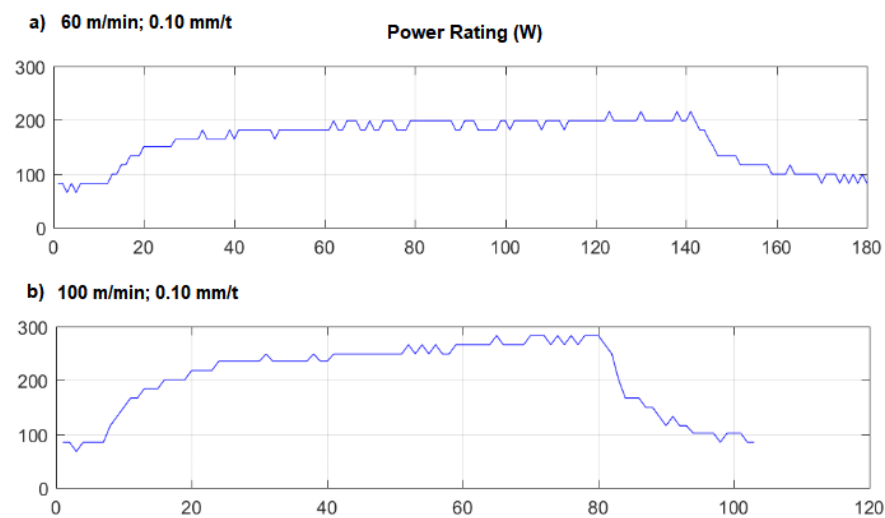


Source: Author.

The power dependence of cutting speed is against the literature that according to Marques (2015), the cutting forces tends to decrease as the cutting speed increases, as the chip-tool contact area becomes smaller and the chip thinner. However, since considering the machining of the VAT 32[®] alloy, the forces are high, promoting high tool wear. Since one of

most common types of wear in carbides tools is the adhesion of material in the cutting edge, it is possible that the power increase can also be motivated to the formation of BUE in the cutting tools, the BUE increases the efforts and forces during machine leading to higher power. In addition, the cutting speed range applied to the experiments can also be too restrict for finish machining. The power increase with cutting speed can be seen in Figure 41, were is maintained the lower feed of 0.1 mm/rot and increased the speed from 60 m/min to 100 m/min.

Figure 41 – Power Consumption during machining using carbide tools; a) 60m/min; b) 100m/min.



Source: Author.

Therefore, according to the statistical analyzes carried out, the best machining condition that allow obtaining lower values of power consumption is v_c of 60 m/min and f of 0.10 mm/t. This condition, consequently allows a lower energy consumption for the machining using the TiAlN-TiN coated carbide tools.

5.2.1.2 Vibration

To the vibration results, the Anderson-Darling normality test assured normal data distribution with a P-value of 0.231. For the statistical analysis, the maximum vibration values were considered, in order to evaluate the effect of the higher vibrations occurred during the process. The analysis of variance indicated that both factors had no significant influence to the vibration results (Table 13). However, according to the Phadke criterion it is possible to state the relevance of the cutting speed and feed. If the F-value is higher than 2, means that the sum

of squares of the factor is at least two times higher than the error sum of squares (MENTEN; PHADKE, 1991). Therefore is possible to highlight statistic relevance for the two factors. Is important to consider the low adjust of the ANOVA regression analysis to the vibration, with a correlation coefficient of only 22.51%, fact that implies in low strength of the linear association between the variables that could have caused the non-statistical significance of the factors. The error has also great contribution to the analysis, with 59.26%, higher than the feed and speed contribution around 20%.

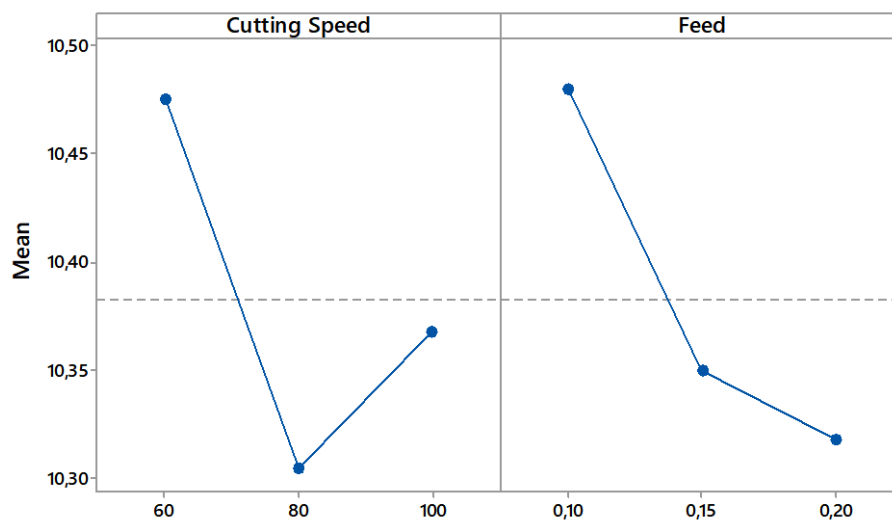
Table 13 – ANOVA to vibration results using carbide tools

<i>Source</i>	<i>DF</i>	<i>Seq SS</i>	<i>Contribution</i>	<i>Adj SS</i>	<i>Adj MS</i>	<i>F-value</i>	<i>P-value</i>
<i>Cutting Speed "v_c" (m/min)</i>	2	0.08919	20.48%	0.08919	0.04409	2.25	0.145
<i>Feed "f" (mm/t)</i>	2	0.08819	20.25%	0.08919	0.04409	2.22	0.148
<i>Error</i>	13	0.25802	59.26%	0.25802	0.01985		
<i>Lack-of-fit</i>	4	0.08784	20.17%	0.08784	0.02196	1.16	0.389
<i>Pure Error</i>	9	0.17018	39.09%	0.17018	0.01891		
<i>Total</i>	17	0.43540	100.00%				
				R-Sq = 40.74%		R-sq (adj) = 22.51%	

Source: Author.

In the Main effects plot the relevance of the feed and the cutting speed variation is clear. Indicating that higher feeds are preferable, as the vibration decreases to the increase of feed. The lowest cutting speed of 60 m/min presented the highest vibration amplitude. The BUE formation can be associated with the high vibration that also favor the chipping and notch wear.

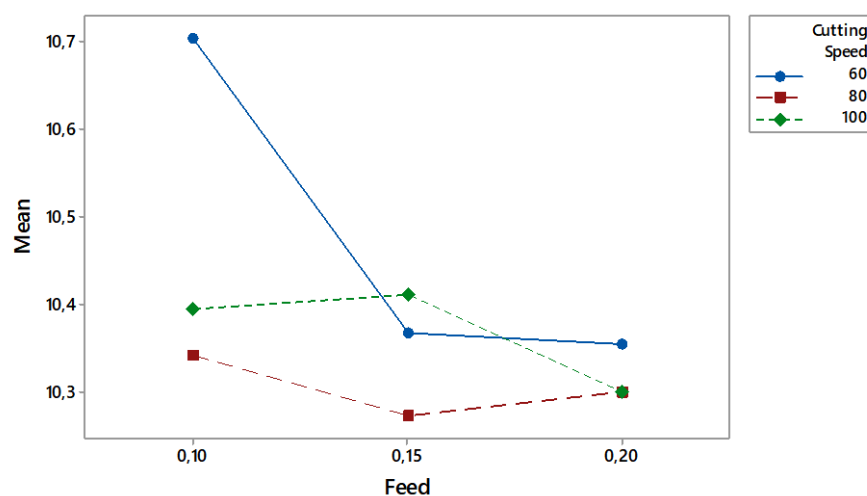
Figure 42 – Main Effects Plot of Vibration using carbide tools.



Source: Author.

In the Interaction plot is possible to observe second order interaction between the factors mostly to the 60m/min and 100m/min speeds. To the 80m/min speed, as the main effect plot highlight better vibration condition is observed. As can be seen in Figure 44 the area around the 80m/min speed presents high density of lower vibration results. The relevance of cutting speed is greater than the feed, allowing good results to both feeds of 0.15 and 0.20 mm/t, if maintained the cutting speed of 80m/min.

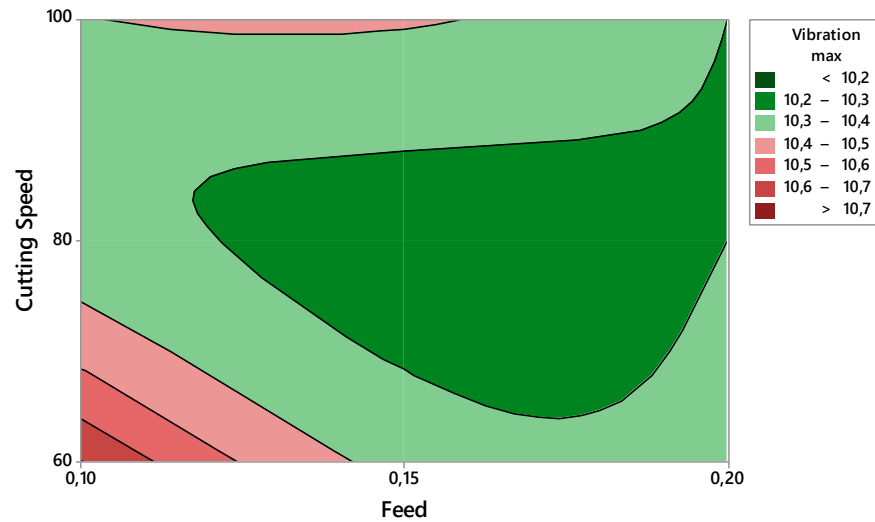
Figure 43 – Interaction Plot of Vibration using carbide tools.



Source: Author.

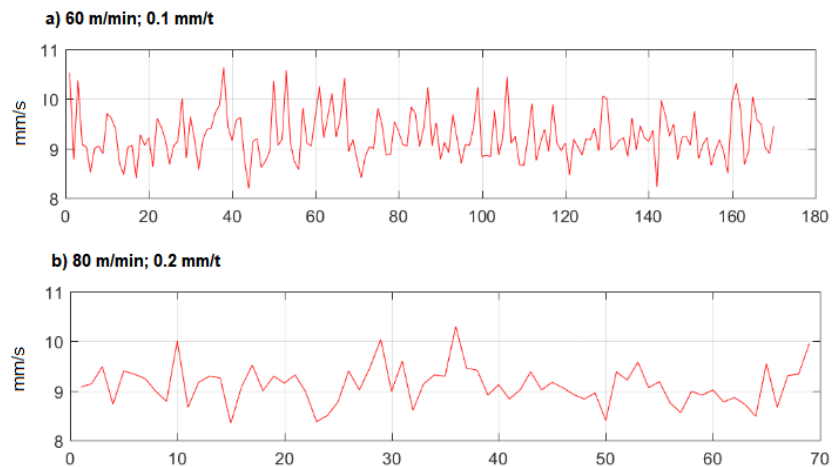
In the contour plot is also possible to observe that high vibration data is obtained to the association of lower cutting speed and feed or to machining at speeds higher than 100m/min. High vibration to the 0.10 mm/t feed can be explained by little material removal in this condition, preventing the tool stabilization and inducing vibration. The increase in vibration to lower speed and feed can be seen in Figure 45.

Figure 44 – Contour Plot of Vibration using carbide tools.



Source: Author.

Figure 45 – Vibration during machining using carbide tools; a) 60m/min; b) 80m/min.



Source: Author.

5.2.1.3 Acoustic Emission

To the AE results, the Anderson-Darling normality test assured normal data distribution with a P-value of 0.425. Similarly to the vibration, the factors had no statistical significance. However, the found F-values are too low thus the contribution of the cutting speed of 3.70% can be disregarded. The contribution of the feed factor is higher than the cutting speed, but lower than the contribution of total error, therefore it can be concluded that, at the studied factor's ranges, the v_c and f exhibit no influence in the AE results. In addition, the square of

the regression coefficient explain only 1.43% of AE data in the linear regression, assuring no dependence of neither factors.

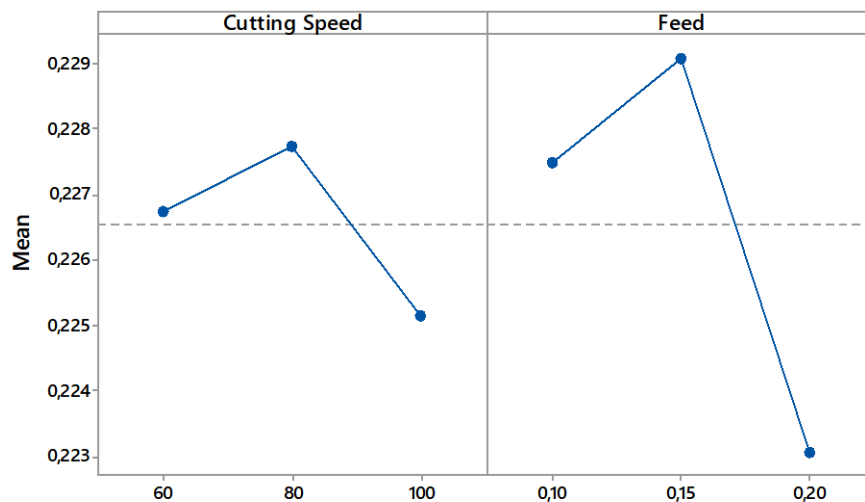
Table 14 – ANOVA to AE results using carbide tools

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed " v_c " (m/min)	2	0.000021	3.70%	0.000021	0.000010	0.32	0.732
Feed " f " (mm/t)	2	0.000116	20.92%	0.000116	0.000058	1.80	0.203
Error	13	0.000418	75.38%	0.000418	0.000032		
Lack-of-fit	4	0.000158	28.50%	0.000158	0.000039	1.37	0.319
Pure Error	9	0.000260	46.87%	0.000260	0.000029		
Total	17	0.000554	100.00%				
				R-Sq = 24.62%		R-sq (adj) = 1.43%	

Source: Author.

Although of non-statistical significance, it is possible to qualitative analyze the results through AE continuous and transient signals and tendencies. In Figure 46 a tendency of higher AE results can be seen to the 80 m/min speed with feed of 0.15 mm/t, such condition also presents high density of data in this region, as can be seen in Figure 47.

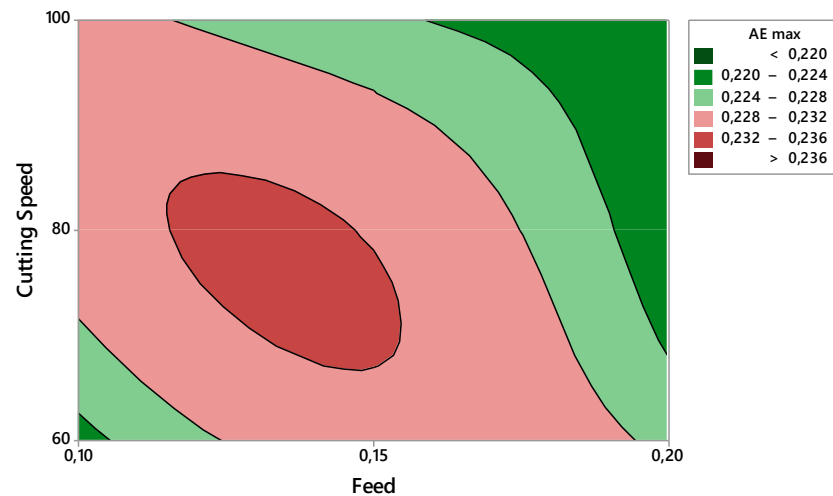
Figure 46 – Main Effects Plot of AE using carbide tools.



Source: Author.

From the main effects plot, the best condition to achieve low AE signals is to apply $v_c=0.20$ mm/t and $f=100$ m/min. It is observed an expressive decrease of AE specially to the application of the highest feed (0.20 mm/t). Indicating that the application of 0.20 mm/t feed represents a condition with adequate amount of material being removed, avoiding the tool damage such as chipping and at the same time assuring the tool anchorage.

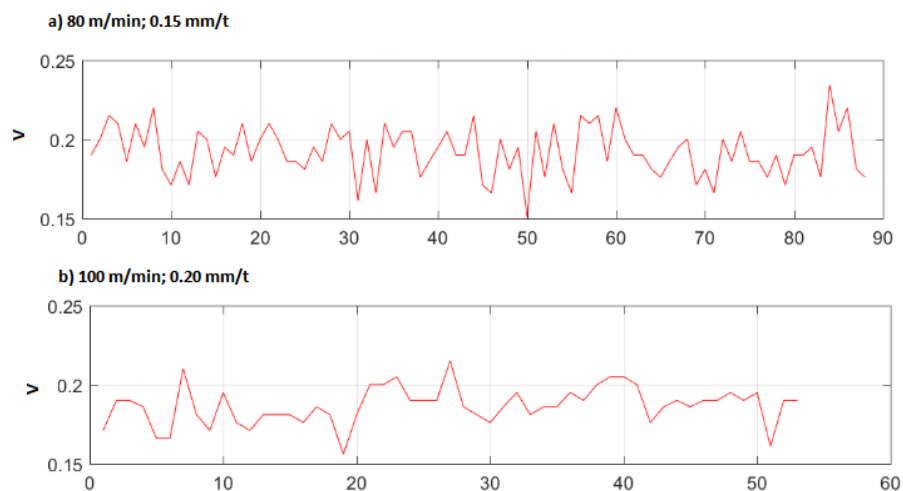
Figure 47 – Contour Plot of AE using carbide tools.



Source: Author.

In Figure 48 is possible to observe several peaks of transient signals during the application of 80m/min and 0.15mm/t. This may have occurred due to increased flank wear during the tests. As the wear increases, it also promotes an increase in friction in the region of contact between the two surfaces, causing an increase in the level of the acoustic emission signal.

Figure 48 – AE during machining using carbide tools; a) Highest AE results; b) Lowest AE results.



Source: Author.

Since the acoustic emission can be caused by any plastic and elastic deformations, both of the workpiece and of the cutting tool, friction, fracture of the workpiece, wear and break of

the tool, it is possible recommend the cutting condition of 100 m/min and 0.20 mm/t, this condition reduces the occurrence of damage phenomena.

5.2.1.4 Roughness

The surface quality analysis was done considering the measured roughness results of Roughness average (R_a), Maximum height of the profile (R_t) and Average maximum height of the profile (R_z). The Anderson-Darling normality test confirmed normal data distribution to all roughness results, with respective P-values of: 0.133 to R_a , 0.728 to R_t and 0.505 to R_z .

The ANOVA indicated that only the feed factor was significant to the roughness (Table 15). The feed factor had strong influence for R_a (P-value=0.028) and R_z (P-value=0.028). While the cutting speed had no statistical significance for any roughness considered. The feed factor had a significant contribution to total roughness data, with similar contribution to R_a (40.51%) and R_z (34.71%). Both contributions are higher than the pure-error's contribution, assuring significance.

Considering the R_t analysis, the v_c and f had no significant influence in the roughness results. The expressive error contribution (66.79%) lead to a low regression coefficient of only 12.67%, which means that ANOVA explains only about one tenth of the results found. However, the cutting speed can be considered relevant (F-value=2.70) to the R_t results as can be seen in Figure 44. R_t is particularly sensitive to anomalies such as scratches and burrs that may not be obvious from measures such as R_a that rely on averages, this fact may have interfered in results favoring the sum of the error's contribution.

Table 15 – ANOVA to Roughness results using carbide tools

ANOVA of Roughness R_a							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “ v_c ” (m/min)	2	0.04591	4.24%	0.04591	0.02295	0.50	0.618
Feed “ f ” (mm/t)	2	0.43830	40.51%	0.43830	0.21915	4.77	0.028
Error	13	0.59780	55.25%	0.59780	0.04598		
Lack-of-fit	4	0.36659	33.88%	0.36659	0.09165	3.57	0.052
Pure Error	9	0.23120	21.37%	0.23120	0.02569		
Total	17	1.08200	100.00%				
R-Sq = 44.75%				R-sq (adj) = 27.75%			
ANOVA of Roughness R_z							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “ v_c ” (m/min)	2	0.9490	7.55%	0.9490	0.4745	0.85	0.450
Feed “ f ” (mm/t)	2	4.3617	34.71%	4.3617	2.1808	3.91	0.047
Error	13	7.2568	57.74%	7.2568	0.5582		
Lack-of-fit	4	3.3105	26.34%	3.3105	0.8276	1.89	0.197
Pure Error	9	3.9463	31.40%	3.9463	0.4385		
Total	17	12.5675	100.00%				
R-Sq = 42.26%				R-sq (adj) = 24.49%			
ANOVA of Roughness R_t							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “ v_c ” (m/min)	2	4.2681	27.79%	4.2681	2.1341	2.70	0.104
Feed “ f ” (mm/t)	2	0.8335	5.43%	0.8335	0.4167	0.53	0.602
Error	13	10.2579	66.79%	10.2579	0.7891		
Lack-of-fit	4	3.6405	23.70%	3.6405	0.9101	1.24	0.361
Pure Error	9	6.6174	13.08%	6.6174	0.7353		
Total	17	15.3594	100.00%				
R-Sq = 33.21%				R-sq (adj) = 12.67%			
Source: Author.							

Source: Author.

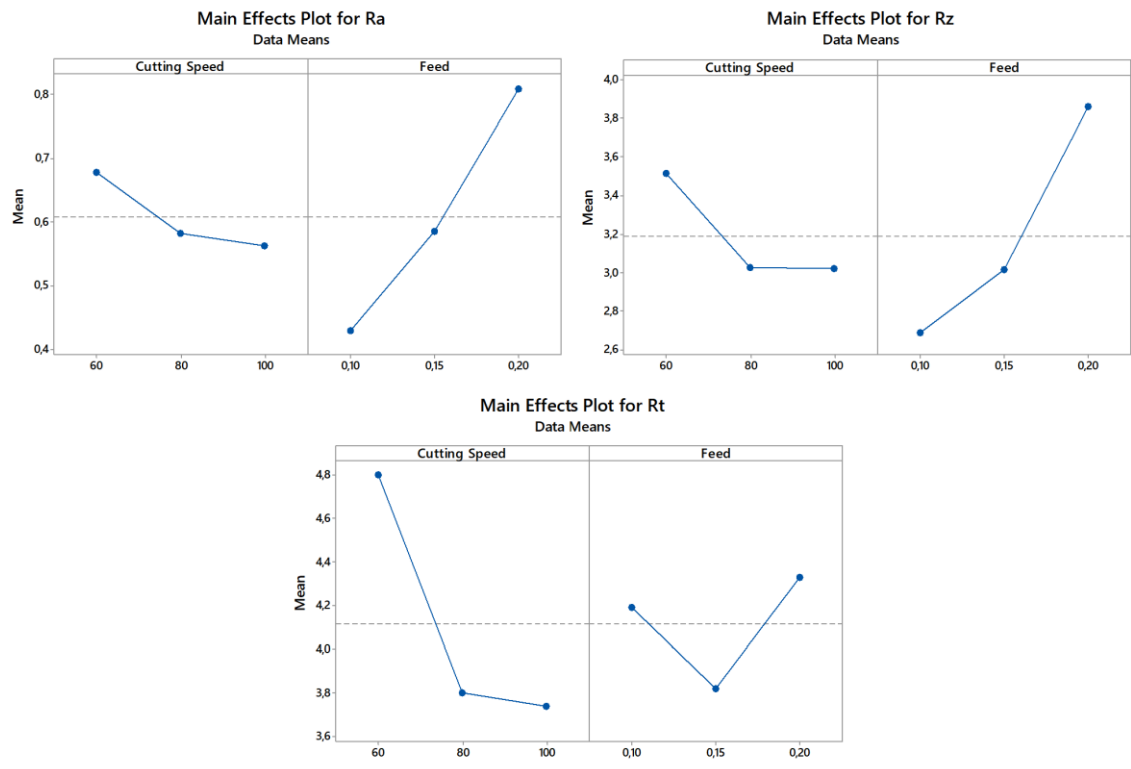
The ANOM indicate a similarity of tendencies to R_a and R_z , confirmed by the ANOVA (Figure 49). The similarity of tendencies between R_a and R_z results support the analysis reliability. The average roughness, even being the most commonly used surface finish parameter, is not sufficient to completely characterize the roughness of a surface. Depending on the application, surfaces with the same R_a can perform quite differently, presenting different profile shapes. R_a is the area between the roughness profile and its centerline divided by the evaluation length (cutoff length), while the R_z , instead of measuring from centerline like R_a , measures the average of the 5 largest peak to valley differences within five sampling lengths. Therefore, the similarity of tendencies and factors significance of R_a and R_z represent the concordance of results considering the sensibility of R_z to the extremes of the measured profile (peaks and valleys).

In the main effects plot (Figure 49) is possible to observe the strong tendency to higher values of roughness with the increase of the feed leading to worse surface quality. The high influence of the feed on roughness is explained in the literature. The feed is considered one of the most influential parameters on the roughness. The increase in feed has a geometric effect

on the roughness, since it contributes to the increase in the distance between peaks in the roughness profile, thus increasing the value of the roughness amplitude.

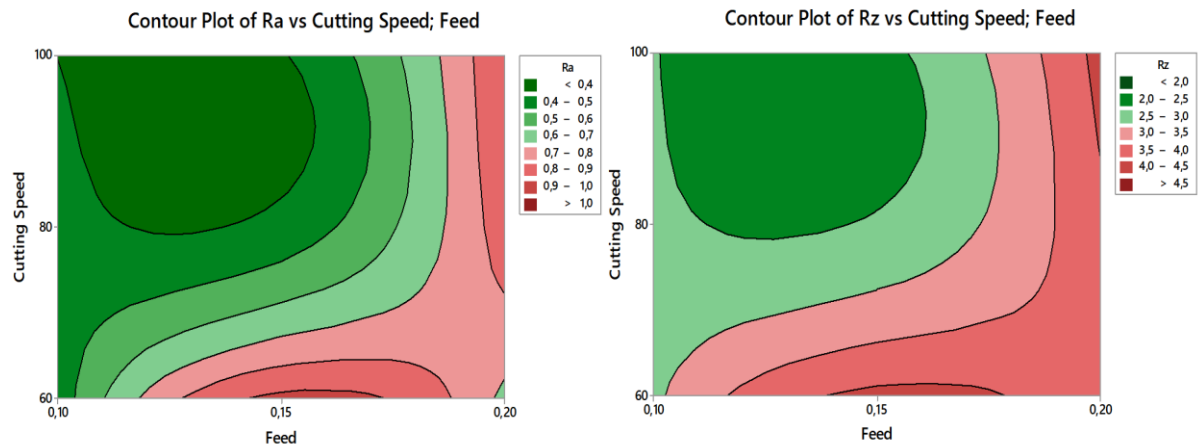
In addition, the observed decrease tendency in roughness to the increase in cutting speed can be explained due to the increase of the temperature for higher speeds that reduce the shear resistance of the workpiece material reducing the machining forces and promoting improvement of the surface finish. However the feed restriction must be observed, once the 0.20 mm/t is associated to the 100 m/min speed the vibration results increase and can be harmful to the surface quality.

Figure 49 – Main Effects Plot of R_a , R_z and R_t using carbide tools.

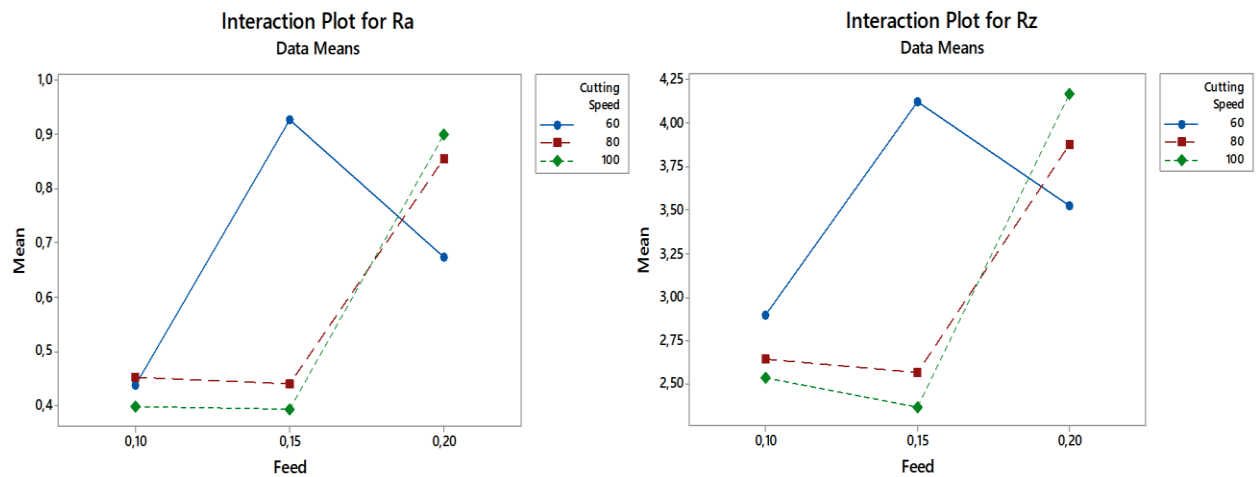


Source: Author.

Therefore, better roughness results can be achieved to the application of $v_c=100$ m/min and $f=0.1$ mm/t, as can be seen in Figure 50. The green region in the plot indicate that maintaining the 100m/min speed, lower roughness can be achieved in feed range from 0.10 to 0.15 mm/t. Less AE transient signals were identified to the 100 m/min speed, supporting low occurrence of tool wear or damage such as chipping in this condition, leading to the possibility of better surface finish.

Figure 50 – Contour Plot of R_a and R_z using carbide tools.

Source: Author.

Figure 51 – Interaction Plot of R_a and R_z using carbide tools.

Source: Author.

The mean value found for R_a and R_z were 0.608 and 3.18 μm . The found average roughness R_a value presented a satisfactory result, being below the normal standard roughness to the application of milling process. The common range to finish machining through milling is from 0.8 to 12.5 μm . Therefore, it is possible to ensure good surface quality by machining the VAT 32[®] superalloy with the applied carbide tools. The combination of factor's levels that provide better surface quality is $v_c = 100$ m/min and $f = 0.1$ mm/t.

5.2.1.5 Tool wear (V_b) in relation to cutting length (L_c)

To parameterize the flank wear data considering the application of the different feeds, the value of V_b was divided by the machined length (L_c). Parameterization is necessary because to the application of smaller feeds, the machined length is much greater than for high feeds. For the 0.10 mm/t, almost twice L_c is covered, therefore increasing the flank wear results. To improve the visualization and interpretation of the wear results, the tool wear value was multiplied by 1000 and divided by the machined length L_c .

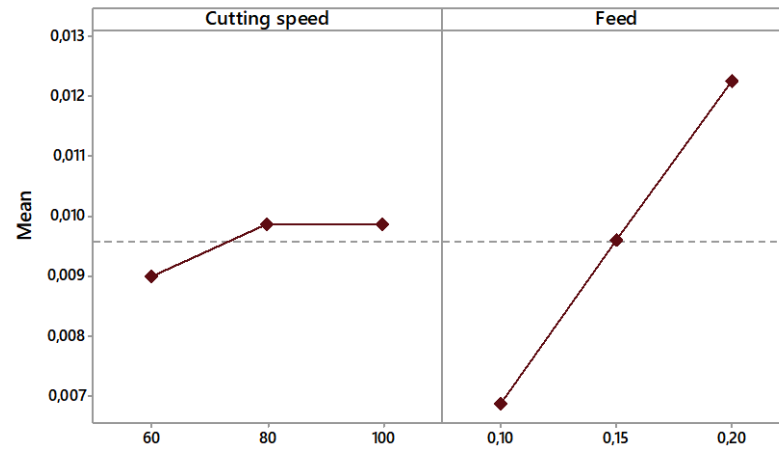
The ANOVA revealed that both cutting speed and feed interfered in the wear results to the carbide tools. Notably the feed (P-value=0.000) exhibits a contribution of 92%, whereas the cutting speed (P-value=0.024) only has 3.4% of contribution. High adjust to the regression model generated by the ANOVA is found, approximately 94% of the data can be explained by the linear regression generated by the analysis of variance.

Table 16 – ANOVA to Wear $V_b \cdot 1000 / L_c$ results using carbide tools.

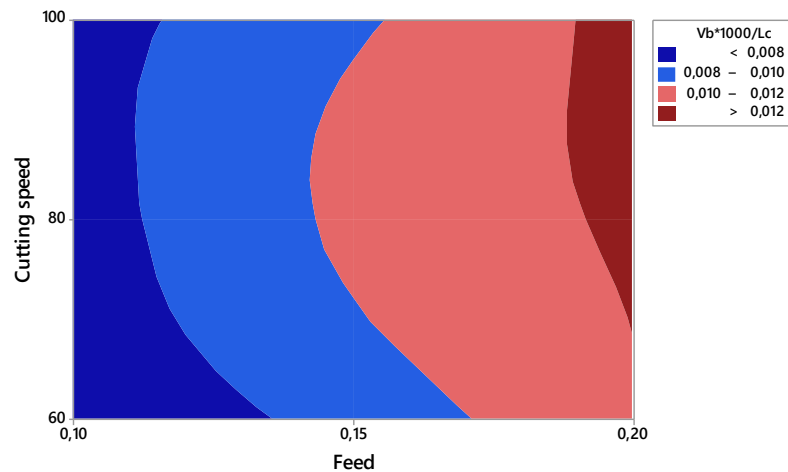
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “v _c ” (m/min)	2	0.000003	3.39%	0.000003	0.000002	5.04	0.024
Feed “f” (mm/t)	2	0.000086	92.25%	0.000086	0.000043	137.32	0.000
Error	13	0.000004	4.37%	0.000004	0.000000		
Lack-of-fit	4	0.000001	1.10%	0.000001	0.000000	0.76	0.578
Pure Error	9	0.000003	3.27%	0.000003	0.000000		
Total	17	0.000093	100.00%				
				R-Sq = 95.63%		R-Sq (adj) =94.29%	
Linear regression: Vb*1000/Lc = 0,009576 - 0,000591 Cutting speed_60 + 0,000297 Cutting speed_80 + 0,000294 Cutting speed_100 - 0,002684 Feed_0,10 + 0,000024 Feed_0,15+ 0,002659 Feed_0,20							

Source: Author.

In the analysis of the main effects, the best condition for obtaining lower wear values can be observed is the application of 0.10 mm/t feed. The cutting speed lead to a variation in wear, best wear results can be achieved with the application of lower cutting speeds. In the contour graph (Figure 53) is possible to observe that only a small region represents the data of high wear values, this result is achieved only for high feed applied.

Figure 52 – Main Effects Plot of $V_b \cdot 1000 / L_c$ using carbide tools.

Source: Author.

Figure 53 – Contour Plot of $V_b \cdot 1000 / L_c$ using carbide tools.

Source: Author.

Therefore, considering the coated carbide tools the best conditions to minimize wear is applying lower cutting speeds and feeds. The best condition observed was with $v_c = 60$ m/min and $f = 0.10$ mm/t.

5.2.2 Application of the experimental Al_2O_3 -MgO ceramic tools

In this section, the statistical analysis of the output variables of the milling machining process using the experimental Al_2O_3 -MgO inserts is presented and discussed.

5.2.2.1 Power Consumption

To the power results, the Anderson-Darling test assured normal data distribution with a P-value of 0.498. In the analysis of variance (Table 17), both factors were significant to a 5% significance level. As considering the contribution, the feed factor with P-value = 0.000 had a higher contribution to the power results (73.11%), while the cutting speed with P-value=0.021 had only 12% of contribution. Therefore, is possible to notice a strong dependence of the power results with the feed variation as can be seen in Figure 54 and 55.

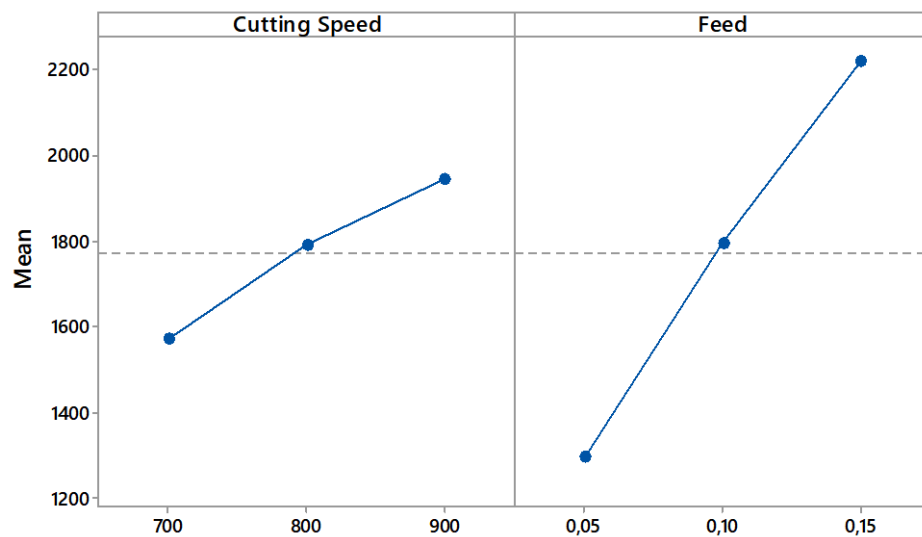
Table 17 – ANOVA to Power Consumption results using Al₂O₃-MgO tools

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed " v_c " (m/min)	2	422431	12.02%	422431	211216	5.31	0.021
Feed " f " (mm/t)	2	2553268	73.11%	2553268	1276634	32.12	0.000
Error	13	516624	14.79%	516624	39740		
Lack-of-fit	4	49168	1.41%	49168	12292	0.24	0.911
Pure Error	9	467456	13.39%	467456	51940		
Total	17	3492323	100.00%	3492323			
				R-Sq = 85.21%		R-Sq (adj) =80.66%	

Source: Author.

The ANOM indicate high power consumption to increase of feed and cutting speed likewise observed to the carbide tool. The dependence of feed can be explained by the increase in the area of the cutting section due to the increase in feed generating increase in the cutting force and consequently in the cutting power in machining. Best power condition is obtained to the application of $v_c = 700$ m/min and $f = 0.15$ mm/t.

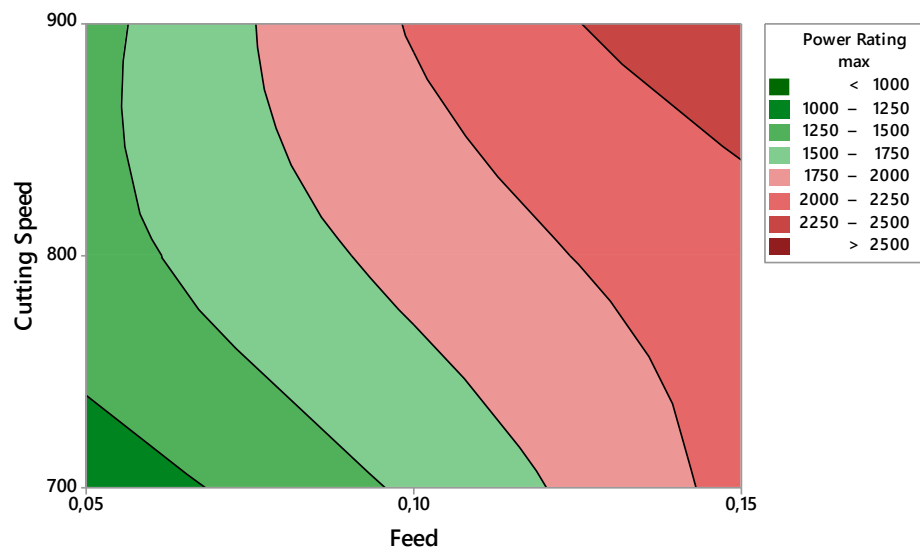
Figure 54 – Main Effects Plot of Power consumption using Al₂O₃-MgO tools.



Source: Author.

In Figure 54 is possible to observe that only the application of low cutting speed and feed assure power results bellow the mean of power results of 1746.9 W. There was a tendency of interaction between factors to the 800 and 900 m/min speeds, fact that may have interfered in the behavior of the power results, leading to an increase in the values for these conditions.

Figure 55 – Contour Plot of Power consumption using $\text{Al}_2\text{O}_3\text{-MgO}$ tools.



Source: Author.

It is important to highlight the increase in the maximum power values obtained for the application of ceramic tools, the average obtained with the carbide tools was 265W while to the $\text{Al}_2\text{O}_3\text{-MgO}$ in the best condition presented mean of 1098 W. The increase in power results can be explained due to the application of higher cutting speeds range, the increase in v_c increase the energy consumption to perform the machining.

5.2.2.2 Vibration

To the vibration results, the Anderson-Darling test assured normal data distribution with a P-value of 0.212. According the ANOVA, both cutting speed and feed had significant influence in the vibration results to the ceramic tools. In Table 18 is possible to notice a stronger influence of v_c , with 42% of contribution to the vibration results during the machining.

Table 18 – ANOVA to Vibration results using Al₂O₃-MgO tools

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed " v_c " (m/min)	2	0,55931	42.39%	0,55931	0,27966	7.60	0.007
Feed " f " (mm/t)	2	0,28207	21.38%	0,28207	0,14104	3.83	0.049
Error	13	0,47819	36.24%	0,47819	0,03678		
Lack-of-fit	4	0,07213	5.47%	0,07213	0,01803	0.40	0.804
Pure Error	9	0,40606	30.77%	0,40606	0,04512		
Total	17	1,31957	100.00%				

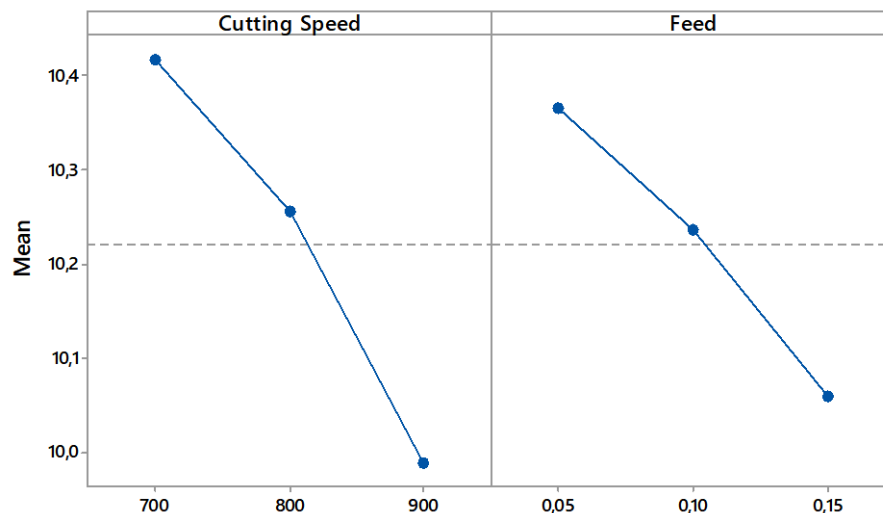
R-Sq = 63.76%

R-Sq (adj) =52.61%

Source: Author.

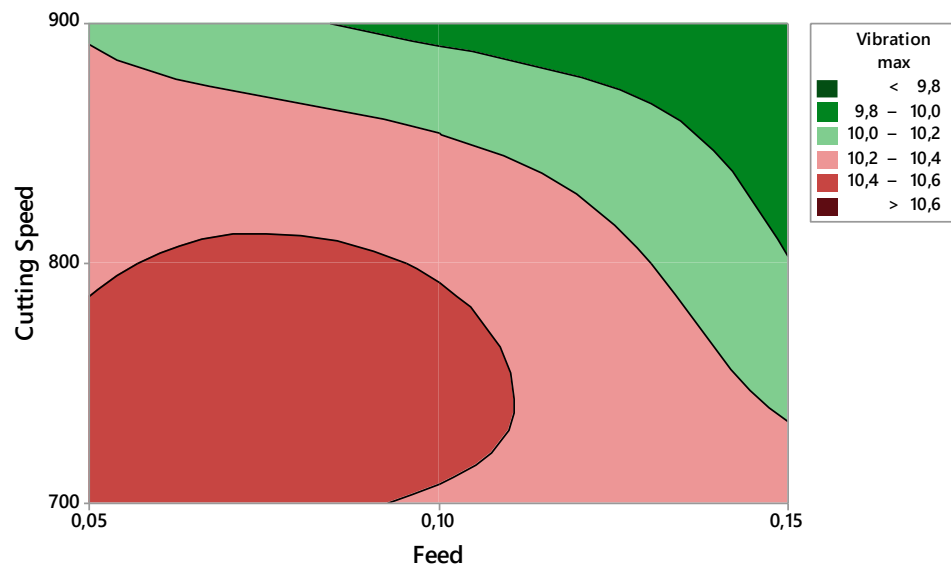
In Figure 56, the dependence of both factors is clear. A tendency of lower vibration results is observed to the increase of cutting speed and feed. The average vibration observed was about 10.2 mm/s, a value very similar to those obtained with the carbide tool (10.3 mm/s), even with the application of higher speeds. However, to the carbide tools no statistical significance was found for any of the factors, being only possible the analysis of means and trends. Such behavior to the ceramic tools ensures the validity of the use of vibration analysis in correlation with the observed values of wear and resulting surface quality for the use of ceramic tools.

The best condition to minimize the vibration results and impacts is $v_c = 900$ m/min and $f = 0.15$ mm/t.

Figure 56 – Main Effects Plot of vibration using Al₂O₃-MgO tools.

Source: Author.

In Figure 57 is possible to notice the change in the vibration results from the application of cutting speeds close to 900 m/min. Although the mean vibration was very similar to both tools, the application of higher cutting speeds, even above 900 m/min is preferred.

Figure 57 – Contour Plot of vibration using $\text{Al}_2\text{O}_3\text{-MgO}$ tools.

Source: Author.

5.2.2.3 Acoustic Emission

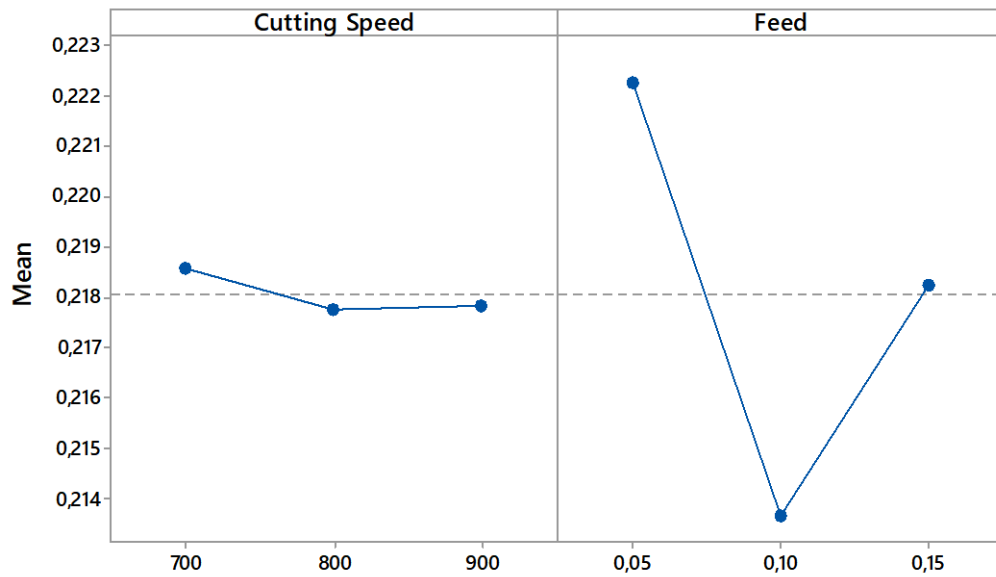
To the AE results, the Anderson-Darling normality test assured normal data distribution with a P-value of 0.529. The ANOVA indicated that the feed was the only factor that had significant influence in the AE results. However, the contribution of the feed is close to the error's contribution, limiting the analysis and significance of the influence. The low value of correlation coefficient also indicates a low adjust to the AE regression equation.

Table 19 – ANOVA to AE results using $\text{Al}_2\text{O}_3\text{-MgO}$ tools

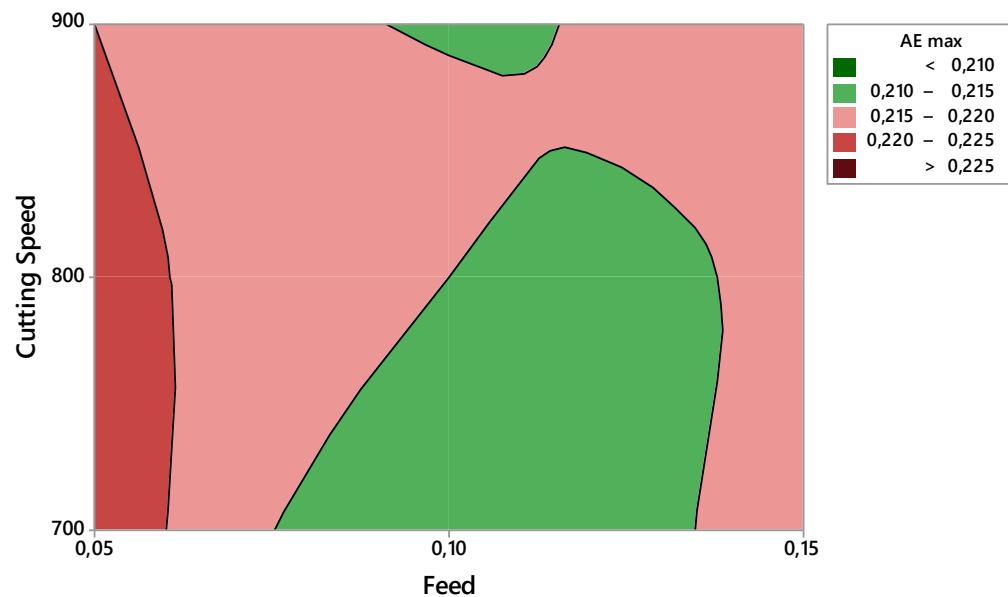
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed " v_c " (m/min)	2	0,000003	0.49%	0,000003	0,000001	0.06	0.945
Feed " f " (mm/t)	2	0,000221	42.99%	0,000221	0,000111	4.94	0.025
Error	13	0,000291	56.52%	0,000291	0,000022		
Lack-of-fit	4	0,000052	10.11%	0,000052	0,000013	0.49	0.744
Pure Error	9	0,000239	46.41%	0,000239	0,000027		
Total	17	0,000515	100.00%				
				R-Sq = 43.48%		R-Sq (adj) = 26.09%	

Source: Author.

From the main effects plot is possible to observe the increase in AE to the 0.05 and 0.15 mm/t feeds (Figure 58). The feed 0.10 mm/t presents better results to all tested cutting speeds as can be seen in Figure 59. The contour plot also evidence that the higher results are relative to the application of the 0.05 mm/t feed to all speeds.

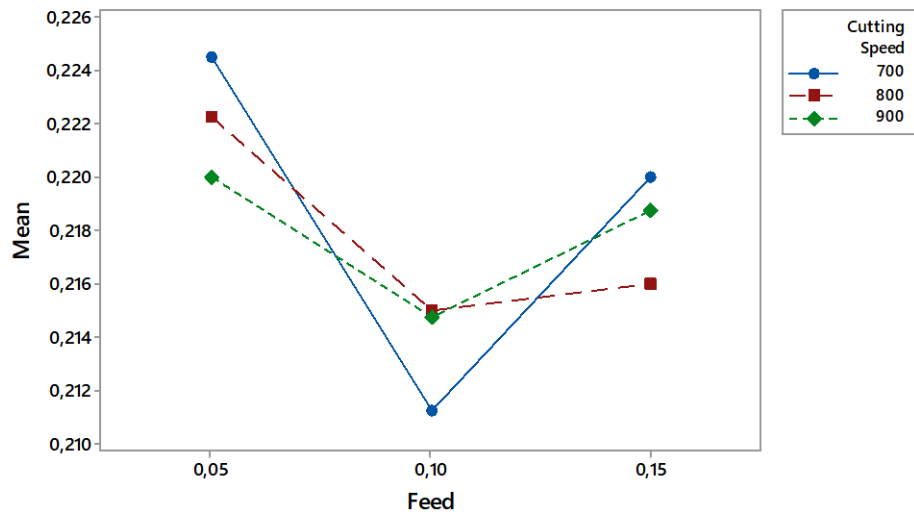
Figure 58 – Main Effects Plot of AE using Al₂O₃-MgO tools.

Source: Author.

Figure 59 – Contour Plot of vibration using Al₂O₃-MgO tools.

Source: Author.

There was significant interaction between the factors to all cutting conditions considering the AE results (Figure 60). The condition that allows best results in AE is the same to the vibration results. The reduction in vibrations directly affect the AE results, since it favors wear and chipping, which are relative to transient peaks in the AE signals.

Figure 60 – Interaction Plot of AE using $\text{Al}_2\text{O}_3\text{-MgO}$ tools.

Source: Author.

5.2.2.4 Roughness

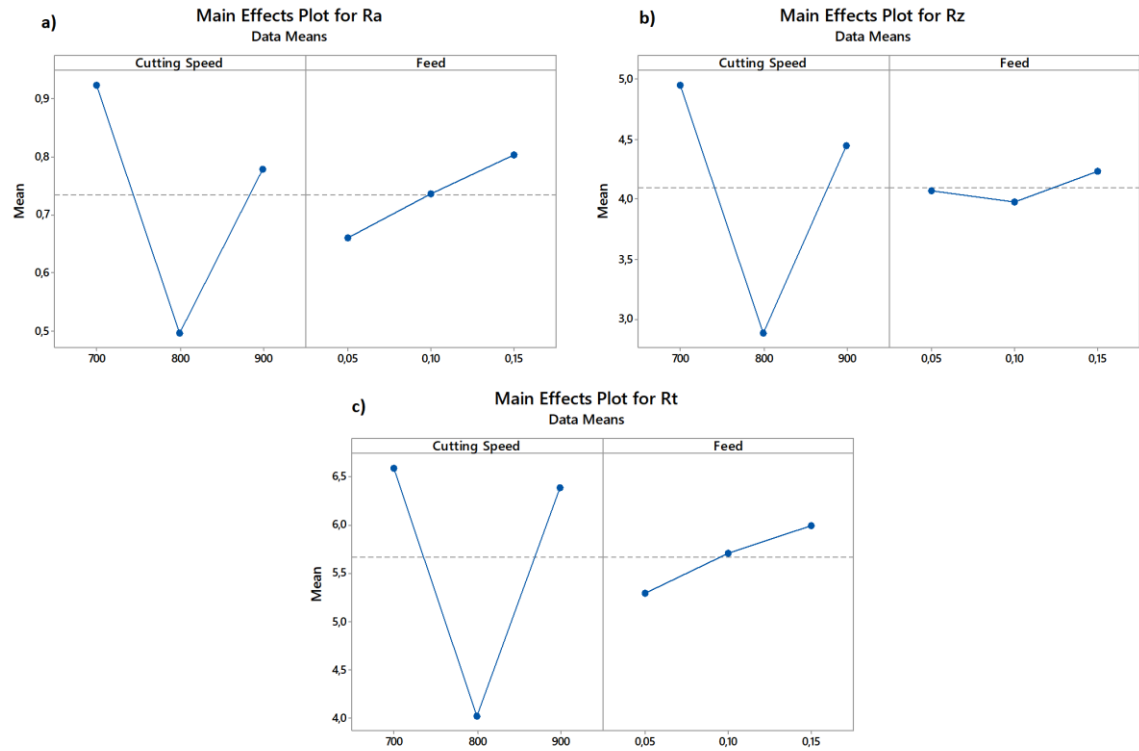
The roughness results measured for the machining using the ceramic tool showed distribution within the normality parameter with P-value of 0.641 (R_a), 0.930 (R_t) and 0.513 (R_z). Unlike for the carbide tools, according to the ANOVA to the ceramic tools, the cutting speed had influence in the roughness, not the feed factor. This means that for ceramics, the speed factor has a high influence on roughness. The cutting speed presented statistical significance to all roughness considered, without exception. It is possible that the variation within the studied feed range was not sufficient to have a significant influence on roughness. For all the studied roughness results, the speed contribution is above 50% with R_a (53.23%), R_t (53.34%) and R_z (65.30%).

Table 20 – ANOVA to Roughness results using Al₂O₃-MgO tools

ANOVA of Roughness Ra							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “vc” (m/min)	2	0.56450	53.23%	0.56450	0.28225	8.47	0.004
Feed “f” (mm/t)	2	0,06250	5.89%	0,06250	0,03125	0.94	0.417
Error	13	0.43343	40.87%	0,43343	0,03334		
Lack-of-fit	4	0,25142	23.71%	0,25142	0,06285	3.11	0.073
Pure Error	9	0,18202	17.16%	0,18202	0,02022		
Total	17	1,06044	100.00%				
R-Sq = 59.13%				R-sq (adj) = 46.55%			
ANOVA of Roughness Rz							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “vc” (m/min)	2	13,8929	65.30%	13,8929	6,94643	12.57	0.001
Feed “f” (mm/t)	2	0,1982	0.93%	0,1982	0,09909	0.18	0.838
Error	13	7,1848	33.77%	7,1848	0,55267		
Lack-of-fit	4	4,3648	20.52%	4,3648	1,09120	3.48	0.056
Pure Error	9	2,8200	13.25%	2,8200	0,31333		
Total	17	21,2758	100.00%				
R-Sq = 66.23%				R-sq (adj) = 55.84%			
ANOVA of Roughness Rt							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “vc” (m/min)	2	24,281	53.34%	24,281	12,1407	7.98	0.005
Feed “f” (mm/rot)	2	1,458	3.20%	1,458	0,7289	0.48	0.630
Error	13	19,779	43.45%	19,779	1,5214		
Lack-of-fit	4	4,502	9.89%	4,502	1,1256	0.66	0.633
Pure Error	9	15,276	33.56%	15,276	1,6973		
Total	17	45,518	100.00%				
R-Sq = 56.55%				R-sq (adj) = 43.18%			
Source: Author.							

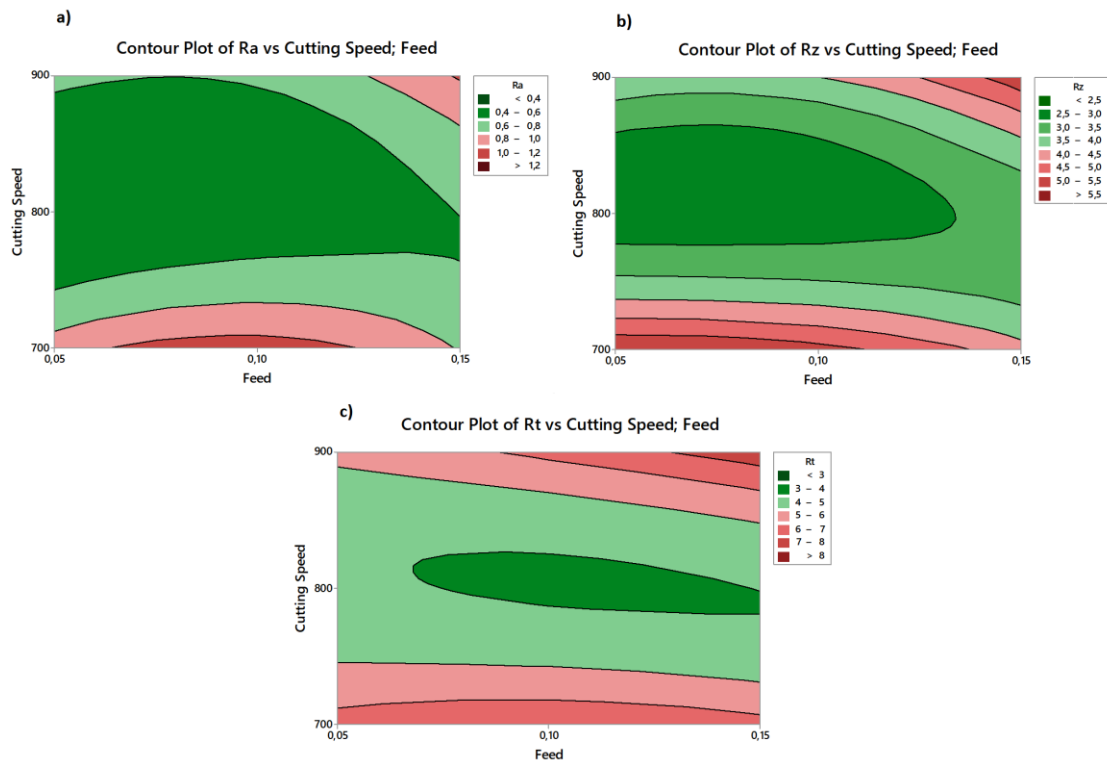
The main effects plots in Figure 61 indicate a similar tendency to all roughness results regarding the variation of cutting speed level. R_a and R_t presented the same behavior to the feed variation. The similar tendency to R_a and R_t is beneficial, and guarantees the accuracy in the analysis of trends of data means (ANOM). Since R_t considers the vertical distance from highest peak to lowest valley evaluated e R_a considers the arithmetic average of results, the same tendency of results assures the inclusion of possible anomalies that could have occurred during the tests. Best results of surface quality can be achieved to the 800m/min speed with association to the lowest feed of 0.05 mm/t.

Figure 61 – Main Effects Plot of roughness using $\text{Al}_2\text{O}_3\text{-MgO}$ tools; a) R_a ; b) R_z and c) R_t .

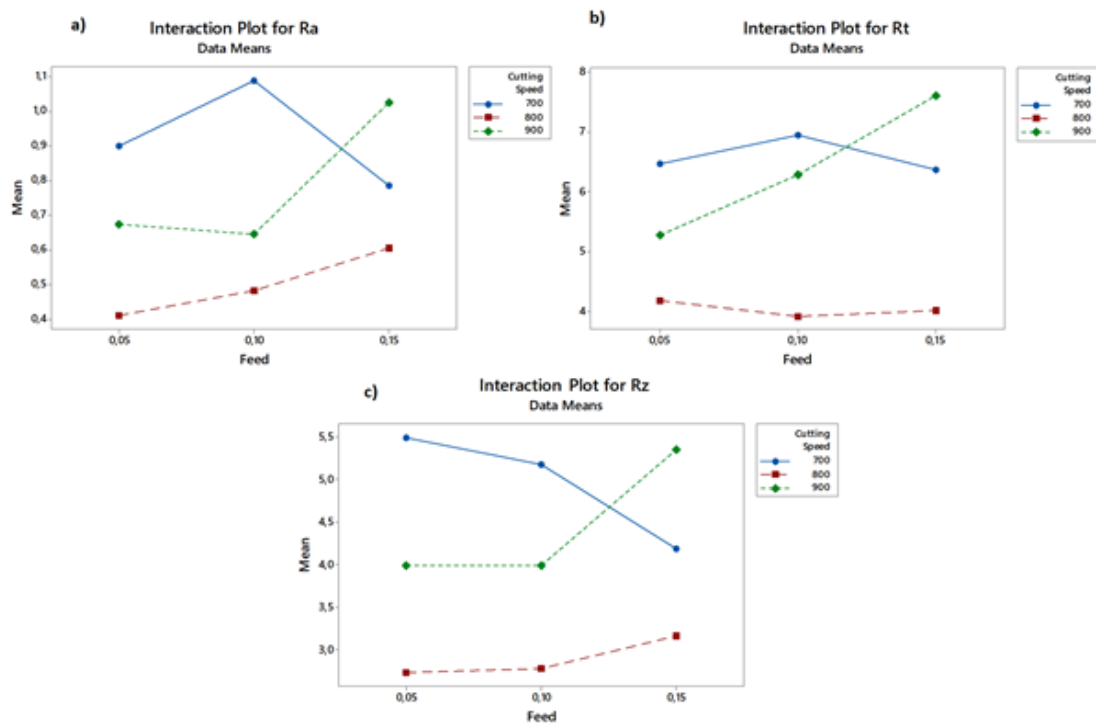


Source: Author.

The major dependence of cutting speeds variation can be highlighted in Figure 62, since the contour lines tend to be longitudinally parallels. The region to better roughness results of R_a and R_z is approximately the same, the center of the graph focusing in the $v_c = 800$ m/min application, the lower roughness results can be obtained to almost all feeds. Figure 63 shows that there was an interaction between the two factors, mainly for conditions with speeds of 700 and 900 m/min. For the application of speed of 800 m/min, where the lowest values of roughness are found, there was no significant interaction between the two factors.

Figure 62 – Contour Plot of R_a , R_t and R_z using Al_2O_3 -MgO tools.

Source: Author.

Figure 63 – Interaction Plot of R_a and R_z using Al_2O_3 -MgO tools.

Source: Author.

The roughness obtained to the use of the ceramic tools were very similar to those found for the use of the carbide tools. The mean of R_a results to the Al_2O_3 -MgO tools was $0.734 \mu m$, and to the carbide tools was $0.608 \mu m$. Both results are within the range of surface finish roughness through milling that is from 0.8 to $12.5 \mu m$. Moreover, with the application of higher cutting speeds to the ceramic tools, is possible to assure more material removal compared to the carbide tools, associated to good results of surface quality.

The good surface quality found may be influenced by the geometry of the cutting inserts. The round geometry allows less effort during machining and prevent the excessive chipping to the cutting edge, improving the surface quality. Considering face-milling the use of inserts with a larger radius can often leave a better finish than other insert geometries. The use of round tools also directly contributes to the sharpening of the chip during machining, thus helping to maintain good roughness values.

5.2.2.5 Tool wear (V_b) in relation to cutting length (L_c)

The ANOVA revealed that only the feed interfered in the wear results to the Al_2O_3 -MgO tools. The feed (P -value=0.000) exhibits a contribution of 75% to the wear observed. However, the cutting speed showed no influence to the wear results. Good adjust to the regression model generated by the ANOVA is found, approximately 70% of the data can be explained by the linear regression generated by the analysis of variance.

Table 21 – ANOVA to Wear $V_b \cdot 1000/L_c$ results using Al_2O_3 -MgO tools

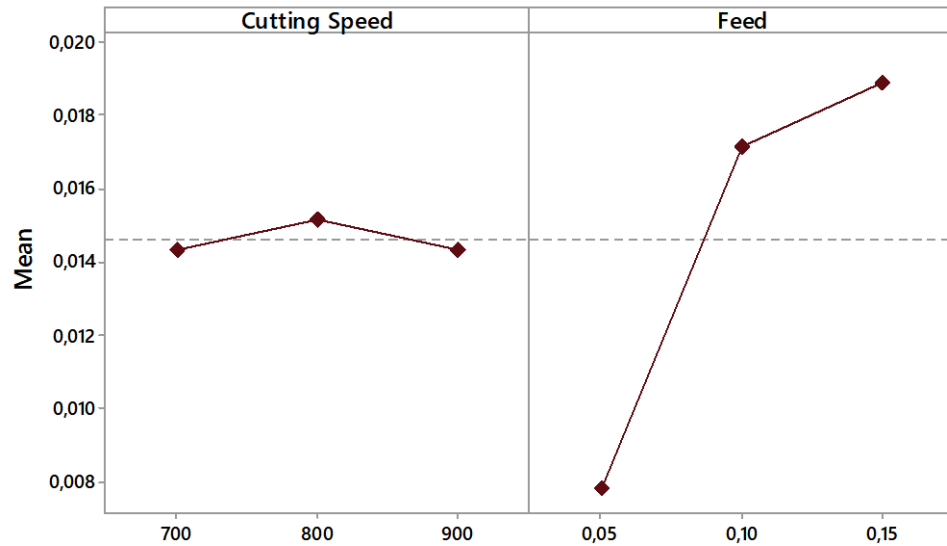
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Cutting Speed “v _c ” (m/min)	2	0.000003	0.47%	0,000003	0.000001	0.12	0.884
Feed “f” (mm/t)	2	0.000424	74.86%	0,000424	0.000212	19.70	0.000
Error	13	0.000140	24.69%	0,000140	0.000011		
Lack-of-fit	4	0.000044	7.71%	0,000044	0.000011	1.02	0.446
Pure Error	9	0.000096	16.98%	0,000096	0.000011		
Total	17	0.000566	100.00%				
R-Sq = 75.31%				R-Sq (adj) =67.71%			
Linear regression: Vb*1000/ Lc = 0,014612 - 0,00679 Feed_0,05 + 0,00252 Feed_0,10 + 0,00426 Feed_0,15 - 0,00028 Cutting Speed_700 + 0,00055 Cutting Speed_800 - 0,00027 Cutting Speed_900							

Source: Author.

Figure 64 shows the graph of the result of the mean values obtained in the tool wear measurements in relation to the cutting length, to improve the visualization and interpretation of the wear results, the tool wear value was multiplied by 1000. Is possible to observe the tendency of increase in wear results with the increase of the applied feed. Unlike for carbide

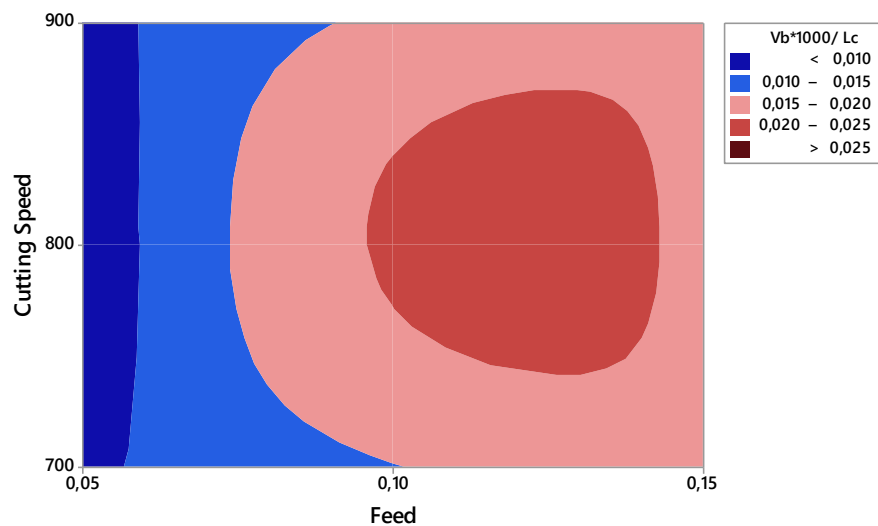
tools, the ceramic tools showed more dependence on feed than on cutting speed. However, the adjustment of the ANOVA measured by the regression coefficient is lower than for the carbide tools. The dependence on the feed is according the literature, since the increase in the feed also increases the amount of heat imputed to the process, leading to higher wear.

Figure 64 – Main Effects Plot of $V_b \cdot 1000 / L_c$ using Al_2O_3 -MgO tools.



Source: Author.

Figure 65 – Contour Plot of $V_b \cdot 1000 / L_c$ using Al_2O_3 -MgO tools.



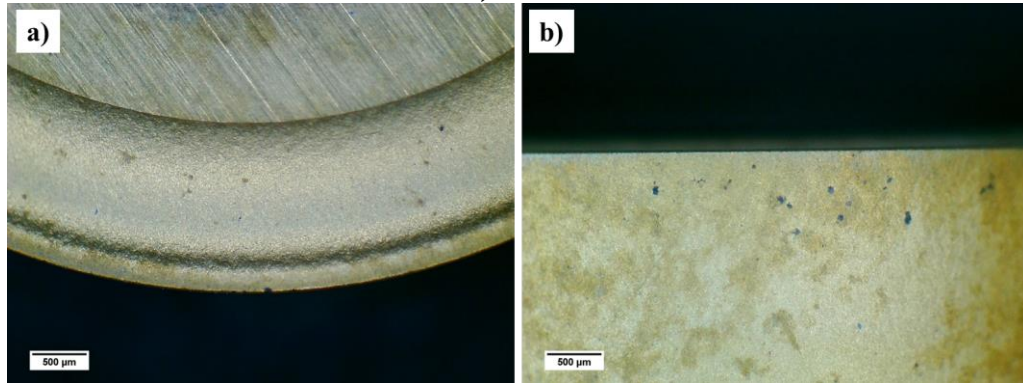
Source: Author.

5.3 CUTTING TOOL PERFORMANCE ANALYSIS

5.3.1 Wear analysis of the TiAlN-TiN coated carbide tools

The main types of wear and damages found in the carbide tools after the tests were quantitatively and qualitatively evaluated. The carbide cutting tool edge before the machining tests is presented in Figure 66.

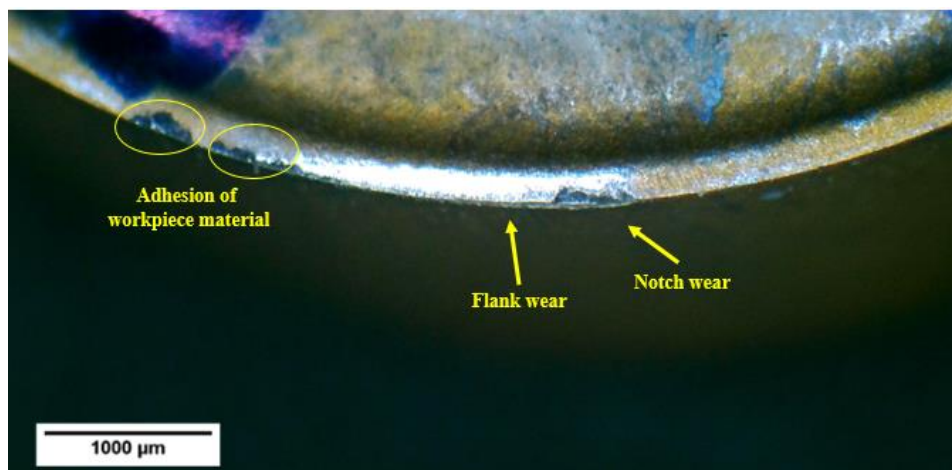
Figure 66 – TiAlN-TiN coated carbide tool cutting edge (magnification 2x). a) Rake face; b) Flank face.



Source: Author.

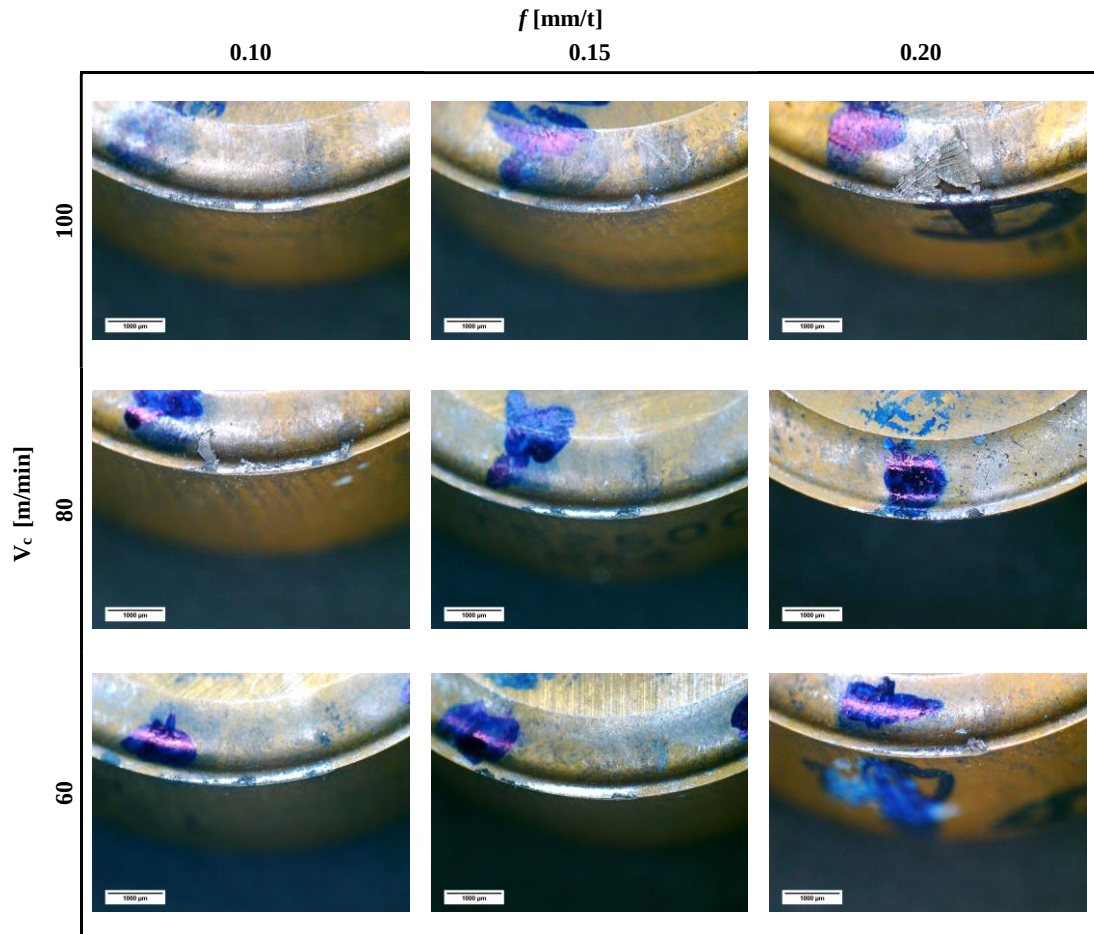
For the application of the coated carbide tools when machining the VAT 32[®] superalloy, it was observed flank and notch wear in the inserts. It was also possible to identify material adhesion and formation of BUE to certain conditions (Figure 67). The wear progression with the variation of cutting parameters is presented in Figure 68.

Figure 67 – Main types of wear observed to the TiAlN-TiN coated carbide tools.



Source: Author.

Figure 68 – Wear progression after machining tests to the TiAlN-TiN coated carbide tools.



Source: Author.

The main mechanisms of wear formation were attrition (adhesion) and abrasion. Crater wear was observed rarely and only to the application of higher cutting speeds, indicating diffusional mechanism of wear formation.

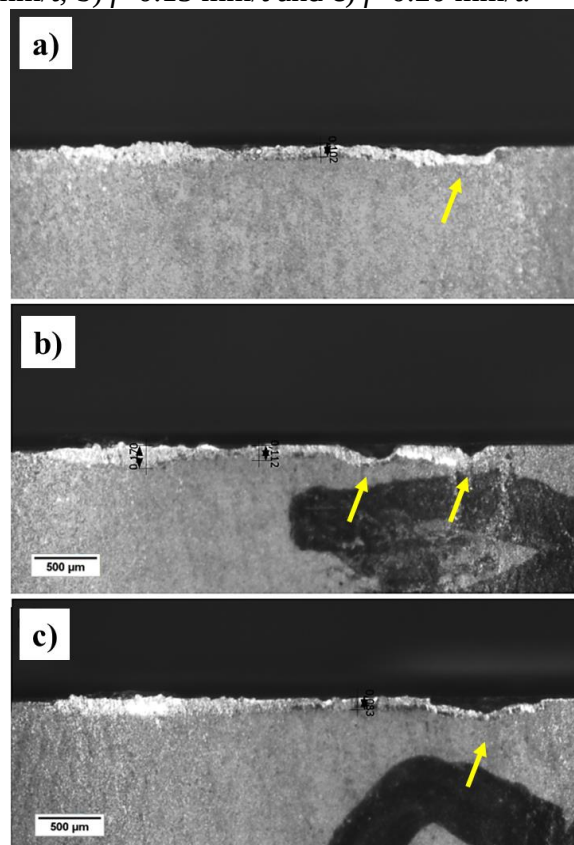
The notch wear was observed to all conditions tested (Figure 69). Notching, primarily in the region of the cutting depth can be consider as the dominant failure mode to carbide tools in the machining of superalloys due to the hardened layer of material during machining, adhesion between chip and tool and friction wear. The notch can be explained by the surface work-hardening during the machining that contributed directly to the appearance of notch wear at the height of the cutting depth (DOC notch). It was also possible to see the progression to the notch wear with the increase of feed (Figure 70). To reduce the notch wear occurrence is recommended the reduction of cutting speed that will lead to reduction in temperature and therefore, reduce the notch by oxidation.

Figure 69 – Notch wear to the coated carbide tools rake face (v_c of 100m/min and f of 0.10 mm/t).



Source: Author.

Figure 70 – Notch wear progression to the coated carbide tools with v_c of 60m/min; a) $f=0.10$ mm/t; b) $f=0.15$ mm/t and c) $f=0.20$ mm/t.

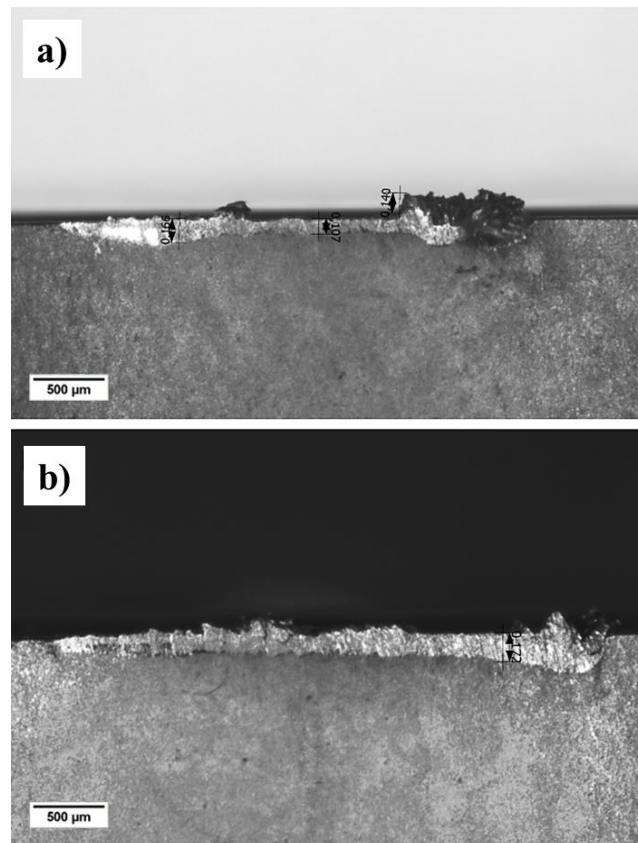


Source: Author.

Large occurrence of adhesion material was observed for the application of high cutting speeds (Figure 71). The adhesion of workpiece material on the tool during machining, causing severe wear, as well as chipping on the exit surface of the tool. Adhesive force plays a significant role to form adhesion between tool and workpiece material. In addition, the high friction, temperature, and pressure provide friendly environment for adhesion. The relative movement between tool and workpiece produces shear forces that removes adhesive point from tool and workpiece materials. Due to adhesion particles from workpiece accumulate at the cutting edge of tool producing the built-up edge (BUE). As the cutting proceeds, this BUE separates from tool leaving an uneven surface on the cutting tool.

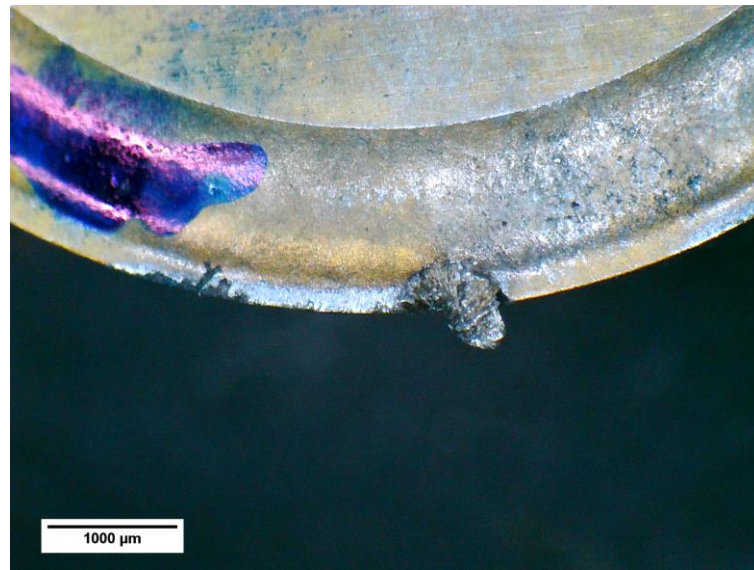
The BUE formation was observed to higher cutting speeds application. To the $v_c=100\text{m/min}$ the occurrence of BUE increased in the inserts cutting edges (Figure 72).

Figure 71 – Adhesion in the coated carbide tools cutting edge with a) $v_c= 80 \text{ m/min}$; b) 100 m/min .



Source: Author.

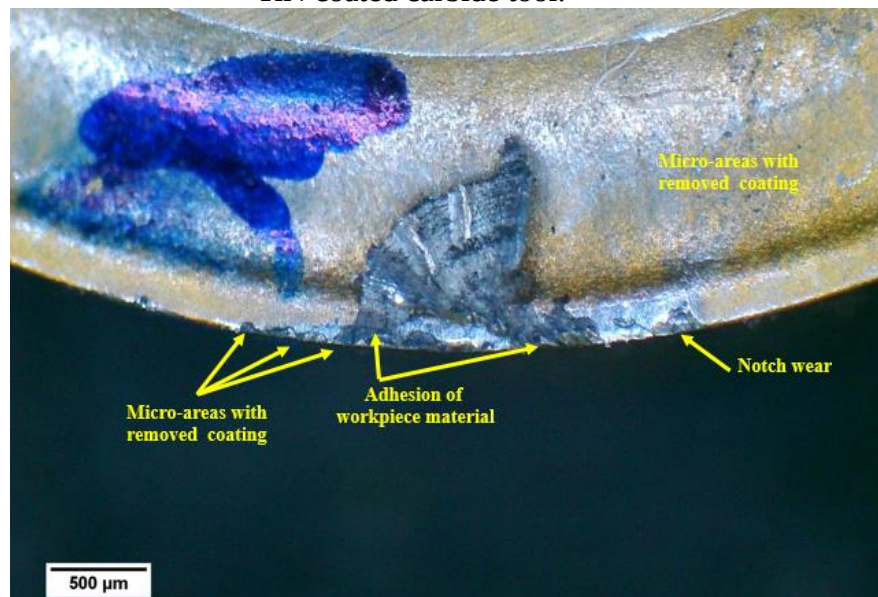
Figure 72 – BUE in the cutting edge to the carbide tool with $v_c = 100$ m/min and $f = 0.2$ mm/t.



Source: Author.

The adhesion of the workpiece material to the tool and its subsequent removal of this adherent material exposes the substrate and can accelerate tool wear. The coating was removed continuously without local massive losses, however the wear scars indicate some areas in which the coating was partially removed (Figure 73). In The BUE formation can also be associated to the machined material, the low thermal conductivity of the VAT 32[®] superalloy generated high temperatures at the cutting edge.

Figure 73 – Wear result to the application of v_c 80 m/min and f 0.20 mm/t to the TiAlN-TiN coated carbide tool.

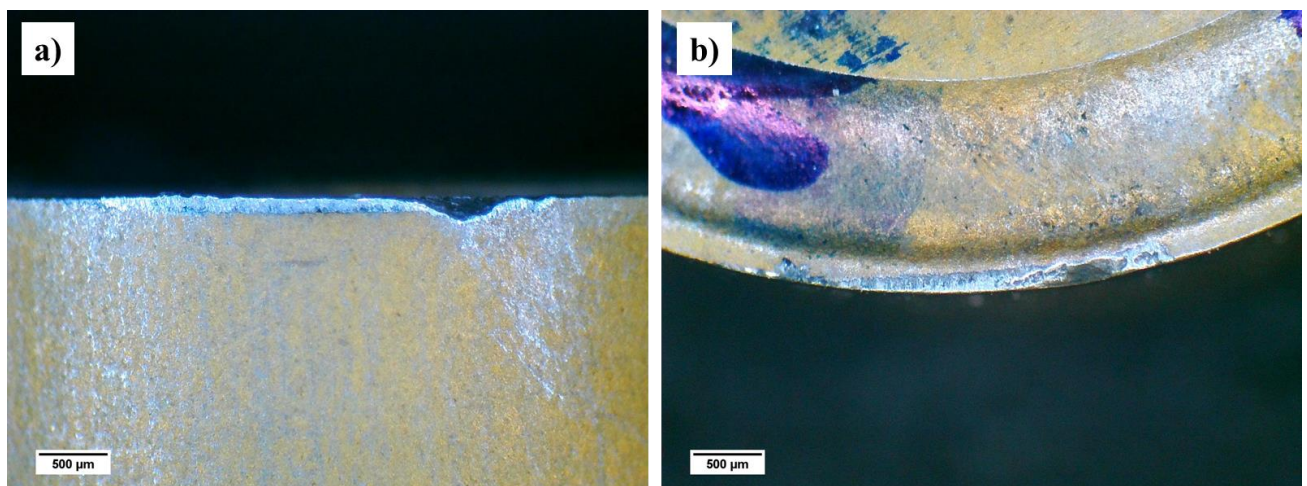


Source: Author.

For the use of the coated carbide tools, it was possible to achieved lower flank wear results, not exceeding the V_b of 0.2 mm. The observed average of flank wear V_b was 0.125 mm. During the milling process, the cutting action progressively changes the original geometry of the cutting tool. Therefore, there is a progressive wear on the rake face of the tool. The flank wear had a low and gradual growth rate.

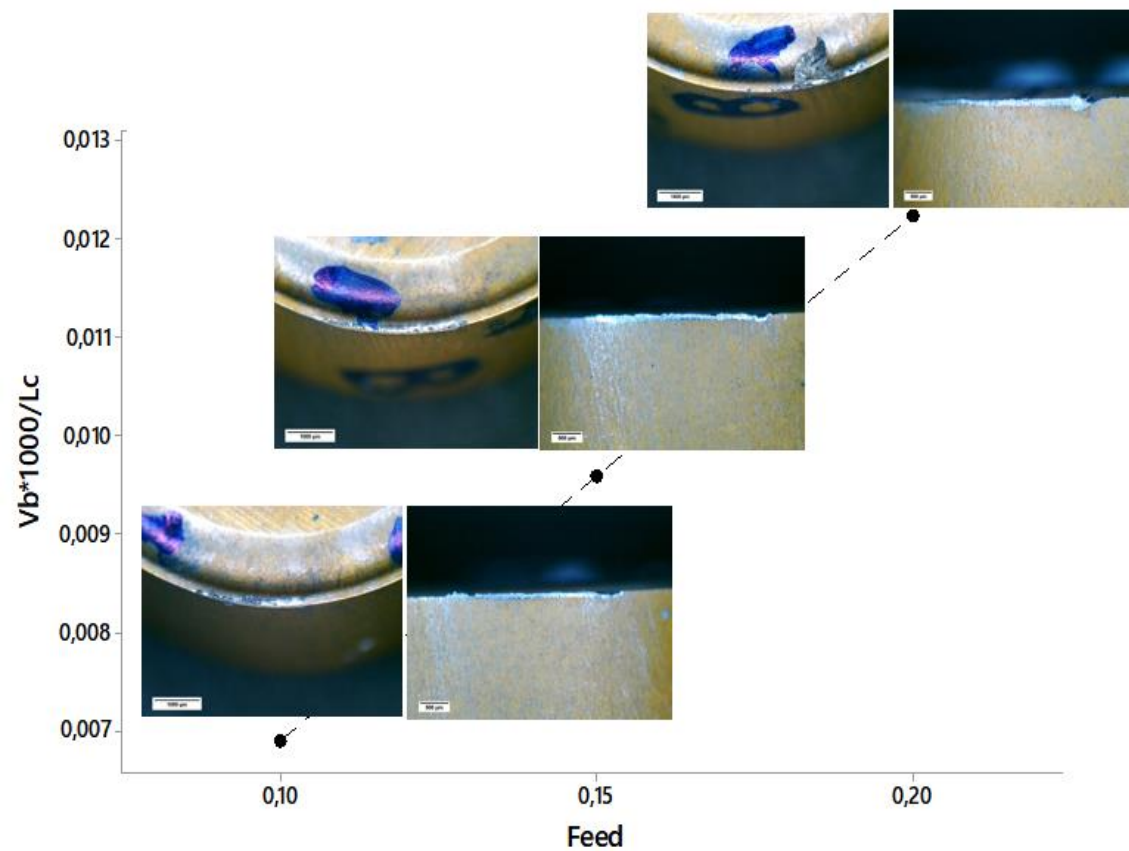
The lowest V_b value obtained was of 0.110 mm for the application of lower cutting speed and feed (v_c 60m/min and f 0.10 mm/t), which is in concordance to the speed that allow the lowest vibration results in the process (Figure 74). To the flank wear in relation to cutting length ($V_b \cdot 1000/L_c$) results, it was possible to observe the increase in wear with the increase of feed (Figure 75). This tendency was observed to all applied cutting speed.

Figure 74 – Wear result to the application of best cutting conditions (v_c 60 m/min and f 0.10 mm/t) to the TiAlN-TiN coated carbide tools. a) Flank face; b) Rake face.



Source: Author

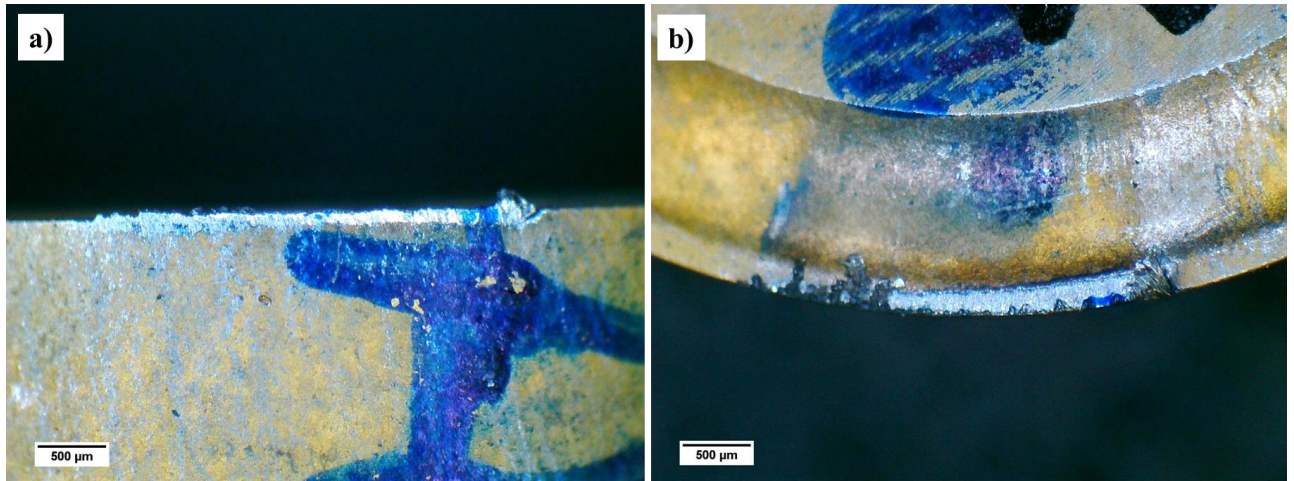
Figure 75 – Increase in $V_b \cdot 1000 / L_c$ due to feed increase to the TiAlN-TiN coated carbide tools (v_c of 60 m/min).



Source: Author

The highest flank wear value found was 0.150 mm to the application of 100m/min and 0.20mm/t (Figure 76), in this condition the values of acoustic emission indicated a higher occurrence of transient signals that indicate high efforts in the machining, as well the occurrence or chipping and the BUE formation.

Figure 76 – Wear result to the application of v_c 100 m/min and f 0.20 mm/t to the TiAlN-TiN coated carbide tools. a) Flank face; b) Rake face.



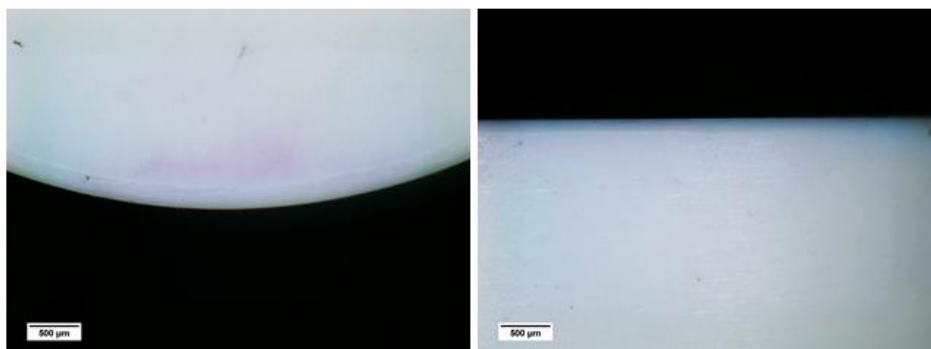
Source: Author.

Therefore, considering the TiAlN-TiN coated carbide tools application, the condition of v_c of 60m/min and f of 0.10 mm/t presented the best results regarding flank wear and $V_b \cdot 1000/L$. This condition allowed less occurrence of material adhesion, chipping or BUE formation.

5.3.2 Wear analysis of the Al_2O_3 -MgO ceramic tools

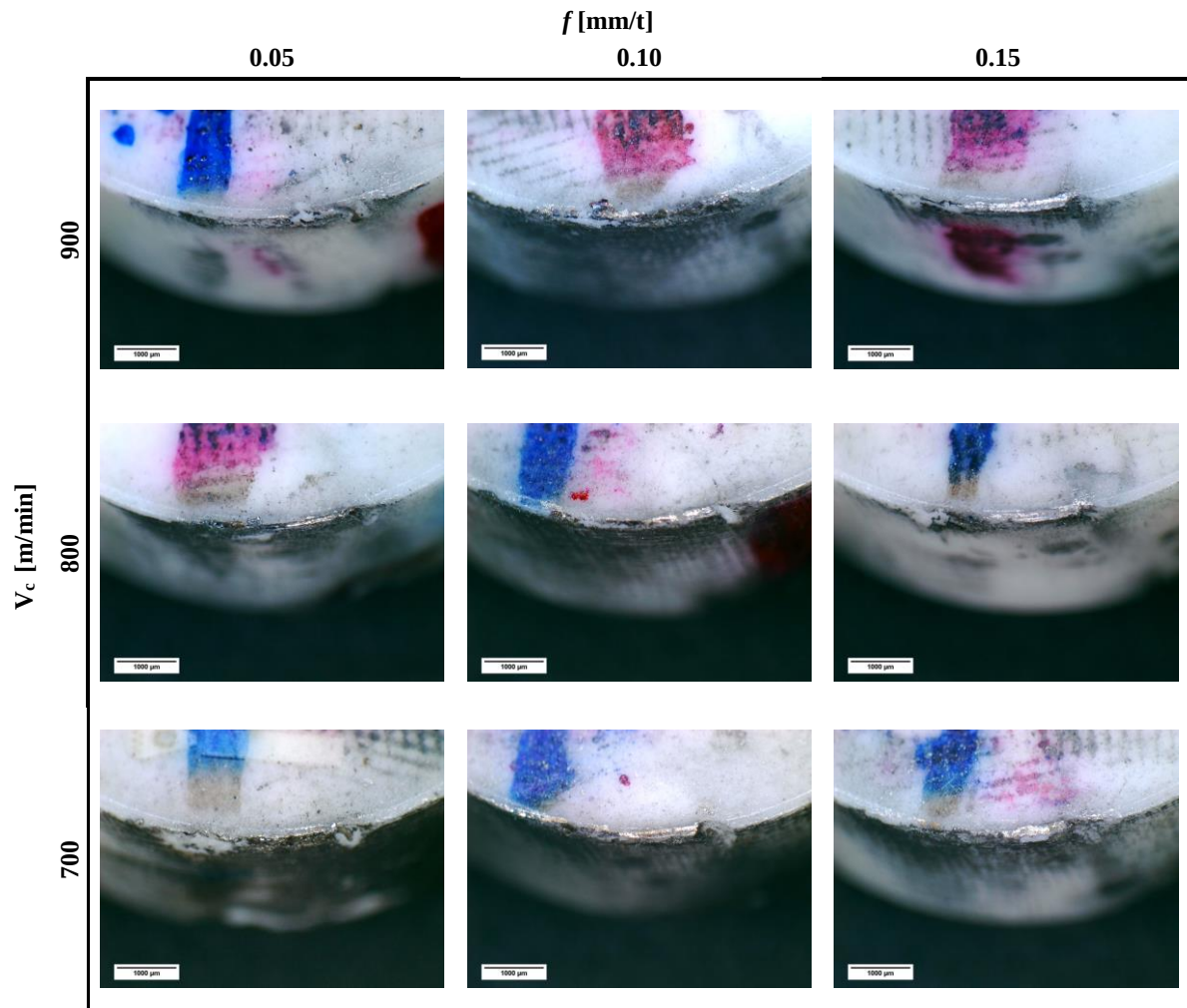
The Al_2O_3 -MgO ceramic cutting tool edge before the machining tests is presented in Figure 77. The wear progression with the variation of cutting parameters is presented in Figure 78.

Figure 77 – Al_2O_3 -MgO ceramic cutting tool before the machining tests.



Source: Author

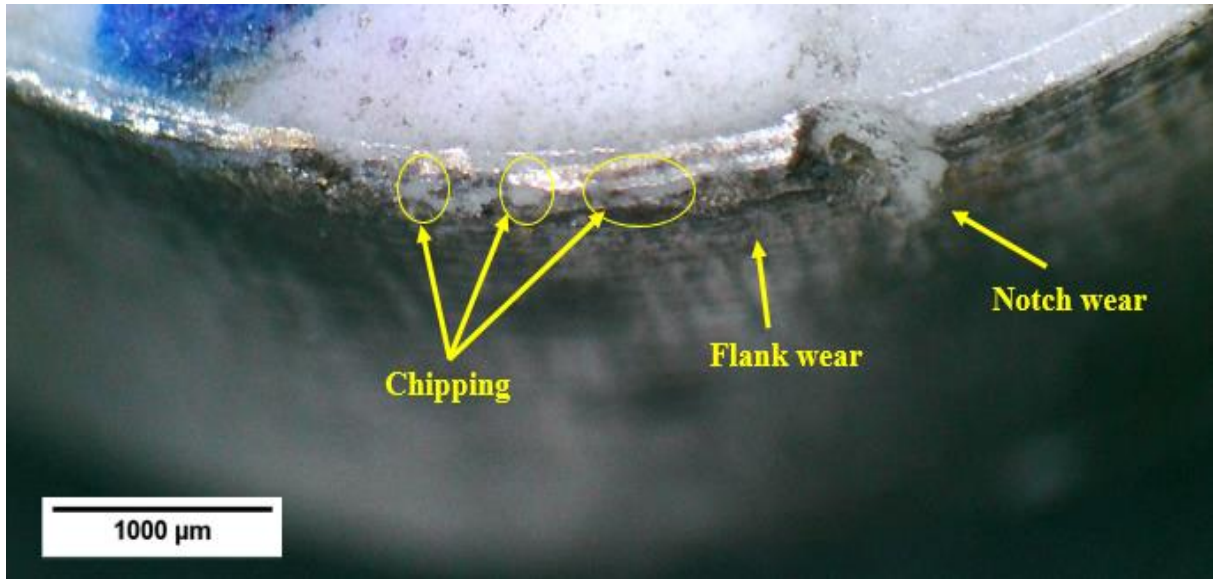
Figure 78 – Wear progression after machining tests to the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools.



Source: Author

After the machining, the main types of wear observed to the ceramic tools were flank and notch wear. In addition, the occurrence of chipping was extensively observed to the ceramic tools application (Figure 79). The abrasive mechanism was identified as the main wear mechanism, which causes the tool's flank wear. The friction is the main mechanism of wear between the tool and the part to be machined, being able to cause abrasion to occur wear leading to eminent reduction of final surface quality.

Figure 79 – Main types of wear observed to the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools.

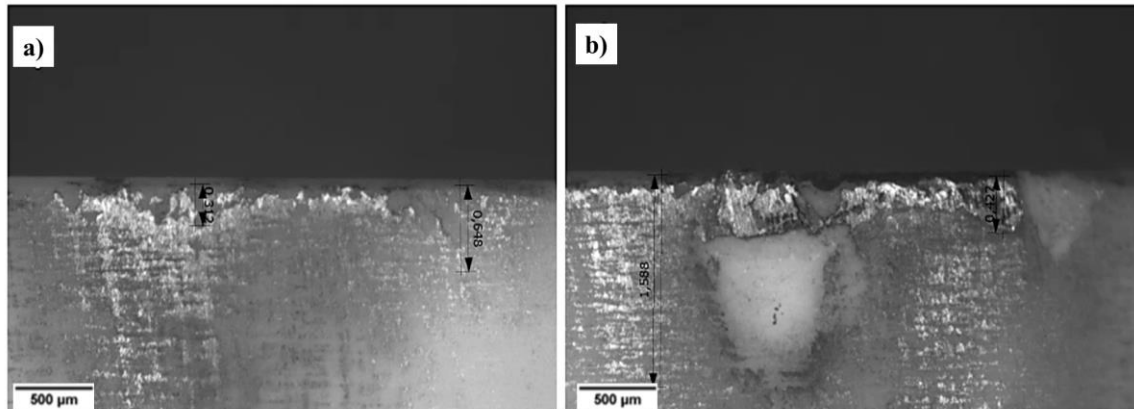


Source: Author

The average of the maximum flank wear (V_b) obtained with the ceramic inserts was 0.33 mm. The mean V_b found to the ceramic tools was higher than the one obtained with the use of the carbide tools (0.125 mm), however, considering the V_b divided by cutting length ($V_b \cdot 1000/L_c$) the values found are very similar, with 0.015 to the ceramic and 0.010 to the carbide tools.

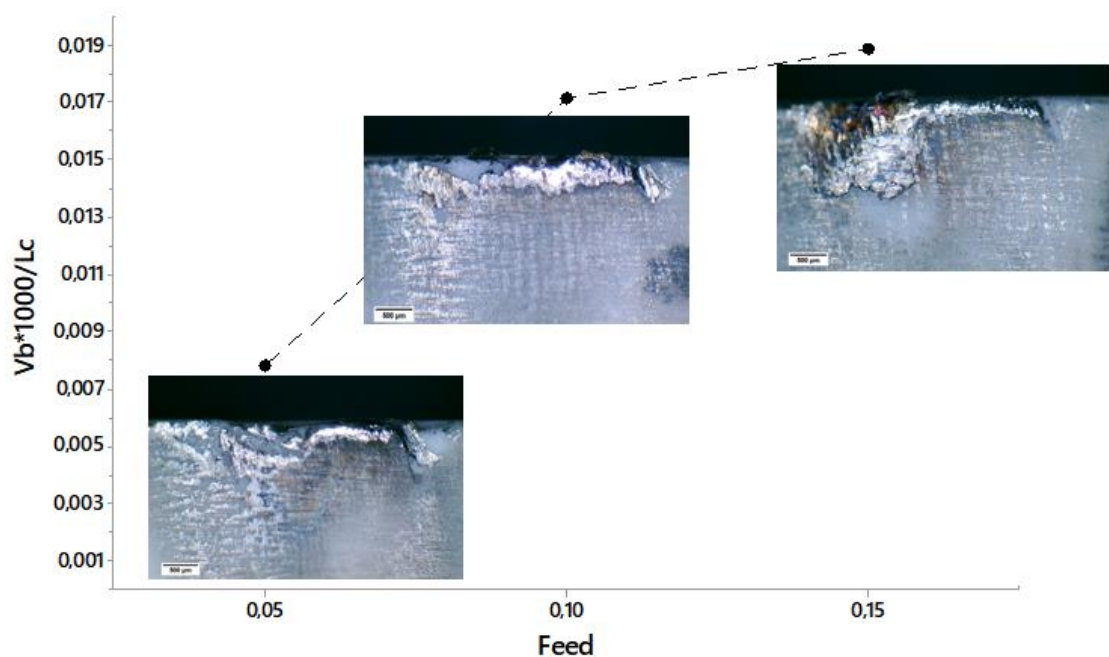
The flank wear presented a very strong dependence of the feed applied. It was observed that flank wear increased with the increase of the feed (Figure 80). The value of V_b divided by cutting length ($V_b \cdot 1000/L_c$) also presented an increase to the feed variation (Figure 81). This behavior can be explained that as the feed increases, the load per tooth also increases leading to an increase in the cutting forces, which leads to higher flank wear results. The high cutting forces also contribute to increase the efforts during machining. Moreover, increasing the feed also affected the surface quality, favoring high roughness results and worst surface quality.

Figure 80 – Increase in flank wear due to feed increase to the $\text{Al}_2\text{O}_3\text{-MgO}$ tools. a) $f = 0.05\text{mm/t}$; b) $f = 0.15\text{ mm/t}$.



Source: Author

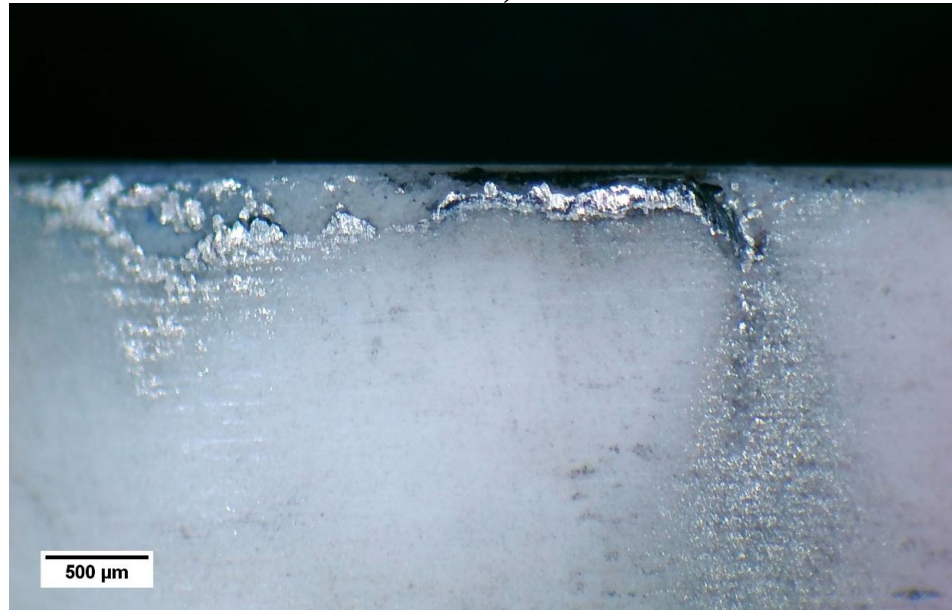
Figure 81 – Increase in $V_b \cdot 1000/L_c$ due to feed increase to the $\text{Al}_2\text{O}_3\text{-MgO}$ tools (v_c of 900m/min).



Source: Author

The high abrasive wear observed to the ceramic tools can also be explained by the presence of several high-hardened carbides in the VAT 32[®]. The application of higher feeds also led to high occurrence of chipping; that can be correlated to the high vibration results measured to the f of 0.015 mm/t (Figure 82). Therefore, the best condition to minimize the flank wear is the application of low feeds.

Figure 82 – Chipping observed to the application of high feeds to Al_2O_3 -MgO tools (v_c of 800m/min).



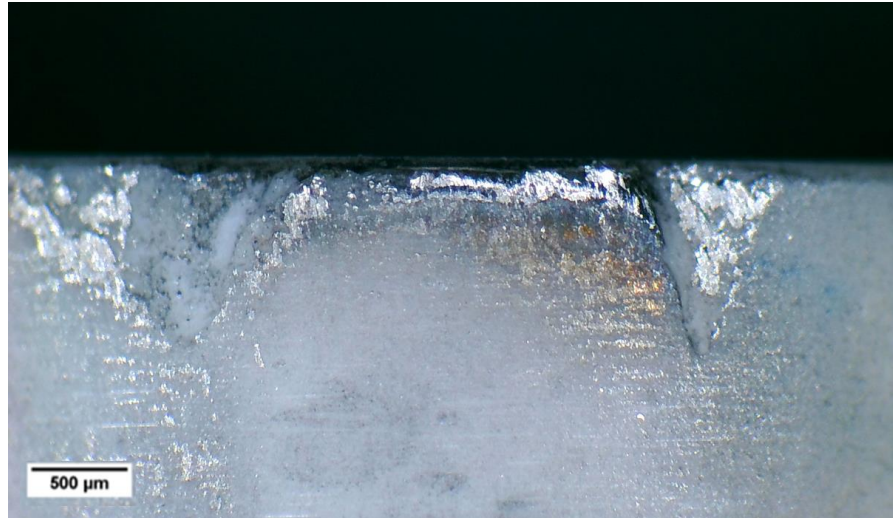
Source: Author

Another important aspect that must be considered to the wear increase is the observed influence that each cutting edge from each insert exhibits in the others insert edges, since three inserts were positioned into the cutter. Each cutting edge have influence in the wear of the other edges. This behavior is the result of the small difference between the assembly of the cutting edges on the cutter. As the difference between the edges increases, the wear of those that remove a greater volume of excess metal increases.

It was observed the high occurrence of notch wear to the ceramic tools (Figure 83). The notch was observed to all tested conditions of cutting speed and feed and all cutting edges presented notch wear incidence.

The occurrence of work hardening during the machining contributed to the notch wear observed. The high occurrence of notch wear in the tools can also be explained by the high abrasion rates caused by the rubbing of hard particles from the workpiece material, which characteristically occurred on rake face, due to strong friction and contact between the workpiece and the tool.

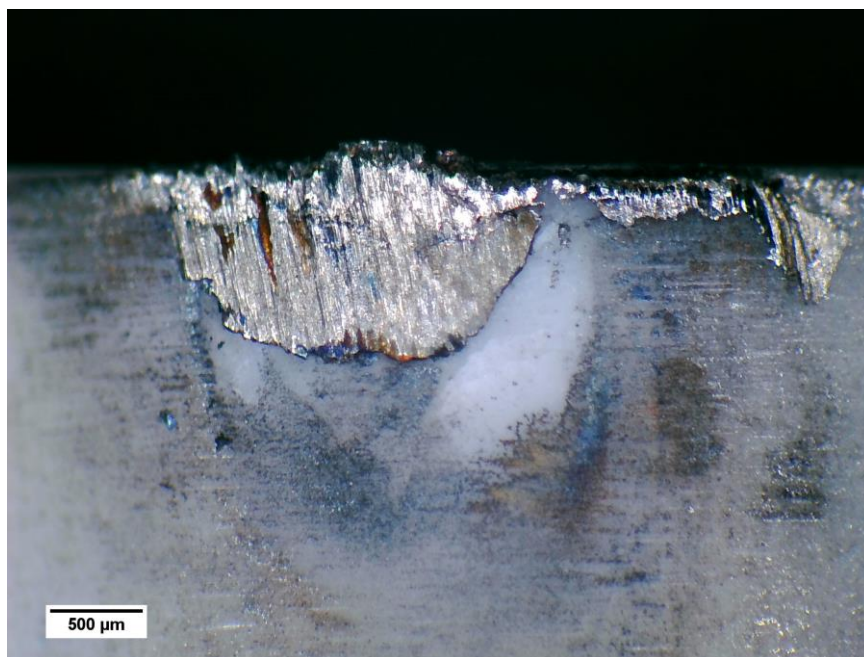
Figure 83 – Notch wear observed in the $\text{Al}_2\text{O}_3\text{-MgO}$ tools (v_c 800m/min and f 0.10 mm/t).



Source: Author

It was observed high adhesion of the machined material in the cutting tools edges (Figure 84). The adhesive wear results due to the atomic interaction of tool and workpiece contact. When a hard material is rubbed over a soft material, particles of soft material stick to the hard material forms adhesive wear. The adhesion caused severe wear, as well as favoring the high incidence of chipping observed to the ceramic tools.

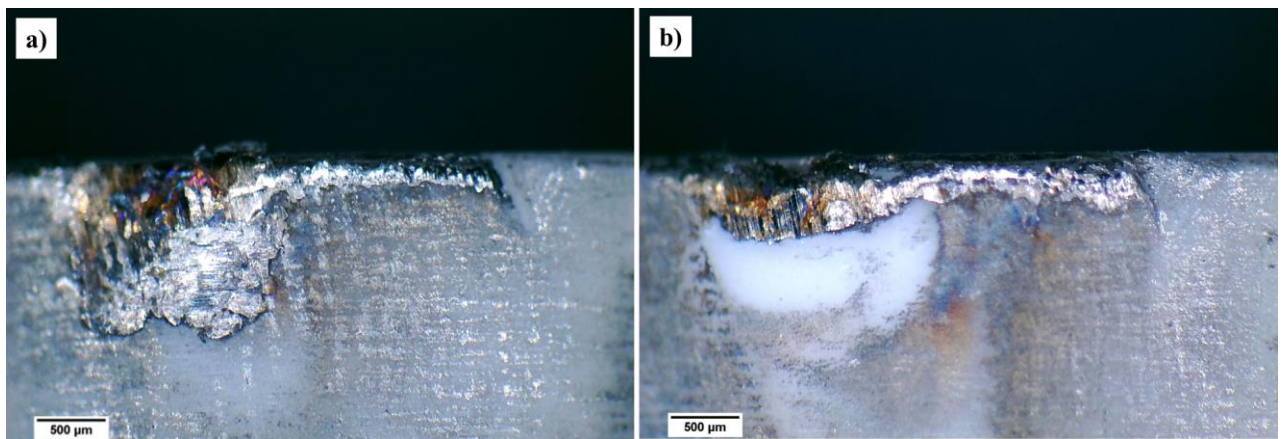
Figure 84 – High adhesion of material in the cutting edge of the $\text{Al}_2\text{O}_3\text{-MgO}$ tools.



Source: Author

The adhesion of material in the cutting tool edge was the main cause of the high incidence of chipping observed (Figure 85). The material adhesion during the machining is characteristic of the machining of superalloys, which leads to the severe flank wear, as well as chipping.

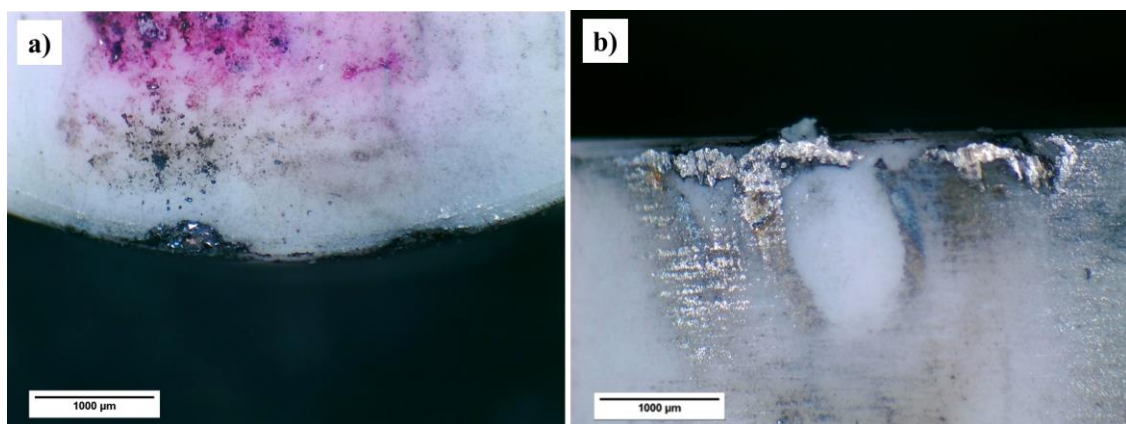
Figure 85 – Chipping caused by high adhesion of material in the cutting edge of the Al_2O_3 -MgO tools (v_c 900 m/min and f 0.10 mm/t). a) Adhesion of material; b) Chipping.



Source: Author

The chipping can also be favored by the heterogeneity of the machined material that presents high carbides in the microstructure. The high hardness carbides led to the increase in the impact of the cutting edges during the milling, which increases the chipping due to the low toughness of the ceramic tools.

Figure 86 – 10 High incidence of chipping in the Al_2O_3 -MgO ceramic tools, insert: a) Rake face; b) Flank face.



Source: Author

Compared to carbide, the ceramic inserts presented a high incidence of chipping, due to the low toughness in relation to the coated carbide inserts. However, it is necessary to consider the inherent dynamic of the milling process. In milling, the cutting process is intermittent. That is, the edge enters and leaves the workpiece at each revolution of the cutter which subjects the edge to a cycle of impact forces and thermal loads at each rotation, which associated with the low toughness, may have contributed to the high chipping of the ceramic tools in comparison to the carbide.

Considering the procedure of the experimental inserts fabrication it is also possible that the pre-existence of processing defects and porosity of the ceramic have contributed to the occurrence of micro cracks and chipping.

To the ceramic tools, it was also observed the formation of BUE (Figure 87). The application of higher speed values associated with higher feeds contributed to the material adhesion, leading to the formation of BUE (Figure 88).

Figure 87 – Built-up edge formation in the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic tools (v_c 800 m/min and f 0.10 mm/t). a) Adhesion of material forming a BUE; b) BUE Contrast profile .

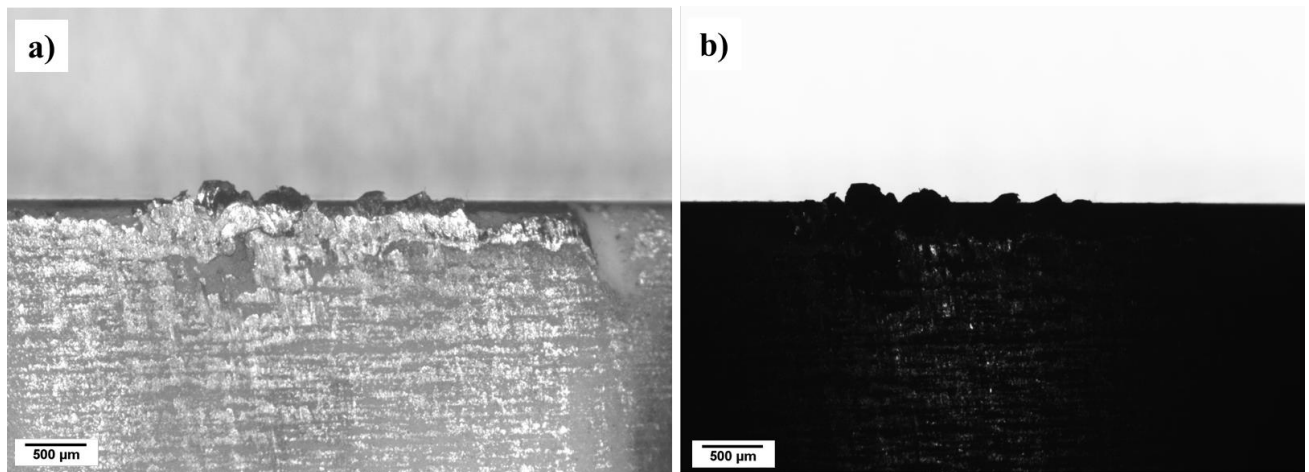
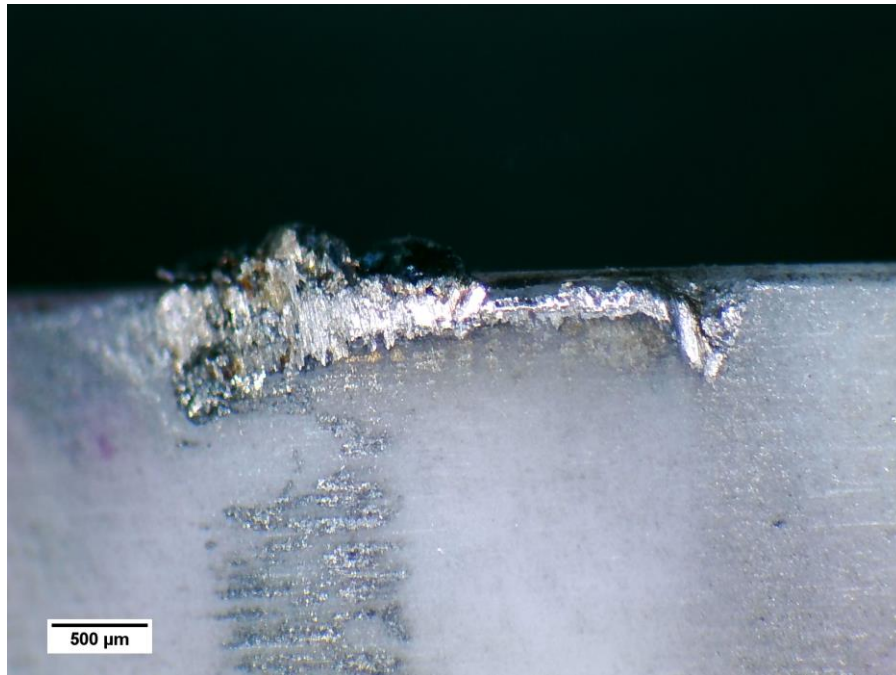


Figure 88 – Built-up edge (BUE) formation found to high cutting speed and feed applied to the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic tools.

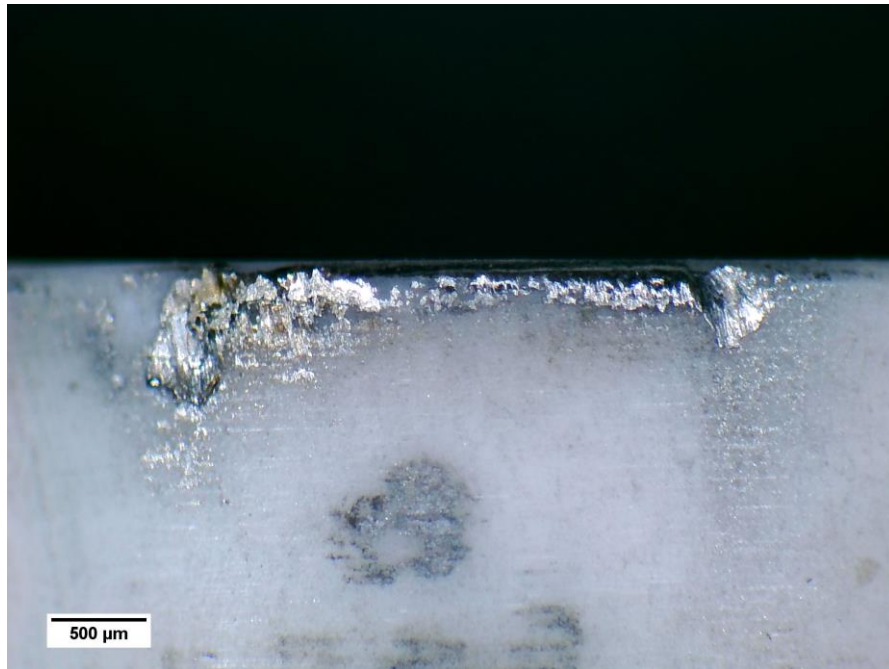


Source: Author

The formation of a built-up edge can be result of the high temperatures achieved during machining. There was also chemical interaction between the machined material and the tool due to the affinity of the alumina tool with the high aluminum content present in the VAT 32[®] alloy and due to the high temperatures reached in the cutting region. The high temperatures reached can be confirmed through the analysis of chips that had the surface clearly affected by the high temperatures during cutting. The low thermal conductivity of the VAT 32[®] characteristic of nickel-based superalloys also justifies the high temperatures reached at the cutting edge, as well as large temperature gradients in the tool, which may have contributed to chipping.

Therefore, considering the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic tools application, the condition of v_c of 900m/min and f of 0.05 mm/t presented the best results regarding flank wear and $V_b \cdot 1000/L$. This condition allowed less occurrence of material adhesion, chipping or BUE formation (Figure 89).

Figure 89 – Wear result to the application of best cutting conditions (v_c 900 m/min and f 0.05 mm/t) to the Al_2O_3 -MgO ceramic tools.



Source: Author

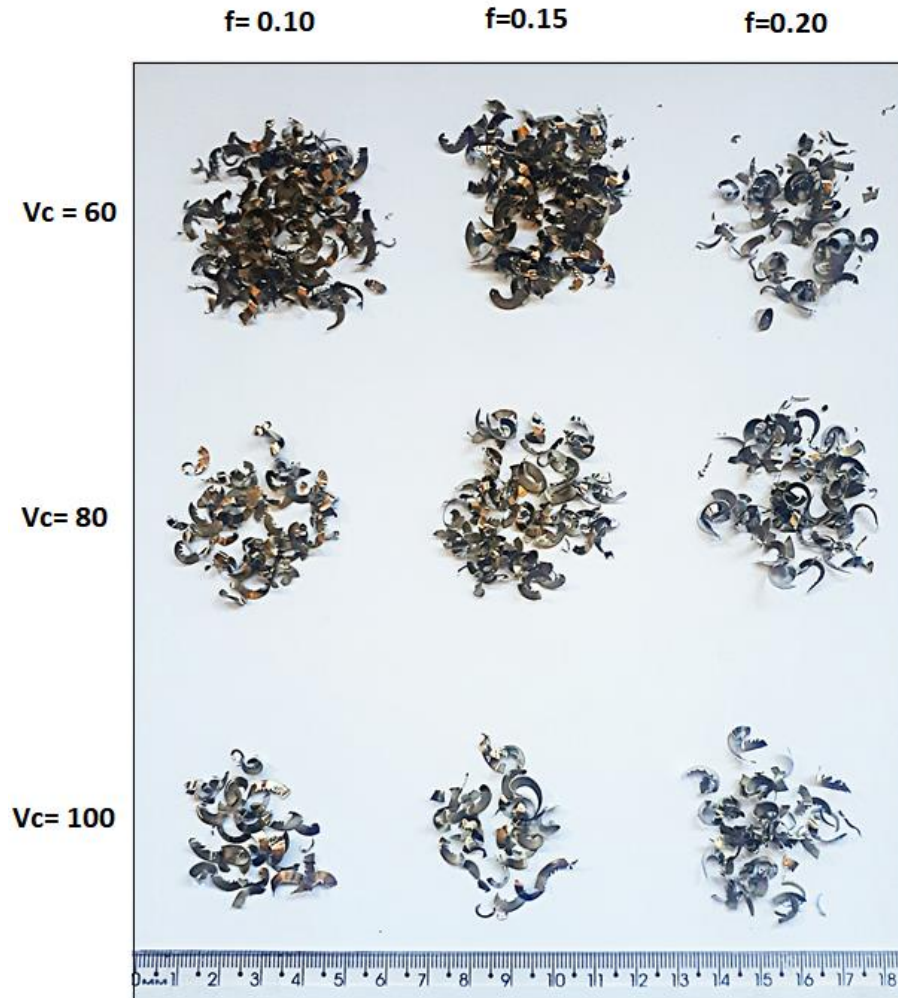
5.4 CHIP ANALYSIS

The classification of resulting chips was conducted according the ISO ABNT NBR 3685:2017 recommendations, specifying the chip's morphology by type (i.e. continuous, discontinuous or segmented) and form. The study of chips allowed a better understanding of the machining process and analysis of the tool-material interface. The quality of the machined surface and tool wear is significantly affected by the shape of produced chips. The shape and size of the chips are key factors in chip breakability (NIMEL SWORNA ROSS AND MANIMARAN, 2019). According to Diniz et al (2013), the chip formation influences several factors related to machining, such as tool wear, cutting efforts and heat generated. Therefore, the chip analysis and study of its forming process is very important as impacts the final economic aspects, operator safety and final surface quality of the workpiece.

The chips obtained for the application of the carbide tools are shown in Figure 90. A small variation in the chip's form with the change of cutting parameters was verified, however, the type was the same to all conditions. The chips obtained can be classified as segmented type with a loose arc form. The segmented chips are reported in literature as characteristic of the machining of nickel-based superalloys (ÖZEL; ULUTAN, 2014; RODRÍGUEZ;

CARBONELL; JONSÉN, 2020). The production of segmented chips is preferred and convenient to collect handle and disposal.

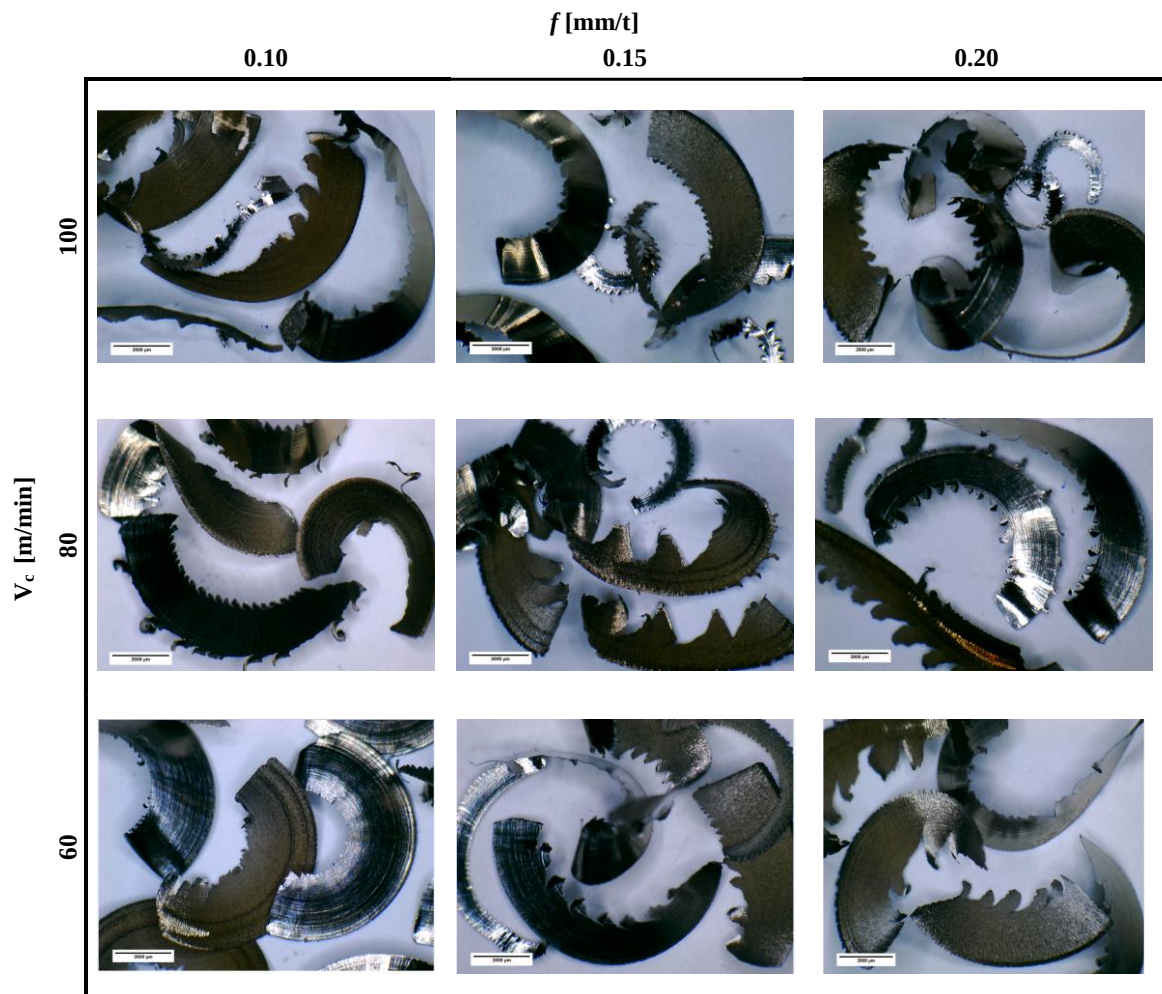
Figure 90 – Chips obtained to the application of the carbide cutting tools.



Source: Author

In Figure 91, the magnification of usual and distinct types of chips observed to each tested condition is presented. It is possible to observe with more details the slightly change in shape according the cutting parameters variation. It is important to consider that in concordant frontal milling, the direction of the cutting speed and feed are, on average the same. Thus, the chip thickness decreases during its formation. The chip thickness is maximum at the beginning of the cut and minimum at the end leading to the occurrence of material crushing and greater friction between the edge and the cutting surface in the tool-material interface.

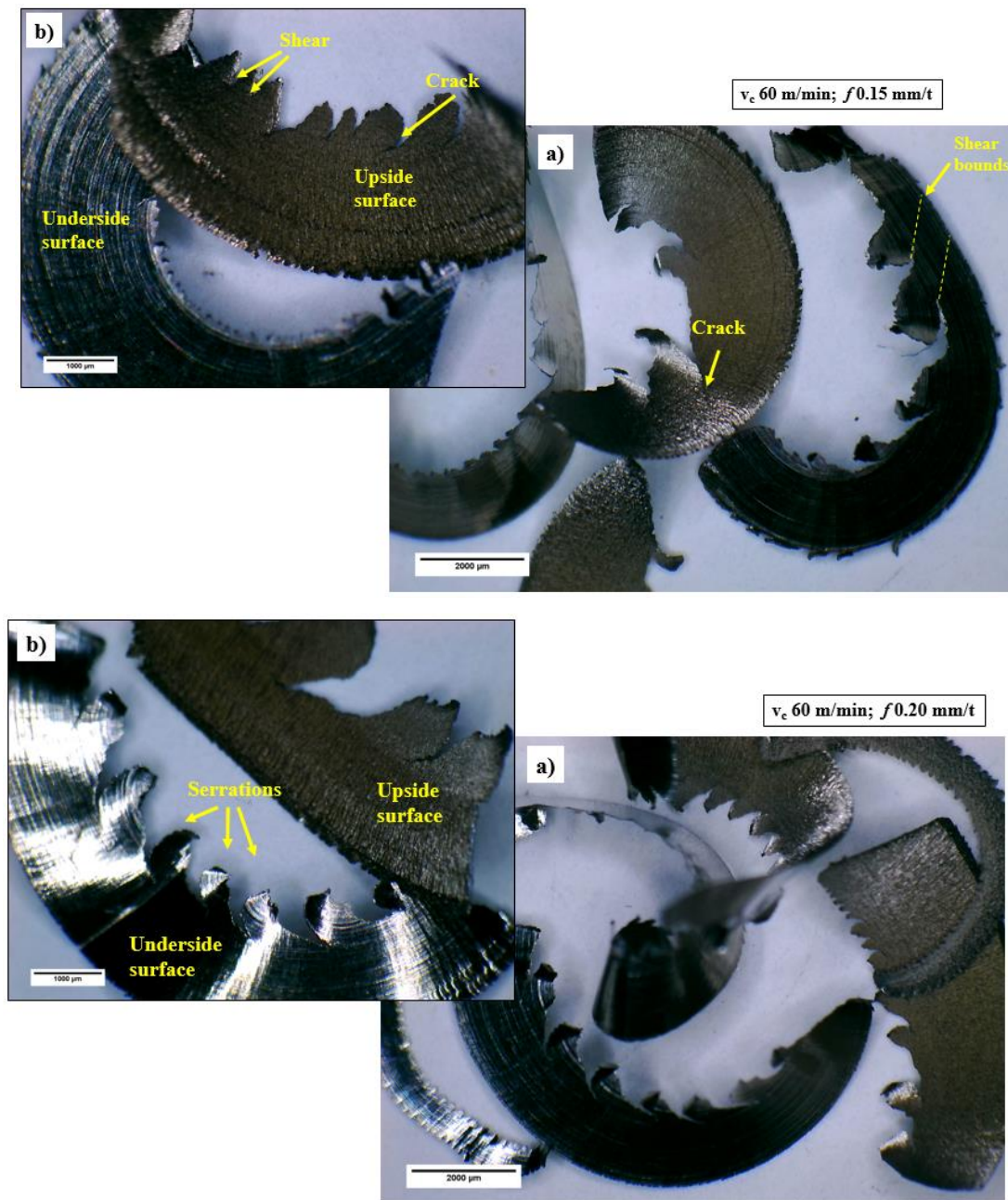
Figure 91 – Chip morphology under different cutting parameters to the application of the carbide cutting tools (Magnification 0.80x).



Source: Author

The segmented (or serrated) chip was observed to all tested conditions. The serrated chip is characterized by the discontinuous formation with still more or less connected elements. Furthermore, this type of chip usually have a higher thickness and present significant variations of deformation degree along the flow path elements (RODRÍGUEZ; CARBONELL; JONSÉN, 2020). The segmented formation was evidenced with feed increase, more to the 0.15 and 0.20 mm/t feeds (Figure 92). As it is reported for titanium and nickel-based superalloys in the literature, the segmentation has been more dominantly affected by the increase in feed (PAWADE, SONAWANE and JOSHI, 2009).

Figure 92 – Segmented chip with serrated type a) Usual type of observed chip (0.80x); b) Magnification (1.25x).

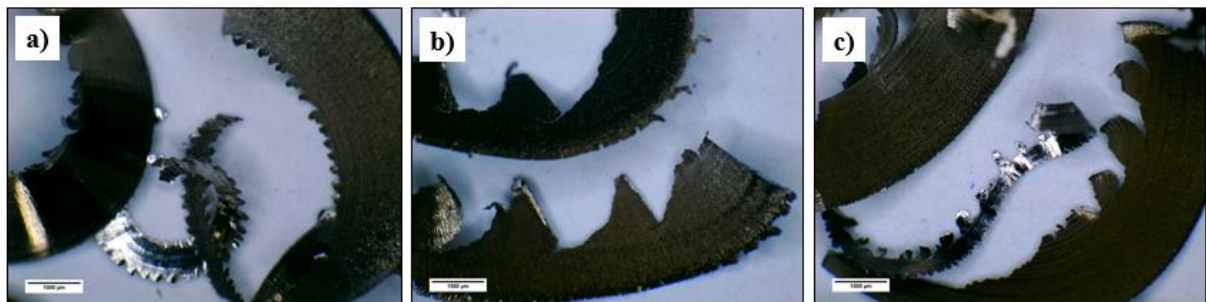


Source: Author

It has been reported that for nickel alloys segmented chips are formed at all levels of cutting speed (PERVAIZ et al., 2014) (Figure 93). The influence of serrated chip formation on machining process outputs (i.e. cutting forces, temperature and surface roughness and integrity) is profound. Therefore, a thorough understanding of mechanics of serrated chip formation in nickel-based super alloy machining is considered essential. The fundamental mechanism of serrated chip formation in nickel-based superalloys has been long debated in

the literature. According to Kitagawa (1997) it occurs due to the thermal softening (i.e. localized shearing), however other authors claims that there is a crack initiation in the primary shearing zone (i.e. a narrow band between the tool tip and the chip free surface), which causes serration in the chips (LI ET AL. (2002); EZUGWU (2003); COELHO ET AL. (2004); ARUNACHALAM RM, MANNAN MA AND SPOWAGE, (2004)). Both theories are supported by experimental evidences, and the common belief is that both mechanisms are in effect (ÖZEL; ULUTAN, 2014). At low cutting speeds, a crack-initiated serration occurs, and at high cutting speeds, localized shearing-based serration occurs due to higher temperatures and it becomes more dominant.

Figure 93 – Segmented chips with serrated type obtained to all cutting speeds. a) v_c 60 m/min; b) v_c 80 m/min; c) v_c 100 m/min.

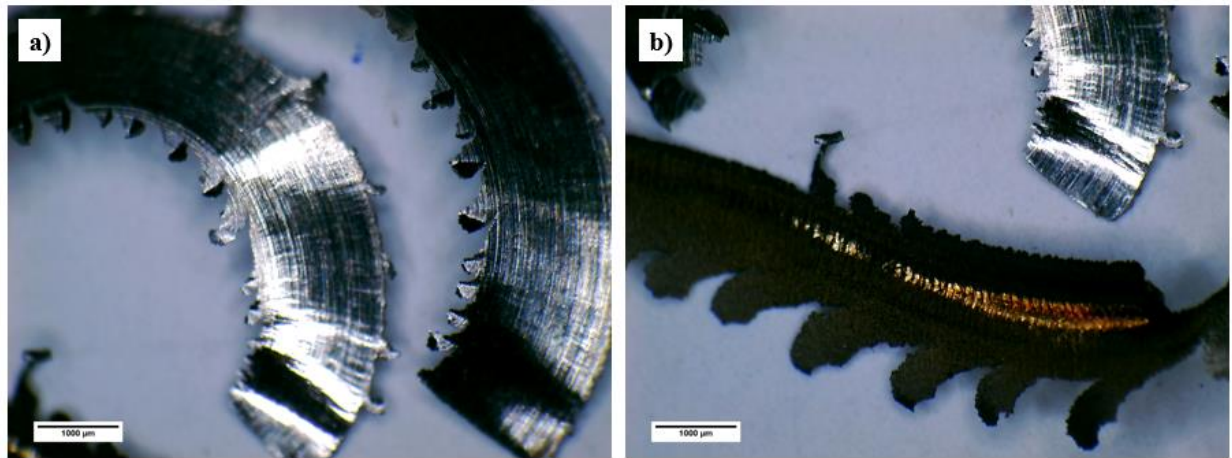


Source: Author.

Özel and Ulutan (2014) investigated the formation mechanism of serrated chip morphology in the orthogonal cutting of nickel based superalloys. They reported the presence of highly serrated shape chips with regions of high plastic deformations (adiabatic shear bands) and cracks mixed in the lamellar shear zones. It is believed that adiabatic shear band is a form of failure mechanism that occurs in both titanium and nickel-based superalloys when they are deformed at a high rate in machining processes. Furthermore, these adiabatic shear bands are commonly the precursors to fracture and both cracks and adiabatic shear bands can coexist in segmented serrated chip formation.

It was observed, in the case of dry milling, that the chip upside and underside surfaces, have changed more color specially to the v_c of 80 m/min and higher feed (Figure 94), so that the upside surfaces of the chips are dark brown and the underside surfaces are dark silver. This is an indication of the high temperature generated in the cutting zone, which leads to chip oxidation and burnt chip.

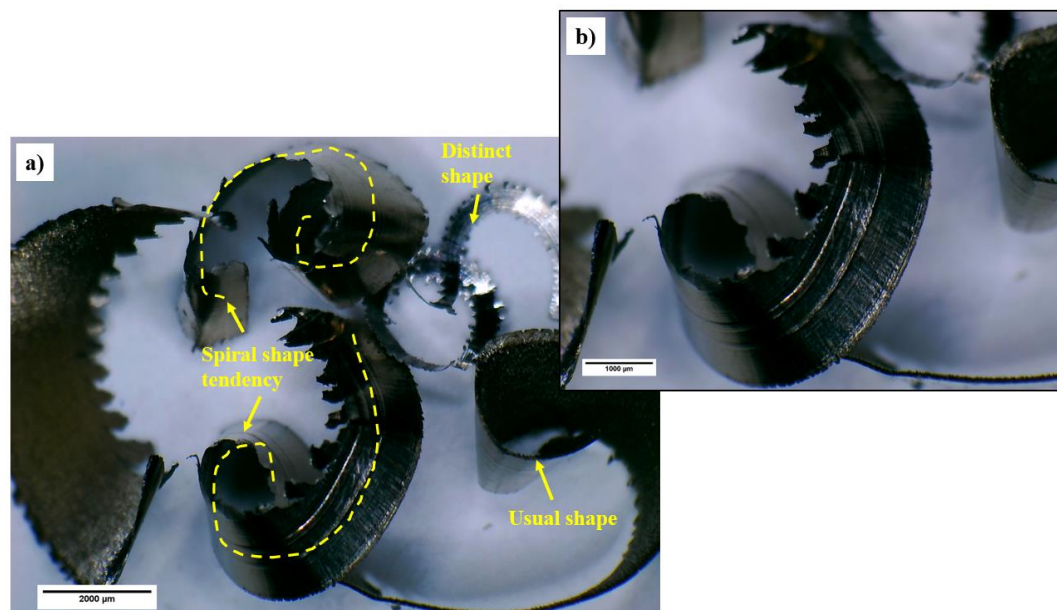
Figure 94 – Chips produced to v_c of 80/min and f of 0.20mm/t. a) Underside surface of usual type of chip (1.25x); b) Change of color in upside region (1.25x).



Source: Author

To all tested conditions, the main chip shape observed was the loose arc form. However, there was an increase in the occurrence of distinct forms of chips to higher cutting speeds applied. To the application of v_c of 100 m/min and f of 0.20 mm/t, the chip tended to form an spiral shape slightly conical (Figure 95).

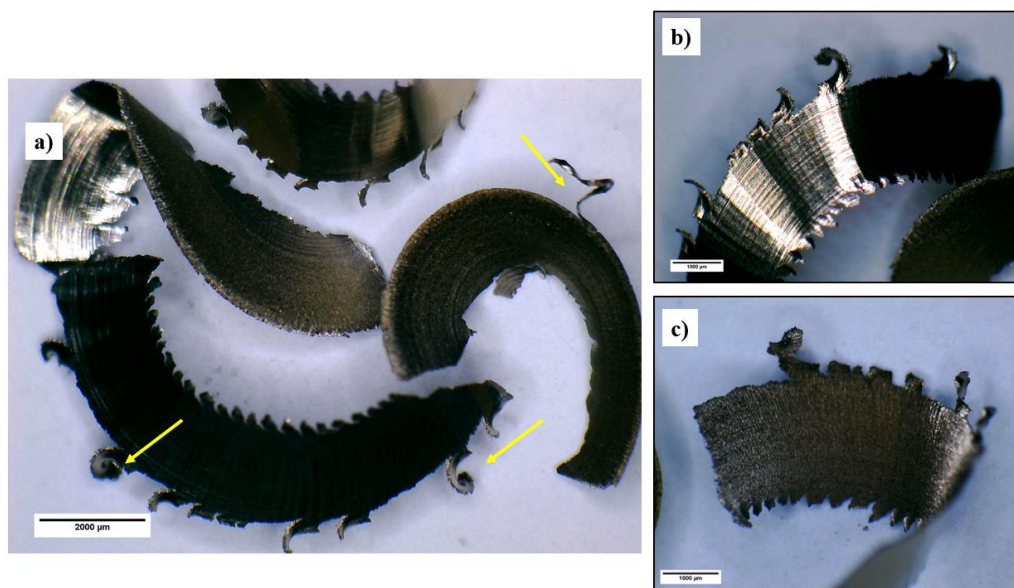
Figure 95 – Change in chip shape to v_c 100 m/min and f 0.20 mm/t. a) Usual and distinct type of observed chip (0.80x); b) Magnification of spiral chip observed (1.25x).



Source: Author

To the condition v_c of 80 m/min and f of 0.10 mm/t it was observed adhesions in the chips extremities (Figure 96). This can be explained due to the formation of heat-affected zones very close to the cutting edge, common in machining operations of superalloys. According Komanduri (1983), the heat-affected zone is very small in case of machining nickel-based superalloys. Less contact area between tool and material causes high magnitude of mechanical stresses in the near vicinity of the cutting edge.

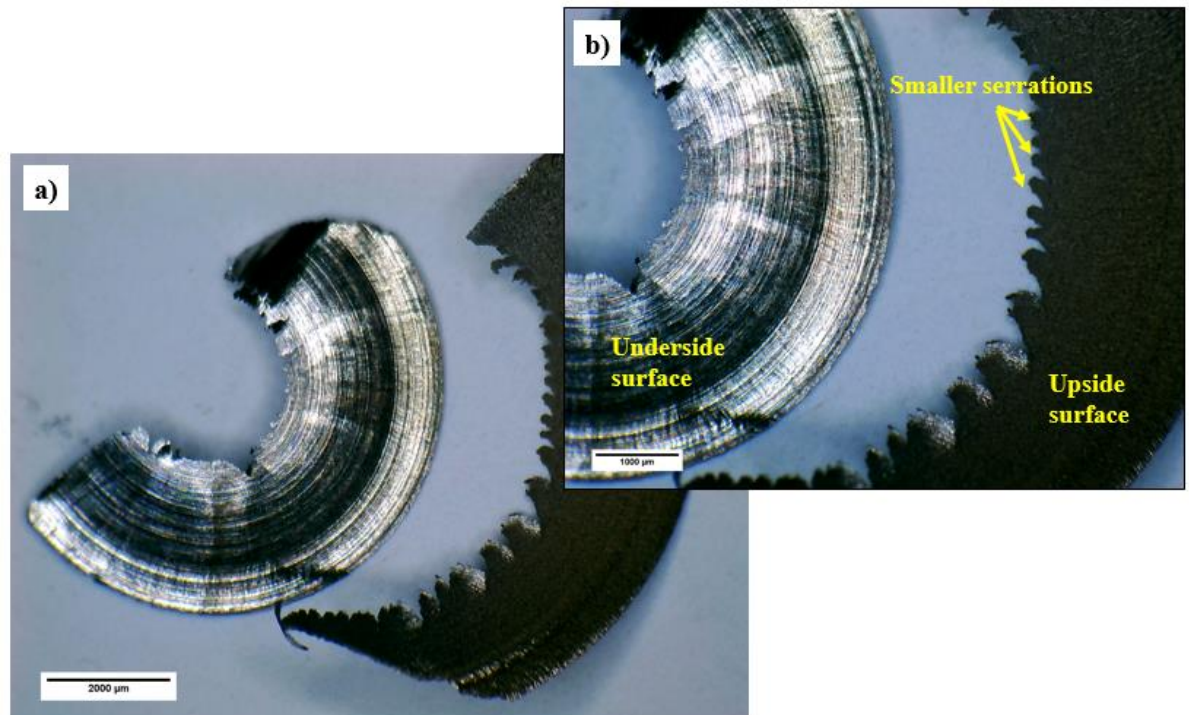
Figure 96 – Chip to v_c of 80 m/min and f of 0.10 mm/t. a) Usual type of observed chip and adhesions (0.80x); b) Chip's underside surface (1.25x); c) Chip's upside surface (1.25x).



Source: Author

To the carbide tools application, the condition of v_c of 60m/min and f of 0.10mm/t presented the best results regarding the formation of chips and preferred type and shape. The obtained small segmented chips presented short serrations, less occurrence of cracks and no adherence of material (Figure 97). The obtained segmented chip is convenient to collect, handle and dispose off. Since the chips break up into small segments the friction between the tool and the chips reduces, resulting in better surface finish. The condition of lower cutting speed and feed (v_c 60m/min; f 0.10mm/t) also led to the best result of tool wear (V_b/L_c).

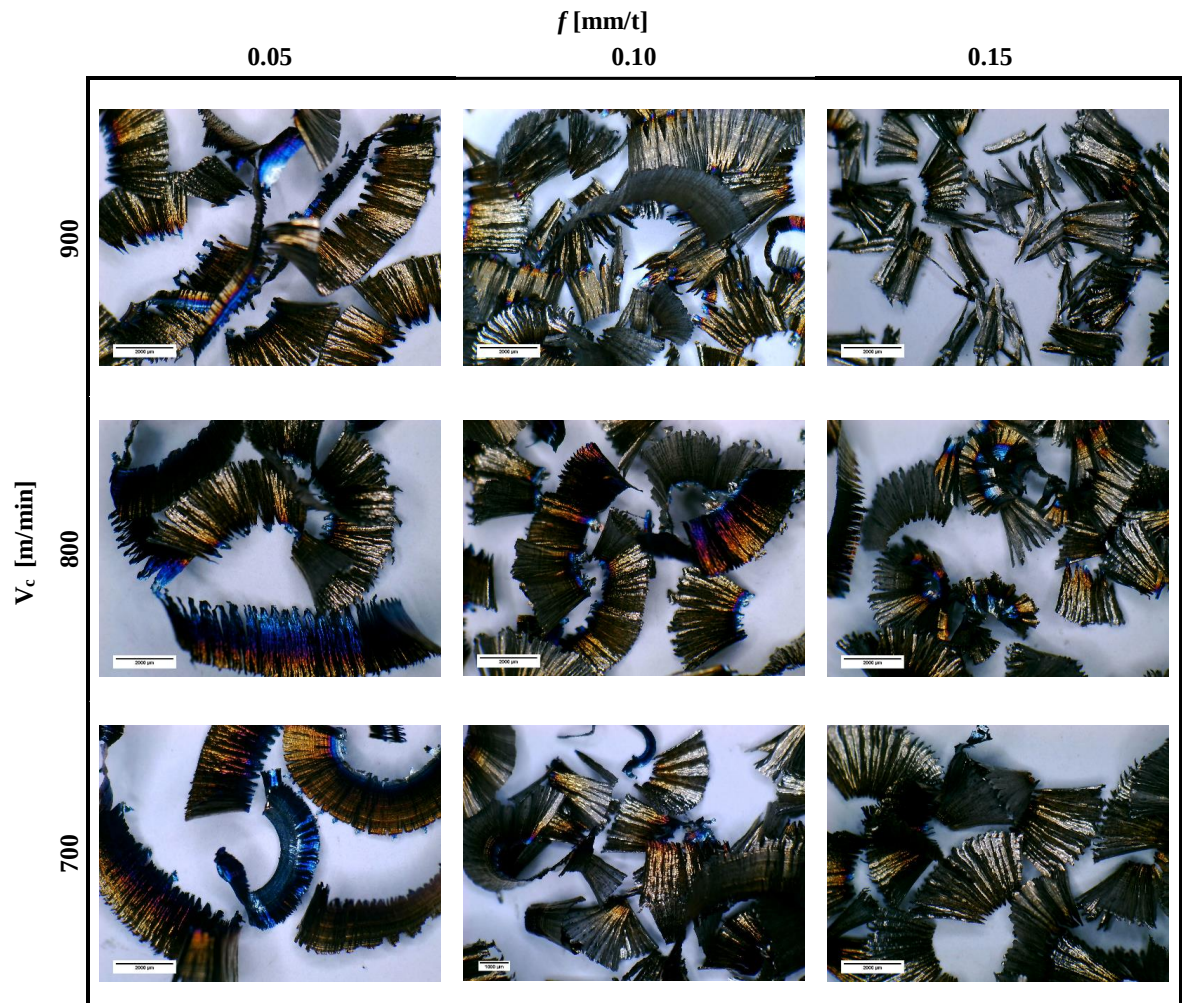
Figure 97 – Chip to v_c of 60 m/min and f of 0.10 mm/t. a) Usual type of observed chip (0.80x); b) Magnification (1.25x).



Source: Author

To the application of the experimental ceramic cutting tools, the chips presented different characteristics of type and form than the generated using the carbide inserts. The chips obtained for the application of the $\text{Al}_2\text{O}_3\text{-MgO}$ tools are shown in Figure 98. The most usual type of chip observed was the shear type with shape of loose arc. The shear chips are made of very distinct connected lamellar groups. These chip elements were sheared in the shear region and partially welded immediately after its formation. The shear chips are formed when there is a decrease in the strength of the material in the shear plane, due to increase in temperature, deformation, heterogeneities of the microstructure, or external vibrations (DA SILVA, 2008; RODRÍGUEZ; CARBONELL; JONSÉN, 2020; VALVERDE JUNIOR; GIANISELLE, 2015).

Figure 98 – Chip morphology under different cutting parameters to the application of the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools (Magnification 0.80x).

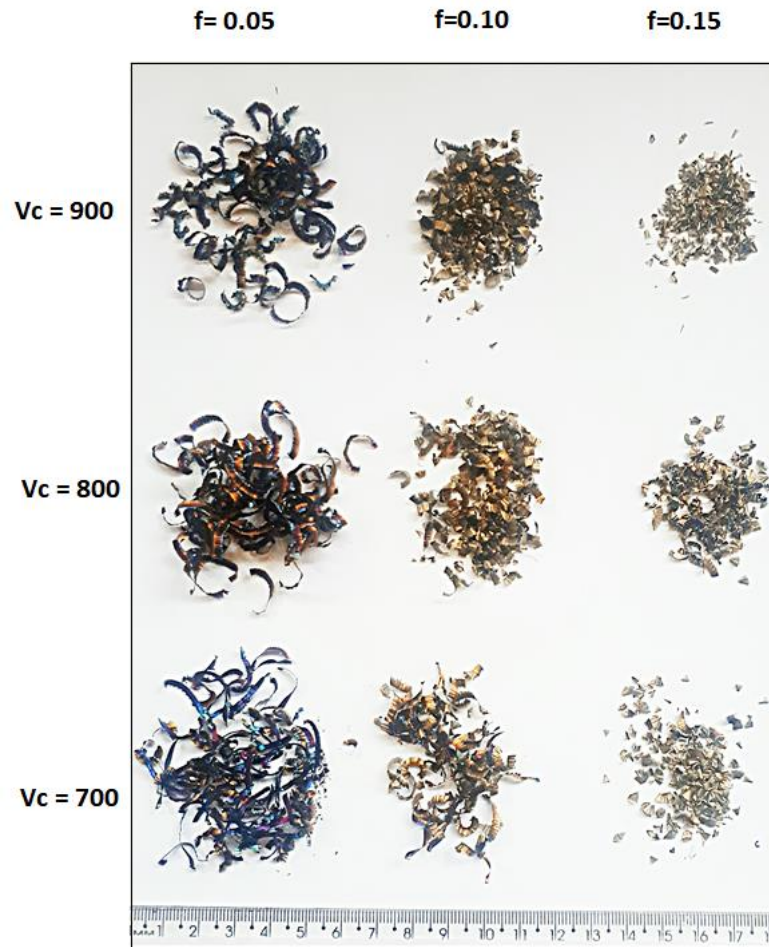


Source: Author

Different from the carbide tools resultant chips, to the ceramic tools application, the type and shape of chips presented great variation with the change of cutting speed and feed levels. As can be seen in Figure 99, an expressive change in the chip's shape characteristics and dimensions was observed.

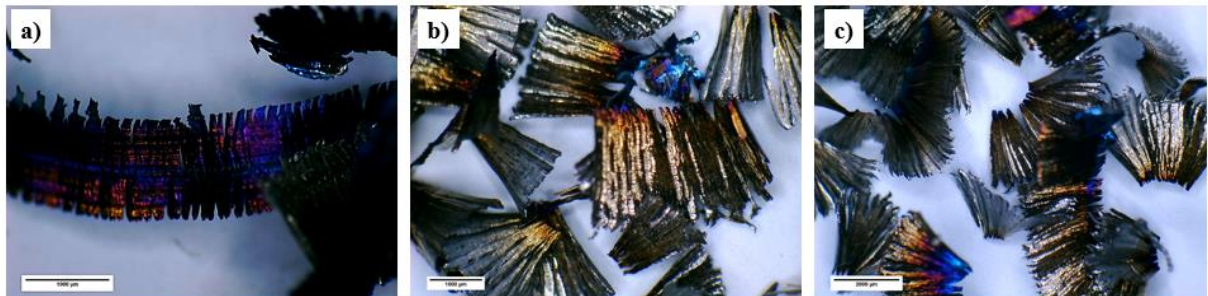
The difference in the type of chip is evidenced by the variation of the feed (Figure 97). As the feed increases the chip tend to break more allowing a smaller shear chip, the shape begins to present more conic spiral tendency than arc form. This phenomenon tendency occurs for all applied cutting speeds. However, the difference in shape is more evident for the speed of 700 m/min (Figure 100) and 900 m/min (Figure 101).

Figure 99 – Chips obtained to the machining with the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools.



Source: Author

Figure 100 – Variation of chip's characteristics to v_c of 700 m/min and different feeds applied using the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools. a) f of 0.05 mm/t; b) f of 0.10 mm/t; c) f of 0.20 mm/t.

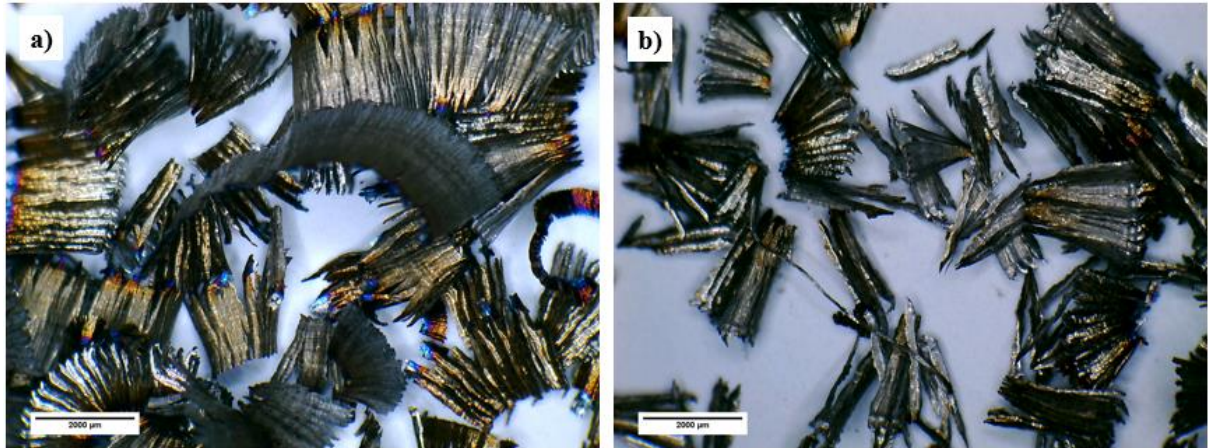


Source: Author

To the cutting speed of 900 m/min the difference of form is notorious (Figure 101). With the increase in feed, due to high heat accumulation, the chips are subjected to more

thermal stresses. This issue led to higher shearing mechanism and large plastic deformation at the cutting zone, resulting in more fragmented chips (Figure 101-b).

Figure 101 – Expressive variation of the chip form to v_c of 900 m/min using the Al_2O_3 -MgO ceramic cutting tools. a) f of 0.10 mm/t; b) f of 0.15 mm/t.



Source: Author

The increase in the feed led to an increase in the cutting forces. By keeping the feed constant and varying the cutting speed (Figure 102), the chip thickness decreases with the increase in the cutting speed, consequently decreasing the machining forces, allowing the obtaining of a more discontinuous type of chip. The dependence of the feed is reported in the literature, where regarding the cutting parameters that most affect the chip shapes, the feed is the most influential just followed by the cutting depth.

Figure 102 – Variation of the chip form to f of 0.10 mm/rev, using the Al_2O_3 -MgO ceramic cutting tools (0.80x). a) v_c of 700 m/min; b) v_c of 800 m/min; c) v_c of 900 m/min.



Source: Author

It was possible to observe different surface colors on the chips obtained with the application of the ceramic tools (Figure 103). The upside change in color is very characteristic to these tool application, not being found to the chips generated by the carbide tools. The colors indicate high temperature during machining. The majority of chips with distinct strong color gradient were obtained to the feed of 0.05mm/t to both cutting speeds of 700 and 800 m/min. Only to the cutting speed of 900 m/min the intense colored zone was located just in the region of the internal upside extremity. To this condition, the chip also showed a change in size and thickness that may have contributed to the change in the heat dissipation flow during machining.

Figure 103 – Chips obtained with f of 0.05 mm/t, using the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools.
a) v_c of 700 m/min; b) v_c of 800 m/min; c) v_c of 900 m/min.

(continue)

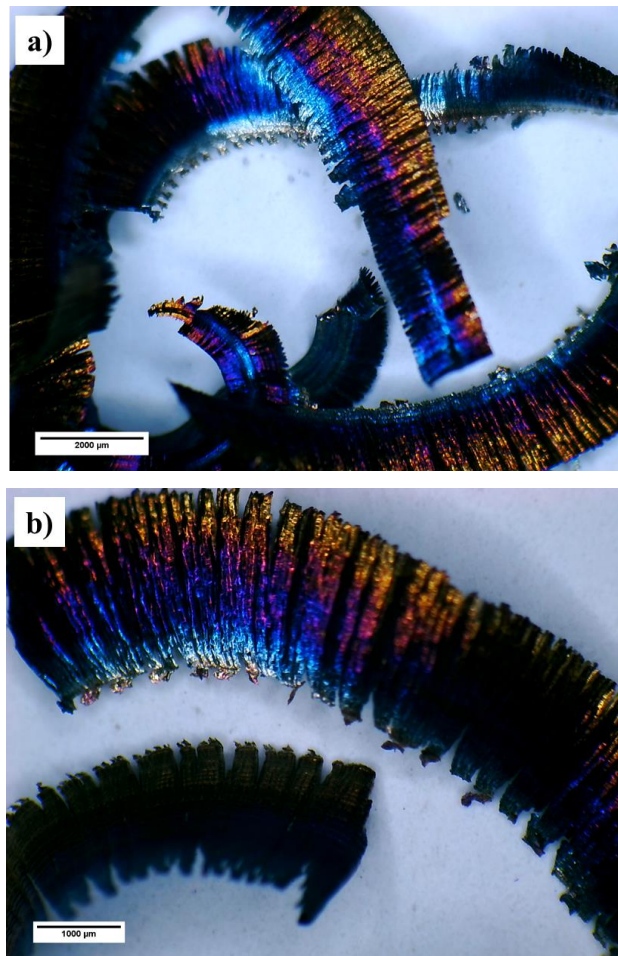
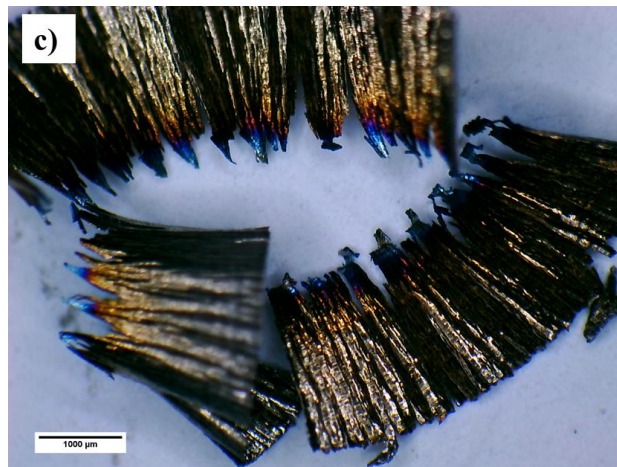


Figure 104 – Chips obtained with f of 0.05 mm/t, using the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools.
a) v_c of 700 m/min; b) v_c of 800 m/min; c) v_c of 900 m/min.

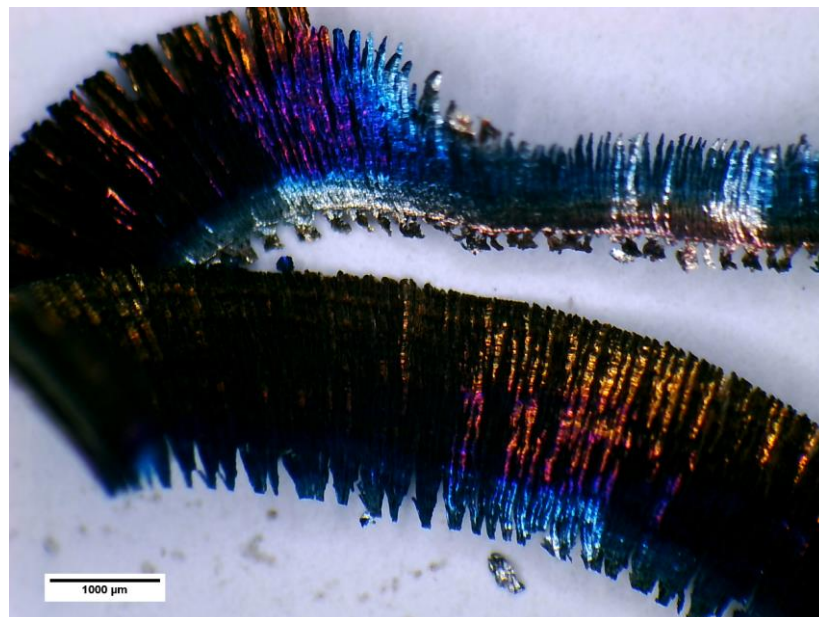
(conclusion)



Source: Author

In Figure 104 is possible to observe the color gradient printed in the chip surface and the shear mechanism of chip formation. It is also possible to identify adhesion of material in some points of the chip that represent higher temperatures (blue colored), indicating that, the application of high cutting speeds have caused a consider elevation in cutting temperatures. The high temperatures can be explained by the machining material properties, the VAT 32[®] superalloy is a highly heat resistant material, implying that the tool and the chip are responsible for dissipating most of the heat generated in the process.

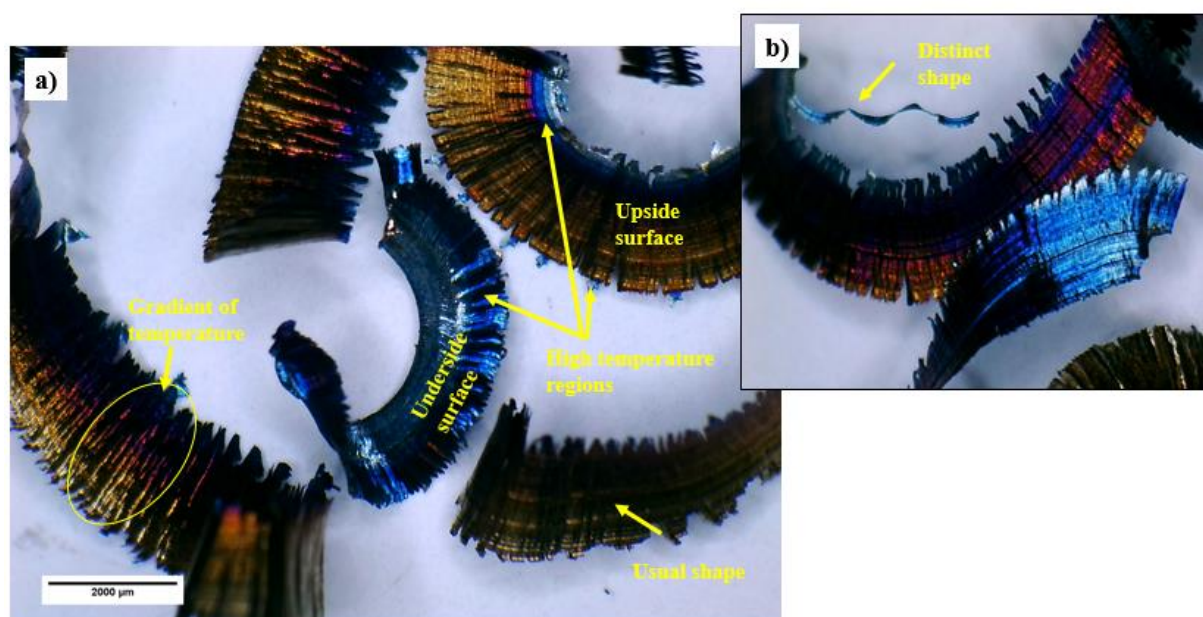
Figure 105 – Chip obtained with v_c of 700 m/min and f of 0.05 mm/t using the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools.



Source: Author

The high hot hardness characteristic of nickel based superalloys is another reason of generating high cutting forces and stress levels at tool tip. The heat generation is conducted into the cutting tool causing much higher level of stresses than the value obtain in case if machining steel. The higher value of heat generation represents severe plastic deformation at shear plane and severe contact conditions at the rake face of the tool resulting in higher cutting pressures, favoring material adherence. To the lower tested cutting speed of 700m/min, apart adherence of material and temperatures gradients, a distinct shape of chip was also observed (Figure 105).

Figure 106 – Chip obtained with v_c of 700 m/min and f of 0.05 mm/t using the $\text{Al}_2\text{O}_3\text{-MgO}$ ceramic cutting tools. a) Usual type and shape of observed chip (0.80x); b) Distinct shape and magnification (1.25x).

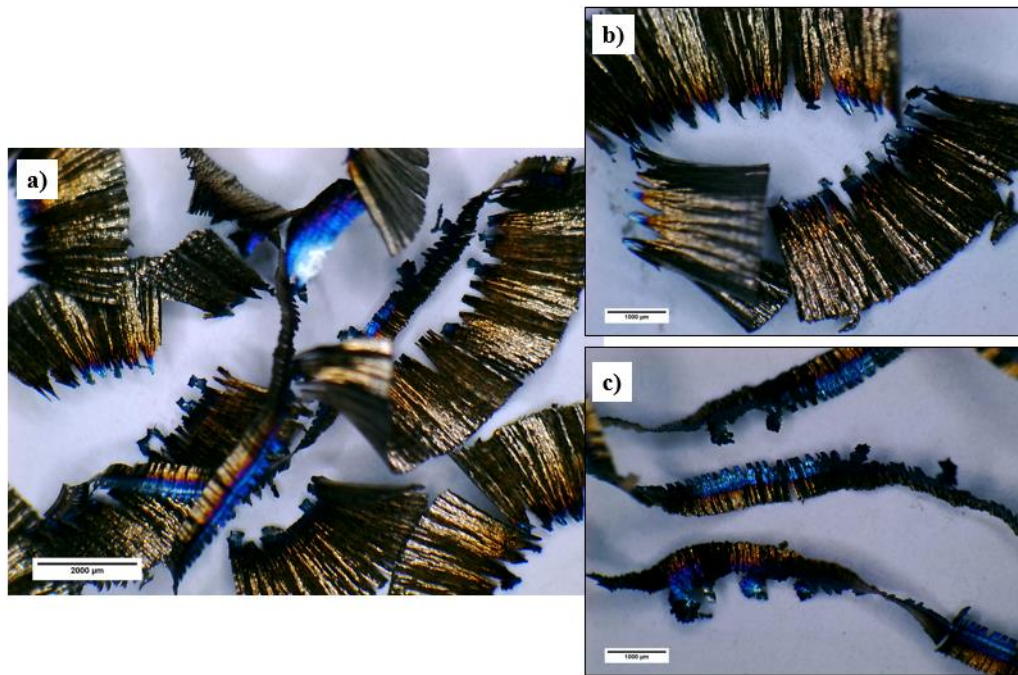


Source: Author

To the ceramic tools application, the condition that favored best chip formation was applying cutting speed of 900m/min combined to lower feed of 0.05 mm/t (Figure 106-a). To this condition was also observed lower amplitude of tool wear (V_b and V_b/L_c) and less vibration during machining, associated to small temperature gradient regions and less variation in shape. The usual chip type observed to this condition was the shear type with loose arc form. The shear chip are made of distinct lamellar portions partially welded, in Figure 103-b it is seen that the layers formed on the upside surfaces of the chip, which are

adjacent to each other, sometimes have overlap in dry milling, which is probably due to higher shearing rate during chip formation in this machining mode.

Figure 107 – a) Chips to v_c of 900 m/min and f of 0.05 mm/t. b) Usual type of observed chip (1.25x); b) Distinct shape (1.25x).



Source: Author

In conclusion, as regarding the chips formation analysis, is possible to affirm that the VAT 32[®] alloy showed a cutting parameter dependent change in the chip formation process to both application of carbide and ceramic tools. Higher dependence in form was verified to the feed parameter. During the process of milling it was observed the occurrence of only segmented chips to the carbide tools and shear chips to the ceramic tools. To the carbide tools best results in chip formation and considering good disposal can be achieved to lower feed and cutting speed (60 m/min; 0.10 mm/t) with small loose arc chips. To the ceramic cutting tools, the most advantageous chip, was formed with the application of higher cutting speeds with low feed (900 m/min; 0.05 mm/t). The shortest and preferable chips were produced while machining using the carbide tools. In any case, the feed needed for the formation of short breaking chips was always the lower applied. The influence of feed was expressive to both cutting tools applied.

5.5 SPECIFIC CUTTING PRESSURE ANALYSIS

The specific cutting pressure “ K_{sm} ” was calculated to all applied machining conditions to the TiAlN-TiN coated carbide and the Al_2O_3 -MgO ceramic tools. The results of power consumption, cutting force, mean chip thickness and cutting area were calculated to both repetitions of the DOE testing matrix, to the carbide tools (Table 22) and the ceramic tools (Table 24). The mean results to K_{sm} to both tools are displayed in Table 23 and 25.

Table 22 – K_{sm} to all tested machining conditions to the TiAlN-TiN coated carbide tools

1st repetition								
v_c	f_z	a_p	P_c	F_{cm}	h_m	b_m	A_m	K_{sm}
60	0.10	0.5	200.380	200.380	0.028	2.549	0.073	2762.17
60	0.15	0.5	220.062	220.062	0.043	2.549	0.109	2022.32
60	0.20	0.5	254.416	254.416	0.057	2.549	0.145	1753.21
80	0.10	0.5	276.841	207.631	0.028	2.549	0.073	2862.12
80	0.15	0.5	261.142	195.856	0.043	2.549	0.109	1799.87
80	0.20	0.5	251.552	188.664	0.057	2.549	0.145	1300.10
100	0.10	0.5	284.218	170.531	0.028	2.549	0.073	2350.71
100	0.15	0.5	309.258	185.555	0.043	2.549	0.109	1705.20
100	0.20	0.5	335.399	201.239	0.057	2.549	0.145	1386.76
2nd repetition								
v_c	f_z	a_p	P_c	F_{cm}	h_m	b_m	A_m	K_{sm}
60	0.10	0.5	199.004	199.004	0.028	2.549	0.073	2743.19
60	0.15	0.5	218.985	218.985	0.043	2.549	0.109	2012.42
60	0.20	0.5	249.784	249.784	0.057	2.549	0.145	1721.29
80	0.10	0.5	236.513	177.385	0.028	2.549	0.073	2445.18
80	0.15	0.5	261.142	195.856	0.043	2.549	0.109	1799.87
80	0.20	0.5	291.730	218.797	0.057	2.549	0.145	1507.76
100	0.10	0.5	302.797	181.678	0.028	2.549	0.073	2504.37
100	0.15	0.5	292.206	175.323	0.043	2.549	0.109	1611.18
100	0.20	0.5	336.400	201.840	0.057	2.549	0.145	1390.90

Source: Author.

Table 23 – Mean of the specific cutting pressure K_{sm} to the TiAlN-TiN coated carbide tools application

v_c	f	a_p	K_{sm}
60	0.10	0.5	2752.68
60	0.15	0.5	2017.37
60	0.20	0.5	1737.25
80	0.10	0.5	2653.65
80	0.15	0.5	1799.87
80	0.20	0.5	1403.93
100	0.10	0.5	2427.54
100	0.15	0.5	1658.19
100	0.20	0.5	1388.83

Source: Author.

Table 24 – K_{sm} to all tested machining conditions to the Al_2O_3 -MgO ceramic tools

1st repetition								
v_c	f_z	a_p	P_c	F_{cm}	h_m	b_m	A_m	K_{sm}
700	0.05	0.5	1161.650	99.570	0.018	2.549	0.045	2225.90
700	0.10	0.5	1523.600	130.594	0.035	2.549	0.089	1460.06
700	0.15	0.5	2152.450	184.496	0.053	2.549	0.134	1374.81
800	0.05	0.5	1803.665	135.275	0.018	2.549	0.045	3024.09
800	0.10	0.5	1803.650	135.274	0.035	2.549	0.089	1512.38
800	0.15	0.5	2195.600	164.670	0.053	2.549	0.134	1227.07
900	0.05	0.5	1546.000	103.067	0.018	2.549	0.045	2304.07
900	0.10	0.5	1921.600	128.107	0.035	2.549	0.089	1432.25
900	0.15	0.5	2577.450	171.830	0.053	2.549	0.134	1280.43
2nd repetition								
v_c	f_z	a_p	P_c	F_{cm}	h_m	b_m	A_m	K_{sm}
700	0.05	0.5	1036.300	88.826	0.018	2.549	0.045	1985.71
700	0.10	0.5	1563.650	134.027	0.035	2.549	0.089	1498.44
700	0.15	0.5	2010.800	172.354	0.053	2.549	0.134	1284.34
800	0.05	0.5	982.235	73.668	0.018	2.549	0.045	1646.85
800	0.10	0.5	1846.600	138.495	0.035	2.549	0.089	1548.39
800	0.15	0.5	2137.350	160.301	0.053	2.549	0.134	1194.52
900	0.05	0.5	1270.000	84.667	0.018	2.549	0.045	1892.74
900	0.10	0.5	2116.800	141.120	0.035	2.549	0.089	1577.74
900	0.15	0.5	2256.100	150.407	0.053	2.549	0.134	1120.79

Source: Author.

Table 25 – Mean of the specific cutting pressure K_{sm} to the Al_2O_3 -MgO ceramic tools

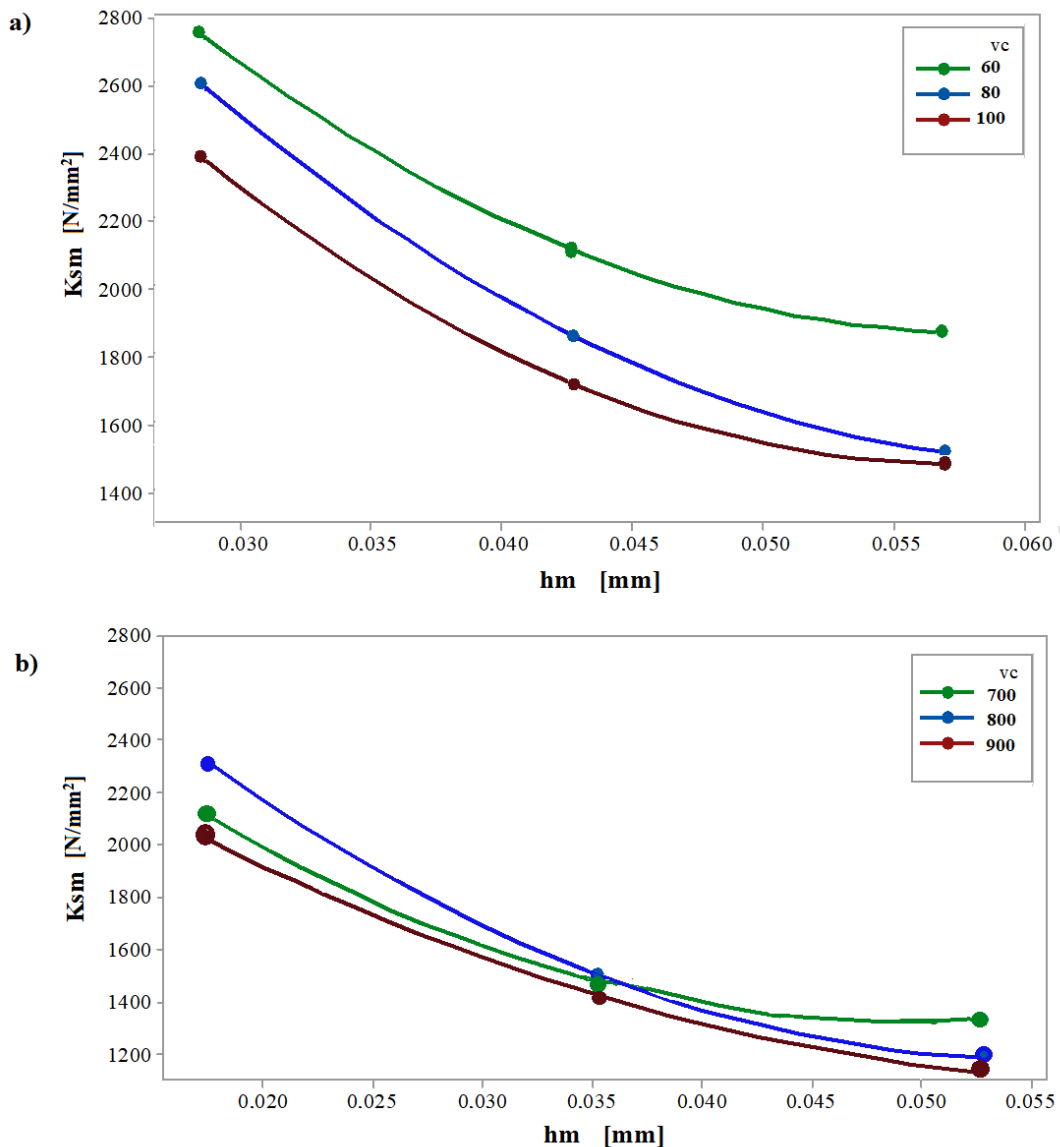
v_c	f	a_p	K_{sm}
700	0.05	0.5	2105.81
700	0.10	0.5	1479.25
700	0.15	0.5	1329.57
800	0.05	0.5	2335.47
800	0.10	0.5	1530.38
800	0.15	0.5	1210.80
900	0.05	0.5	2098.40
900	0.10	0.5	1504.99
900	0.15	0.5	1200.61

Source: Author.

With the calculated K_{sm} results it was possible to obtain the specific cutting pressure per mean chip thickness plot ($K_{sm} \times h_{sm}$) to both applied tools (Figure 107). It was possible to notice the cutting speed “ v_c ” high influence in the K_{sm} results, to both tools the lowest value of K_{sm} was found to the highest v_c applied. The specific cutting pressure usually decreases with the increase of the cutting speed (BATISTA; RODRIGUES; COELHO, 2017; RIGATTI, 2010) due to higher temperature generation in the tool-workpiece interface, allowing to ease the cut,

then reducing the necessary force to machine the material. The K_{sm} reduction behavior was stronger to the carbide tools application (Figure 107-a), with direct influence. The heat generated to the application of higher cutting speeds lead to consequent reduction of the material shear resistance, in addition to a slight reduction in the chip-tool contact area, favoring the tendency to reduce the specific cutting pressure.

Figure 108 – Specific cutting pressure K_{sm} per cutting thickness. a) TiAlN-TiN coated carbide tools application; b) Al_2O_3 -MgO ceramic tools application

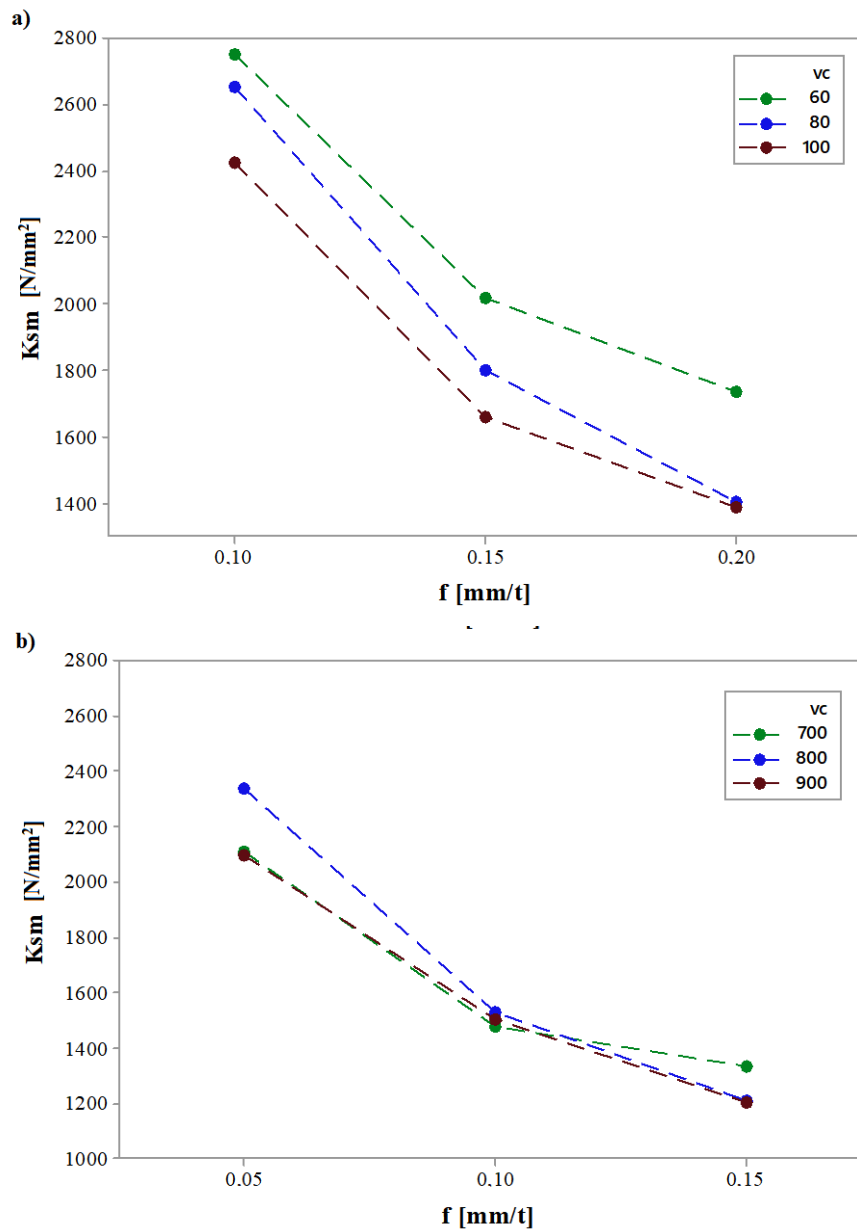


Source: Author.

The feed applied also presented high influence to the K_{sm} results (Figure 108), to the application of both carbide and ceramic tools. It was observed that with the increase on the feed, the mean cutting thickness was increased than leading to lower K_{sm} results. This can be

explained by the improvement to machine the material as the feed is increased. The increase in the feed also expand the cutting section area which is inversely proportional to the specific cutting pressure, leading to a significant reduction in K_{sm} .

Figure 109 – Feed influence to all cutting speed tested in the specific cutting pressure per cutting thickness. a) TiAlN-TiN coated carbide tools application; b) Al_2O_3 -MgO ceramic tools application.

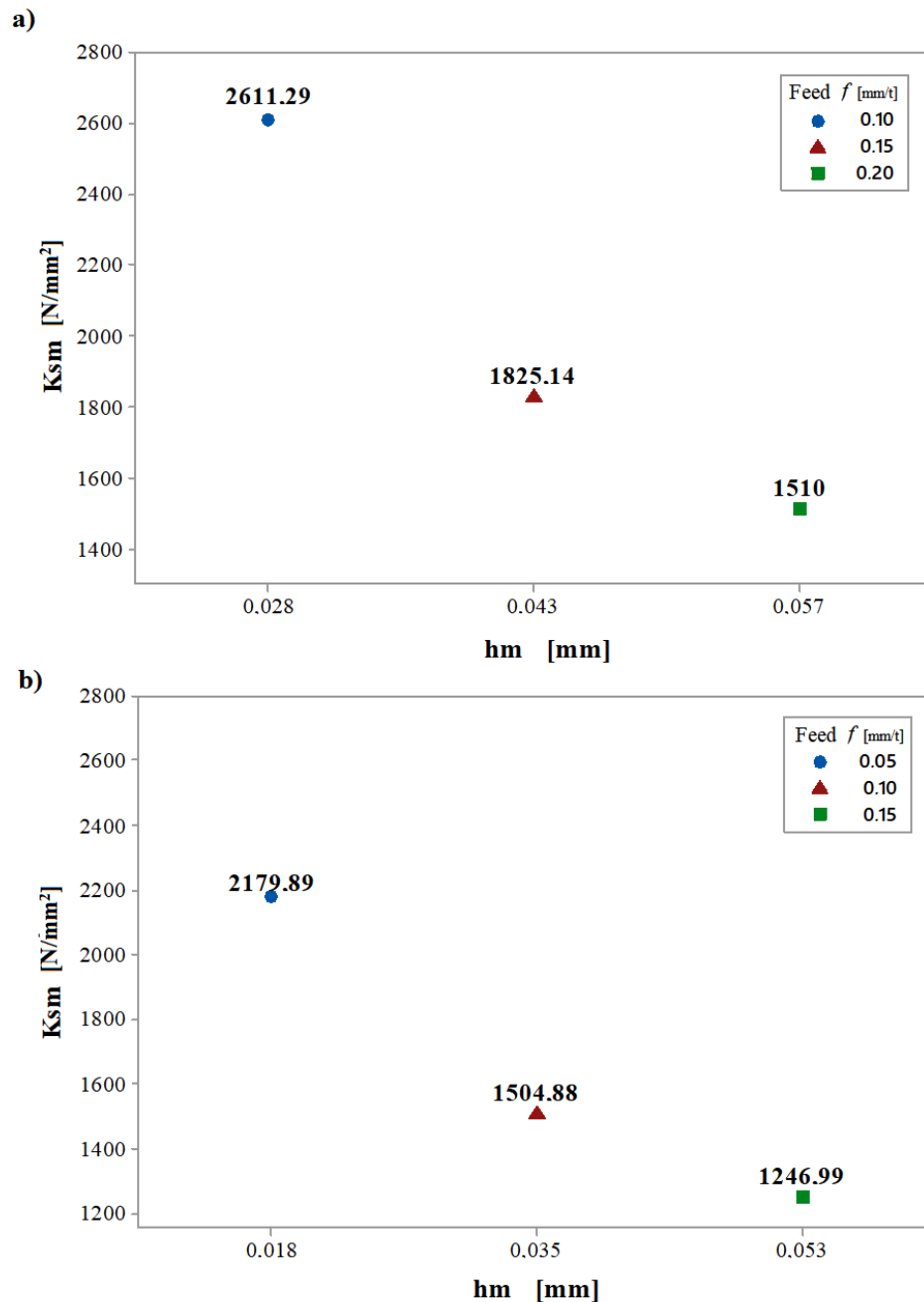


Source: Author.

If considered the average of resulting K_{sm} to all cutting speeds (Figure 109), it is possible to see that even to the maximum feed applied to the carbide tools ($f = 0.20$ mm/t) the

resultant K_{sm} (1510 N/mm²) was higher than to the maximum feed with the ceramic tool application resulting in a K_{sm} of 1246.9 N/mm² (Figure 109-b).

Figure 110 – Feed influence to the average K_{sm} (mean of v_c). a) TiAlN-TiN coated carbide tools application; b) Al₂O₃-MgO ceramic tools application.



Source: Author.

The observed results are in accordance with the literature that highlight the feed impact in the specific pressure. According to Diniz, Marcondes, and Coppini (2006), during the chip formation process, a portion of the removed material slides between the tool's flank face and

the workpiece, which generates the lateral chip flow. For lower feeds, the amount of material turned into chips is nearly similar to the generated by the lateral chip flow. In these cases, the force consumed by this phenomenon is relatively greater. When the feed increases, almost all the volume of material turns into chips, and the specific energy decreases (RIGATTI, 2010). The feed is more sensitive than the depth of cut or the cutting speed (NIEGULSKA-GRDZKA; NEJMAN; JEMIELNIAK, 2018).

Since the characteristics inherent to the cutting tools (material, coating, geometry) also add many influential variables to the specific cutting pressure, considering the comparison between the carbide and the ceramic application, it was observed that the overall mean K_{sm} result was lower to the ceramic tools application (1643.92 N/mm^2) than the carbide tools (1982.14 N/mm^2). The difference was significantly large, representing an increase of almost 20% in the value for the application of carbide tools. In literature, it is agreed that the K_s are lower for ceramic tools (RIGATTI, 2010), since the ceramic tools maintain high hot hardness and are inert (specially alumina-based tools), reducing diffusive wear that may occur to carbide inserts, that usually have more chemical affinity with the workpiece material causing to modify the cutting section area (ALAUDDIN, 1993; SILVA, 1994). Furthermore, the change of friction coefficient for the two different materials, also alters the difficulty in machining.

Finally, it is important to highlight that the results of specific cutting pressure " K_{sm} " obtained for both carbide and ceramic tools are in accordance to the average K_s found to similar materials, such as the Inconel 718, which presents a general K_s value around 2840 N/mm^2 , varying from 3580 (finishing machining) to 2760 (rough machining).

Nevertheless, the K_{sm} results to both cutting tools verify the low variability for the cutting power data used in calculation (Maximum power consumption), since the variation tendency followed the usual trends found in literature (i.e. decrease to high feeds or cutting speeds).

5.6 SUMMARY OF MAIN RESULTS

In this section, the main results summary is presented considering all statistical analysis of power consumption, vibration, acoustic emission, roughness, flank wear per cutting length and wear mechanisms to both commercial carbide (Table 26) and experimental ceramic (Table 27) cutting tools.

Table 26 – Main results to TiAlN-TiN coated carbide tools

(continue)

Power Consumption		
Results	Cutting speed - v_c (m/min)	Feed - f (mm/tooth)
Data normality	Yes (P-value = 0.896)	
ANOVA (P-value)	0.000	0.002
ANOVA (F-value)	52.22	9.93
Factors contribution	76.06%	14.47%
R-sq		90.53%
Data mean (W)		265.65
Best condition	60	0.10 – 0.15
Worst condition	100	0.20
2nd order interaction	No	
Vibration		
Data normality	Yes (P-value = 0.231)	
ANOVA (P-value)	0.145	0.148
ANOVA (F-value)	2.25	2.22
Factors contribution	20.48%	20.25%
R-sq		40.74%
Data mean (mm/s)		10.38
Best condition	80	0.2
Worst condition	60	0.10
2nd order interaction	Yes	
Acoustic Emission		
Data normality	Yes (P-value = 0.425)	
ANOVA (P-value)	0.732	0.203
ANOVA (F-value)	0.32	1.80
Factors contribution	3.70%	20.92%
R-sq		24.62%
Data mean		0.226
Best condition	100	0.20
Worst condition	80-60	0.15
2nd order interaction	Yes	
Roughness R_a		
Data normality	Yes (P-value = 0.133)	
ANOVA (P-value)	0.618	0.028
ANOVA (F-value)	0.50	4.77
Factors contribution	4.24%	40.51%
R-sq		44.75%
Data mean (μm)		0.608
Best condition	100-80	0.10
Worst condition	60	0.20
2nd order interaction	Yes	
Roughness R_z		
Data normality	Yes (P-value = 0.505)	
ANOVA (P-value)	0.450	0.047
ANOVA (F-value)	0.85	3.91
Factors contribution	7.55%	34.71%
R-sq		42.26%
Data mean (μm)		3.189
Best condition	80-100	0.10
Worst condition	60	0.20
2nd order interaction	Yes	
Roughness R_t		
Data normality	Yes (P-value = 0.728)	
ANOVA (P-value)	0.104	0.602
ANOVA (F-value)	2.70	0.53

Table 27 – Main results to TiAlN-TiN coated carbide tools

(conclusion)

<i>Factors contribution</i>	27.79%		5.43%
<i>R-sq</i>		33.21%	
<i>Data mean (μm)</i>		4.115	
<i>Best condition</i>	100-80		0.15
<i>Worst condition</i>	60		0.10 and 0.20
<i>2nd order iteration</i>		Yes	
$V_b \cdot 1000/L_c$			
<i>Data normality</i>		Yes (P-value = 0.362)	
<i>ANOVA (P-value)</i>	0.024		0.000
<i>ANOVA (F-value)</i>	5.04		137.32
<i>Factors contribution</i>	3.39%		92%
<i>R-sq</i>		95.63%	
<i>Data mean (V_b)</i>		0.125	
<i>Data mean ($V_b \cdot 1000/L_c$)</i>		0.010	
<i>Best condition</i>	60		0.10
<i>Worst condition</i>	80-100		0.20
<i>2nd order iteration</i>		Yes (only to 80-100 v_c)	

Source: Author.

Table 28 – Main results to Al_2O_3 -MgO ceramic tools

(continue)

Power Consumption			
Results	Cutting speed - v_c (m/min)		Feed - f (mm/tooth)
<i>Data normality</i>		Yes (P-value = 0.498)	
<i>ANOVA (P-value)</i>	0.021		0.000
<i>ANOVA (F-value)</i>	5.31		32.12
<i>Factors contribution</i>	12.02%		73.11%
<i>R-sq</i>		85.21%	
<i>Data mean (W)</i>		1746.9	
<i>Best condition</i>	700		0.05
<i>Worst condition</i>	900		0.15
<i>2nd order iteration</i>		Yes	
Vibration			
<i>Data normality</i>		Yes (P-value = 0.212)	
<i>ANOVA (P-value)</i>	0.007		0.049
<i>ANOVA (F-value)</i>	7.60		3.83
<i>Factors contribution</i>	42.39%		21.38%
<i>R-sq</i>		63.76%	
<i>Data mean (mm/s)</i>		10.20	
<i>Best condition</i>	900		0.15
<i>Worst condition</i>	700		0.05
<i>2nd order iteration</i>		Yes (only to 700 and 800 v_c)	
Acoustic Emission			
<i>Data normality</i>		Yes (P-value = 0.529)	
<i>ANOVA (P-value)</i>	0.945		0.025
<i>ANOVA (F-value)</i>	0.06		4.94
<i>Factors contribution</i>	0.49%		42.99%
<i>R-sq</i>		43.48%	
<i>Data mean</i>		0.22	
<i>Best condition</i>	800 and 900		0.10
<i>Worst condition</i>	700		0.05
<i>2nd order iteration</i>		Yes	

Table 29 – Main results to Al₂O₃-MgO ceramic tools

(conclusion)

Roughness R_a			
Data normality	Yes (P-value = 0.641)		
ANOVA (P-value)	0.004		0.417
ANOVA (F-value)	8.47		0.94
Factors contribution	53.23%		5.89%
R-sq		59.13%	
Data mean (μm)		0.754	
Best condition	800		0.05
Worst condition	700		0.15
2nd order interaction	Yes (only to 700 and 900 v_c)		
Roughness R_z			
Data normality	Yes (P-value = 0.513)		
ANOVA (P-value)	0.001		0.838
ANOVA (F-value)	12.57		0.18
Factors contribution	65.30%		0.93%
R-sq		66.23%	
Data mean (μm)		4.094	
Best condition	800		0.10
Worst condition	700		0.15
2nd order interaction	Yes (only to 700 and 900 v_c)		
Roughness R_t			
Data normality	Yes (P-value = 0.930)		
ANOVA (P-value)	0.005		0.630
ANOVA (F-value)	7.98		0.48
Factors contribution	53.34%		3.20%
R-sq		56.55%	
Data mean (μm)		5.614	
Best condition	800		0.05
Worst condition	700 and 900		0.15
2nd order interaction	Yes (only to 700 and 900 v_c)		
$V_b \cdot 1000 / L_c$			
Data normality	Yes (P-value = 0.359)		
ANOVA (P-value)	0.884		0.000
ANOVA (F-value)	0.12		19.70
Factors contribution	0.43%		74.83%
R-sq		75.31%	
Data mean (V_b)		0.33	
Data mean ($V_b \cdot 1000 / L_c$)		0.015	
Best condition	900		0.05
Worst condition	800		0.15
2nd order interaction	Yes		

Source: Author.

6 CONCLUSION

The conclusions obtained with the machinability analysis of the VAT 32[®] superalloy based on the analysis of the input and output variables of the milling machining process are:

- It was possible to successfully accomplish the machining of the VAT 32[®] superalloy within standard surface quality ranges considering the milling process, proving the alloy's machinability by milling with the application of the studied cutting tools.
- Even with the literature reporting the poor machinability of nickel superalloys due to the short life of the cutting tool and the severe surface damage of the machined workpiece, it was possible to verify through wear and surface quality analysis that low levels of flank wear and specific wear have been achieved, to both ceramic and carbide tools, in association with good surface quality within standard rate.
- The presence of high hardened carbides and the property of poor heat dissipation of the material were found as the main causes that led to the increase of wear in both cutting tools during the machining of the VAT 32[®] superalloy.
- It was possible to observe that the high temperatures achieved during the machining limited the cutting speed for both ceramic and carbide tools.
- The application of dry-machining as a method to carry the milling with the ceramic tools was proven to be a viable option to machine the VAT 32[®] superalloy.
- The statistical analysis applied (ANOVA) was considered effective to study the machinability response of the VAT 32[®] superalloy during the process, allowing the analysis of roughness, vibration, acoustic emission and power consumption. It was possible to identify the factors that influenced the process, in addition to find the best factor's levels and conditions of machining.
- Excellent roughness results were found for machining with the carbide tools and good roughness results to the application of the ceramic tools proving the applicability of both tools and the good machinability of the alloy in specific conditions.
- The best condition applied to machine the VAT 32[®] superalloy using the commercial was with cutting speed of $v_c = 60$ m/min and feed of $f = 0.10$ mm/t. Being the feed the most critical factor.
- The best condition applied to machine the VAT 32[®] superalloy using the experimental inserts was with cutting speed of $v_c = 900$ m/min and feed of $f = 0.05$ mm/t.

- The results of specific cutting pressure found to both carbide and ceramic tools are similar to other nickel based superalloys consulted in literature, verifying the feasibility to machine the VAT 32[®] by milling.

The conclusions obtained with the investigation of the experimental inserts composition of 99.75% Al₂O₃ and 0.25% MgO to be applied as cutting tool material are:

- The use of 0.25% MgO by weight as a sintering additive to the alumina was effective to promote densification, reducing porosity and allowing good performance of low flank wear per cutting length.
- The experimental composition assured high chemical stability during the machining making possible to apply high cutting speeds to machine the VAT 32[®] and increase the material removal rate.
- The experimental composition associated with the round geometry assured stability of the cutting tool even at high cutting speeds, presenting good vibration results to the application of $v_c = 900$ m/min.
- The surface quality results observed after the machining assured that the tested composition is suitable to be applied as cutting tool presenting the necessary mechanical properties to machine the alloy.

The conclusions obtained with the investigation of the application feasibility of the Al₂O₃-MgO ceramic experimental inserts in comparison to the TiAlN-TiN coated carbide commercial inserts are:

- The average of wear per cutting length for the ceramic cutting tools was very similar to the carbide tools, assuring the applicability of the experimental ceramic tools.
- The ceramic inserts, even without chip breakers (simple geometry), presented good roughness results similar to the carbide application. The ceramic inserts also allowed the formation of segmented chips that are recommend due to easy handling and disposal.
- The analysis of variance applied to the machining with the ceramic tools presented more statistical significance of factors for the outputs of the process than the carbide tools, assuring more reliability of the data analysis and possibility to study tendency of results.

- The proven high significance of the cutting parameters to the roughness results considering the machining using the ceramic tools allows the precision of surface quality analysis and assures the affirmation of the experimental tools applicability.
- The application of round geometry inserts provided high tool stability, with low vibration values, good productivity, providing good surface quality (considering the studied process).
- Regarding the feed for the ceramic tools the lowest feed of $f = 0.05\text{mm/t}$ allowed the obtaining low wear and good roughness results. The highest feed of $f = 0.15\text{ mm/t}$ led to higher values of wear and roughness found, as well as greater power consumed, even with lower values of vibration and emission to this condition.
- Regarding the speed for the ceramic tools, the highest applied cutting speed of 900 m/min made possible to achieve better values of roughness and wear, associated with lower vibrations, and acoustic emission results. The only response that was negatively affected by the use of the 900m/min speed was the power consumption, which indicated greater energy consumption in this condition.
- The lower specific cutting pressure obtained to the ceramic tools (1643.92 N/mm^2) in comparison to the carbide tools application (1982.14 N/mm^2) indicated the accordance with the machining parameters range designated to use the $\text{Al}_2\text{O}_3\text{-MgO}$ composition to machine de VAT 32[®] superalloy and favors its use by proving the material's lower resistance to cutting during the process.

7 RECOMMENDATIONS FOR FUTURE RESEARCH DIRECTIONS

Progress have been made to improve the knowledge of the VAT 32[®] superalloy machinability response during the milling process. The results of this research work also provided contribution to validate the application of the Al₂O₃-MgO composition as material for alumina-based ceramic cutting tools. However, there are many points for future research directions to improve the main findings and address to the research area.

As regarding the directions to build upon the work main findings, the in-deep investigation of following items is suggested:

- *Mapping of the cutting tool surface*: To evaluate the tool's edge to all cutting conditions by analyzing SEM images of main types of wear and applying the analysis Energy-dispersive X-ray spectroscopy (EDS) to analyze inclusions of the machined material, identification of present elements and concentration, specially to favorable built-up edge conditions.
- *Tool wear and life analysis*: To determine the experimental and commercial inserts life within the parameters that lead to the best roughness and wear results, according the ISO 8688-1:2016 standard. It is recommended to consider the end-of-life criteria of mean flank wear (V_b) of 0.3 mm and maximum flank wear of 0.6 mm, or the presence of catastrophic damage (edge breakage or chipping).
- *Morphology study of chips*: To characterize the mechanism of chips formation by SEM images, identification of shear bands to segmented chips, identification of correlation between the formation of shear bands in the generated chips.
- *Morphology study of machined surfaces*: To analyze the surfaces of the machined specimens by SEM and OM images, with the application of different tools, to investigate the presence of surface voids, feed marks, rough and smooth surface portions on the machined surfaces that may improve chip morphology explanation.
- *Address the machinability analysis*: To improve the specific cutting pressure analysis, by the determination of the Kienzle coefficients (K_{s1} and $1-z$).
- *Optimization analysis*: To confirm the combination of input variable settings that optimize the process response variables and estimate out-of-range parameters by applying detailed analysis of the resulting residuals, analysis of regression equations, multiple-comparison tests, and run confirmation trials to best observed conditions.

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