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High speed turning of Inconel 718 using PVD-coated PCBN tools

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ABSTRACT

Five different coatings and two PCBN grades were evaluated when high speed turning Inconel 718. Tool life was 40% higher when employing TiSiN coated over uncoated inserts at 200 m/min. When operating at 300–450 m/min however, coatings provided no appreciable benefit. Workpiece surface roughness varied between ~0.25 and 1.05 μm Ra while cutting forces were <300 N. Increased workpiece microhardness and microstructural deformation were apparent with worn inserts. Medium cBN content (65%) inserts generated near surface compressive residual stresses of approximately −440 MPa as opposed to values of −90 MPa (measured parallel to feed) when using low cBN content (50%) tools.

1. Introduction

Polycrystalline cubic boron nitride (PCBN) 'compacts' for cutting tools appeared during the 1970s, initially with the introduction of high cBN content (~85–95%) materials employing a metal alloy, carbide or ceramic binder/second phase. During subsequent decades the range of PCBN products expanded with grades encompassing variations in cBN grain size (~0.5–10 μm) and binder content (~2–60%) together with an extended range of associated ceramic materials and reinforcement in order to allow for wider work material usage and improved performance [1]. Focus has also recently centred on binderless cBN products with applications including ultraprecision machining of hardened steels [2,3].

Despite these developments the scope for PCBN use still remained somewhat restricted, in that the turning and to a lesser extent milling of hardened ferrous alloys (50–65 HRC), sintered alloys, chilled/nickel-chromium cast irons, pearlitic grey irons and a limited range of Ni/Co based superalloys, were the main focus of attention, both technical and cost factors limiting operation with mainstream workpiece materials. Attempts to broaden this field through the use of more cost effective micron scale cBN coatings on carbide or ceramic substrates, has met with only limited success and despite positive reports of progress [4], there are few commercial products. In contrast, the deposition of ceramic coatings on PCBN tools has proved more successful and over the last decade or so there has been growth in commercial products and the number of academic papers citing related machinability work on hardened steels [5,6], and to a lesser extent superalloys [7].

The rationale for using PCBN over carbide or more conventional ceramic tooling is increased productivity/tool life through the employment of significantly higher cutting speeds. For complex aerospace alloys such as Inconel 718 in the solution treated and aged condition, the cutting speed limit for coated carbides is ~80 m/min, whereas it is suggested that this can be raised to between 200 and 400 m/min or possibly higher with appropriate uncoated PCBN tooling [8,9]. Nevertheless, compared with the machining of hardened steels, the performance of PCBN in relation to nickel based superalloys as a group, has been less effective, not least due to developments with lower cost whisker reinforced alumina products. The current paper assesses the feasibility of a number of coatings on PCBN tooling for improving machinability when high speed turning Inconel 718, as a benchmark for potential application on a wider range of superalloys.

2. Experimental work

The turning trials were performed on a MHP MT-80 CNC turning centre having a variable spindle speed of 3000 rpm rated at 30 kW. The workpiece material was a bar (108 mm diameter × 375 mm length) of Inconel 718 nickel based superalloy in the solution treated and aged condition with a bulk hardness of ~44 HRC. The majority of tests utilised rhomboid shaped (CNGA120408), medium concentration (65% cBN content) PCBN tipped inserts with 4 cutting edges (double sided) supplied by Seco Tools

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(product code: CBN170). These employed a 2 μm grain size and TiCN binder/second phase together with SiC whisker reinforcement, which was designed to provide greater toughness and improved wear resistance for machining high temperature strength superalloys. The performance of low concentration PCBN inserts (CNGA120412) containing 50% cBN content and TiC ceramic binder (product code: DCC500), was assessed against the CBN170 tools in terms of workpiece residual stress. The hardness of the DCC500 grade was ~2550 HV with a thermal conductivity of 38 W/mK. The PCBN blanks were produced by Element Six. All inserts were delivered with a honed edge radius of 25 μm. This was selected over a chamfered edge condition due to the moderate hardness and ductility of the workpiece material and in order to minimise strain hardening effects.

A variety of physical vapour deposited (PVD) coatings from different manufacturers were investigated and applied on the CBN170 inserts only, see Table 1 for details. All of the coatings were multi-layered except for the TiSiN product, while inserts with the AlCrN coating had non-uniform thicknesses on the rake and flank faces. Additionally, the CrAlN coating was supplied with 2 different thicknesses of 3.0 and 5.5 μm, which were denoted as CrAlN 1 and CrAlN 2 respectively. All inserts were held in a Seco Jetstream toolholder (PCLNR2525M12JET), which incorporated special inducer nozzles to direct cutting fluid into the cutting zone. This provided principal and minor cutting edge angles of 95° and 5° respectively, a normal clearance angle of 6° together with normal rake and inclination angles of −6°.

Table 1
Details of coatings used.

Coating	Thickness (μm)	Hardness (HV)	Configuration
TiSiN	1.5	~3570–4080	Single layer
TiSiN/TiAlN	2.0	~3060–3570	Multilayer
AlCrN	2.95 (F)/1.62 (R)	3200	Multilayer
CrAlN 1	3.0	3000	Multilayer
CrAlN 2	5.5	3000	Multilayer

(F) – flank face; (R) – rake face.

Tool wear was measured using a Wild M3Z toolmakers microscope equipped with a digital micrometre platform and connected to a digital camera for image capture. The toolholder was clamped onto a Kistler 9257A platform dynamometer for cutting force assessment. This was attached to a bespoke fixture to enable mounting on the lathe tool turret. A Mitutoyo Surftest 301 portable unit was used to measure workpiece surface roughness at regular intervals during experiments. This employed a cut off length of 0.8 mm and evaluation distance of 4.0 mm. Cross sectioned workpiece samples were hot mounted, ground and polished according to established procedures and subsequently etched with Kalling's No. 2 reagent. Microhardness depth profile measurements were undertaken using a Mitutoyo microhardness tester fitted with a Knoop indenter operating at a load of 25 g with a dwell time of 15 s. A Leica optical microscope with a digital camera was utilised for workpiece microstructural analysis, while a scanning electron microscope (SEM) was employed for high resolution images.

The experimental work was carried out over 3 phases. Depth of cut and feed rate was kept constant at 0.2 mm and 0.15 mm/rev respectively to reflect industry acceptable finishing conditions, while the end of test criterion was a maximum flank wear (VB_{max}) of 0.2 mm. All trials were performed wet using a water based emulsion with ~10% soluble oil, which was delivered at a pressure of 10 bar and flow rate of 6.5 l/min unless otherwise stated. Phase 1 involved a full factorial experiment (18 tests) using uncoated and coated CBN170 inserts to assess the effect of coating type and cutting speed on tool life/wear, cutting forces and workpiece surface roughness, see Table 2 for test conditions.

Workpiece integrity evaluation in terms of surface damage, subsurface microstructure and microhardness was undertaken in Phase 2 work, but only for selected test conditions from Phase 1 due to limitations in workpiece material and coated insert numbers. Test specimens were produced using uncoated CBN170 inserts (new and worn) and coated inserts (all 5 products but in the new condition only) at a cutting speed of 300 m/min, as this had provided the best balance of productivity and tool life/wear progression in Phase 1. Worn uncoated and TiSiN coated inserts were also evaluated at a cutting speed of 200 m/min, as these recorded the longest tool lives, together with new and worn uncoated CBN170 inserts at 450 m/min. Worn coated inserts were generally not considered as there was no major difference in tool life compared to equivalent uncoated products.

Table 2
Phase 1 experimental test array and corresponding factor levels.

Test no.	Cutting speed (m/min)	Insert coating type
1	200	Uncoated
2	200	TiSiN
3	200	TiSiN/TiAlN
4	200	AlCrN
5	200	CrAlN 1
6	200	CrAlN 2
7	300	Uncoated
8	300	TiSiN
9	300	TiSiN/TiAlN
10	300	AlCrN
11	300	CrAlN 1
12	300	CrAlN 2
13	450	Uncoated
14	450	TiSiN
15	450	TiSiN/TiAlN
16	450	AlCrN
17	450	CrAlN 1
18	450	CrAlN 2

Phase 3 research was confined to a limited assessment on the influence of insert condition, cutting fluid pressure and PCBN grade on workpiece residual stress, see Table 3. Residual stress was measured using the blind hole drilling method to a depth of 512 μm below the machined surfaces. Test samples for evaluation were 27 mm thick × 100 mm diameter discs which were cut from the ends of the Inconel 718 bar. These were face turned at appropriate conditions to maintain a cutting speed of 300 m/min.

Table 3
Phase 3 experimental test array and corresponding factor levels.

Test	PCBN grade	Insert condition	Cutting fluid pressure
A	DCC500	New	10 bar
B	DCC500	Worn	10 bar
C	DCC500	New	100 bar (24 l/min)
D	CBN170	New	10 bar

3. Results and discussion

Fig. 1 shows the evolution of flank wear against machining time for the various coated/uncoated PCBN inserts in Phase 1 trials. The longest tool life of ~8.8 min was achieved when turning at 200 m/min using the TiSiN coated insert in Test 2, which was ~40% higher than the corresponding uncoated product in Test 1 (~6.4 min). In contrast, all of the remaining coated inserts at this cutting speed (Tests 3–6) machined for less than 1 min. The principal failure mode for all inserts operating at 200 m/min was depth of cut notching, although flank and crater wear together with adhered chips were also prevalent, see examples in Fig. 2. The notch wear observed was likely caused by a combination of tool-workpiece welding/adhesion and seizure of the strain hardened serrated chips at the depth of cut position leading to pullout/tearing of the tool material. Oxidation and stress concentration considerations were judged to play a lesser role, the use of fluid to envelope the