Journal of Materials Processing Technology 162–163 (2005) 609–614

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Machining of nickel-base, Inconel 718, alloy with ceramic tools under finishing conditions with various coolant supply pressures

E.O. Ezugwu [a,*], J. Bonney [a], D.A. Fadare [b], W.F. Sales [c]

[a] Machining Research Centre, FESBE, London South Bank University, London SE10AA, UK
[b] Department of Mechanical Engineering, University of Ibadan, Nigeria
[c] Manufacturing Research Centre, Department of Mechanical and Mechatronics Engineering, Pontifical Catholic University of Minas Gerais, Belo Horizonte, MG, Brazil

Abstract

Machining of Inconel 718 with whisker reinforced ceramic tool gave better performance in terms of tool life under high-pressure coolant supplies up to 15 MPa compared to conventional coolant supplies. The use of 15 MPa coolant supply pressure tend to suppress notching during machining thus improving tool life, while the use of higher coolant supply pressure of 20.3 MPa did not show improvement in tool life due probably to accelerated notch wear caused by water jet impingement erosion. Cutting forces decreased with increasing coolant supply pressure due to improved cooling and lubrication at the cutting interface as well as effective chip segmentation ensured by the momentum of the coolant jet. Surface roughness generated were well below the rejection criteria. This can be attributed to the round shape of the insert which tend to encourage smearing of the machined surface with minimum damage. Microstructure analysis of the machined surfaces show evidence of plastic deformation and hardening of the top layer up to 0.15 mm beneath the machined surface as a result of increase in dislocation density.

Keywords: Inconel 718; High-pressure coolant supply; Notching; Water jet impingement erosion; Cutting forces; Hardness depth; Plastic deformation

1. Introduction

Tool materials with improved room and elevated temperature hardness like cemented carbides (including coated carbides), ceramics and cubic boron nitride (CBN) are frequently used for machining nickel base superalloys. Despite recent advances in cutting tool materials, machining of nickel base superalloys at high speed conditions generally reduces the hardness and strength of cutting tools due to associated rise in cutting temperature. A temperature close to the melting point of Inconel 718 (1300°) has been recorded when machining with mixed oxide ceramic tool at a speed of 120 m min^{-1} and a feed rate of 0.1 mm rev^{-1} [1]. This generally weakens the bond strength of the tool substrate, thus accelerating tool wear by mechanical and/or thermally related wear mechanisms and possibly plastic deformation of the cutting edge of the tool.

The poor machinability of Inconel 718 is associated with the following factors: the tendency of nickel base alloys to galling and welding especially on the tool rake face, the tendency to form built-up-edge (BUE) at lower speed conditions, the presence of hard abrasive carbides in their microstructures that can accelerate the tool wear, and their relatively low thermal conductivity (22.3% lower than that of Steel CK 45). These characteristics are at the expense of the high temperature properties of superalloys used in aeroegines such as high creep and corrosion resistance as well as elevated temperature strength.

A credible route for achieving maximum performance from the available cutting tools when machining nickel base superalloys is to complement their outstanding properties with efficient cooling and lubrication techniques in order to minimise heat generated at the primary shear zone, chip–tool and tool–workpiece interfaces. One such technology that is gaining wide acceptance in the manufacturing industry is the use of high-pressure cooling technology. High-pressure cooling technique was first proposed and tested by Pigott and Col-

* Corresponding author.
E-mail address: ezugwueo@lsbu.ac.uk (E.O. Ezugwu).

0924-0136/$ – see front matter
doi:10.1016/j.jmatprotec.2005.02.144

well [2] who demonstrated a seven- to eight-fold increase in tool performance when machining steel. The cooling technology has now been perfected by the provision of efficient high-pressure cooling systems and tooling which is very appealing to industry in terms of costs [2–6].

The advantages of high cooling technology include significant improvement to tool life, effective chip segmentation and efficient cooling and lubrication. The penetration of the high-energy jet into the tool–chip interface reduces the temperature gradient and eliminates the seizure effect, offering adequate lubrication at the tool–chip interface with a significant reduction in friction in addition to alteration of the chip flow conditions resulting in the lowering of component forces and consequently tool wear rate [7]. The success of implementing this technology across the metal removal industries will therefore depend on increased research activities providing credible data for in depth understanding of high-pressure coolant supplies at the tool–chip, tool–workpiece interfaces and integrity of machined components.

2. Experimental procedures

A computer numerically controlled (CNC) lathe with a speed range from 18 to 1800 rpm was used for the machining trials. The lathe is driven by an 11 kW stepless motor which provides a torque of 1411 N m. Machining trials were conducted using 200 mm diameter × 300 mm long cast, solution treated, vacuum induction melted and electroslag remelted Inconel 718 alloy bars. The chemical composition and mechanical properties of the workpiece are given in Tables 1 and 2, respectively. A high lubricity emulsion coolant containing alkanolamine salts of the fatty acid and dicyclohexylamine was used for the machining trials. This coolant type is designed for delivery at high pressures due to its anti-foaming and non-splitting characteristics. The coolant under normal flow was applied by flooding the cutting interface at an average flow rate of 5 l/min using the CNC lathe coolant delivery system. The high-pressure coolant was supplied by an external high powered pump at a flow rate ranging from 20 to 50 l/min and directed via a nozzle on the tool holder to the region where the chip breaks contact with the tool. Whisker reinforced ceramic insert with ISO tool designations RNGN 120700 were used for the machining trials. The nominal composition and physical properties of the inserts are given in Table 3.

Table 1
Chemical composition (wt.%) of Inconel 718

C	0.08
Mn	0.35
Si	0.35
S	0.15
Cr	18.6
Fe	17.8
Mo	3.1
Nb and Ta	5.0
Ti	0.9
Al	0.5
Cu	0.3
Ni	Balance

Table 2
Mechanical properties of Inconel 718

Tensile strength (MPa)	1310
Yield strength (MPa)	1110
Elastic modulus (GPa)	206
Hardness (HV_{100})	427–454
Density (g cm^{-3})	8.19
Melting point (°C)	1300
Thermal conductivity (W/m K)	11.2

Table 3
Composition and mechanical properties of ceramic inserts

Al_2O_3 (wt.%)	75
SiC (wt.%)	25
Hardness (HV_3)	2000
K1C (MPa $m^{1/2}$)	5.2

The following cutting conditions were employed in this investigation:

- Cutting speed (m min^{-1}): 200, 270, 300.
- Feed rate (mm rev^{-1}): 0.1, 0.2.
- Depth of cut (mm): 0.5.
- Coolant concentration (%): 6.
- Coolant supply pressure (MPa): 11, 15, 20.3.

The tool rejection criteria for finishing operation were employed in this investigation. A cutting tool was rejected and further machining stopped based on one or a combination of the following rejection criteria in relation to ISO Standard 3685 for tool life testing:

- Average flank wear ≥0.3 mm.
- Maximum flank wear ≥0.4 mm.
- Nose wear ≥0.5 mm.
- Notching at the depth of cut line ≥0.6 mm.
- Surface roughness ≥3.0 μm.
- Excessive chipping (flaking) or catastrophic fracture of the cutting edge.

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

3. Results and discussion

3.1. *Performance of Whisker reinforced alumina ceramic tool*

Fig. 1 shows gradual improvement in tool life line when machining with increasing coolant pressure up to 15 MPa. Increase in tool life up to 71% was observed when machining

Inconel 718 at a speed of 250 m min^{-1} and a feed rate of 0.2 mm rev^{-1} (Table 4). It can also be observed in Table 4 that doubling the feed rate from 0.1 to 0.2 mm rev^{-1} had no adverse effect on tool performance, instead evidence of increased tool life was recorded when machining at coolant pressures up to 15 MPa.

Compared to results obtained when machining Inconel 718 under roughing conditions with coolant pressures up to 20.3 MPa, the performance of the ceramic tool reduced significantly due to excessive notching at the depth of cut region [8]. Improvement in tool performance when machining with coolant supply pressure up to 15 MPa suggests that the SiC whisker reinforced ceramic tools will perform better under high-pressure coolant supplies if a critical coolant pressure is not exceeded and if the right cutting conditions are employed. This is evident from finish machining with 20.3 MPa coolant supply pressure when a 63% drop in tool life was recorded at a cutting speed of 270 m min^{-1} and a feed rate of 0.2 mm rev^{-1} (Table 4). This is caused by rapid notch wear rate of the ceramic tool when machining with 20.3 MPa coolant pressure (Fig. 2) hence the drop in tool life under all speed conditions investigated. Notching phenomenon under the influence of high-pressure water jet cutting action occurred on a random basis as loose ceramic tool materials are easily eroded resulting in the lower tool life recorded when machining with 20.3 MPa coolant supply pressure (Fig. 1). Fig. 2 also illustrates the steady increase in notch wear rate with increasing cutting speed observed when machining with conventional and high-pressure coolant supplies up to 15 MPa. The least notch wear rates were recorded when machining with 15 MPa coolant supply pressure hence longer tool life were recorded, while accelerated wear rates occurred when turning with 20.3 MPa coolant supply

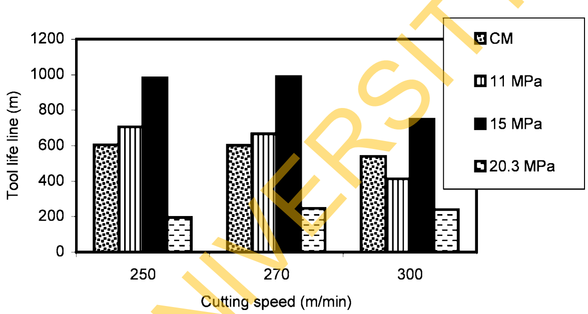


Fig. 1. Tool life line recorded after finish machining with whisker reinforced alumina ceramic tools at a feed rate of 0.1 mm rev^{-1}.

Table 4
Percentage variation in tool life relative to conventional coolant supply when machining Inconel 718 with SiC whisker reinforced alumina ceramic tool

Speed (m min^{-1})	Feed rate (mm rev^{-1})	11 MPa	15 MPa	20.3 MPa
250	0.1	16.9	62.4	−67.8
270	0.1	10.8	64.6	−58.7
300	0.1	−23.3	38.9	−55.6
250	0.2	42.4	70.6	−62.1
270	0.2	26.7	69.8	−63.4
300	0.2	−18.8	15.6	−62.5

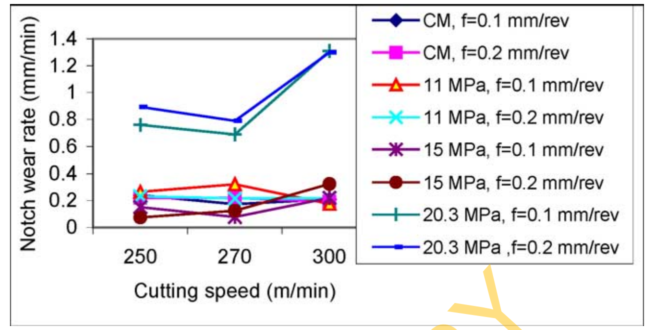


Fig. 2. Notch wear rates at various speed conditions when finish machining with whisker reinforced alumina ceramic tools.

pressure resulting in poor tool performance. The micrograph of the worn ceramic tool after machining with 20.3 MPa coolant supply pressure (Fig. 3(a)) shows that notching at the depth of cut region of the tool extends across the rake face. Generally notching on the rake face of the ceramic tool was not pronounced when machining with conventional and coolant pressures up to 15 MPa (Fig. 3(b)). This therefore reinforces the fact that machining with ceramics under the cutting conditions investigated with coolant pressures of 20.3 MPa pressure significantly encourages the formation of notch wear. The mechanism of accelerated notch wear on both the rake and flank faces of ceramic tool when machining Inconel 718 was attributed to water jet impingement (hydrodynamic) erosion [8]. The erosion process is accelerated by increasing coolant pressure because of the creation of a higher stagnation pressure with severe erosion capabilities which is detrimental to brittle materials such as ceramics.

3.2. Cutting forces

Lower cutting forces were recorded with increasing coolant supply pressure when machining Inconel 718 with SiC whisker reinforced alumina ceramic tool (Fig. 4). This is because coolant supply at high-pressure is able to access the cutting interface, ensuring effective cooling, lubrication and reducing the cutting interface temperature. This will consequently result in uniform flank wear and the gradual wear rate recorded. The reduction in cutting forces observed is also partly due to the chip segmentation when machining with high-pressure coolant supplies (Fig. 5(a)). Higher forces were recorded when machining with conventional coolant flow where continuous type chips were generated (Fig. 5(b)). Coolant supply at high-pressure tends to lift up the chip after passing through the deformation zone resulting to a reduction in the tool–chip contact length/area [6]. Chip segmentation is considerably enhanced, as the chip curl radius is reduced significantly, due to targeted maximum coolant pressure/force on to the chip which aids the chip shearing process and consequently lowering cutting forces. The chip curl radius also depends on the coolant pressure and the flow rate. Therefore at a given power, smaller chip curl radius could be achieved at a lower coolant pressure with a high coolant flow rate [4].

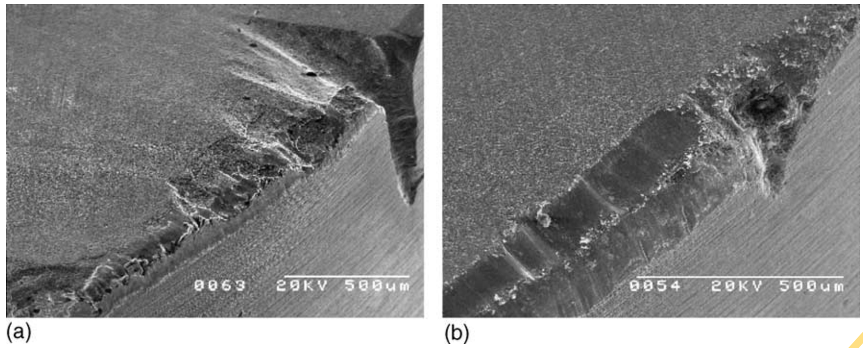


Fig. 3. Flank and notch wear after machining Inconel 718 (a) with 20.3 MPa coolant supply at a speed of 300 m min^{-1} a feed rate of 0.2 mm rev^{-1} and (b) with conventional coolant at a speed of 270 m min^{-1} a feed rate 0.2 mm rev^{-1}.

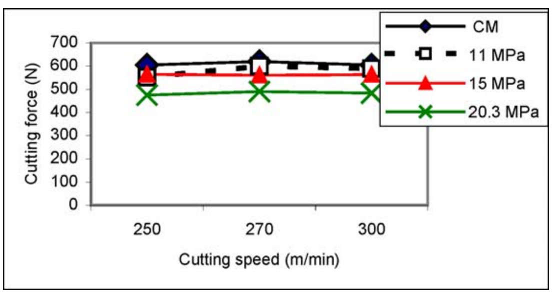


Fig. 4. Cutting forces recorded when finish machining with whisker reinforced alumina ceramic cutting tools at various cutting speeds and a feed rate of 0.2 mm rev^{-1}.

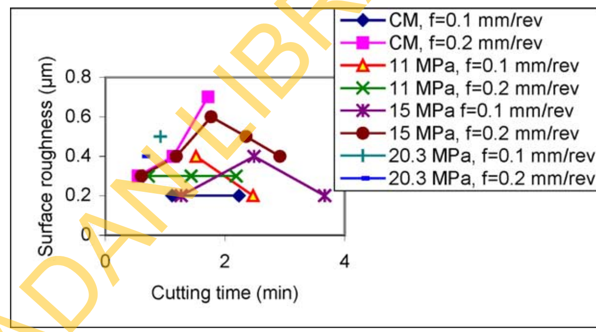


Fig. 6. Surface roughness values recorded when machining with ceramic tools at a cutting speed of 270 m min^{-1}.

The chips generated when machining with ceramic tools under both conventional and high-pressure coolant supplies comprise of highly segmented needle like (compressed) chips joined together in a continuous fashion. The chips are of the catastrophic shear localised type with sharp serrated edges. The mechanism for shear localised chip formation involves initially plastic instability and strain localisation at a narrow band with a gradual build-up of segments on the shear plane with negligible deformation by upsetting work material by the advancing tool [9].

3.3. Surface finish

Fig. 6 show curves for the surface roughness values recorded when machining Inconel 718 with whisker reinforced ceramic tools under conventional and high-pressure coolant supplies. Generally improved surface roughness values, well below the stipulated rejection criterion of 3 µm, were obtained when machining with the SiC whisker reinforced Al_2O_3 ceramic tools under the cutting conditions investigated. This is to a greater extent due to the round shape (RNGN 120700) of the ceramic tool with a large contact radius (6 mm) with the workpiece material, thus its ability to produce high quality surface finish. This is in agreement with the established equation,

$$R_a = \frac{0.321 f^2}{r}$$

where f is the feed rate and r is the nose radius (contact radius in this case) of the tool. The equation show that the bigger the nose radius the better the surface finish generated, hence a better surface finish is generated when machining Inconel 718 alloy with round whisker reinforce Al_2O_3 ceramic tools under high-pressure and conventional coolant supplies.

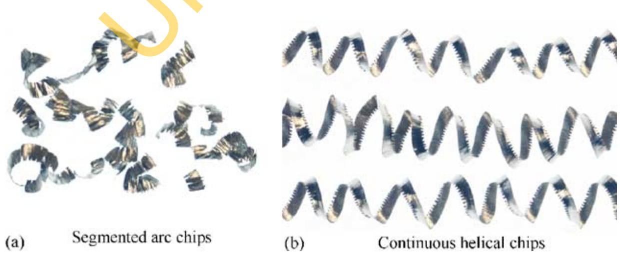


Fig. 5. Chips generated when finish machining Inconel 718 with whisker reinforced ceramic tools under (a) coolant supplies up to 20.3 MPa (b) conventional coolant flow.

3.4. Surface Integrity of machined surface

Fig. 7(a) and (b) are micrographs of surfaces generated when machining Inconel 718 under finishing conditions with conventional and high-pressure coolant supply. It can be seen that the surfaces generated consist of well-defined uniform feed marks running perpendicular to the direction of relative work-tool motion with no evidence of plastic flow. No surface tears and chatter marks were observed after machining

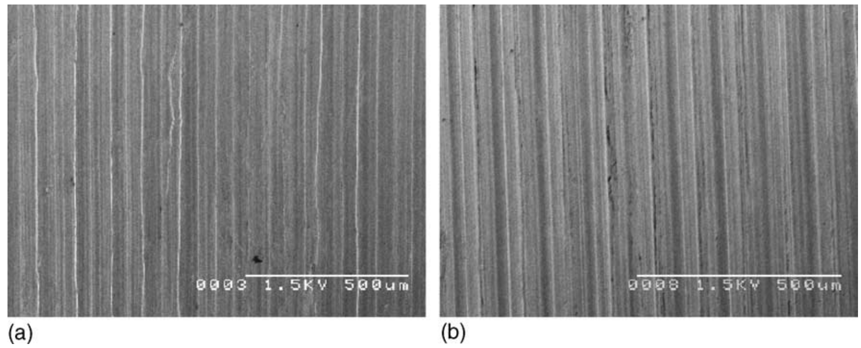


Fig. 7. Surfaces generated after finish machining Inconel 718 with whisker reinforced Al_2O_3 ceramic tools with 15 MPa coolant supply (a) at a speed of 250 m min^{-1} and a feed of 0.1 mm rev^{-1} and (b) at a speed of 270 m min^{-1} and a feed of 0.1 mm rev^{-1}.

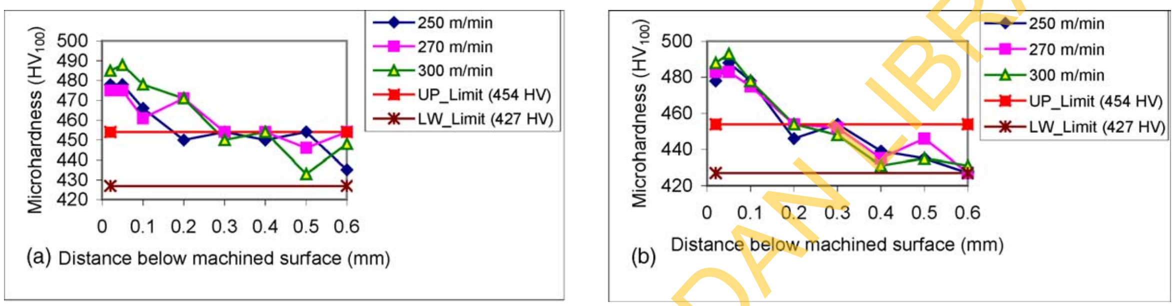
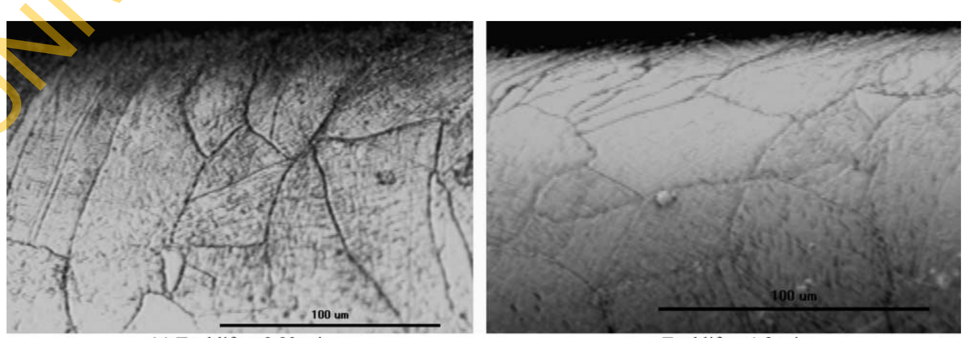


Fig. 8. Hardness variation of machined surface after machining Inconel 718 with whisker reinforced Al_2O_3 ceramic tools: (a) feed rate of 0.2 mm rev^{-1}under conventional coolant supply and (b) feed rate of 0.2 mm rev^{-1}under 11 MPa coolant supply.

Inconel 718 with whisker reinforced Al_2O_3 ceramic tools. Generally the machined surfaces generated conform to the standard specification established for machined aerospace components.

Microhardness measurements from the machined surface indicate increased hardness of the material at the top surface up to 0.2 mm beneath the machined surface under the finishing conditions investigated (Fig. 8). This can be associated with increase in the dislocation density due to plastic deformation. Also Inconel 718 has an austenitic structure, hence this deformation process results to work hardening of the deformed layer beneath the machined surface [10]. Further away from the machined surfaces, the hardness decreases until it reaches the hardness of the base material between 427 and 454 HV. Increasing the cutting speed or the feed rate increases the hardness and depth of the affected layer as increased cutting temperature leads to increased thermal activities of the alloy matrix.

Plastic deformation of the machined surfaces can be clearly seen in Fig. 9 where the microstructures of the etched machined surfaces show shear deformation in the cutting direction. The average depth of the plastically deformed layer when machining Inconel 718 with whisker reinforced ceramic tools with conventional coolant flow, ranges from 40 to 60 μm and 30 to 50 μm with high-pressure coolant supplies. Reduction in the plastically deformed layer when machining with high-pressure coolant supplies may be associated with more efficient cooling obtained relative to conventional



(a) Tool life = 2.83 min Tool life = 1.3 min

Fig. 9. Microstructure of Inconel 718 after finish machining whisker reinforced Al_2O_3 ceramic tools under 110 bar coolant supply at (a) speed 250 m min^{-1}, feed rate of 0.1 mm rev^{-1} and (b) speed of 300 m min^{-1} and feed rate of 0.2 mm rev^{-1}.

coolant flow. Surface defect characteristics such as laps, tearing and cracks were not observed in the etched samples.

4. Conclusions

Machining of Inconel 718 alloy with SiC whisker reinforced alumina ceramic tool under high-pressure coolant supplies tends to improve tool life with increasing coolant pressure up to 15 MPa under finish machining conditions. Lower tool life were generated with 20.3 MPa coolant supply pressure due to accelerated notching.

Lower cutting forces where generated when machining Inconel 718 with whisker reinforced ceramic tool at higher coolant supply pressures due to improved cooling and lubrication (low frictional forces) at the cutting interface and also as a result of chip segmentation caused by the high-pressure coolant jet.

Accelerated notch wear on both flank and rake faces of the SiC whisker reinforced alumina ceramic tool during machining can also be caused by water jet impingement erosion of the ceramic cutting tool by the high-pressure coolant.

Very low surface roughness values were recorded when machining Inconel 718 alloy with the SiC whisker reinforced alumina ceramic tool. This is due to the big contact radius (6 mm) of the ceramic tools.

Hardening of the top surface, up to 0.2 mm beneath the machined surfaces occurred when machining with conventional and high-pressure coolant supplies. This is associated with the increase in dislocation density due to plastic deformation of the machined surface.

Plastic deformation of the surface layers extends on average to between 30 and 50 μm below the machined surface when machining with ceramic tools under the high-pressure coolant conditions investigated.

Acknowledgements

The authors would like to thank Rolls-Royce plc, Houghton plc, Pumps and Equipment (Warwick) UK Ltd. and Sandvik Coromant for their support that enabled this work to be carried out.

References

[1] B.M. Kramer, On tool materials for high speed machining, J. Eng. Ind. 109 (1987) 87–91.
[2] R.J.S. Pigott, A.T. Colwell, Hi-jet system for increasing tool life, SAE Quart. Trans. 6 (3) (1952) 547–566.
[3] M. Mazurkiewicz, Z. Kubala, J. Chow, Metal machining with high-pressure water-jet cooling assistance—a new possibility, J. Eng. Ind. 111 (1989) 7–12.
[4] R. Crafoord, J. Kaminski, S. Lagerberg, O. Ljungkrona, A. Wretland, Chip control in tube turning using a high-pressure water jet, in: Proceedings of the Institution of Mechanical Engineers, Part B, vol. 213, 1999, pp. 761–767.
[5] A.R. Machado, J. Wallbank, The effect of high-pressure jet on machining, in: Proceedings of the Institution of Mechanical Engineers Part B, vol. 208, 1994, pp. 29–38.
[6] E.O. Ezugwu, A.R. Machado, I.R. Pashby, J. Wallbank, The effect of high-pressure coolant supply when machining a heat-resistant nickel-based superalloy, Lubric. Eng. 47 (9) (1990) 751–757.
[7] E.O. Ezugwu, J. Bonney, Y. Yamane, An overview of the machinability of aeroengine alloys, J. Mater. Process. Technol. 134 (2003) 233–253.
[8] J. Bonney, High-speed machining of nickel-base, Inconel 718, alloy with ceramic and coated carbide cutting tools using conventional and high-pressure coolant supplies, PhD Thesis, London South Bank University, June 2004.
[9] R. Komanduri, B.F. Von Turkovich, New observations on the mechanism of chip formation when machining titanium alloys, Wear 69 (1981) 179–188.
[10] S. Kalpakjian, Manufacturing Processes for Engineering Materials, 2nd ed., Addison-Wesley Publishing Company, 1991.