Evaluation of the Performance of Different Nano-Ceramic Tool Grades when Machining Nickel-Base, Inconel 718, Alloy

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High-speed machining of aerospace alloys can be enhanced by the use of advanced cutting tool materials such as nano-grain size ceramics that exhibit improved physical and mechanical properties than their micron grain counterparts. The performance of recently developed nano-grain size ceramic tool materials were evaluated when machining nickel base, Inconel 718, in terms of tool life, tool failure modes and wear mechanisms as well as component forces generated under different roughing conditions. The tools were rejected mainly due to wear on the tool nose. It is also evident that chemical compositions of the tool materials played significant role in their failure. The alumina base ceramics performed better than the silicon nitride base ceramics. Severe abrasion wear was observed on both rake and flank faces of the cutting tools while cutting forces increased with increasing cutting speed when machining with the silicon nitride base nano-ceramic tools. This is probably due to the lower superplastic flow temperature of the nitride base nano-ceramics. The alumina base ceramics are more susceptible to chipping at the cutting edge than the silicon nitride base ceramics despite their higher edge toughness.

***Keywords**: Inconel 718; nano-grain size ceramics; tool wear, superplastic flow, cutting forces*

Introduction

The automotive, aerospace and power industries have witnessed increased demand for critical components made from materials such as titanium and nickel base alloys primarily because of their light weight and high strength to weight ratios. This informed the need to explore ways to economically manufacture advanced components from these alloys. Nickel base alloys are considered as difficult to machine material when compared to steels with the same properties at room temperature since they maintain plastic deformation resistance at elevated temperature which impair machinability. They also exhibit high creep, corrosion resistance and strength. Because of their austenitic matrix, like stainless steel, they work-harden rapidly during machining in comparison to other materials, thus accelerating tool wear. Other factors that adversely affect machinability include the tendency of nickel base alloys to galling and welding especially on the rake face of cutting tools, the tendency to form built-up-edge (BUE) at relatively low cutting speeds, the presence of hard abrasive carbides in their microstructures that can accelerate the tool wear, the relative low thermal conductivity which can ensure high cutting temperature in the cutting edge of the tool. All these encourage the need to develop new cutting tool materials that will improve machinability and ensure longer tool life and better surface integrity of machined components. Cemented carbides (including coated carbides), ceramics, cubic boron nitride (CBN) and polycrystalline diamond (PCD) are the preferred tool materials currently employed when machining difficult-cut-materials. CBN and PCD tools are efficient when machining at higher speed conditions. A major disadvantage with these tools is usually their cost, hence the quest for cheaper tool material(s) that can equally perform well at higher cutting conditions. Ceramic tools are currently being used in larger quantities to machine difficult-to-cut alloys at high speed conditions due to their improved fracture toughness, thermal shock resistance and lower expansion coefficient (Kim, 1994).

The past decade has seen the development of advanced ceramics with sub-micron grain size for structural applications. These ceramics exhibit high strength, resistance to wear and corrosion at elevated temperature conditions where metallic alloys could not cope (Dominguez-Rodriguez et al., 1998 and Besson et al., 1998). The fine grained ceramics also called nano-ceramics have high specific surface area, improved thermal shock resistance, improved hardness and superplastic behaviour as well as low thermal expansion coefficient (4.5 x 10-6 ºC-1) (Besson et al., 1998; Vaβen et al., 1999 and Nordal et al., 2002). Powdered nano-ceramic is defined as a material where the major phase (or at least one constituent) has a grain size in the nanometer range (Vaβen et al., 1999). They have good formability properties due to their superplastic behaviour and hence can be formed into complex geometry. Superplasticity is defined as the ability of polycrystalline solids to exhibit exceptionally large elongation in tension (Xie et al., 2000 and Wakai et al., 1999). The properties of nano-ceramics to a greater extent depend on the processing technique employed. These are carried out in an environment free of contamination which is relatively difficult to achieve. Various processing techniques for the nano-ceramics have been developed such as such as gel precipitation technique (colloidal processing), hydrothermal synthesis, inert gas condensation method and aerosol process (Vaβen et al., 1999; Nordal et al., 2002; Kear et al., 2001 and Kaya et al., 2002). Because the mechanical properties of nano-ceramics surpass that of conventional ceramics, their potential as a cutting tool material for machining applications, especially for difficult-to-cut alloys, had to be explored.

Experimental Procedures

The machining trials were carried out on a CNC Centre 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. 200 mm diameter and 300 mm long cast solution treated, vacuum induction melted and electroslag remelted Inconel 718 alloy bars were used for the machining trials. The chemical composition and physical properties of the workpiece are given in Tables 1 and 2 respectively. Up to 6 mm thickness of the top surface of each bar was removed prior to actual machining trials in order to eliminate any surface defect that can adversely affect the machining result.

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Table 1. Composition of Inconel 718 (wt. %).

Si	S	Cr	Fe	Mo	Nb&Ta	Ti	Al	Ci	Ni
0.35	0.15	18.6	17.8	3.1	5.0	0.9	0.5	0.3	bal

Table 2. Physical properties of Inconel 718.

Tensile strength (MPa)	Yeld strength (MPa)	Elastic modulus (Gpa)	Hardness (HRC)	Density g cm^{-3}	Melting point (ºC)	Thermal conductivity W/mK
1310	1110	206	38	8.19	1300	11.2

Table 3. Chemical and physical properties of ceramic tool materials.

Code	Al_2O_3 (wt. %)	TiCN (wt. %)	ZrO_2 (wt. %)	Si_3N_4 (wt. %)	SiC (wt. %)	Y_2O_3 (wt. %)	Hardness (HV_5)	Edge toughness (MPa $m^{1/2}$)
T1	75	20	5	-	-	-	1779	10.54
T2	75	20	5	-	-	-	1530	7.32
T3	4.5	18.2	-	68.3	4.5	4.5	1670	6.92
T4	-	-	-	75	25	-	1637	8.62

Nano-ceramic inserts coded T1, T2, T3 and T4 with ISO tool designations SNGN 120412 were used for the machining trials. The nominal composition and physical properties of the inserts are given in Table 3.

The following cutting conditions were employed in this investigation:

- Cutting speed (m min-1): 230, 250, 270
- Feed rate (mm rev-1): 0.125, 0.15
- Depth of cut (mm): 1.5-3.0 Ramping tool path programming
- Coolant concentration (%): 6

These conditions can be applied for rough machining of nickel-base alloys in the manufacturing industry. A general purpose coolant containing alkaline salts of the fatty acids (Tri-(2-Hydroxyethyl)-Hexahydrotriazine) was used in all the machining trials. The tool rejection criteria for roughing operation were employed in this investigation. These values were considered in relation to ISO Standard 3685 for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of the following rejection criteria:

1) Average flank wear ≥ 0.4 mm
2) Maximum flank wear ≥ 0.7 mm
3) Nose wear ≥ 0.5 mm
4) Notching at the depth of cut line ≥ 1.0 mm
5) Surface roughness ≥ 6.0 µm
6) Excessive chipping (flaking) or catastrophic fracture of the cutting edge.

Cutting forces generated during the machining trials were measured using three components piezoelectric tool post dynamometer. Tool wear was measured with a travelling microscope connected to a digital readout device at a magnification of 25x. Surface roughness was measured at various intervals with a stylus type instrument.

Results and Discussions

Figures 1 and 2 show the tool lives obtained when machining Inconel 718 with the nano-ceramic tools at the cutting conditions investigated. The alumina base nano-ceramic tool T2 gave the best overall performance in terms of tool life followed by the T1 tool grade. Tools T1 and T2 have similar chemical compositions and with processing differing only in the extent of firing resulted in their different mechanical properties (Table 3). Addition of zirconium oxide (ZrO_2) improves the toughness and resistance to fracture of the alumina base tools (D`Errico et al 1999). Tool T1 should theoretically perform better than T2 tool because of its higher hardness and edge toughness (Table 3). This indicates that the performance of the nano-ceramic cutting tools can be improved by optimising the mechanical properties. Although T1 tool grade exhibited improved edge toughness needed for efficient machining, it is susceptible to failure by micro-chipping at the cutting edge because of its extreme hardness with associated brittleness. This, consequently, result in accelerated nose wear (Figure 3). This is because of the reduction in tool-chip and tool-workpiece contact areas at high speed conditions and the concentration of high temperature generated to a relatively smaller area closer to the cutting edge and the consequent increase in shear stresses at the cutting edge.

The Si_3N_4 based nano-ceramic tools T3 and T4 gave the least performance in terms of tool life, with the T4 tool grade showing the worst performance. The high nose wear rate and increasing cutting forces recorded at high cutting speeds when machining with T4 tool grade is contrary to expectation as its hardness and edge toughness is comparable with the best performing alumina base nano-ceramic tool T2. This flaw may probably be attributed to the softening of the constituent materials and the consequent weakening of their bond strength due to elevated temperature generated when machining at high speed conditions.

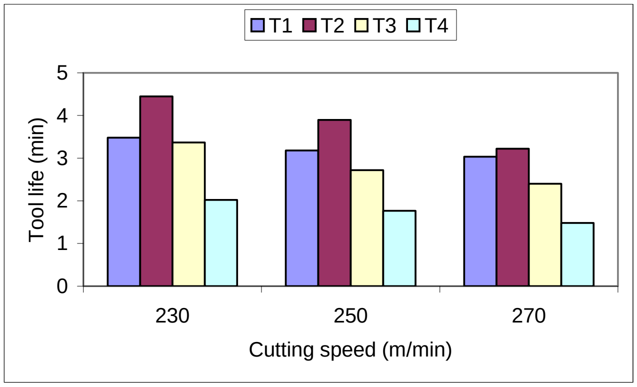

Figure 1. Tool life obtained when machining Inconel 718 with ceramic cutting tools at a feed rate of 0.125 mm/rev.

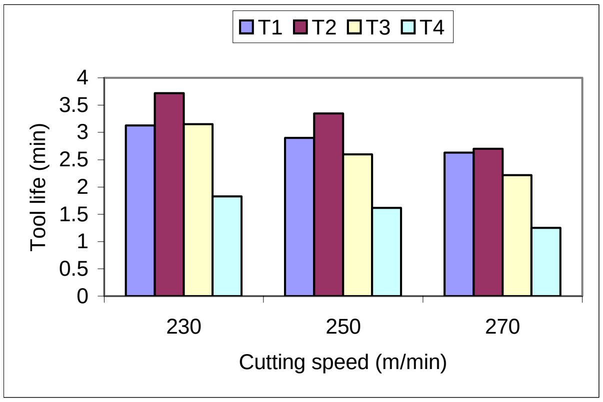

Figure 2. Tool life obtained when machining Inconel 718 with ceramic cutting tools at feed rate of 0.15 mm /rev.

Typical wear patterns observed when machining with the ceramics tools are nose, flank and notch wears. The alumina base nano-ceramics, T1 and T2 grades, are more susceptible to chipping during machining (Figures 3 and 4). The smooth regions on the worn rake and flank faces can be attributed to thermally related wear mechanism. The Si_3N_4 nano-ceramics tools experienced severe abrasive wear (Figures 5 and 6). T3 tool grade experienced abrasion mainly on the flank face, while the T4 tool grade showed severe abrasion wear on both the rake and flank faces. There are two possible ways that abrasion wear can occur when machining with ceramic tools. Hard wear debris (micro-chipped ceramic tool particles) and work material (hard carbide phases) are sandwiched between the machined surface and the tool at the cutting interface.These hard particles plough through the tool, removing tiny fragments or lumps of tool particles by mechanical action (Stachowiak et al., 1994). This type of wear mechanism has been reported when machining steel with ceramic tools (Goh et al., 1996). Abrasion wear mechanism in ceramic cutting tools can also be caused by plastic flow of the tool material due to the high temperature conditions encountered at the cutting interface (Stachowiak et al., 1994 and Goh et al., 1996). The lamina chip flow abrades the tool by stretching the contacting plasticised tool layer until necking. This type of abrasion wear can be seen clearly as parallel ridges in Figures 5 and 6 and is referred to as superficial or discrete plastic deformation. The mechanism for the formation of ridges on the worn flank face is attributed to seizure between the workpiece and the tool flank face. This leads to the establishment of a flow zone where the speed of the workpiece material increase gradually to the cutting speed employed during machining (Goh et al., 1996).

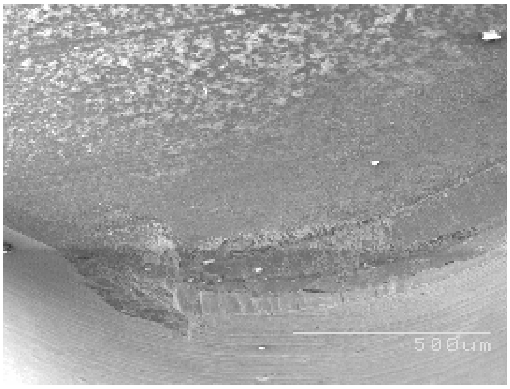

Figure 3. Wear generated after machining Inconel 718 with nano-ceramic T1 cutting tool at a cutting speed of 270 m/min and a feed rate of 0.125 mm/rev.

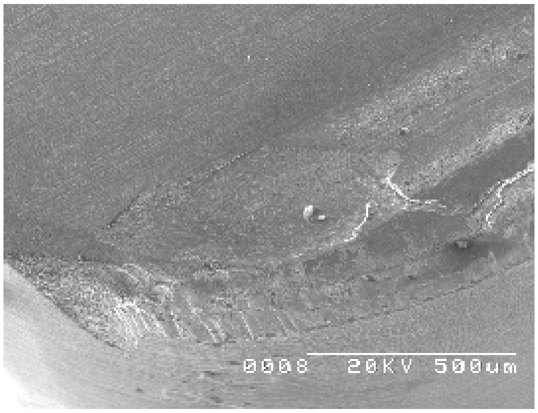

Figure 4. Wear generated after machining Inconel 718 with nano-ceramic T2 cutting tool showing micro-chipping and flaking of the cutting edge when machining at a cutting speed of 230 m/min and a feed rate of 0.15 mm/rev.

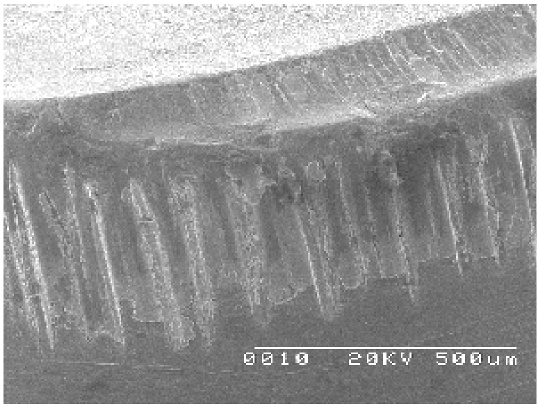

Figure 5. Wear generated after machining Inconel 718 with nano-ceramic T3 cutting tool at a cutting speed of 270 m/min and a feed rate of 0.125 mm/rev.

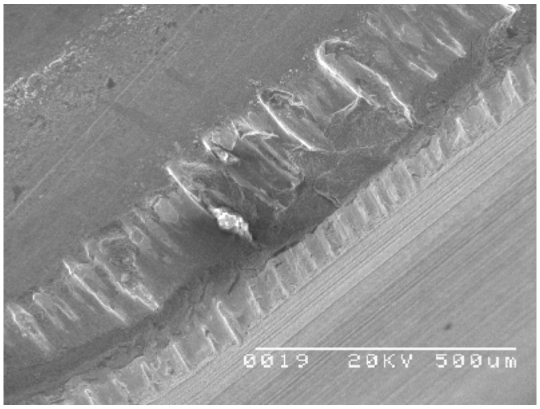

Figure 6. Wear generated after machining Inconel 718 with nano-ceramic T4 cutting tool at a cutting speed of 270 m/min and a feed rate of 0.125 mm/rev.

Generally flank wear rate is lower than the nose wear rates when machining with the nano-ceramic tools hence tools were rejected mainly due to wear on the tool nose. Figure 7 shows that the nose wear rates of the Si_3N_4 base tools, T3 and T4, are higher than their alumina based counterparts. In fact, the alumina based tool grades T1 and T2 exhibited similar nose wear rates when machining at the higher speed of 270 m min-1. The high nose wear rates observed particularly for T4 tool grade, could be attributed to the high superplastic property of the Si_3N_4 base ceramic. This tends to promote the softening of the tool material at higher speed conditions. Addition of alumina (Si_3N_4), titanium carbonitride (TiCN) and silicon carbide (SiC) to the T3 tool grade contributed to raising its softening temperature. Temperatures generated at the tool-workpiece interface when machining Inconel 718 at a speed of 120 m min-1 and a feed rate of 0.1 mm rev-1 can be very close to the melting point (1300ºC) of the alloy (Kramer, 1987). The possibility of generating higher temperatures within the range of the superplasticity of the nano-grain ceramic tools is eminent under the high speed rough machining conditions investigated in this study. Superplastic behaviour of β- Si_3N_4 generally occurs between 1350ºC – 1700ºC (Zhan et al., 2000). The tool-chip contact length/area generally reduces when machining at higher speed conditions, thus shifting the region of maximum temperature closer to tool nose that is already experiencing maximum normal and shear stresses. Under these circumstances de-bonding of tool material particles occurs, leading to increased nose wear rates, as the cutting forces required for efficient shearing of the workpiece material increases.

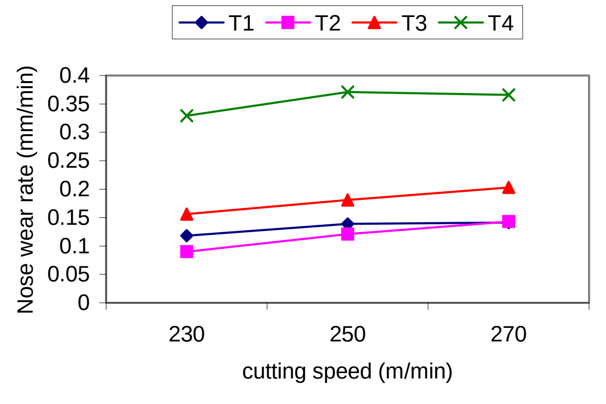

Figure 7. Nose wear rate when machining Inconel 718 with ceramic cutting tools at a feed rate of 0.125 mm/rev.

Chipping/fracture of the cutting edge (Figures 3 and 4) was observed only when machining with the alumina base T1 and T2 tool grades despite the improved edge toughness (Table 3). Flaking on the rake face was also observed on the worn T2 tool grade. Constant variation of the component forces as a result of the machining technique employed (ramping or taper turning) can induce high cyclic loading on the tool thus aiding the chipping process (es).

Understanding the behaviour of forces during machining is beneficial to tool design and component manufacture as excessive forces can induce vibrations which are detrimental to the quality of the machined components, hence cutting conditions are selected to prevent this from happening. Cutting forces generated during machining can either decrease with increasing speed or have the opposite effect (Li et al., 1994). In the first instance, the high temperature generated at the cutting interface results in the softening of the workpiece material. This results in the lowering of the shear strength of the workpiece material and hence lower cutting forces are required at high speed machining conditions. In the second scenario, the cutting forces increase with increasing cutting speed. Here the rate of tool material softening is higher than that of the workpiece material resulting in higher tool wear rates and hence increased cutting forces are required when machining at higher speed conditions (Zhan et al., 2000).

Figure 8 shows variations in cutting forces when machining with the nano-ceramic tools at various cutting speeds. The cutting forces decreased with increasing cutting speed as expected when machining with alumina base nano-ceramic tools T1 and T2. This shows that the tools maintain their hardness at higher speed conditions. Cutting forces generated when machining with the Si_3N_4 base nano-grain size tool grades T3 and T4 increased with increasing cutting speed contrary to expectation as both tools have mechanical properties comparable to the alumina base nano-ceramic tools. The effect of temperature on the softening and/or superplasticy of the ceramic tools used for machining can be explained with the forces recorded. The lowest cutting forces were recorded with the Si_3N_4 based T3 and T4 tools when machining at the lower speed of 230 m min-1 where temperature generated are below the critical value for superplastic flow. Despite the lower cutting forces generated when machining with the Si_3N_4 base T4 tool grade at the lower speed conditions, its performance is the worst, suggesting weaker bonding strength between Si_3N_4 and SiC tool material particles. Further increase in cutting speed resulted in a sharp increase in cutting forces. It is therefore reasonable to suggest that the superplastic flow temperature of T4 tool grade is significantly low and not suitable for machining Inconel 718.

The surface roughness values recorded in all the cutting conditions investigated are well below the stipulated rejection criterion of 6mm as illustrated in Figure 9. This figure however shows a gradual deterioration in the surface finish with prolonged machining and that increase in feed rate do not produce any significant change in the surface finish generated. The Si_3N_4 base T4 tool grade gave higher surface roughness value of 8 μm when machining at a feed rate of 0.125 mm rev-1.

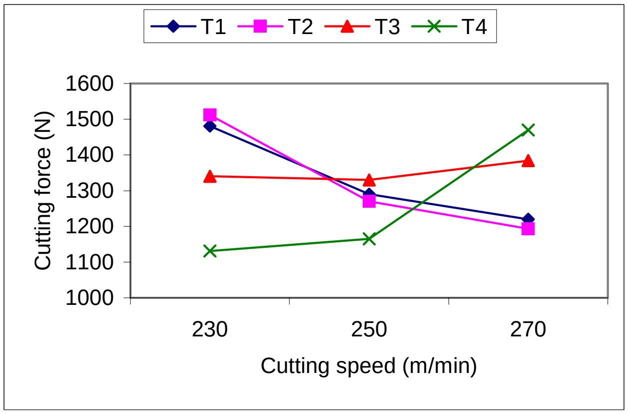

Figure 8. Cutting forces generated when machining Inconel 718 with ceramic cutting tools at a feed rate of 0.125 mm/rev.

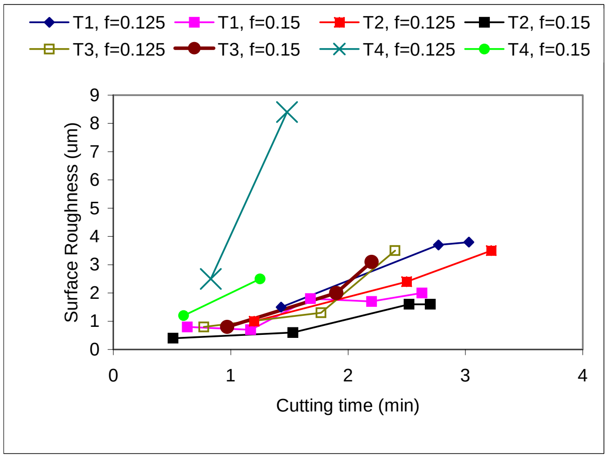

Figure 9. Surface roughness values recorded when machining Inconel 718 at a speed of 230 m min-^{1} with ceramic cutting tools.

Conclusions

1. i) The alumina (Al_2O_3) base nano-ceramic T2 tool grade gave the best performance in terms of tool life and surface roughness under the conditions investigated. This is followed by the T1 tool grade and lastly by the nano-grain Si_3N_4 base T3 and T4 tool grades in that order;
2. ii) Increase in cutting conditions generally led to increased nose wear rate. The highest wear rate occurred when machining with Si_3N_4 base nano-grain ceramic T4 grade;
3. iii) Nose wear is the dominant failure mode when machining Inconel 718 with all the nano-ceramic tools due primarily to excessive stresses and temperature generated at the tool tip caused by reduced tool-chip and tool-workpiece contact lengths/areas;
4. iv) Cutting forces decreased with increasing speed except for the nano-grain Si_3N_4 base tools which increased due to the relatively high nose wear rates;
5. v) Efficient exploitation of the nano-ceramics as cutting tool materials can be achieved if the critical superplastic temperature can be raised well above the cutting interface temperatures.

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