MACHINING OF INCONEL® 751 WITH CERAMIC TOOLS

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Abstract. *The aim of this work is to study the tool wear (types and mechanisms) that predominates in ceramic tools after turning nickel base superalloy - Inconel® 751 in tool life tests. DOE techniques was used with the following input variables: tool materials [Sialon (Al_2O_3 + Si_3N_4), Whisker (Al_2O_3 + SiC) and Mixed (Al_2O_3 + TiC)], cutting speed, tool geometry and lubri-cooling atmosphere (dry, argon rich and oxygen rich). In each machining test a new tool edge was used up to the end of the tool life with interruptions for wear measurements. At the end of these tests the tools were analyzed with the help of an optical and a scanning electron microscopy. The results showed that the cutting speed, the tool geometry and the lubri-cooling atmospheres have influenced the types of wear and tool life. Notch wear (VB_N), average flank wear (VB_B) and nose wear (VB_C) prevailed depending upon the cutting conditions and tool material used. Overall Sialon tools showed the best performance, followed by the Mixed and the Whisker ceramics. The lowest tool life was found in dry condition and notch wear was accelerated by oxygen rich atmosphere, particularly at low cutting speeds. Attrition, abrasion and diffusion were the dominant wear mechanisms found.*

Keywords*: base superalloy, machining of nickel alloy, tool wear; tool life*

1. INTRODUCTION

The nickel alloys, also known as superalloys are used in the manufacture of mechanical components in the aerospace and automotive industries, due to their high mechanical strength at high temperatures, high creep resistance and fatigue strength and excellent corrosion resistance. Its field of application includes components working at temperatures above 500 °C, such as blades, discs and turbine components and elements of exhaust system of engines (Machado *et al.*, 2009; ASM Handbook Vol. 2, 1990). Currently, nickel alloy 751 is widely used for making the exhaust valves of diesel engines (Special Metals, 2004).

The superalloys are known as low machinability materials due to several factors, including (Ezugwu *et al.*, 1999): (i) a major part of their strength is maintained during machining due to their high temperature properties; (ii) work hardening occurs rapidly during machining, which is a major factor contributing to notch wear at the tool nose and/or depth of cut line; (iii) cutting tools suffer from high abrasive wear owing to the presence of hard abrasive carbides in the superalloy; (iv) chemical reaction occurs at high cutting temperatures when machining with commercially available cutting tool materials, leading to a high diffusion wear rate; (v) welding/adhesion of nickel alloys onto the cutting tool frequently occur during machining, causing severe notching as well as spalling on the tool rake face due to consequent pull-out of the tool materials; (vi) production of a tough and continuous chip, which is difficult to control during machining, thereby contributing to the degradation of the cutting tool by seizure and cratering; and (vii) the poor thermal diffusivity of nickel-based alloys often generates high temperature at the tool tip as well as high thermal gradients in the cutting tool.

Several tools were used over time for machining the nickel-based alloys, such as cemented carbide, ceramic coated and uncoated - pure or mixed, and the ultrahard tools. Although currently cutting tools incorporate advanced technologies in its design, the problems historically encountered in machining of superalloys persist. Breakdown phenomena such as cracking, spalling and chipping can be observed more frequently in interrupted cuts, such as in milling. But the wear occurs in both continuous cutting processes, as is the case of turning, and in interrupted cuts, when major damages are prevented. The main forms of wear on a cutting tool are: crater wear, flank wear and notch wear (Machado *et al.*, 2009; Ezugwu *et al.*, 1999; Childs *et al.*, 2001). The flank wear and the notch wear are the main causes of rejection of the cutting tools in continuous cutting operations and, although the interaction of the mechanisms is complex, there may be development of diffusion wear, abrasion, adhesion, and others (Ezugwu *et al.*, 1999; Costes *et al.*, 2007).

In the present work a study on the wear mechanisms when using three types of ceramic tools under two different atmospheres is conducted when turning Inconel 751superalloy.

2. EXPERIMENTAL PROCEDURES

Two types of toolholders with different cutting geometries – Tab. 1 (Kennametal, 2008), three types of ceramic inserts [SiAlON (Si_3N_4 + Al_2O_3), Whisker (Al_2O_3 + SiC) and Mixed (Al_2O_3 + TiC) – ISO SNGN 120716] (Kennametal, 2006; Kennametal, 2007) and three types of lubri-cooling atmospheres (dry, argon rich and oxygen rich) were used in the present investigation. The cutting speeds selected for the experiments were 150 m/min and 300 m/min while depth of cut, feed rate and tool nose radius were kept constant in 2.0 and 0.2 mm/rev and 1.2 mm, respectively.

Table 1. Cutting geometries of the tools

Angles	Cutting geometries	
	CG1 (ISO CSSNR 2525 M12)	CG2 (ISO CSXNR 2525 M12)
χ_R	45°	85°
χ'_R	45°	5°
α_o	8°	6°
β_o	90°	90°
γ_o	-8°	-6°
ϵ_r	90°	90°
λ_s	0°	-6°

The Ni alloy tested showed approximately 30 HRc of hardness and the following chemical composition (wt%) (Villares Metals, 2008): Ni 71.12%, 16.70% Cr, Fe 6.97%, 2.34% Ti; Al 1.33%, 0.88% Nb, Mn 0.27% Si 0.13%, Mo 0.08% C 0.06%, Cu 0.04% Co 0.04%, W 0 , 02%, V 0.01%, S 0.001%, P 0.001%. They were used in cylindrical bars with the dimensions of ∅ 105 x 250 mm.

The turning tests were carried out on a CNC lathe - Romi Multiplic 35D model, belonging to the Machining Research Laboratory – LEPU of the Federal University of Uberlandia – UFU – Brazil. Measurements of wear were done by optical microscopy using a stereomicroscope Olympus model SZ6145TR with digital camera and Image-Pro Express 5.1 software. A scanning electron microscopy – SEM Zeiss EVO 40 model was used for tool wear mechanisms analysis. Figure 1 shows the set up of the system ready for a test.

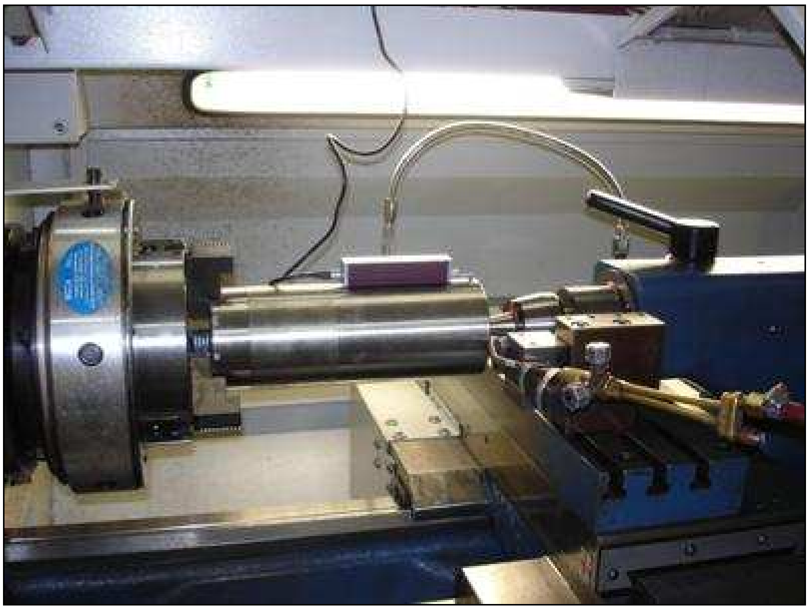

Figure 1. Experimental set up

A 2^3 factorial design (Montgomery, 2001) was used whose levels of the input variables (cutting speed, tool geometry and atmosphere) are summarized in Fig. 2. Since the variable 'atmosphere' has three levels, they were analysed in pairs (three times) to fulfill the DOE requirements. In order to investigate the effects of the input variables on the tool lives statistical analysis was performed using Statistica 7.0 and Microsoft Excel 2010 softwares.

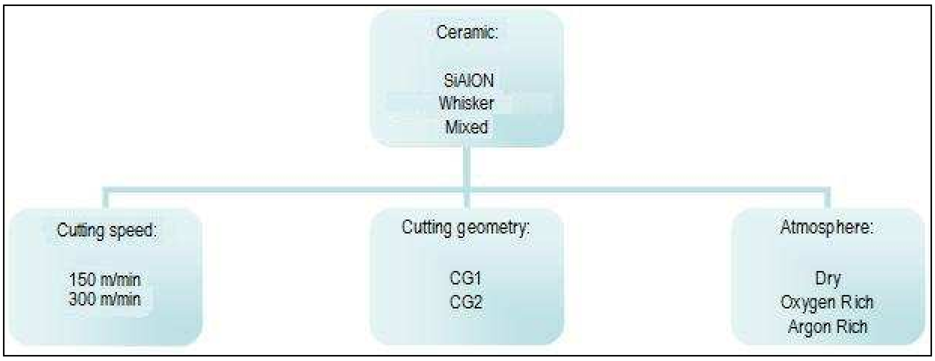

Figure 2. Scheme of tests with the ceramic inserts

The end of tool life criteria adopted in the tests are shown in Tab.2.

Table 2. End of tool life criteria used in the tests (ISO 3685, 2000)

Type of wear	Maximum value (mm)
Notch wear (VB_N)	1.00
Average flank wear (VB_B)	0.40
Max. flank wear (VB_{Bmax})	0.60
Nose wear (VB_C)	0.60

3. RESULTS AND DISCUSSION

3.1. Considerations on the wear

The SiAlON (Si_3N_4 + Al_2O_3) tools showed the best performance among all the inserts, followed by the Mixed (Al_2O_3 + TiC) and the Whisker (Al_2O_3 + SiC) ceramics. The lowest tool life was found in dry condition and notch wear was accelerated by oxygen rich atmosphere, particularly at low cutting speeds.

During the tests three types of wear were detected on the ceramic tool used. They are identified as follows.

- SiAlON (Si_3N_4 + Al_2O_3) → Average flank wear (VB_B) – Fig. 3;
- Mixed (Al_2O_3 + TiC) → Notch wear (VB_N) and nose wear (VB_C) - Fig. 4;
- Whisker (Al_2O_3 + SiC) → Notch wear (VB_N) - Fig. 5.

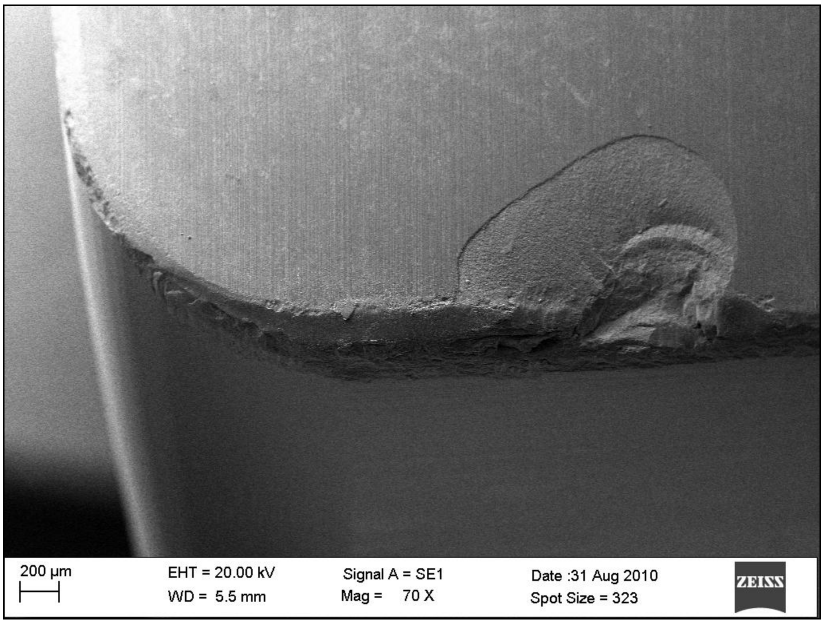

Figure 3. Average flank wear (VB_B) on SiAlON (Si_3N_4 + Al_2O_3) ceramic, after 60s. A large chipped area is also seen on the rake face

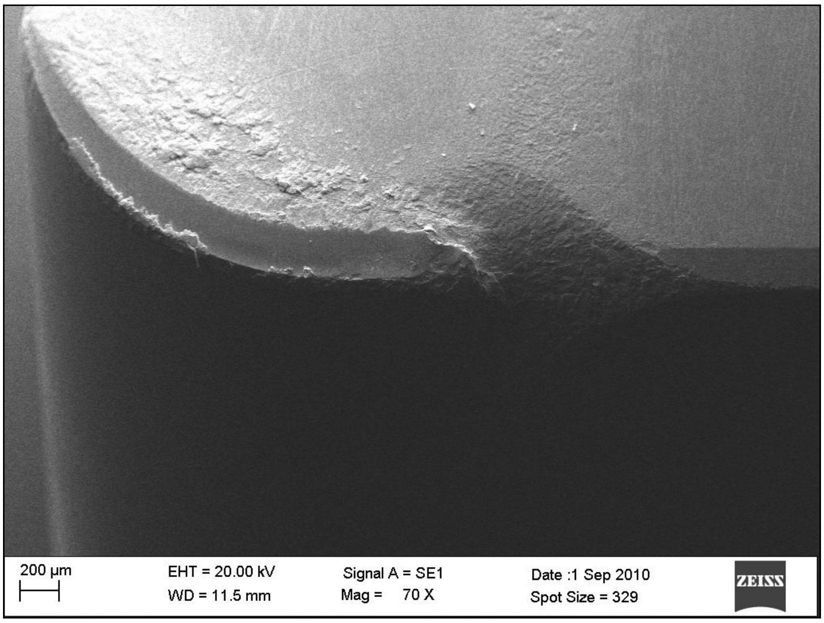

Figure 4. Notch wear (VB_N) and nose wear (VB_C) on Mixed (Al_2O_3 + TiC) ceramic, after 60s

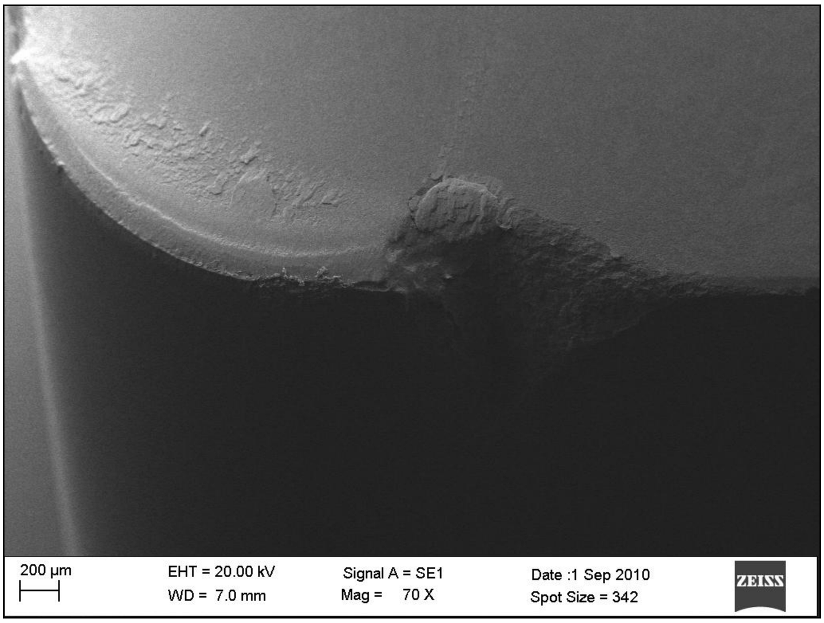

Figure 5. Notch wear (VB_N) on Whisker (Al_2O_3 + SiC) ceramic, after 20s

The chemical and adhesive interactions between the Ni alloys and ceramics are weak and do not favour the diffusion wear mechanism, although at higher cutting speeds (Cs = 300 m/min) heat generation is intense and can be spread among the materials (ASM Handbook Vol. 5, 1994; ISO 3685, 2000).

The influence of cutting geometry (CG) on the average flank wear (VB_B) and nose wear (VB_C) of the ceramic inserts was most favourable to first geometry (CG1), that inhibited wear mechanisms at both cutting speeds (Cs = 150 m/min and and Cs = 300 m/min) where the temperatures are relatively low and high, respcetively (ASM Handbook Vol. 16, 1989; Grzesik, 2008).

Observing the colour of the chips during machining red staining could be seen on their edges, results also found in the tests with ceramic materials done by Liao and Shiue (1996). The highest temperatures tend thus to favour the thermally activated mechanisms such as diffusion and oxidation at the tool edges (Shaw, 1986).

3.2. Influence of cutting speed, cutting geometry and atmosphere over the tool life

The influence of the input variables: cutting speed (Cs), cutting geometry (CG), atmosphere (A) and the material of the insert (MI) on the tool life (t) was verified using statistical tools – ANOVA (Montgomery, 2001).

The materials of the inserts (MI) were compared in pairs for two different atmospheres (A), varying the cutting speed (Cs) and the cutting geometry (CG). The maximum p value accepted was 0.20 and correlation coefficient R^2> 0.90 for all comparisons.

Tables 3 to 11 show the influence of these input variables on tool lives (t) of the ceramic inserts.

Table 3. Effects of the input variables on tool lives of SiAlON (Si_3N_4 + Al_2O_3) x Mixed (Al_2O_3 + TiC) inserts in Dry x Oxygen rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-119,37	31,84	-3,74	0,013320
CG	-80,87	31,84	-2,53	0,051941
A	46,12	31,84	1,44	0,207226
MI	-89,62	31,84	-2,81	0,037373

Table 4. Effects of the input variables on tool lives of SiAlON (Si_3N_4 + Al_2O_3) x Mixed (Al_2O_3 + TiC) inserts in Dry x Argon rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-97,25	31,92	-3,04	0,018672
CG	-82,00	31,92	-2,56	0,037069
MI	-68,00	31,92	-2,13	0,070641
Cs by CG	74,50	31,92	2,33	0,052312

Table 5. Effects of the input variables on tool lives of SiAlON (Si_3N_4 + Al_2O_3) x Mixed (Al_2O_3 + TiC) inserts in Argon rich x Oxygen rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-139,37	16,61	-8,38	0,000394
CG	-55,12	16,61	-3,31	0,021057
A	31,62	16,61	1,90	0,115350
MI	-57,37	16,61	-3,45	0,018173

Table 6. Effects of the input variables on tool lives of SiAlON (Si_3N_4 + Al_2O_3) x Whisker (Al_2O_3 + SiC) in Dry x Oxygen rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-123,00	24,05	-5,11	0,000624
CG	-69,75	24,05	-2,89	0,017613
MI	-105,50	24,05	-4,38	0,001757
Cs by MI	77,50	24,05	3,22	0,010464

Table 7. Effects of the input variables on tool lives of SiAlON (Si_3N_4 + Al_2O_3) x Whisker (Al_2O_3 + SiC) x in Dry x Argon rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-107,12	26,29	-4,07	0,006549
CG	-65,12	26,29	-2,47	0,048032
MI	-79,87	26,29	-3,03	0,022879
Cs by MI	58,12	26,29	2,21	0,069113

Table 8. Effects of the input variables on tool lives of SiAlON (Si_3N_4 + Al_2O_3) x Whisker (Al_2O_3 + SiC) in Argon rich x Oxygen rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-130,37	13,84	-9,41	0,000032
A	27,62	13,84	1,99	0,086197
MI	-82,62	13,84	-5,96	0,000560
Cs by MI	57,87	13,84	4,18	0,004135

Table 9. Effects of the input variables on tool lives of Mixed (Al_2O_3 + TiC) x Whisker (Al_2O_3 + SiC) in Dry x Oxygen rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-41,87	19,25	-2,17	0,081616
CG	-57,62	19,25	-2,99	0,030336
A	43,37	19,25	2,25	0,073997
Cs by A	-42,37	19,25	-2,20	0,078988

Table 10. Effects of the input variables on tool lives of Mixed (Al_2O_3 + TiC) x Whisker (Al_2O_3 + SiC) in Dry x Argon rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-39,12	24,24	-1,61	0,145182
CG	-52,37	24,24	-2,16	0,062725
A	37,37	24,24	1,54	0,161681
Cs by A	-39,62	24,24	-1,63	0,140758

Table 11. Effects of the input variables on tool lives of Mixed (Al_2O_3 + TiC) x Whisker (Al_2O_3 + SiC) in Argon rich x Oxygen rich atmospheres

Var.	Effect	Std. Err.	t	p
Cs	-81,50	19,66	-4,14	0,001995
CG	-50,00	19,66	-2,54	0,029207
MI	-25,25	19,66	-1,28	0,208003
Cs by CG	49,75	19,66	2,53	0,029851

It is observed that the cutting speed caused reduction in tool lives when changed from 150 to 300 m / min. This result is consistent with the literature (Machado *et al.*, 2009; Trent and Wright, 2000), where higher amount of heat generation in the fastest cutting speed enhances the wear mechanisms, decreasing tool life.

Figures 6 to 8 illustrate the effect of the main variables on the tool life (t) of the several insert materials.

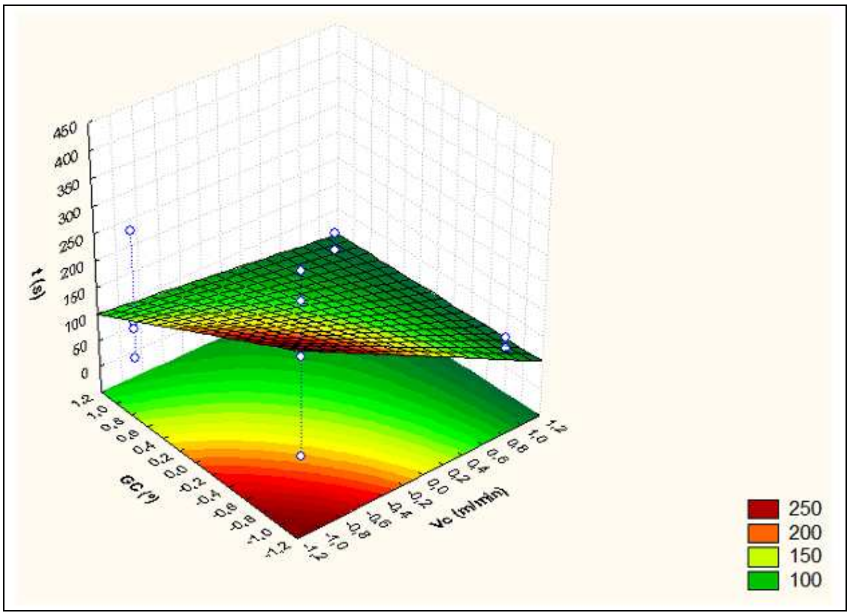

Figure 6. Influence of inputs parameters on the tool life . SiAlON ceramic inserts ($Si_3N_4 + Al_2O_3$) x Mixed ceramic (Al_2O_3 + TiC)

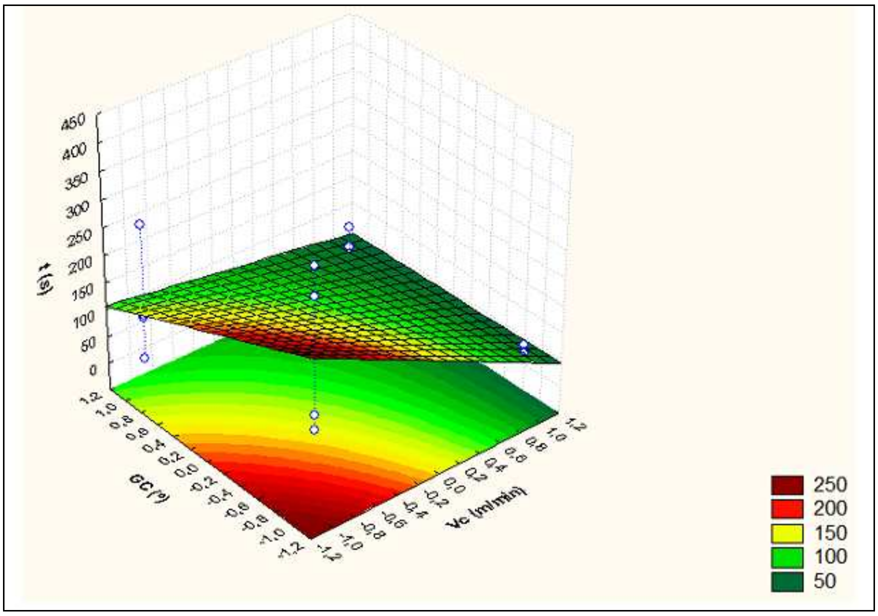

Figure 7. Influence of inputs parameters on the tool life . SiAlON ceramic inserts ($Si_3N_4 + Al_2O_3$) x Whisker ceramic (Al_2O_3 + SiC)

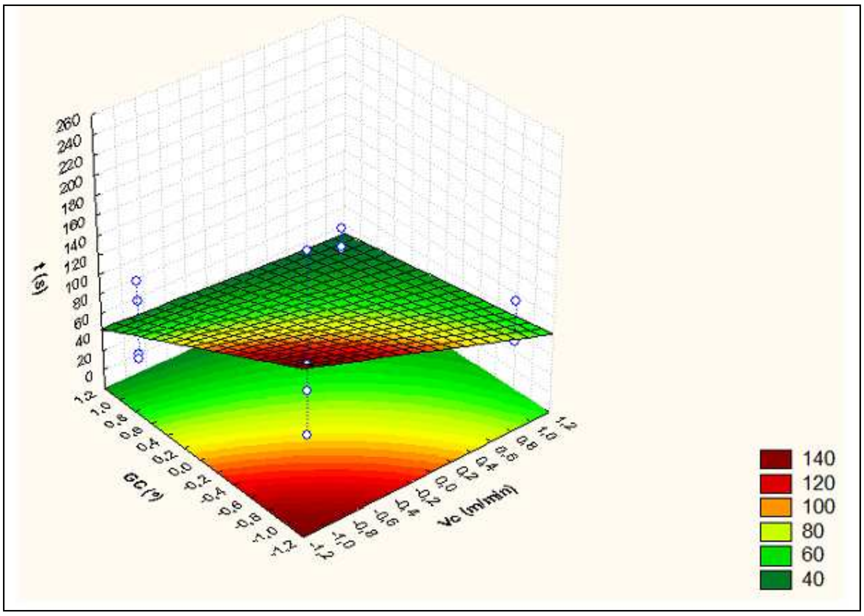

Figure 8. Influence of inputs parameters on the tool life . Mixed ceramic inserts (Al_2O_3 + TiC) x Whisker ceramic (Al_2O_3 + SiC)

The change of the ceramic tool geometry from CG1 to CG2 decreased the tool lives in all factorial design. Hence, the geometry with $\chi_R = 45°$, $\gamma_o = -8°$, $\alpha_o = 8°$ and $\lambda_s = 0°$ was more appropriate to machine the Inconel® 751, overcoming the geometry where these angles are 85°, -6°, 6° and 6°, respectively. The CG2 tool geometry was very vulnerable to microchipping.

With respect to ceramic tool material, SiAlON showed the best results. It was followed by the mixed and then by the whisker ceramic, that showed the worst performance. Literature (Ezugwu *et al.*, 1999) indicates that all the three ceramics used are suitable for machining nickel alloys, and the SiAlON and Whiskers usually have excellent results when the notch wear predominates. The results of this study indicate that beyond the notch, flank and edge wear were also present and thus the Whisker ceramic tools could not present the same performance of the others. In addition, the SiAlON tools showed good resistance against notch wear, making flank wear dominant, with longer tool lives.

4. CONCLUSIONS

The results showed that the cutting speed, tool geometry and atmospheres influenced the types of wear and tool lives of the ceramics tested. Notch wear (VB_N) was the dominant type of wear, followed by average flank wear (VB_B) and nose wear (VB_C).

The shortest tool life were found in normal atmosphere (dry) and the development of notch wear (VB_N) was accelerated by oxygen rich atmosphere, particularly at low cutting speeds.

The interaction of the cutting geometry number 2 and higher cutting speed favoured the development of nose wear (VB_C) of the inserts tested.

The SiAlON ceramics (Si_3N_4 + Al_2O_3) is not prone to the development of notch wear, presenting the longest tool life among all tools tested. For this type of tool material average flank wear (VB_B) was dominant, followed by nose wear (VB_C).

Chipping on the secondary cutting edge was observed when the CG2 cutting geometry was used in all ceramic materials.

The wear mechanisms that predominate during machining are attrition, abrasion and diffusion due to high temperatures generated during cutting.

5. ACKNOWLEDGEMENTS

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