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DOI:
[10.1016/j.cirp.2016.04.044](https://doi.org/10.1016/j.cirp.2016.04.044)

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Document Version
Peer reviewed version

Citation for published version (Harvard):
Soo, S, Khan, S, Aspinwall, D, Harden, P, Mantle, AL, Kappmeyer, G, Pearson, D & M'Saoubi, R 2016, 'High speed turning of Inconel 718 using PVD-coated PCBN tools', *CIRP Annals - Manufacturing Technology*, vol. 65, no. 1, pp. 89-92. <https://doi.org/10.1016/j.cirp.2016.04.044>

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Checked for eligibility: 05/05/2016.

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

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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 ~0.25-1.05 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.

Coating, Surface integrity, Nickel alloy

1. Introduction

Polycrystalline cubic boron nitride (PCBN) 'compacts' for cutting tools appeared during the 1970's, 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 200-400 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 \times 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 (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	$\sim 3570\text{-}4080$	Single layer
TiSiN/TiAlN	2.0	$\sim 3060\text{-}3570$	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 $\sim 10\%$ 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 \times 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 $\sim 40\%$ 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 cutting edge and the limited depth of cut employed in relation to the tool nose radius of 0.8 mm, minimising adverse interaction at the depth of cut position. A possible reason for the inferior performance in Tests 3-6 was the poor integrity and uniformity of the AlCrN and CrAlN coatings especially over the honed edge radius. These imperfections could have been due to inappropriate coating process conditions or insufficient surface treatment/preparation of the PCBN substrate. 'Pores' were also visible on the surfaces of the TiSiN/TiAlN

inserts due to droplet deposits from the PVD coating process and their subsequent removal, see Fig. 3 for SEM micrographs of tools prior to cutting. Unfortunately, a new batch of coated inserts could not be supplied due to restrictions on resources and time. Low film thickness distribution near the cutting edge and weak adhesion strength generally has a detrimental effect on machining performance as outlined by Bouzakis et al. [10]. The inserts coated solely with TiSiN exhibited a more consistent edge profile similar to the uncoated tools. This coupled with its higher hardness most likely led to its superior tool life.

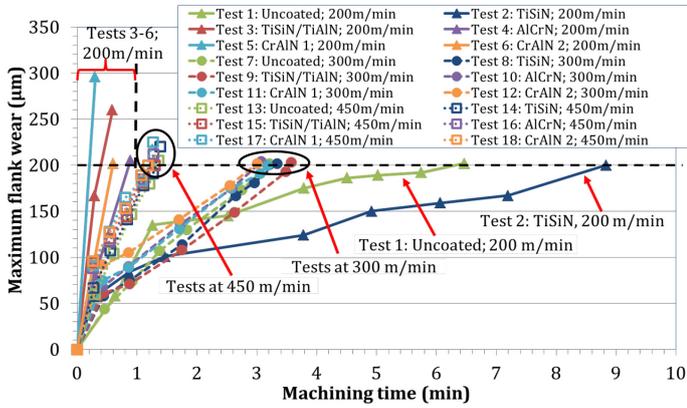


Fig. 1. Insert flank wear progression against time in Phase 1 tests.

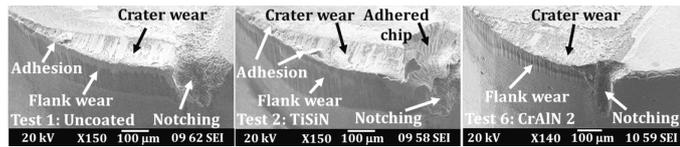


Fig. 2. Sample SEM micrographs of insert wear scars at test cessation when turning at 200 m/min.

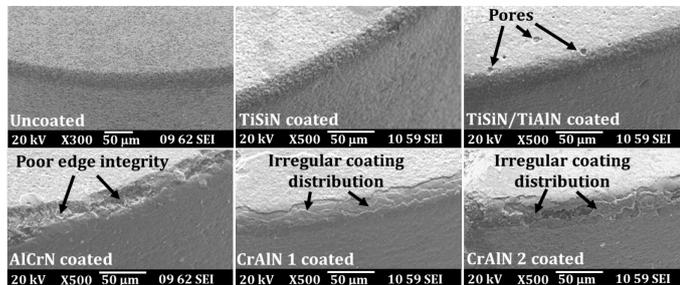


Fig. 3. SEM micrographs of insert edges in the new condition.

When operating at the intermediate cutting speed of 300 m/min (Tests 7-12), none of the coatings provided any significant benefit in terms of tool life, which varied from ~3.0 to 3.5 min. This was higher than results reported by Bushlya et al. [7], who obtained tool lives of ~2.7 min (at 0.3 mm flank wear) when turning Inconel 718 at similar parameters using uncoated and TiN coated round PCBN inserts (50% cBN content). A further increase in cutting speed to 450 m/min (Tests 13-18) produced the same trend but with tool life dropping to only ~1.2 min. Unlike the majority of trials at 200 m/min, uniform crater and flank wear were the principal wear modes in all experiments carried out at 300 and 450 m/min, with signs of minor chipping apparent in some cases at test cessation, see representative SEM images of insert wear scar in Fig. 4. Although the occurrence of notch wear and level of adhered chips/material diminished at higher cutting speeds, the undoubted elevation in cutting temperature subsequently caused the removal of the coatings exposing the PCBN substrate, hence the similarity in recorded

performance for both coated and uncoated products. There were also no visible signs of tool fracture beneath the wear land or thermal cracking in any of the inserts, which was seen in previously published work [7] when turning aged Inconel 718 at cutting speeds ≥ 300 m/min using coated and uncoated PCBN.

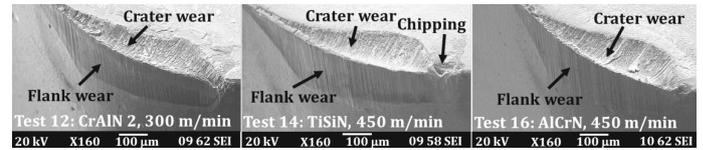


Fig. 4. Representative SEM micrographs of insert wear scars at test cessation when turning at 300 and 450 m/min.

For most of the experiments, workpiece roughness decreased gradually with increasing insert flank wear, from initial values of 0.75-1.05 $\mu\text{m Ra}$ (tools in the new condition) to ~0.25-0.50 $\mu\text{m Ra}$ at test cessation, possibly due to nose radius wiper flat formation. The only exceptions were in Tests 3-6, which showed minimal change in roughness over the trial duration due to the very short cutting time. In addition, statistical analysis of the data indicated that variation in cutting speed and coatings had no significant effect on surface roughness, regardless of the tool condition.

Cutting forces increased steadily with machining time from an average of ~120 N at test commencement to ~175 N at the end of tool life in the large majority of trials, with Test 2 reaching a maximum ~210 N. The radial/thrust force component when using new inserts generally ranged from ~85-115 N, but which saw a more substantial rise (compared to cutting force) to 190-284 N when turning with worn tools. Similarly, feed force was typically found to increase by two-fold over the test duration from initial values of ~40-60 N. In general, increasing cutting speed led to a decreasing trend in all 3 force components, which was likely due to thermal softening of the workpiece material and reduction in tool-chip contact length. Despite this, corresponding analysis of variance (ANOVA) calculations showed that both cutting speed and coating type were not statistically significant with respect to machining forces for both new and worn inserts.

Apart from typical feed marks, no major damage or flaws were detected following examination of workpiece surfaces turned with new inserts. Inspection of surfaces machined with worn inserts however revealed the presence of microcracks measuring ~10-15 μm in length, with a distribution of ~1-2 cracks per 10,000 μm^2 . This was observed on all specimens irrespective of operating parameters and insert coating.

In general, no significant strain hardening was observed on surfaces cross sectioned parallel to the feed direction when utilising new tools, irrespective of coating or cutting speed. An increase in workpiece hardness of up to ~60 $\text{HK}_{0.025}$ above the bulk value (~490 $\text{HK}_{0.025}$) was however apparent to a depth of ~50 μm when employing the worn TiSiN coated insert at 200 m/min. This was attributed to greater adhered material and extended tool life. Strain hardening was also evident albeit at somewhat lower levels, when using uncoated worn inserts at cutting speeds of 300 and 450 m/min.

No major change in workpiece microhardness (average range ~30 $\text{HK}_{0.025}$) was observed perpendicular to the feed direction when turning with new inserts at 300 m/min except for Test 12 involving the CrAlN 2 coating, which showed a hardened layer of up to 544 $\text{HK}_{0.025}$, see Fig. 5. This was possibly due to the greater coating thickness (5.5 μm) compared to the other products (1-3 μm), resulting in a larger cutting edge radius and likely increased rubbing as well as material deformation. All of the specimens turned using worn inserts typically exhibited elevated hardness levels of up to ~80 $\text{HK}_{0.025}$ above the bulk value extending to a depth of ~100 μm below the workpiece surface.

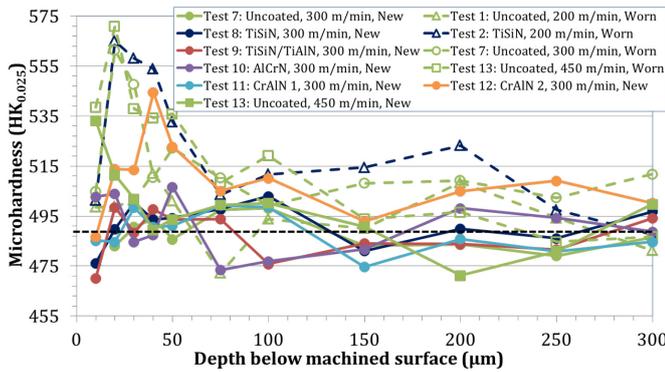


Fig. 5. Microhardness profiles perpendicular to feed direction.

Optical cross sectional micrographs produced in Phase 2 work showed the presence of grain elongation/bending to a depth of $\sim 8\text{-}12\ \mu\text{m}$ in the direction perpendicular to the feed for specimens turned with new tools, see examples in Fig. 6a and 6b. The extent of microstructural deformation increased marginally to $\sim 15\ \mu\text{m}$ beneath the machined surface when utilising worn inserts due to the anticipated rise in tool-workpiece ploughing/contact, see Fig. 6c. Conversely, no evidence of subsurface microstructural damage were observed in any of the samples viewed parallel to the feed direction as shown in Fig. 6d, 6e and 6f (a portion of the feed spacing is evident), regardless of tool condition and cutting speed.

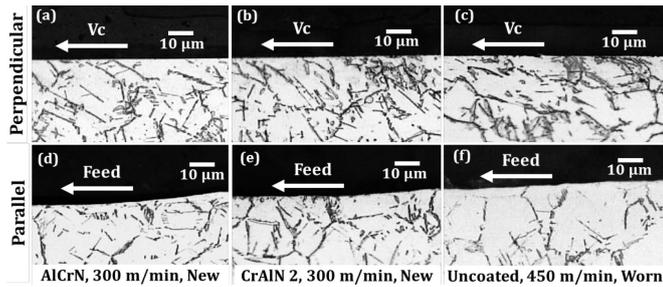


Fig. 6. Micrographs of workpiece microstructure; (a-c) perpendicular and (d-f) parallel to feed direction.

Fig. 7 shows the residual stress depth profiles measured in the feed and cutting directions for Phase 3 work using uncoated inserts. Typically, near surface compressive residual stresses were obtained in all samples evaluated in the feed direction while corresponding results for the cutting direction were predominantly tensile (except in Test D with the CBN170 insert), which crossed over to the compressive regime after $\sim 15\text{-}20\ \mu\text{m}$. The latter was possibly due to the relatively high cutting speed (300 m/min) employed. In contrast, highly tensile surface residual stresses (~ 800 and $1800\ \text{MPa}$) were detailed by M'Saoubi et al. [9] when turning Inconel 718 using new and worn uncoated CBN170 tools at 200-300 m/min, which was possibly due to less effective external flood cooling and a higher flank wear criterion (0.4 mm). The use of a DCC500 worn insert in Test B induced the highest subsurface residual stress levels (-1268 and $-930\ \text{MPa}$ in the feed and cutting directions respectively) with the depth of penetration extending to $\sim 450\ \mu\text{m}$, as opposed to $\sim 100\text{-}150\ \mu\text{m}$ when machining with new inserts. Increasing cutting fluid pressure to 100 bar in Test C was found to raise the maximum compressive residual stress by $\sim 40\text{-}60\%$ compared to Test A (10 bar) due to its greater cooling efficiency. The magnitude of compressive residual stresses recorded was also considerably higher by up to $\sim 105\%$ when utilising the CBN170 insert (Test D) over the DCC500 (Test A), which was attributed to the higher thermal conductivity in the former ($\sim 53\ \text{W/mK}$).

Measurement uncertainty was $\pm 61\ \text{MPa}$ at depths of $8\text{-}56\ \mu\text{m}$, $\pm 11\ \text{MPa}$ at a depth of $256\ \mu\text{m}$ and $\pm 24\ \text{MPa}$ at a depth of $512\ \mu\text{m}$.

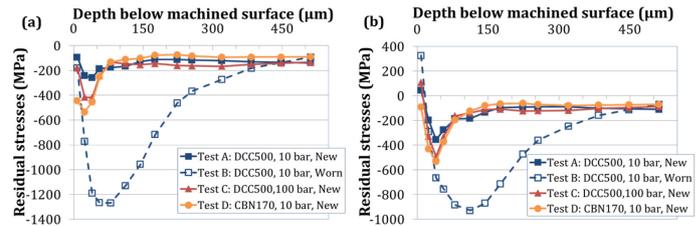


Fig. 7. Residual stress depth profiles in (a) feed and (b) cutting direction.

4. Conclusions

The TiSiN coating provided an increase in tool life ($\sim 40\%$) over uncoated PCBN when machining at 200 m/min. All of the other coating products tested lasted < 1 min, their performance compromised by poor coating integrity at the cutting edge. No benefit however was derived from coatings when operating at cutting speeds ≥ 300 m/min. Depth of cut notching was the principal tool wear mode when turning at 200 m/min, while uniform flank and crater wear were dominant at higher cutting speeds. An increase in workpiece microhardness was generally observed for surfaces machined with worn tools, while microstructural deformation (up to a depth of $\sim 15\ \mu\text{m}$) was only apparent on samples viewed in the cutting direction. Substantially greater subsurface compressive residual stresses were obtained when utilising the medium cBN content (CBN170) insert and increased cutting fluid pressure (100 bar).

Acknowledgements

Thanks are due to UET Lahore, Pakistan and the University of Birmingham, UK for provision of a research studentship. We are also indebted to Rolls Royce, Element Six and Seco Tools for additional finance, workpiece material, tooling and technical support. Finally, we would like to acknowledge Teer Coatings, Oerlikon Balzers and Seco Tools for supplying the coatings.

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