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EFFECT OF MACHINING PARAMETERS ON CHIP FORMATION IN DRY-MILLING OF THE NICKEL-BASED SUPERALLOY VAT 32®

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Abstract. *The purpose of this research was to study the machinability of the recent developed nickel-based VAT 32® superalloy through the investigation of chip formation during the dry-milling using TiAlN-TiN coated carbide inserts. The cutting parameters considered in this study were the cutting speed, feed, and depth-of-cut. A full factorial design was applied as DOE to machining tests. The determination of optimal parameters was done by the analysis and characterization of the generated chip's mechanism of formation, type and shape according the ISO ABNT NBR 3685:2017 standard. The optimal condition to assure best segmented chip formation was found to* v_c *= 60 m/min, f = 0.10 mm/t and* a_p *= 0.50 mm, with lower results of flank wear and roughness (*V_b*=0.12 mm and* R_a*=0.43 µm). The tests proven the feasibility of milling the VAT 32® by assuring standard segmented chip formation associated with flank wear and mean roughness results within usual range to the milling.*

Keywords: *Chip formation, Milling, Superalloy, dry machining, Carbide tools, TiAlN-TiN.*

1. INTRODUCTION

Superalloys are 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 remarkable properties allow its applications in 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). However, the superalloy's manufacturing industry is facing serious challenges to incorporate the required modifications caused by the market's environmental standards (FARINA et al, 2013).

In order to attend to a more restrict serie 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. Table 1 presents the nominal chemical composition of the VAT 32® superalloy.

Table 1. Nominal chemical composition of the VAT 32® superalloy (FARINA et al, 2013)

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

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 super alloys, as pointed out by Davoodi and Eskandari (2015) and Molaiekiya, Aramesh and Veldhuis (2020).

The chip formation has influence on several factors related to machining, specially to the surface integrity, but also to tool wear, cutting efforts and heat produced during machining (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. Greater understanding of the influencing factors (e.g. cutting conditions; tool and work material; chip former design.) and their interactions is essential to achieve efficient chip breaking and hence chip control.

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).

In this work, 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 shape. 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). Since the chip formation influences several factors related to machining, the 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. Furthermore, the chip analysis allows a better understanding to the materials behavior during the milling process.

2. METHODOLOGY

2.1 Cutting tools

The applied inserts are composed of a body of cemented carbide and a wear-resistant coating with two layers. Figure 1-a presents the commercial inserts dimensions. The coating is composed of titanium aluminum nitride (Ti,Al)N layer followed by a second titanium nitride (TiN) layer (Figure 1-b). Both layers were deposed 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. The inserts code-key is RNMG120400-MR4, following the ISO 1832:2012 standard for the designation of indexable inserts for cutting tools. 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.

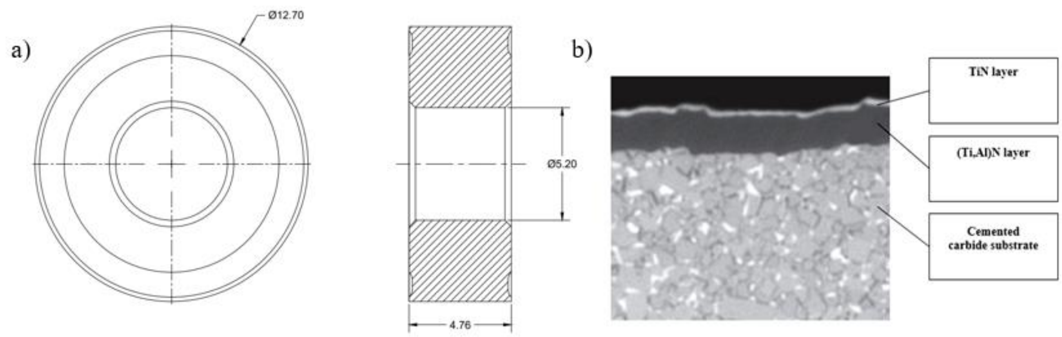


Figure 1. Coated carbide inserts specifications. a) Dimensions; b) Coating layers (Adapted from SECO, 2020).

2.2 Test specimen and equipments

To perform the machining tests, the VAT 32® superalloy specimen (workpiece) dimension was 59x85x30 mm (Figure 2). 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.

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.

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 coated carbide tools application. Then, the definitive testing phase was executed with selected parameters. The milling tests were conducted without any application of cutting fluids.

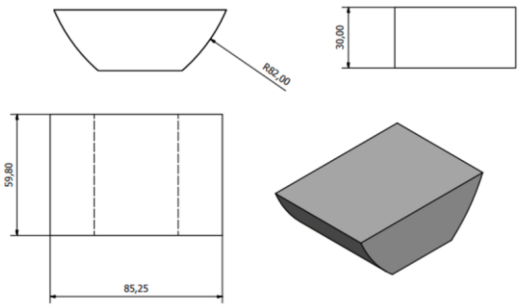


Figure 2. Machining test specimen.

2.3 Testing methodology and data analysis

The experimental design applied to the machining experiments was a 3-levels full factorial design (FFD), with 2 factors. The first factor, is the applied cutting speed (v_c) with three levels (60; 80 and 100 m/min). The second factor is the feed (f) again with three levels (0.1; 0.15 and 0.20 mm/t). The depth of cut was maintained constant in 0.5 mm to both cutting tools. 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, summarizing 18 experiments. During the tests, each experiment consisted in two passes throughout the test specimen characterizing the process as face concordant asymmetric milling.

Table 2. Machining Parameters.

Factors	**Level 1**	**Level 2**	**Level 3**
Cutting Speed [m/min]	60	80	100
Feed [mm/t]	0.10	0.15	0.20
Depth of cut [mm]	0.50	-	-

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).

3. RESULTS AND DISCUSSION

The resulting chips to the application of the Ti,AlN-TiN coated carbide inserts, can be classified as segmented type with a loose arc form (shape). A small variation in the chip's shape was observed with the rise of cutting parameters amplitude, however, the observed type was the same to all conditions. 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.

In Figure 3, 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.

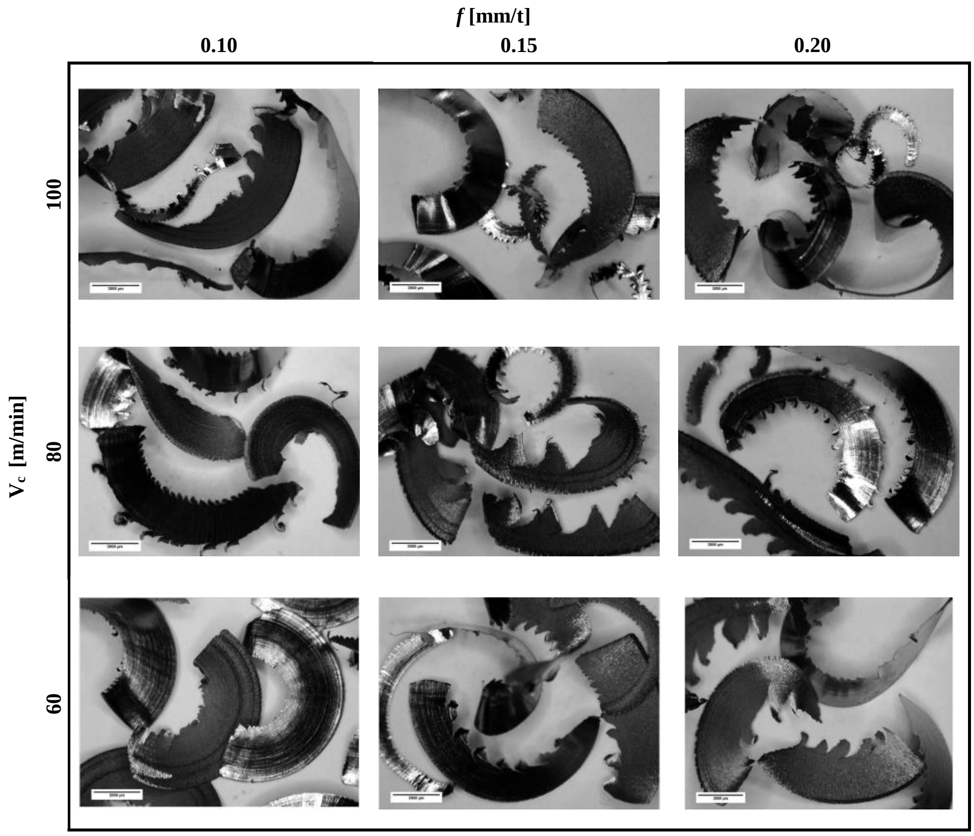
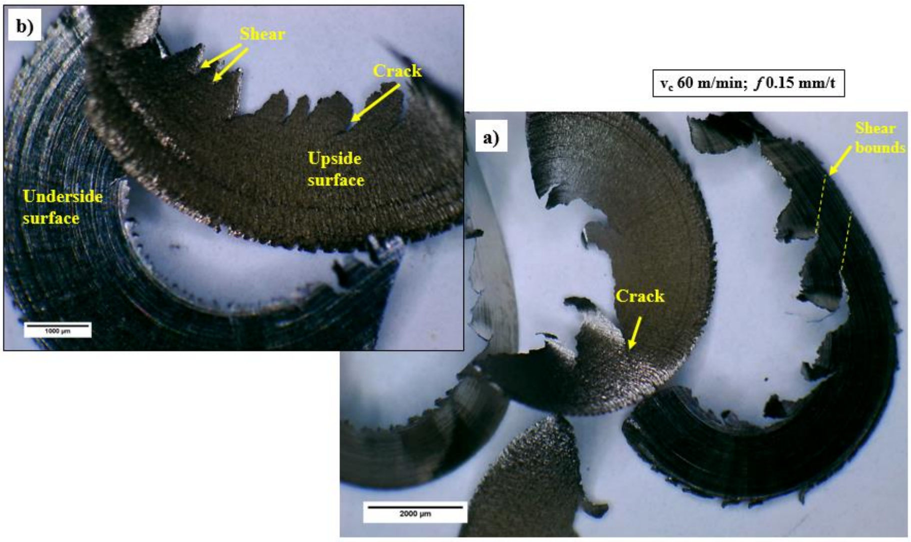


Figure 3. Chip morphology under different cutting parameters to the application of the TiAlN-TiN coated carbide cutting tools (Magnification 0.80x).

The segmented (or serrated) chip, observed to all tested conditions, is characterized by the discontinuous formation with still existence of connected elements after the end of the cut. 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 4). 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).



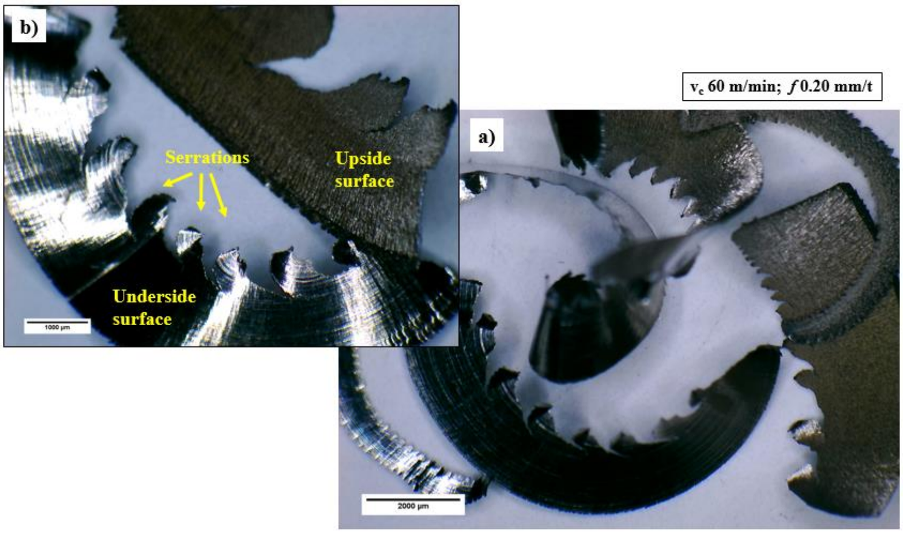


Figure 4. Segmented chip with serrated type a) Usual type of observed chip (0.80x); b) Magnification (1.25x).

It has been reported that for nickel alloys segmented chips are formed at all levels of cutting speed (PERVAIZ et al., 2014) (Figure 5). 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). 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.

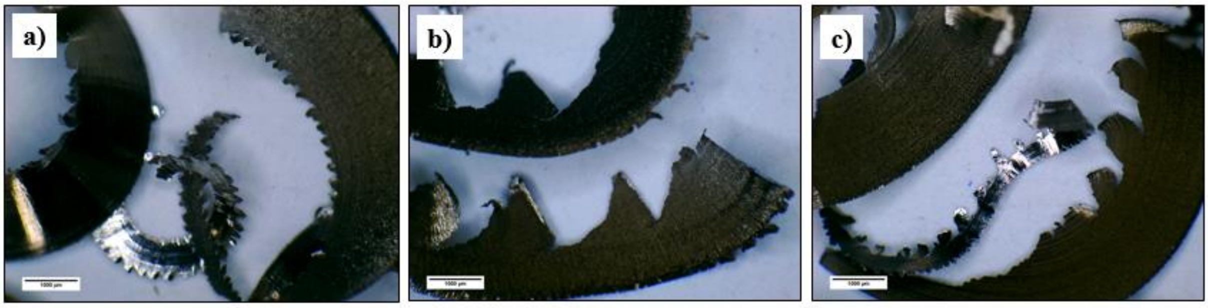


Figure 5 – Segmented chips with serrated type obtained to all cutting speeds. a) v_c 60 m/min; b) v_c 80 m/min; c) v_c 100 m/min.

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 6), 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.

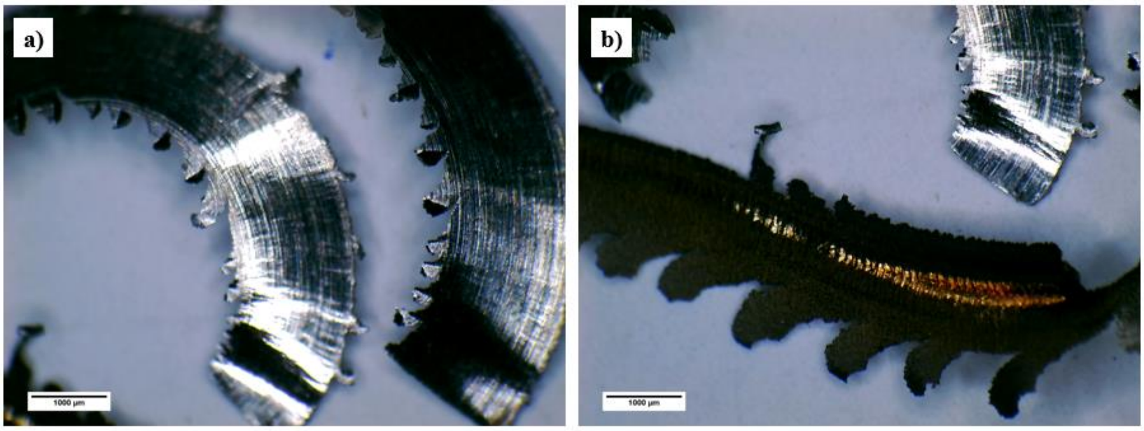


Figure 61 – Chips produced to v_c of 80/min and *f* of 0.20mm/t. a) Underside surface of usual type of chip (1.25x); b) Change of color in upside region (1.25x).

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 7).

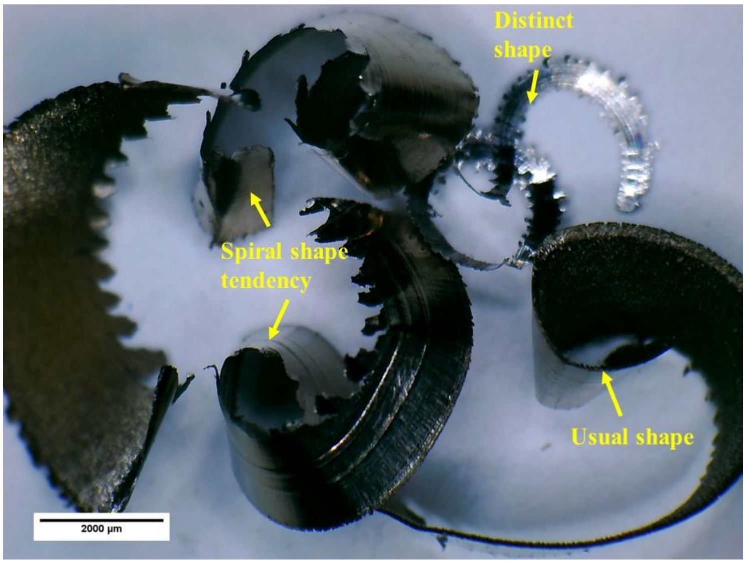


Figure 7 – Usual and distinct type of observed chip to v_c100 m/min and *f* 0.20 mm/t (0.80x).

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 8). 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.

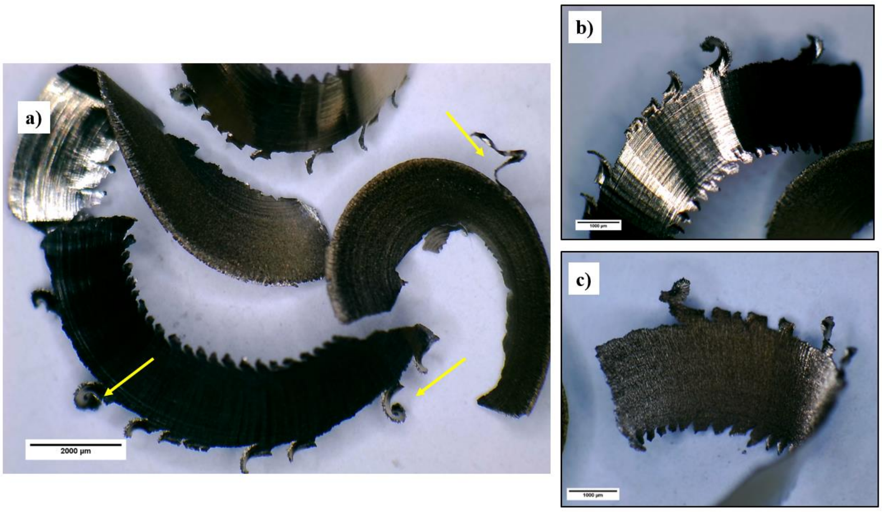


Figure 8 – Chip to v_c of 80 m/min and *f* of 0.10 mm/t. a) Usual type of observed chip and adhesions (0.80x); b) Chip's underside surface (1.25x); c) Chip's upside surface (1.25x).

It was observed 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 9). 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 of 0.12 mm (flank wear).

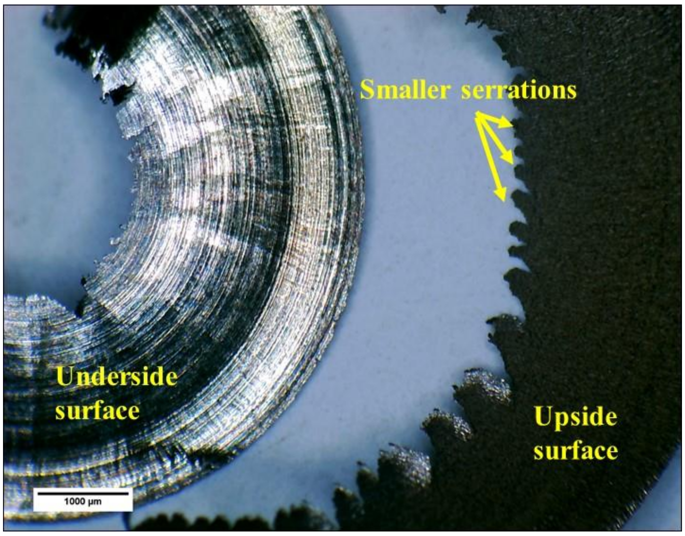


Figure 9 – Usual type of observed chip to v_c of 60 m/min and *f* of 0.10 mm/t (1.25x).

4. CONCLUSION

To the coated carbide inserts application, the condition of cutting speed of 60m/min and feed 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. The obtained segmented chip is convenient to collect, handle and disposal. Since the chips break up into small segments the friction between the tool and the chips reduces, resulting in better surface quality. 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 of 0.12 mm. The feasibility to machine the VAT 32® superalloy with TiAlN-TiN coated carbide inserts was proven due to the lower flank wear obtained with association to the formation of segmented chips.

5. ACKNOWLEDGEMENTS

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