EVALUATION OF NANO-GRAIN SIZE CERAMICS WHEN MACHINING Ti-6Al-4V ALLOY UNDER CONVENTIONAL COOLANT FLOW

Rosemar Batista Da Silva
Álisson Rocha Machado
Faculty of Mechanical Engineering, Federal University of Uberlândia, Av. João Naves de Ávila, 2.121, Uberlândia – MG, 38.400-089, Brazil.
alissonm@mecanica.ufu.br
Emmanuel O. Ezugwu
John Bonney
Machining Research Centre, Faculty of Engineering, Science and the Built Environment,
London South Bank University, 103 Borough Road, London, SE1 0AA, England, U.K.
ezugwueo@lsbu.ac.uk
Éder Silva Costa
Federal Center of Technological Education of Minas Gerais - CEFET-MG. Divinópolis Division Unit - Campus V, 35502-036, Divinópolis – MG, Brazil
eder@div.cefetmg.br

Abstract. *Although conventional micron-grain size ceramic tools have not proved better when machining titanium alloys, advances in nano-technology have generally led to improved mechanical properties of cutting tools, especially ceramics. This paper evaluates the performance of two grades of nano-grain size ceramic tools (Al_2O_3 and Si_3N_4 base) when turning Ti-6Al-4V alloy, at cutting speeds up to 200 m/min, using conventional coolant flow. Tool life, failure modes, component forces, surface roughness and run-out of machined surfaces were recorded and used to assess the performance of the cutting tools and to formulate the mechanism(s) responsible for tool wear. Comparative trials were carried out with micron-grain size silicon carbide (SiC_w) whisker reinforced alumina ceramic tools. Tests results show that notch wear rate reduced when machining with silicon nitride (Si_3N_4) base nano-ceramic tool relative to alumina based nano ceramic and micron-grain ceramics. Tool failure was mainly due to severe abrasive wear on the nose region and chipping/fracture of the cutting edge. The micron grain whisker reinforced alumina ceramic tool gave the worst performance, followed by alumina (Al_2O_3) based nano-ceramic tools. Lower surface roughness and run-out values were recorded after machining with nano-ceramic tool materials.*

Keywords: *Nano-ceramic tools, Titanium alloy, Cutting and feed forces, Surface Roughness, Run-out*

1. INTRODUCTION

Titanium alloys are predominantly used within the medical, chemical and aerospace industries because of their excellent corrosion resistance and low strength-to-weight ratio relative to other materials such as steel (60% density of steel) (Sandvik Coromant, 2003). Machining of titanium alloys at higher cutting conditions pose constant challenges due to their poor machining characteristics such as; formation of tough continuous type chips and their low thermal conductivity (86% lower than that of AISI 1045 steel) (Mantle and Aspinwall, 1998), and excessive built-up of heat at the cutting interface. This gives rise to galling - a standard difficulty in all forming operations with titanium - and probably leading to increased oxygen and nitrogen pick-up at the workpiece surface. Additionally, titanium alloy also has a low elastic modulus which leads to distortion of the workpiece (Petty, 1968). Researchers are continuously seeking effective methods to machine titanium alloys using combination of cutting tools and cutting parameters in order to minimize solution wear during machining. Machining titanium alloys with ceramic tools has not been successful because of the chemical interactions between the ceramic tools and titanium alloys (Li and Low (1964); Komanduri (1989); Dearnley and Grearson (1986)). Performance of ceramic tools during machining depends on their physical, mechanical and chemical properties (North, 1986).

Advances in nano-technology have generally led to improved mechanical properties of cutting tools, especially ceramic tools. Mechanical properties, such as the hardness, strength and density are related to the grain size of cutting tool substrate. The use of finer grained substrate generally produce densely packed compact tools after sintering. Wear resistant capabilities of ceramic cutting tool materials are also associated with their grain size. Nano-grain ceramic cutting tool materials have been developed to further enhance their machining performance. Despite the fact that nanoceramics and conventional ceramics generally have the same composition, the production process of the former require high temperature and pressure for efficient sintering in order to reduce the number of agglomerates in their powders, thus ensuring a denser phase powder than conventional ceramics (Vaβen and Stöver, 1999). The sintering pressures can exceeded 8 GPa and temperature in excess of 1000ºC. The density of nanoceramic powder has significant influence on the mechanical properties such as ductility at low temperature, superplasticity at elevated temperatures and hardness. It is therefore anticipated that this technique will produce cutting tools with improved wear resistance, hardness and toughness relative to conventional ceramics (Zhang *et al*, 1996). Kear *et al* (2001) compared the abrasive wear resistance between micron and nano-grained ceramic particles of TiO_2 and concluded that the latter presented about 10% less resistance than the former. They also observed a reduction of about 50% in the friction coefficient, surface roughness (R_a) between 20-50 nm, the development of surface plasticity and improved toughness for the nano-grained TiO_2. Bhaduri & Bhaduri (1997) also investigated the toughness behavior of Al_2O_3-ZrO_2 nanoceramic and observed a slight drop in hardness with improved toughness in relation to conventional ceramics. The improved hardness observed with reduction in grain size of SiC nanoceramics (Vaβen and Stöver, 1999) was attributed to lesser of porosities within the phases with higher density of particles. Furthermore, they observed an excellent thermal shock resistance in materials such as SiC/C-composites with a SiC matrix grain size lower than 200 nm, in spite of the low thermal conductivity relative to conventional ceramics. Kim (1994) verified that increasing the pore size and inter-granular porosity lead to reduction of fracture toughness in ceramic tools. Ezugwu *et al* (2004a) observed that micron grain whisker reinforced alumina ceramic tool out performed the nano-grain ceramic tools grades (Al_2O_3 and Si_3N_4) at cutting speed range of 230-270 m/min, feed rate range of 0.125-0.15 mm/rev under conventional coolant flow when machining Inconel 718. Silicon nitride (Si_3N_4) base nano-ceramic also gave the worst performance in terms of tool life due to high nose wear rates attributed to the softening of tool materials and consequent weakening of their bond strength when machining at higher speed conditions. A curious fact was that nano grain ceramic tools were more stable in terms of recorded tool life when machining at higher cutting speeds in excess of 230 m/min and at a feed rate of 0.125 mm/rev

This study attempts to evaluate the performance of two grades of nano-grain size ceramic tool materials (Al_2O_3 and Si_3N_4) and of micron-grain size silicon carbide (SiCw) whisker reinforced alumina ceramic tool in high speed turning of Ti-6Al-4V alloy, up to 200 m/min, using conventional coolant flow.

2. EXPERIMENTAL PROCEDURE

All the machining trials were carried out using a CNC Lathe with 11 kW motor drive and a speed range from 18 – 1800 rpm, providing a torque of 1411 Nm. The workpiece material used in the machining trials was a commercially available alpha-beta Ti-6Al-4V (IMI 318) alloy. The chemical composition and physical properties of the workpiece material are given in Tables 1 and 2 respectively. Two grades of nano-grain size ceramic tool materials, Al_2O_3 (mixed alumina) and Si_3N_4 (silicon nitride based) coded T1 and T2 respectively and a micron-grain size silicon carbide (SiCw) whisker reinforced alumina ceramic tool (T3) with ISO tool designations SNGN 120412 were used for the machining trials. The mechanical properties and nominal chemical composition of the inserts are given in Table 3.

Table 1. Nominal chemical composition of Ti-6Al-4V alloy (wt. %) (Mantle and Aspinwall (1998); Dearnley and Grearson (1986))

	Chemical composition (wt. %)								
	Al	V	Fe	O	C	H	N	Y	Ti
Min.	5.50	3.50	0.30	0.14	0.08	0.01	0.03	50 ppm	Balance
Max.	6.75	4.50		0.23					

Table 2. Physical properties of Ti-6Al-4V alloy (Mantle and Aspinwall (1998); Dearnley and Grearson (1986))

Tensile strength (MPa)	0.2% Proof stress (MPa)	Elongation (%)	Density ($g\ cm^{-3}$)	Melting point (°C)	Measured hardness (C.I. – 99%)* HV100	Thermal conductivity at 20ºC ($W\ m^{-1} K^{-1}$)
900-1160	830	8	4.50	1650	Min.= 341 Max. = 363	6.6

* CI: Confidence interval of 99 %, represented by the minimum (Min.) and maximum (Max.) values.

Table 3. Mechanical properties and chemical composition (wt%) of nano and micron grain ceramic tools material.

Tool code	Hardness (HV_5)	Edge toughness (MPa $m^{1/2}$)	Al_2O_3	SiC	Si_3N_4	TiCN	Y_2O_3	ZrO_2
T1	1779	10.54	75.0	-	-	20.0	-	5.0
T2	1670	6.92	4.5	4.5	68.3	18.2	4.5	-
T3	2000	8.00	70.0	30.0	-	-	-	-

The following cutting conditions were employed in this investigation:

- Cutting speed, S (m/min): 110, 130 and 200
- Depth of cut, DOC (mm): 0.5
- Feed rate, f (mm/rev): 0.15
- Tool geometry: Approach angle: 40°, back rake angle: -5°, side rake angle: 0°, clearance angle: 6°
- Coolant type: Hocut 3380 at a concentration of 6%
- Coolant delivery method: conventional coolant flow (CCF) at a flow rate of 2.7 L/min.

Tool rejection criteria for finishing operation were employed in this investigation. The values were established in accordance with ISO Standard 3685 for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of rejection criteria:

1) Average flank wear ≥ 0.3 mm
2) Maximum flank wear ≥ 0.4 mm
3) Nose wear ≥ 0.3 mm
4) Notching at the depth of cut line ≥ 0.6 mm
5) Surface roughness value ≥ 1.6 µm (Center line average)
6) Excessive chipping (flaking) or catastrophic fracture of the cutting edge**.**

Component forces (cutting force, F_c, and feed force, F_f) generated during the machining trials were recorded with the aid of a piezoelectric tool post dynamometer at the beginning of cut when the cutting edge has not undergone pronounced wear. The signals of the forces generated during machining are fed into a charge amplifier connected to the dynamometer. The amplifier converts the analogue signal to digital signal that can be read on a digital oscilloscope. Tool wear was measured using a toolmaker's microscope at a magnification of 20 times. This is connected to a digital micrometer XY table with resolution of 0.001 mm. The worn inserts were examined in the scanning electron microscope (SEM) and micrographs taken for analysis. Surface roughness values were recorded at beginning of cut after the first complete pass with a portable stylus type instrument. The average of three readings at different locations on the machining workpiece bar represents the surface roughness value of the machined surface.Up to 9 experimental trials were carried out in this study, and it is important to note that replications of experimental trials were performed for some machining conditions. For such cases, average of tool lives was recorded. Additionally, tests were always repeated on occurrence of abnormal and unpredictable tool failure.

3. RESULTS AND DISCUSSIONS

3.1. Cutting Time and Wear Rate

Figures 1 and 2 show cutting time and notch wear rate recorded when machining Ti-6Al-4V alloy with ceramic tools using conventional coolant flow. Increase in cutting speed generally accelerated tool wear, consequently reducing tool life. The Si_3N_4 base T2 grade however exhibited improved performance at a speed of 130 m/min. Both the nano and micron grained tools gave poor performance in terms of tool life as previously believed when machining Ti-alloys. It is also clear from the machining results that improved properties of the nanoceramic tool have negligible effect on performance. This means that tool performance is more chemically and/or thermally related. Machining with the T1 tool grade gave higher wear rate when machining at a cutting speed of 110 m/min. Severe notching which often lead to catastrophic tool failure occurred when machining with the T1 grade at speeds in excess of 110 m/min (Figures 2 and 3 (a) and (b)). This type of wear occurs on a purely random manner and cannot be predicted. Lower wear rates increasing with increasing cutting speed were observed when machining with alumina based nanograin T2 and T3 micrograin tools. The T2 grade gave the best overall performance in terms of tool wear rate, followed by the T3 tool grade. Although T1 and T3 tool grades have theoretically improved edge toughness desired for efficient machining, their relatively poor performance in terms of tool life and notch wear rates can be associated with their higher hardness with associated brittleness (Table 3). Comparison of tools T1 and T2 suggest that the higher TiCN content in T1 grade may be responsible for accelerated notch wear due to increased affinity of TiC to the titanium workpiece material. This will lead to a loss of the edge sharpness, which adversely affects the surface finish generated during machining. Ceramic tools generally exhibit lower fracture toughness than carbides as well as poor thermal and mechanical shock resistance. Additionally, ceramic tools have high reactivity with titanium alloys.

Examination of the worn cutting edges revealed irregular unevenly worn rake faces (Figure 3 (a), (b), (c) and (f)). However severe abrasive wear with smooth aspect was visible when machining with tools T2 and T3 grades (Figure 3 (d) and (e)). Notch wear at the depth of cut can be observed in Figure 3 (a), (d) and (f) which appeared to have mainly formed by a type of fracture process. Severe chipping which lead to tool failure was also observed after machining with tools T1 and T3 at cutting speed of 200 m/min, as illustrated in Figures 3 (b) and (f) respectively.

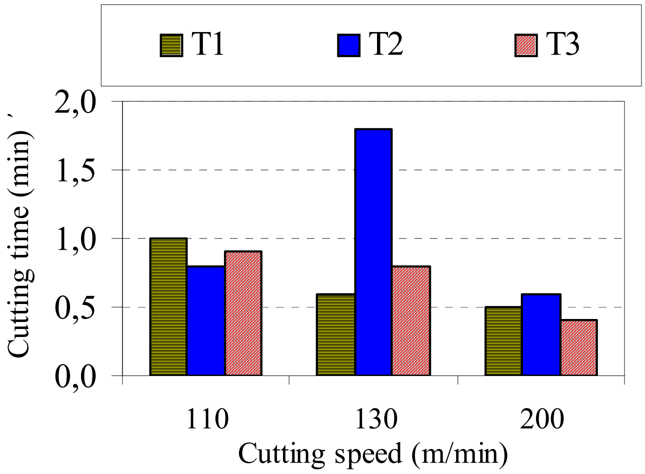

Figure 1. Cutting time when machining Ti-6Al-4V alloy with three grades of ceramic tools (T1: Al_2O_3 base, T2: (Si_3N_4 base) T3: (SiCw)) at various speed conditions using conventional coolant flow.

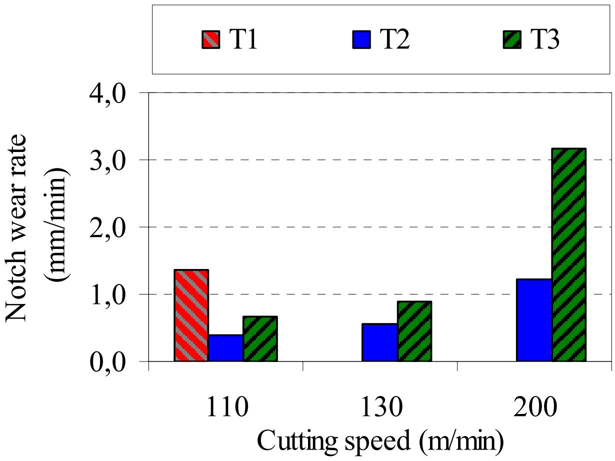

Figure 2. Notch wear rate when machining with three grades of ceramic tools (T1, T2, T3) under conventional coolant flow.

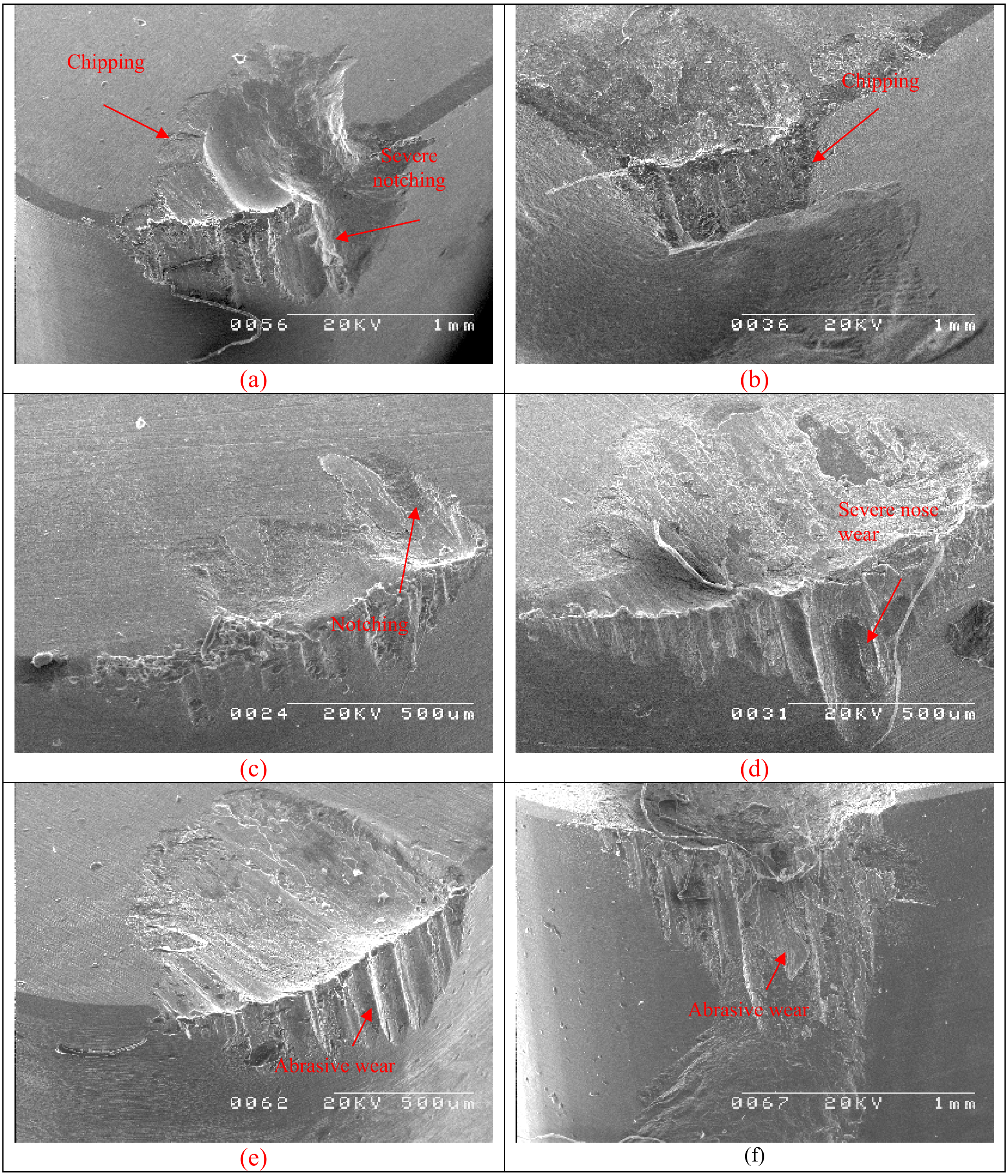

Figure 3. SEM images of wear observed after machining with different ceramic tool grades: T1 (a: 130 m/min), (b: 200 m/min), T2 (c: 110 m/min), (d: 200 m/min), and T3 (e: 130 m/min) and (f: 200 m/min)

3.2. Component Forces

Figure 4 shows variation of component forces with cutting speed when machining Ti-6Al-4V alloy with different ceramic tool grades under conventional coolant flow at various cutting speeds. Component forces generated during machining are proportional to stresses on the tool cutting edge. Therefore high compressive forces at the cutting edge will lead to accelerated tool wear and plastic deformation of the tool edge. These can adversely affect the cutting edge geometry. Prolong machining leads to accelerated tool wear as a result of high cutting edge temperature (Ezugwu *et al*, 2002). Cutting forces generated were higher than feed forces in all the conditions investigated. The components forces generated increased with increasing cutting speed especially when machining with tools T1 and T3. Evidence of decreasing cutting forces with increasing cutting speed up to 120 m min^{-1} was reported by Ezugwu *et al* (2004a) when finish turning of Ti-6Al-4V alloy with uncoated carbides. The increase in cutting forces with increasing cutting speed in this case may be attributed to the very high wear rate of the ceramic tools (Figure 3). This tends to increase frictional forces during machining and the consequent loss/blunting of the sharp cutting edge.

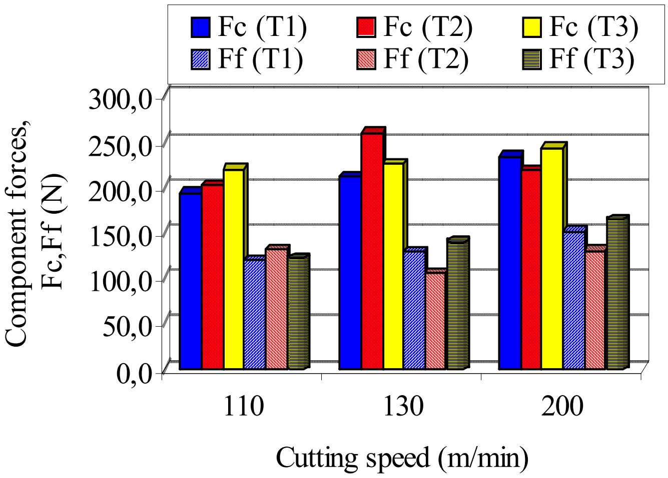

Figure 4. Component forces (F_c and F_f) recorded when machining Ti-6Al-4V alloy with three grades of ceramic tools (T1: Al_2O_3 base, T2: (Si_3N_4 base) T3: (SiCw)) under conventional coolant flow

3.3. Surface Finish and Run-out of Machined Surface

In turning operation a machined surface with minimum form and geometric distortion is always desired. The quality of machined surfaces depends on the ability of a cutting tool to maintain a sharp cutting edge for longer machining periods. In other words, the quality of machined surface is related to cutting tool wear. Figure 5 illustrates the surface roughness values recorded, when machining Ti-6Al-4V alloy with ceramic tools using conventional coolant flow. Surface roughness values recorded are above the stipulated rejection criterion of 1.6 µm due to the high tool notch wear rates. Increase in cutting speed when machining with Si_3N_4 base nano-grain T2 tool grade had negligible effect on the surface roughness value recorded. Higher surface roughness values of 12.5 µm and 7.5 µm were recorded when machining with the alumina base nano-ceramic T1 tool at cutting speeds of 130 and 200 m/min, respectively. Surface roughness values slightly above 1 µm, were recorded by Ezugwu *et al* (2004a) when machining Ti-6Al-4V alloy with uncoated carbides under conventional coolant flow and in an argon enriched environment at cutting speed range of 110-130 m/min. Surface roughness value of about 2 µm has been recorded after rough machining Inconel 718 alloy, with different nano-grain ceramic tool grades at a speed of 230 m/min (Ezugwu *et al,* 2004b).

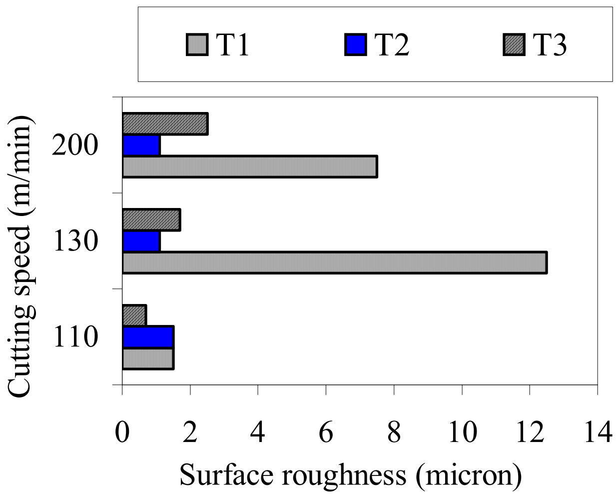

Figure 5. Surface roughness values after machining Ti-6Al-4V alloy with different ceramic grade tools (T1: Al_2O_3 base, T2: (Si_3N_4 base) T3: (SiCw)) at various speed conditions using conventional coolant flow.

Figure 6 is a plot of the variation in surface run-out with speed when machining with various ceramic tools. It can be observed that run-out values increased with increasing cutting speed for all tool grades and cutting conditions investigated. The silicon nitride based (T2) nano-grain size tool grade gave the lowest run-out values (≤ 10 μm) while the nano-grain (T1) tool grade gave the highest run-out values, rising to 20 μm at the higher speed conditions of 200 m/min (100% greater than the value obtained with T3 tool at the same cutting speed). In all cases, the run-out values recorded are well below the stipulated rejection criterion of 100 μm. Ceramic tools have high chemical reactivity with titanium alloys and are therefore more susceptible to accelerated tool wear, especially under higher cutting conditions, compared to other tool materials such as carbides and PCD tools. Reduction of hot hardness at elevated temperatures conditions during machining can lead to the weakening of the inter-particle bond strength and the consequent acceleration of tool wear (North, 1986). Typical tool failure modes observed when machining Ti-6Al-4V alloy with ceramic tools are chipping of cutting edge, severe notching and eventually catastrophic tool failure (Figures 3 (a)-(e)). These types of wear occur on a purely random manner and cannot be predicted, leading to a loss of the edge sharpness which adversely affects the dimensional tolerance of a machined component.

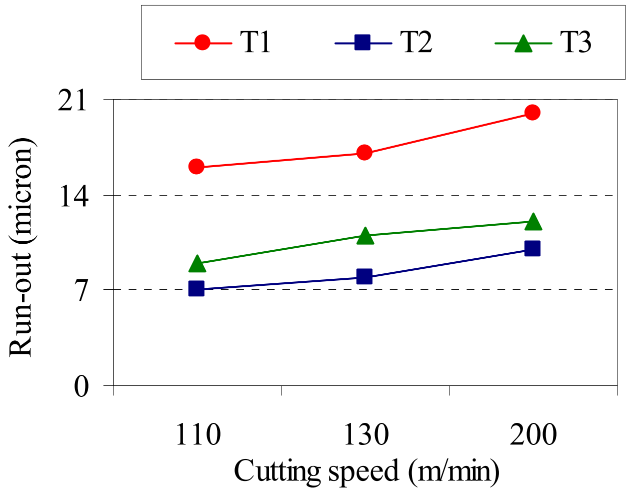

Figure 6. Run-out variation after machining Ti-6Al-4V alloy with different ceramic tool grade (T1: Al_2O_3 base, T2: (Si_3N_4 base) T3: (SiCw)) with the conventional coolant flow.

4. CONCLUSIONS

1. Machining Ti-6Al-4V alloy with different ceramic tool grades did not demonstrate satisfactory performance in terms of tool wear rate and tool life, due to severe abrasive wear and chipping of the cutting edge.
2. The silicon nitride (Si_3N_4) base nano-ceramic tool (T2) performed better in terms of tool wear rate, surface roughness and run-out compared to the mixed alumina (Al_2O_3) base-nano-ceramic tool (T1) and whisker reinforced micron-grain size ceramic tool (T3) under the conditions investigated. The ranking order for the ceramic tool performance is as follows: T2, T3, T1.
3. Component forces increased with increasing cutting speed when machining Ti-6Al-4V alloy with ceramic tools (especially with T1 and T3) due to high wear rates and consequent chipping of the tool cutting edge which occur in a random manner.
4. Lower surface roughness and run-out values was obtained when machining Ti-6Al-4V alloy with silicon nitride (Si_3N_4) base nano-ceramic (T2) tool.

5. ACKNOWLEDGMENTS

The authors would like to acknowledge the support of Rolls-Royce plc and the financial support from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq Brazil) that enabled this study to be completed.

6. REFERENCES

BHADURI, S. & BHADURI, S.B., 1997, "Enhanced low temperature toughness of Al_2O_3-ZrO_2 nano/nano composites", NanoStructured Materials, Elsevier Science Ltd, Acta Metallurgica Inc, USA, Vol. 8, n. 6, pp. 755-763.

DEARNLEY, P.A. and GREARSON, A.N., 1986, "Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI 318", Materials Science and Technology, Vol. 2, January 1986, pp.47-58.

EZUGWU, E.O., BONNEY, J. and OLAJJIRE, K.A., 2002, "Evaluation of the Machinability of Nickel-Base, Inconel 718, Alloy with Nano-Ceramic Cutting Tools", Tribology Transactions, Vol. 45, n. 4, pp. 506-511.

EZUGWU, E.O., DA SILVA, R.B., BONNEY, J. and MACHADO, A.R., 2004a, "The Effect of Argon Enriched Environment in High Speed Machining of Titanium Alloy", Awaiting publication in Tribology Transactions.

EZUGWU, E.O., BONNEY, J., DA SILVA, R.B. and MACHADO, A.R., 2004b, "Evaluation of the Performance of Different Nano-ceramic tool grades when Machining Nickel-Base, Inconel 718, Alloy", Journal of the Brazilian Society of Mech. Sci. & Eng., ABCM, Vol. XXVI, No. 1, January-March 2004, pp.12-16.

KEAR, B.H.; COLAIZZI, J.; MAYO, W.E. & LIAO, S.-C., 2001, "On the processing of nanocrystalline and nanocomposite ceramics", Scripta Materialia, Elsevier Science Ltd., Vol. 44, pp. 2065-2068.

KIM, S., 1994, "Material Properties of Ceramic Cutting Tools", Key Engineering Materials, Trans. Tech. Publications, Switzerland,Vol. 96, pp. 33-80.

KOMANDURI, R., 1989, "Advanced Ceramic Tool Materials for Machining", Inter. J. Refratory Mat. & Hard Metal, Vol. 8, pp. 125-132.

LI, X.S. and LOW, I.M., 1994, "Ceramic Cutting Tools – An Introduction", Advanced Ceramic Tools for Machining Application – I , Key Engineering Materials, Trans. Tech. Publications, Switzerland – Germany – UK – USA, Vol. 96, p. 257.

MANTLE, A.L. and ASPINWALL, D.K., 1998, "Tool Life and Workpiece Surface Roughness when High Speed Machining a Gamma Titanium Aluminide", Progress of Cutting and Grinding, Proceedings of the Fourth International Conference on Progress of Cutting and Grinding, October 5-9, Urumqi and Turpan, China, International Academic Publishers, pp. 89-94.

NORTH, B., 1986, "Ceramic Cutting Tools", SME Technical Paper, SME, Dearborn, Michigan, MR 86-451,

PETTY, E.R., 1968, "Physical Metallurgy I - Physical Metallurgy of Engineering Materials", Instituition of Metallurgists, George Allen and Unwin Ltd, London, p. 304.

SANDVIK Coromant, 2003, "Turning titanium - developments in application technology", Metalworking World, Editor Christer Richt, Sandviken, Sweden, p. 15.

VAβEN, R. & STÖVER, D., 1999, "Processing and properties of nanophase ceramics", Journal of Materials Processing Technology, Elsevier Science Ltd, Vol. 92-93, pp. 77-84.

ZHANG, Z.; ZHU, Y. & HU, L., 1996, "Nanostructured SiC ceramics prepared a nex process-crystallization of interfacial glass", NanoStructured Materials, Elsevier Science Ltd, Acta Metallurgica Inc, USA, Vol. 7, n. 4, pp. 453-459.