EVALUATION OF THE MACHINABILITY OF Ti-6Al-4V ALLOY WITH (SiCw) WHISKER REINFORCED ALUMINA CERAMIC CUTTING TOOL UNDER VARIOUS COOLING ENVIRONMENTS

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Abstract. *This paper evaluates the machinability of titanium-base, Ti-6Al-4V, alloy with silicon carbide (SiC_w) whisker reinforced alumina ceramic tool using various cooling environments such as: conventional coolant flow, high-pressure coolant supplies and in an argon enriched environment at cutting speeds up to 500 m min^{-1}. Tool life, failure modes, cutting and feed forces and surface integrity of machined surfaces were used to assess the performance of ceramic cutting tool under the cooling environments investigated. Comparative trials were carried out with PCD tool under conventional cooling flow. The test results show that silicon carbide whisker reinforced (WG 300 grade) alumina ceramic tools are not suitable for machining titanium alloys, even when using other cutting environments, due to the to the accelerated tool wear and chipping/fracture of the cutting edge associated with chemical interactions between the ceramic tools and titanium alloys. Although chipping/fracture of the cutting edge was observed in all the cutting conditions investigated, which occurs in a random manner, tool wear rate of ceramic tool was reduced when using high-pressure coolant supplies relative to conventional coolant flow and argon gas at cutting speeds up to 200 m min^{-1}. Higher surface roughness values up to 5.5 µm (well above the stipulated rejection criterion of 1.6 µm) were produced when machining with (SiCw) whisker reinforced alumina ceramic tool. The ranking order of performance of the cooling environments is as follows: high-pressure coolant supplies, argon enriched environment and conventional coolant flow. PCD tools exhibited longer tool life with regular nose wear pattern compared to ceramic tools.*

Keywords: *titanium alloy, cooling environments, whisker reinforced alumina ceramic tool, PCD tool, surface integrity*

1. Introduction

Titanium-base, Ti-6Al-4V alloy is the workhorse of the titanium industry accounting for about 60% of the total titanium production and also is highly utilized in the aerospace titanium industry (80%-90% of the titanium used on airframes) especially in production of sections of the aircraft such as fuselage, landing gear, wing and gas turbine engines for static and rotating components because of their outstanding strength to density ratios relative to other materials (Boyer, 1996). Ti-6Al-4V alloy contains lower β-stabilizing contents, which offers highly weldability property. This alloy is also used in automotive industry to produce connecting rods, drive shafts, crankshafts among others because of their excellent corrosion resistance and low strength-to-weight ratio relative to other materials such as steel (60% density of steel) (Sandvik, 2003). Because of the non-toxic and biocompatible characteristics of titanium alloys, they are suitable for application in medical area for production of surgical implants and prosthetic devices such as dental implants, bone and joint replacement, maxilla and cranium/facial treatments as well as in production of surgical instruments (ASH Handbook 1998). A good combination of their properties ensures better operations up to temperatures of about 315ºC (Boyer, 1996). However, the high temperature generated when machining Ti-6Al-4V alloy mainly due to the high strength, relatively poor thermal conductivity compared to Inconel 718 and AISI 1045 steel (Mantle and Aspinwall, 1998) and low modulus of elasticity impair its machinability hence it is referred to as difficult-to-machine material. Also the heat generated during machining is concentrated at the tool tip as consequence of the very highly sheared chips with a short contact length between the chip and the rake face (Yang, 1970). The contact zone observed when machining titanium alloys is only 50% of equal cutting conditions employed when machining steels (Richt, 2003). The major factor hindering the machinability of this Ti-6Al-4V is its high chemical reactivity with most of cutting tool materials at elevated temperatures (> 550ºC) and consequent welding onto the tool tip, as well as tendency to form adiabatic shears bands and/or rapid work hardening during machining, which adversely affect tool life (Shaw (1967), Komanduri and Von Turkovich (1981) and Ezugwu and Wang (1997). These characteristics pose considerable machinability problems for titanium (Miller (1996), Vigneau (1997) and Gatto and Iuliano (1997)). Success in the machining of titanium alloys will depend on the correct selection of cutting tool, cutting environment and the choice of compatible cutting conditions for each machining operation (North, 1986).

The ability of a tool to sustain high cutting temperatures is dependent upon the properties of the tool material. According to Ezugwu and Wang (1997) and Trent and Wright (2000) an ideal cutting tool for machining titanium should possess the following properties during machining: hot hardness to maintain a sharp and consistent cutting edge at elevated temperature, high resistance to abrasion in order to avoid alteration in dimensions by rubbing action, chemical inertness to depress the tendency to react with titanium and chemical stability to prevent the formation of a built-up edge, good thermal conductivity to minimise thermal gradients and thermal shocks, high fracture toughness (if an insert is not sufficiently tough, then induced shock load alone can lead to premature fracture of the cutting edge during machining), good fatigue resistance to withstand the chip segmentation process and high compressive, tensile and shear strength. Szeszulski *et al.* considers wear resistance, chemical inertness and toughness main factors affecting the performance of cutting tools when machining aerospace alloys, especially nickel and titanium alloys.

Although some studies developed worldwide by Seco Tools (2002a), Hartung and Kramer (1982), Nabhani (2001), Lee (1981), Machado *et al.* (2004) and Magalhães and Ferreira (2004) have reported the superiority of PCD tools compared to cemented carbides, in terms of wear rate, and hence longer tool life, when machining of titanium alloys, cemented carbides when machining titanium alloys, cemented carbides are the preferred tool materials for machining titanium alloys with cutting fluids in the range of 56 to 150 m min^{-1} (López de Lacalle *et al.* (2000), Fitzsimmons and Sarin (2001), Nabhani (2001), Ezugwu *et al.* (2002) and Venugopal *et al.* (2003)) due to their improved performance in terms of tool wear and lower cost relative to other cutting tool materials commercially available (Deanrley and Grearson (1986), Jawaid *et al.* (1999) and Seco Tools (2002b)). Ceramic tool materials generally have three properties which distinguish them from cemented carbides: chemically inert, highly resistant to abrasive wear and capable of superior heat dispersal during chip forming process (Whitfield, 1988). Combined, these properties lead to increase the rate of metal removal by increasing tool life. Silicon carbide (SiC_w) whisker reinforced alumina ceramic has silicon-carbide whiskers added to a matrix of aluminium oxide. The whisker reinforces the hard and somewhat brittle aluminium oxide, allowing it to better withstand mechanical stresses. As result, they are suitable for machining high-nickel materials like Inconel and hardened alloy steels, which require cutting materials, which are highly resistant to abrasion and cratering. The fracture toughness of silicon carbide (SiC_w) whisker reinforced alumina ceramic (for instance, WG300 grade) is enhanced by the phenomenon of whisker “pull-out” where the whiskers generally pull out during the fracture process. Additionally, under actual cutting conditions where temperatures at the tool-chip interface may reach over 1000ºC, whisker reinforced alumina ceramic will retain high strength and hardness well beyond the point at which a cemented carbide material has softened, deformed or failed completely (Smith, 1986). Ceramic tools have also been used for used for machining of titanium alloys in several studies carried out by Deanrley and Grearson (1986), Lee (1981), Komanduri (1989), Li and Low (1994), Klocke *et al.* (2002) and Komanduri and Reed Jr (1983). Nevertheless, they are not commercially recommended for machining titanium alloys under dry or conventional coolant flow because of their poor performance due to excessive wear rates as a result of the poor thermal conductivity, relatively low fracture toughness and high reactivity with titanium alloys (Deanrley and Grearson, 1986). The reduction of hot hardness at elevated temperature conditions lead to the weakening of the inter-particle bond strength and the consequent acceleration of tool wear. Performance of ceramic tools during machining depends on their physical, mechanical and chemical properties (North, 1986).

Since improving machinability of titanium has been a topic of constant interest, today´s research are encouraged by the need to develop new cutting tool materials as well as to encounter other alternative machining technologies or environments that will improve its machinability and ensure longer tool life and better surface finish of machined components. At the time of this investigation, there were no detailed papers on the wear behaviour SiC_w ceramic when machining titanium alloys. Because the mechanical properties of SiC_w ceramic, its potential need to be explored in machining of titanium alloys. Therefore, this study envisages to evaluate machinability of Tti-6Al-4V alloy with silicon carbide (SiC_w) whisker reinforced alumina ceramic cutting tool under various cooling environments (high-pressure coolant supplies, argon enriched environment, conventional coolant flow and dry condition) at cutting speeds up to 500 m min^{-1}. Tool life, failure modes, cutting and feed and analysis of surface integrity of machined surfaces were used to assess the performance of the whisker reinforced alumina ceramic inserts under the cooling environments investigated.

2. Experimental procedure

A comprehensive testing procedure was carried out to evaluate the performance of silicon carbide (SiC_w) whisker reinforced alumina ceramic when machining Ti-6Al-4V alloy at high cutting conditions typical of finish turning under conventional coolant flow, high-pressure coolant supplies of 11 Mpa and 20.3 Mpa and in an argon enriched environment. The machining trials were carried out using a CNC Center Lathe with a speed range from 18 - 1800 rpm. The lathe is driven by an 11kW stepless motor, which provides 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 Tab. 1 and Tab. 2 respectively. Up to 3 mm thickness of material at the top surface of the workpiece was removed in order to eliminate any surface defect that can adversely affect the machining result. The physical properties and nominal chemical composition of the inserts are given in Tab. 3.

Table 1. Nominal chemical composition of Ti-6Al-4V alloy (wt. %)

	Chemical composition (wt. %)								
	Al	V	Fe	O	C	H	N	Y	Ti
Min.	5.50	3.5	0.3	0.14	0.08	0.01	0.03	50 ppm	Bal.
Max.	6.75	4.5		0.23					

Table 2. Physical properties of Ti-6Al-4V alloy

Tensile strength (MPa)	0.2% Proof stress (MPa)	Elongation (%)	Density ($g\ cm^{-3}$)	Melting point (°C)	Thermal conductivity at 20ºC ($Wm^{-1}K^{-1}$)	Measured hardness (C.I. – 99%)[(1)] HV_{100}
900-1160	830	8	4.50	1650	6.6	Min.= 341 Max. = 363

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

Table 3. Mechanical properties and chemical composition of whisker reinforced ceramic and PCD tool materials

Tool material	ISO designation	Hardness (Knoops) GPa	Chemical composition (wt.%)	Density ($g\ cm^{-3}$)	Thermal Conductivity at 20ºC ($W\ m^{-1}K^{-1}$)	Average grain of substrate (μm)
Whisker reinforced ceramic (WG 300 grade)	CNGN120412TN WA1	94.5 HRA	70% (Al_2O_3, Y_2O_3, Zr_2O) 30% SiC	3.7	32	Whiskers with 0.5μm of diameter
PCD (20 grade)	CCMW120408F-L1	50.0	Diamond + Co residue	4.12	540	10

The following cutting conditions were employed in this investigation:

- Cutting speed, S ($m\ min^{-1}$): 140, 200, 400 and 500;
- Depth of cut, DOC (mm): 0.5;
- Feed rate, f ($mm\ rev^{-1}$): 0.15;
- Tool geometry: Approach angle: 95°, back rake angle: -6°, end relief angle: 6°, side rake angle: -6°, side relief angle: 6°;
- Coolant type: Hocut 3380 which is a high lubricity emulsion coolant containing alkanolamine salts of fatty acids and dicyclohexylamine applied at a concentration of 6%;
- Coolant delivery methods: - Conventional coolant flow (CCF) or overhead cooling at a flow rate of 2.7 *l* min^{-1};
  - High pressure coolant supply of 11 MPa at flow rate of 18.5 *l* min^{-1};
  - High pressure coolant supply of 20.3 MPa at flow rate of 24 *l* min^{-1}.

The distance from the nozzle to the cutting zone was kept at 100 mm when machining under conventional coolant flow. When using high pressure coolant system the jet of cutting fluid was delivered to region where the chip breaks contact in the tool (tool-chip interface) via a tool holder with an external nozzle with diameter of 2 mm and is kept at a distance of 13.5 mm from the cutting zone. The argon gas was delivered to the machining environment through a hose connected to a valve where the flow rate of the gas could be adjusted and supplied to the cutting interface at a constant flow rate of 12 *l* min^{-1} through the same tool holder employed for high pressure coolant supply. Thermal conductivity of argon at a temperature of 27°C (300K) is 0.0177 $Wm^{-1}K^{-1}$. Machining trials under conventional coolant flow were carried out only at a speed of 140 m min^{-1}. Comparative trials were also carried out with polycrystalline diamond (PCD 20 grade) tools under conventional coolant flow only at cutting speeds up to 200 m min^{-1}.

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) Excessive chipping (flaking) or catastrophic fracture of the cutting edge**.**
6) Surface roughness value ≥ 1.6 μm (Centre line average)

Tool wear measurements were carried out at various machining intervals using a tool makers microscope connected to a digital read out device at a magnification of x20 fitted with 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. Component forces (cutting force, F_c, feed force, F_f) generated during the machining trials were recorded with the aid of a piezoelectric tool post dynamometer after 30 seconds of machining time, 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 a dynamometer. This amplifier converts the analogue signal to digital signal that can be read on a digital oscilloscope. Surface roughness (Ra) values were recorded after each 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. The microstructure of machined surfaces were examined and photographed with metallurgical optical microscope with attached camera.

3. Results and discussion

3.1. Wear rate and tool life

Figures 1 and 2 show nose wear rate and tool life, respectively, recorded when machining Ti-6Al-4V alloy with silicon carbide (SiCw) whisker reinforced alumina ceramic and PCD inserts using conventional coolant flow, high-pressure coolant supplies of 11 Mpa and 20.3 Mpa and in argon enriched environment and various cutting speeds. Machining with SiCw ceramic tools under conventional coolant flow was carried out only at a speed of 140 m min^{-1}. PCD inserts were used only under conventional coolant flow at speeds up to 200 m min^{-1}. Increase in cutting speed generally accelerated tool wear, consequently reducing tool life of both cutting tools as expected due to a reduction in tool-chip tool-workpiece contact length and the consequent increase in both normal and shear stresses at the tool tip. The reduction in tool chip and tool-workpiece contact areas will also tend to concentrate the high temperature generated to a relatively smaller area as well as shifting the highest temperature closer to the cutting edge. Higher nose wear rates were also observed when machining with SiCw ceramic tools under conventional coolant flow and using both high pressure coolant supplies compared to PCD tool. Figure 1 also shows that machining with SiCw ceramic inserts in presence of argon provided highest nose wear rate in all the cutting speeds investigated, hence worst performance in terms of tool life relative to conventional and high pressure coolant supplies due probably to poor thermal conductivity of argon which tends to accelerate tool wear. Additionally, the poor thermal conductivity of argon can only prevent combustion of taking place during machining and most of the heat generated tends to concentrate at the cutting interface. This tends to further accelerate tool wear during machining. It is clear from Fig. 2 that that shorter tool life was obtained when machining Ti-6Al-4V alloy with SiCw ceramic tools in all conditions investigated relative to PCD tools due to the high reactivity of titanium alloys with ceramic tools (Deanrley and Grearson, 1986). Up to 57 min tool life was achieved when machining with PCD tools against less than 2.7 min with SiCw ceramic tool under conventional coolant flow at a speed of 140 m min^{-1}. Machining with PCD tools provided up to 2100% and 300% improvement in tool life when machining Ti-6A-4V alloy under conventional coolant flow at speeds of 140 m min^{-1} and 200 m min^{-1}, respectively, relative to ceramic tools. Figures 1 and 2 also show that machining under high pressure coolant supplies of 11 MPa and 20.3 MPa resulted to decrease tool wear rate and consequently providing marginal improvement in tool life compared with argon and conventional coolant flow. However when machining with 20.3 MPa coolant supply pressure, tool life were slightly lower compared to coolant pressure of 11MPa. This can be attributed to the physical phenomenon observed when the critical coolant pressure is exceeded (Pigott and Colwell, 1952). Lower tool life has been reported when coolant pressures in excess of 2.8 MPa were employed as a result of the critical boiling action of the coolant at the tool edge since it was possible to sweep the tool surface faster by the higher jet speed, thus lowering the rate of boiling and cutting down heat transfer. The optimum coolant pressure appears to have a relationship with the total heat generated during machining (Nagpal and Sharma, 1973). It has also been reported that any increase in coolant pressure in certain cases does not improve tool life when turning Ti-6Al-4V alloy with CBN tools at high cutting speeds up to 250 m min^{-1}, depth of cut of 0.5 mm and feed rate of 0.15 mm rev^{-1} (Ezugwu and Da Silva, 2005) and also when machining Inconel 718 at cutting speeds lower than 50 m min^{-1} and a feed rate o 0.25 mm rev^{-1} (Ezugwu and Bonney, 2003). This probably explains why proportional and/or further improvement in tool life was not recorded with SiCw ceramic tools at higher coolant pressure of 20.3 MPa.

Typical wear patterns observed when machining titanium alloys with ceramic cutting tools are notching and chipping of cutting edge, while flank and nose wear modes are typically encountered when machining with PCD tools. Here severe nose wear rate is dominant failure mode observed when machining with SiCw ceramic tools at all the machining environments at lowest cutting speed of 140 m min^{-1} as illustrated in Figs. 3 (a), (b), (d) and (f). Abrasion wear mechanism involves the loss of tool material by a hard particles trapped between the tool and workpiece material. The particles could be dislodged tool materials, fragments of built-up-edge or hard carbides and oxides already existing in the workpiece. The high compressive stresses acting at the tool-workpiece interface keep trapped hard particles between the machined surface and the tool. As the tool rubs over the machined surface, the particles plough through the tool removing material at the flank face. Abrasive wear at the rake face of the tool is due to sliding action of hard particles located at the under side of the chip as it passes over the rake face of the tool (Trent and Wright, 2000). SiC particles present in whiskers reinforced alumina ceramic tools may be responsible for abrasive mechanism wear here that generated severe nose wear. In some cases this phenomenon lead to chipping of cutting edge and eventually to catastrophic tool failure occurred when machining at speeds in excess of 140 m min^{-1} as illustrated in Fig. 3 (c). This type of wear occurs on a purely random manner and cannot be predicted. 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 and PCD tools as well as poor thermal and mechanical shock resistance. Additionally, ceramic tools have high reactivity with titanium alloys. Nose wear mode was the dominant failure mode observed when machining with PCD tool in all the conditions investigated. Figure 3 (f) shows a typical PCD worn insert after machining Ti-6Al-4V alloy under conventional coolant flow at a speed of 140 m min^{-1} where can be seen a regular nose wear spread along the flank face and also the evidence of crater wear developed on the rake face of the tool. So, it is clear from the machining results that improved properties of the silicon carbide (SiCw) whisker reinforced alumina ceramic tools have negligible effect on performance compared with ceramic tools commonly tested in machining of titanium alloys.

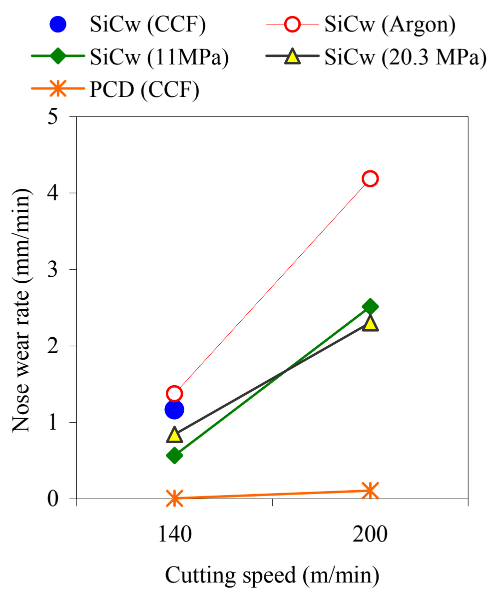


Figure 1. Nose wear curves when machining Ti-6Al-4V alloy with silicon carbide (SiCw) whisker reinforced alumina ceramic and PCD inserts under various machining environments

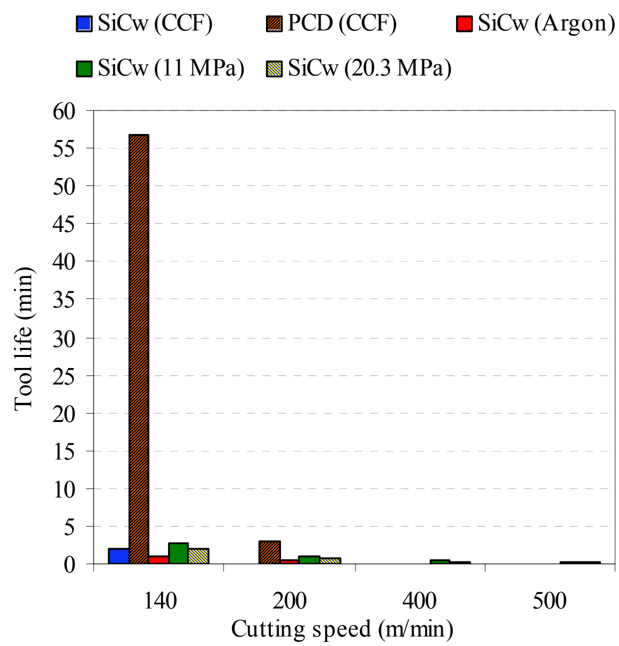


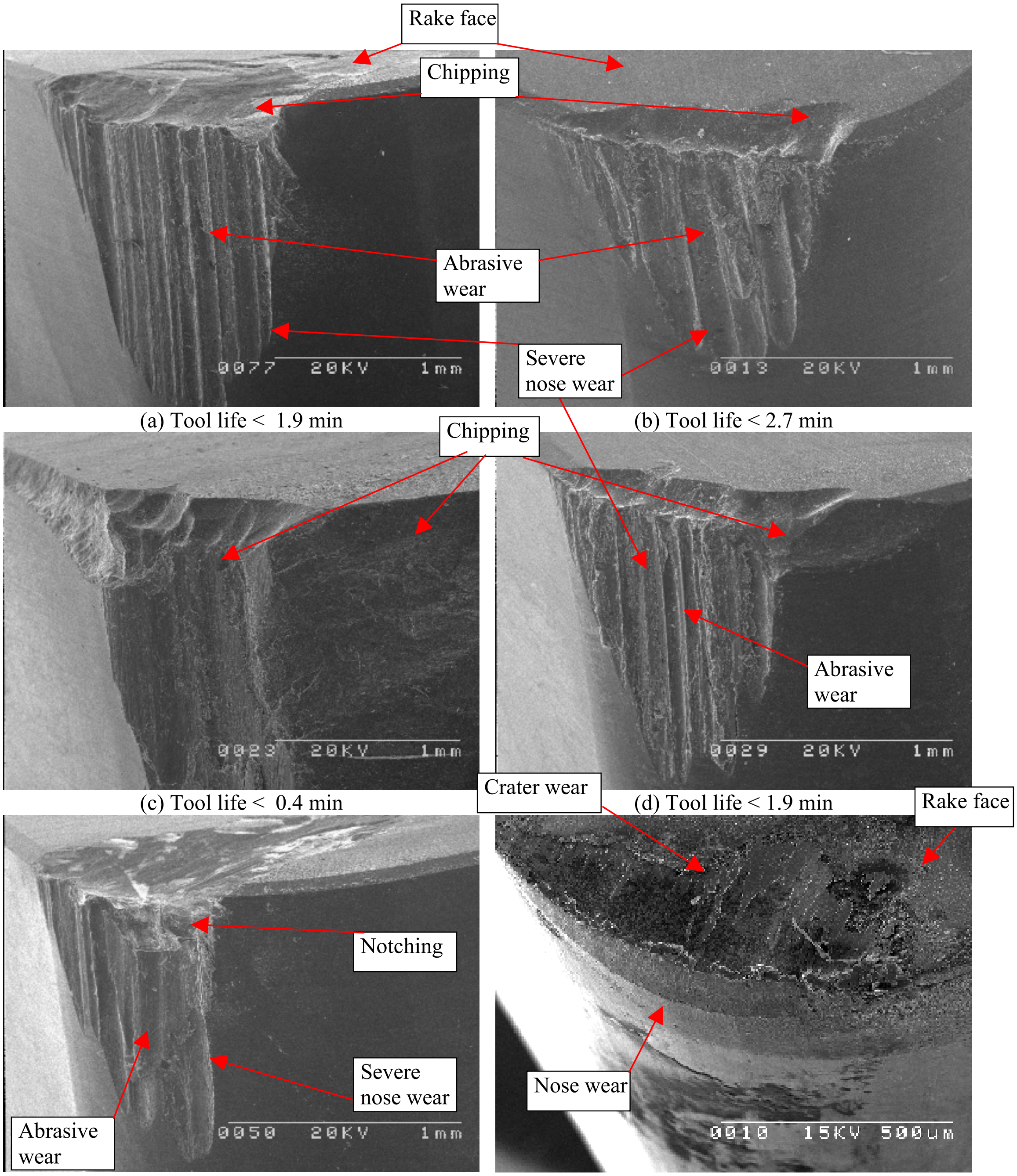
Figure 2. Tool life when machining Ti-6Al-4V alloy with silicon carbide (SiCw) whisker reinforced alumina ceramic and PCD inserts under various machining environments

3.2. Cutting and feed forces

Figures 4 and 5 show plot of cutting forces and feed forces, respectively, recorded when machining Ti-6Al-4V alloy with silicon carbide (SiCw) whisker reinforced alumina ceramic and PCD inserts at various cutting speeds and under various machining environments. Note that cutting and feed forces generated with SiCw ceramic tools were recorded only in presence of argon and with high pressure coolant supplies. It can bee seen that cutting forces generated during machining are higher than feed forces, as expected. Higher cutting forces were generated when machining under high pressure coolant supplies compared to argon enriched environment due to high wear rates. Figure 4 also shows that cutting forces generated with SiCw ceramic tools generally decreased with increasing cutting speed up to a speed of 400 m min^{-1} in all the machining environments, unlike when machining with PCD tools where cutting forces increased with cutting speed up to 200 m min^{-1}. Li and Low (1994) reported that cutting forces generated during machining can either decrease or increase with increasing speed. An explanation for the first phenomenon is based on the softening of workpiece material as a result of high temperature generated at the cutting interface. As a consequence, the shear strength of the workpiece material is lowered and hence lower cutting forces are required at high speed machining conditions. On other hand, cutting forces can also increase with increasing cutting speed when the wear rate of the tool increases due to the softening of tool material, hence higher cutting forces are required when machining at high speed conditions Zhan *et al.*, 2000). Figure 5 shows that similarly to cutting forces, higher feed forces were generated when machining under high pressure coolant supplies compared to argon enriched environment. Feed forces generally increase with cutting speed when machining under high pressure coolant supplies, unlike with argon. The lowest feed forces were recorded when machining in presence of argon. Minimum variation in feed forces with cutting speed was observed when machining with PCD tools.

3.3. Surface integrity analysis

Recorded surface roughness values recorded when machining with silicon carbide (SiCw) whisker reinforced alumina ceramic tools in all the conditions investigated vary between 2.1 µm and 5.5 µm, well above the stipulated rejection criterion of 1.6 µm, whereas surface roughness values recorded with PCD tools were 0.8 µm and 0.5 µm when at cutting speeds of 140 m min^{-1} and 200 m min^{1}, respectively, under conventional coolant flow. No evidence of plastic deformation was observed in machined surfaces of titanium alloy after machining with silicon carbide (SiCw) whisker reinforced alumina ceramic tools in all the conditions investigated. This is clearly illustrated in Figure 6 (a) and (b) which show the microstructures of the machined surface produced when machining with silicon carbide (SiCw) whisker reinforced alumina ceramic tools under conventional coolant flow and under high pressure coolant supply of 11 MPa at a lowest cutting speed of 140 m min^{-1} respectively.



(a) Tool life < 1.9 min (b) Tool life < 2.7 min

(c) Tool life < 0.4 min (d) Tool life < 1.9 min

(e) Tool life < 0.6 min (f) Tool life = 56.7 min

Figure 3. (a-e) Wear observed in (SiCw) whisker reinforced alumina ceramic tools after machining Ti-6Al-4V alloy under conventional coolant supply at a speed of (a) 140 m min^{-1}, coolant pressure of 11 MPa at speeds of (b) 140 m min^{-1} and (c) 400 m min^{-1}; coolant pressure of 20.3 MPa at a speed of (d) 140 m min^{-1} and in an argon enriched environment at a speed of (e) 200 m min^{-1}; (f) PCD worn tool under conventional coolant supply at a speed of 140 m min^{-1}

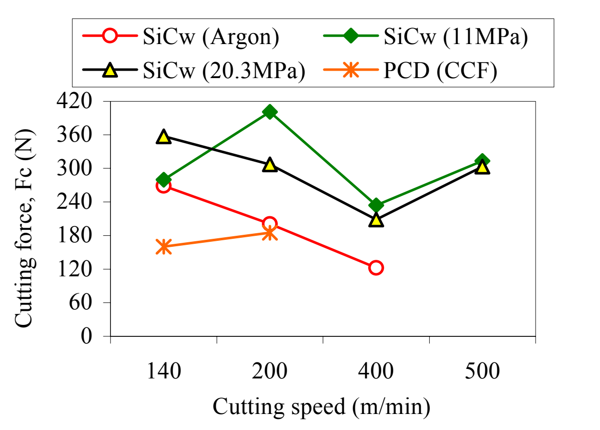


Figure 4. Cutting forces (F*c*) recorded during machining Ti-6Al-4V alloy with (SiCw) whisker reinforced alumina ceramic and PCD inserts under various cutting conditions (after 30 sec machining time)

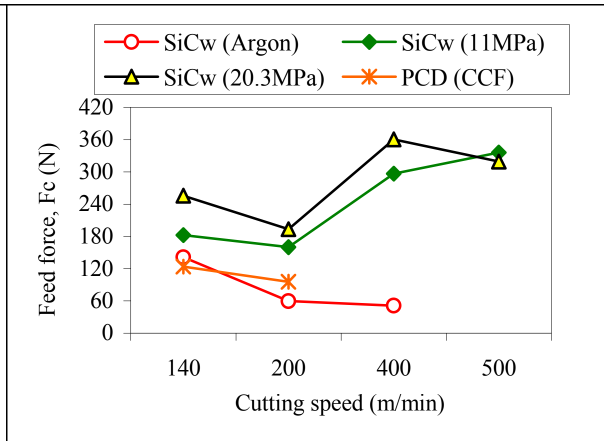
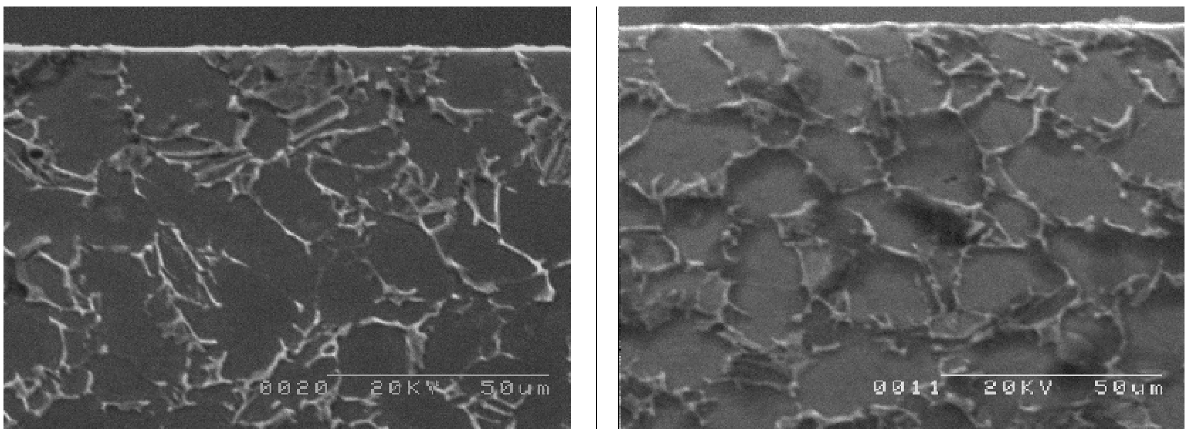


Figure 5. Feed forces (F*f*) recorded during machining Ti-6Al-4V alloy with (SiCw) whisker reinforced alumina ceramic and PCD inserts under various cutting conditions (after 30 sec machining time)



Tool life < 1.9 min

(b) Tool life < 2.7 min

Figure 6. Microstructure of Ti-6Al-4V alloy after machining with silicon carbide (SiCw) whisker reinforced alumina ceramic under (a) conventional coolant flow and (b) coolant pressure of 11 MPa at a cutting speed of 140 m min^{-1}

4. Conclusions

1. Machining Ti-6Al-4V alloy with silicon carbide (SiCw) whisker reinforced alumina ceramic cutting tools did not demonstrate satisfactory performance in terms of tool wear rate and tool life in all the conditions investigated, due to severe abrasive wear and chipping of the cutting edge;
2. Severe nose wear and chipping of cutting edge were the dominant tool failure modes when machining Ti-6Al-4V alloy whisker alumina ceramic tool while a regular nose wear spread along the flank face was responsible for PCD tool failure mode;
3. Machining in presence of argon with SiCw ceramic inserts provided highest nose wear rate in all the cutting speeds investigated, hence the lowest tool life relative to conventional and high pressure coolant supplies due probably to poor thermal conductivity of argon as well as its poor lubrication characteristics which tend to concentrate more heat at the cutting region, thus weakening the strength of the cutting tools and accelerating the tool wear.
4. Up to 2100% and 300% improvement in tool life were achieved when machining Ti-6A-4Valloy with PCD tools under conventional coolant flow at speeds of 140 m min^{-1} and 200 m min^{-1}, respectively, relative to ceramic tools.
5. Machining under high pressure coolant supplies of 11 MPa and 20.3 MPa resulted to decrease tool wear rate and consequently providing marginal improvement in tool life compared with argon and conventional coolant flow.
6. Machining with (SiCw) whisker reinforced alumina ceramic cutting tools under high pressure coolant supplies gave generally higher cutting and feed forces than when machining in presence of argon in all the conditions tested due to the high wear rates.
7. Machining with (SiCw) whisker reinforced alumina ceramic tools provided higher surface roughness values up to 5.5 µm, well above the stipulated rejection criterion of 1.6 µm;
8. No evidence of plastic deformation was observed in machined surfaces of titanium alloy after machining with silicon carbide (SiCw) whisker reinforced alumina ceramic tools in all the conditions investigated.

5. Acknowledgements

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

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