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Effect of Cutting Conditions on Machinability of Superalloy Inconel 718 During High Speed Turning with Coated and Uncoated PCBN Tools

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Abstract

Inconel 718, an efficient superalloy for energy and aerospace applications, is currently machined with cemented carbide tools at low speed (v_c≈60 m/min) due to its unfavorable mechanical and thermal properties. The article presents results of superalloy machinability study with uncoated and coated PCBN tools aiming on increased speed and efficiency. Aspects of tool life, tool wear and surface integrity were studied. It was found that protective function of the coating, increasing tool life up to 20%, is limited to low cutting speed range. EDX and AFM analyses suggested dominance of chemical and abrasive wear mechanisms. Residual stress analysis has shown advantageous compressive surface stresses.

Keywords: Ni-based superalloy; Machinability; PCBN; Tool wear; Residual stresses

1. Introduction

Creation and use of efficient and sustainable equipment for energy sector depends on the materials selected for their design and on the production costs of components manufactured from them. Nickel-iron based superalloy Inconel 718 possesses advantageous service mechanical and thermal properties: high strength at elevated temperatures, high oxidation and corrosion resistance and low thermal conductivity [1]. Yet these same properties reduce its machinability. Currently low production efficiency, with cutting speed around 60 m/min for traditionally used cemented carbide tools, requires increased speeds through application of new tool materials. Attempts on application of PCBN tools, which are the first choice for high speed machining, has been made in 1990-th. Tools available in that period had high cBN content (90-95%) with metallic or ceramic (AlN, AlB_2) binder [2]. Application of such tools was limited to the cutting speed of 90-120 m/min [2]. Machinability of other Ni-based superalloys with PCBN tools has also been the object of study [3, 4]. It was found that content and type of alloying elements plays a crucial role on tool life of PCBN tools. Chemical reactions of cBN with alloying elements (Fe, Cr, Ni, Ti, etc.) stemmed from high cutting temperature were found to govern the wear rate of the tools [3]. Recent developments in the PCBN materials related to optimization of cBN content and a type of binder has led to extension of cutting speed range to 200-300 m/min [5, 6]. Application of ceramic binder of TiN, TiC, Ti(C,N), etc., reduces the amount and exposure of cBN particles to the chemical wear. Another approach for increase in efficiency of machining Inconel 718 is through application of coatings. When machining with cemented carbides, application of coatings allows an increase in cutting speed from ~30 m/min up to ~60-100 m/min [7]. Issues of surface integrity in machining Inconel 718 with PCBN tools were given very limited attention. Arunachalam et al. [8] have conducted an assessment of residual stresses generated on the

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machined surface when facing aged Inconel 718. The results has shown that machining with PCBN tools results in the generation of advantageous compressive stresses, but the distribution of the residual stresses into the subsurface was not studied.

The aim of the presented study is to assess the machinability of aged Inconel 718 when high speed turning with uncoated and coated PCBN tools. The following issues are addressed: cutting forces, tool life, tool wear mechanisms and surface integrity.

2. Experimental details

Continuous longitudinal turning was selected as the machining operation. All tests were conducted on a modern CNC lathe. Workpiece material was the heat-resistant superalloy Inconel 718 in solution annealed and aged state (~ 45 HRC). A bar of 70 mm in diameter and 250 mm in length was machined with polycrystalline cubic boron nitride (PCBN) tools. PCBN tools were selected in uncoated and titanium nitride (TiN) coated state. PCBN grade with low content of cBN (approx. 50%) was selected for the tests following the tool manufacturer recommendations. Grade with ceramic TiC-based binder and cBN with grain size of 0.5-2 μm was selected (see Figure 1.a).

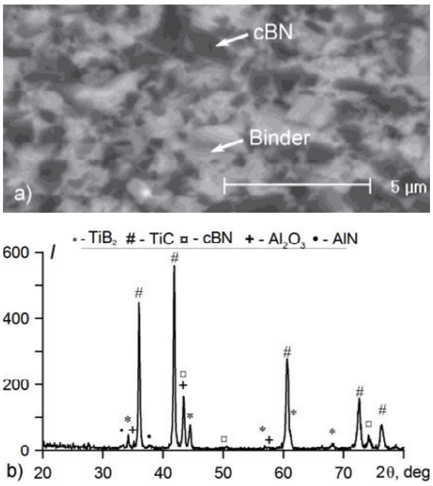

Fig. 1. (a) SEM of microstructure and (b) XRD phase analysis of PCBN tool material

RNGN120300E25 inserts with honed edge radius were used throughout the tests, which along with corresponding toolholder provided *6°* inclination and *–6°* rake angles. Cutting conditions were selected to cover finishing operations. Three selected speeds are v_c=250, 300 and 350 m/min and three feed rates are f=0.1, 0.15 and 0.2 mm/rev. Depth of cut was fixed for all tests, equaling a_p=0.3 mm. All tests were performed with use of *Sitala D 201-03 (Shell)* 8% semi-synthetic coolant supplied at 5 bar and 40 l/min.

Surface roughness, cutting forces, tool wear and wear morphology were analyzed for all tests. *9121 type Kistler* dynamometer was used for recording forces. XRD analysis of tool material was done with Cu Kα source on *DRON-3M* diffractometer. Analysis of residual stresses was done on the same diffractometer, but Co Kα source with diffraction angle of 111º in plane {311} was used instead. sin$^2\psi$ method with ψ= –30, –20, –10, 0, 10, 20, 30º was used for stress estimation. Material removal by electropolishing with step of 20 μm was applied in order to measure profiles of residual stresses. Scanning electron microscope *HRSEM FEI Nova NanoLab 600* was used for inspection of wear morphology and focused ion beam milling of worn-out tools. Energy dispersive X-Ray analysis was performed with *ISIS 300 Microanalysis System* at 15 kV. Atomic force microscope *AFM Dimension 3100* in tapping mode was applied for the study of topography of worn tools. *MikroCAD 3-D* system was used for evaluation of edge radius for new and worn tools. SEM imaging has revealed that PCBN tools have limited-to-moderate adhesion of workpiece material and thus the tools were etched prior 3-D optical microscopy and AFM, which is the common practice.

3. Results and discussion

3.1. Performance of uncoated and coated PCBN tools

Figure 2.a shows cutting forces for different tools in their unworn state. General tendency is that coated and uncoated PCBN tools give close to similar forces, yet coated tools have force level about 10 % higher. For the case of coated tools lower force level due to lower friction coefficient and higher cutting temperatures is expected. But in this study the observed opposing behavior can mostly be attributed to variations in tool microgeometry. 3-D optical measurements have revealed that uncoated tools have edge radius r_β =15-18 μm, while for coated PCBN tools r_β =20-22 μm.

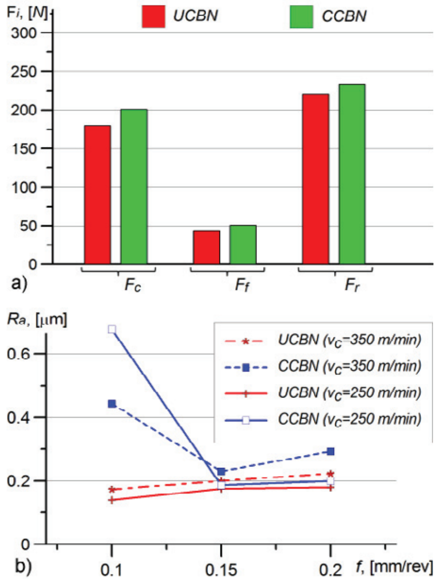

Fig.2. (a) Comparison of cutting force components (v_c=350 m/min, f=0.15 mm/rev); (b) surface roughness under the variation of feed

Similar effect of tool microgeometry was observed when studying the quality of machined surface. Surface roughness (see Figure 2.b) has higher values for coated tools as a result of increased edge radius. This effect is normally associated with minimum chip thickness h_{1min}, when the tool ceases to remove material below a certain value of h_1 leading to the plastic deformation of the being removed material. This effect becomes especially strong for round tools where h_{1min} region falls on surface-generating part of the edge. For the selected tools feed has a strong effect on h_{1min} by thinning the chip cross-section. Side-flow was observed on the machined surface at conditions of small feed which was a result of plastic deformation and flow of material located below h_{1min} value. The most frequent occurrence of side flow was recorded for coated PCBN tools, leading to increase in roughness (Figure 2.b). This particular behavior can be attributed to workpiece material softening due to low thermal conductivity of TiN coating (28 W/m·K) [9] and consuquent flow towards the minor cutting edge. For larger feeds roughness increases as expected from the viewpoint of process kinematics.

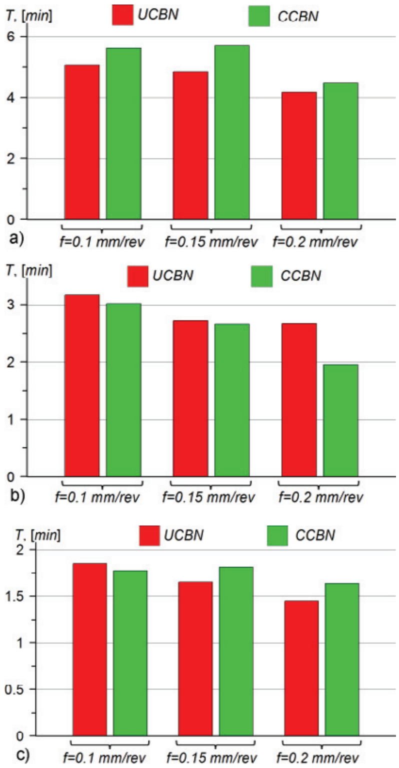

Fig. 3. Tool life comparison for uncoated and coated tools under variation of cutting speed: (*a*) v_c=250 m/min; (*b*) v_c=300 m/min; (*c*) v_c=350 m/min

Relatively low performance of coated PCBN tools in terms of roughness is partly countered by higher tool life. Figure 3 presents the tool life comparison between coated and uncoated tools for all test conditions at wear criterion of VB_{max}=0.3 mm. Tool life for PCBN tools proved to have a limited dependency on feed rate, showing a small (about 15%) reduction in with increase in feed. This can be explained by the simultaneous action of mechanical and thermal loads. According to Proskuriakov [4], when finish turning Ni-based superalloys with PCBN tools, doubling feed rate leads to increase in cutting temperature by approximately 40–60 °C. This is expected to intensify tool material softening and chemical wear for PCBN tools.

It can also be seen (Figure 3.a) that at speed 250 m/min coated PCBN tools have approximately 20% longer tool life than uncoated. The gap is rapidly closing with increase in speed and becomes negligible at speed 350 m/min. This behavior can be explained by the fact that the protective mechanism of TiN coating has a temperature-limited range. It is known [10] that titanium nitride begins to oxidize with formation of rutile (TiO_2) even at 650 °C, yet the reaction achieves significant intensity at temperature above 1000 °C. According to Proskuriakov [4] cutting temperature reaches this level at speed around 240–270 m/min for PCBN tools with high cBN content and correspondingly high thermal conductivity.

The same effect is attributed to the significant decrease in tool life with the increase in cutting speed (see Figure 3). Increase in speed from 250 m/min to 350 m/min leads to a drop in tool life by more than 250%. At these temperatures chemical wear due to reactions of cBN with alloying elements (Cr, Ni, Fe, Nb, etc.) is believed to be one of the main wear mechanisms when machining Ni-based superalloys [3].

3.2. Morphology of tool wear

Appearance of intensive rake cratering and grooving on the tool clearance (see Figure 4) is normally attributed to chemical wear when machining superalloys [11]. It can be seen that grooving has varying intensity along the edge line. Closer to minor cutting edge grooving ceases and flank wear becomes uniform. Such behavior closely follows temperature field found in hard machining with PCBN round tools and tools with large nose radius [12]. Increase in the cutting speed and application of coating leads to extension of grooving to the minor cutting edge and increase in its depth.

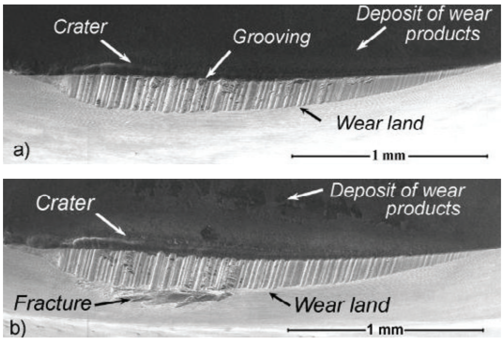

Fig. 4. (a) SEM of worn out UCBN tool (v_c=250 m/min, f=0.1 mm/rev); (b) SEM of worn out CCBN tool (v_c=350 m/min, f=0.1 mm/rev)

Additionally to grooving, deposits of wear products were found on the rake face of PCBN tools, their intensity increasing with cutting speed. Apart from the above defects PCBN tools have experienced fracture beneath the wear land, Figure 4.b. For both uncoated and coated tools fracture was found to be dependent mostly on the cutting speed. Feed has a less significant influence on fracture.

When the tool life criterion (VB_{max}=0.3 mm) was reached, cutting conditions of above $v_c \geq 300$ m/min and $f \geq 0.15$ mm/rev resulted in an appearance of fracture on the tool flank, yet severe fracture was observed under v_c=350 m/min and $f \geq 0.15$ mm/rev for both coated and uncoated PCBN tools.

No transfer layer was observed on the crater or on the wear land, which is regarded as a typical feature of tool wear in hard machining of alloyed steels [13]. Several other tool deterioration mechanisms were observed: thermal cracking and delamination of coating (see Figure 5), but their influence on the tool life was limited.

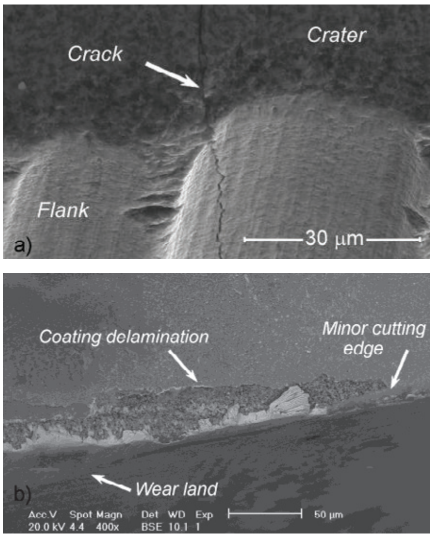

Fig. 5. (a) Thermal cracking on PCBN tools; (b) coating delamination on the minor cutting edge

Focused Ion Beam milling of the crater has revealed that cracks are not superficial and extend deep into the tool bulk. Cracks are perpendicular to the edge line, have significant length and stretch outside crater and flank wear land. Cracking was not found to lead either to edge chipping or tool failure, probably due to its minor intensity, averaging 2-4 cracks per edge. Figure 5.a also depicts the edge line where it can be seen that edge radius (r_β) has smaller size than for a new tool. 3-D optical measurement of edge radius for worn out tools has confirmed that radius decreases, as compared to the original size, down to r_β=5-15 µm for both tool types. Closer to the minor cutting edge, where wear land becomes uniform and absent of grooving, edge radius increases up to r_β=25 µm. Delamination of coating in the same minor cutting edge region was observed, Figure 5.b. Removal of coating in the surface formation region of the edge can play both positive and negative role. It leads to decrease in the size of edge radius and through that to reduction of h_{1min} and ploughing effect. This plays a positive role in the formation of surface roughness and subsurface deformation [14]. Additionally, removal of the coating, serving as the thermal barrier, is expected to reduce local temperature in the region, which normally is attributed to formation of undesirable tensile residual stresses [15]. On the other hand, application of TiN coating reduces friction coefficient and through that shearing force acting on the tool clearance face and machined surface. This in turn is expected to reduce subsurface deformation of the machined component.

3.3. Wear mechanisms of PCBN tools

Presence of a deposit of wear products on the rake face, when machining with PCBN tools, is typically attributed either to formation of low-melting-point eutectic between tool and workpiece materials which is subsequently ejected from the cutting zone, or to chemical reactions of tool material with workpiece, coolant, etc. [16], or both. As the tool material is a composite with cBN and binder grains, chemical reactions and eutectics with both can be decisive wear mechanisms. Indeed, Klimenko et al. [16] have shown formation of Fe-Fe_2B eutectics with cBN, while Gimenez et al. [17] found formation of Fe-C perlite-like structures of as a result of interaction of steel with TiC binder of PCBN insert. Other reactions of cBN with Ni (Ni_3N), Mo (Mo_2N), Cr (Cr_2B), etc. in superalloys are possible at temperatures developing in the cutting zone [3].

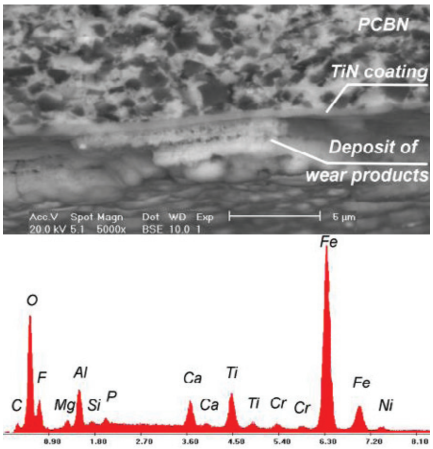

Fig. 6. SEM and EDX analysis of deposit of wear products on CCBN rake (v_c=250 m/min, f=0.15 mm/rev)

Figure 6 presents SEM image of a fracture surface of the rake face of coated PCBN insert showing tool bulk, coating and the deposit of two layers of wear products. Two layers are a result of two passes during which the tool life criterion of VB_{max}=0.3 mm was reached. It can be seen that the deposit has a porous structure consisting of individual particles bound together. According to conclusions of Klimenko et al. [16] such structure can be a result of ejection of eutectic melt from the cutting zone in the shape of droplets and subsequent their reaction with environment and coolant. EDX analysis of the wear products has detected high concentrations of iron and oxygen implying formation of iron oxides. Evident peaks corresponding to aluminium and titanium come from the binder of tool material consisting of TiC, TiB_2 and small concentrations of Al_2O_3 and AlN, see Figure 1.b. Presence of Mg, Ca and F is a result of dilution of coolant concentrate with hard water, which has relatively high concentrations of Ca^{2+} and Mg^{2+} ions (>100 ppm) in the region.

Several studies [5, 13] addressing hard machining of highly alloyed steels have identified formation of holes on surfaces of worn tools, which was attributed to diffusion- or chemical-related decomposition of the binder and successive adhesive pull out of cBN particles. Atomic Force Microscopy (AFM) was applied to analysis of topography of worn surfaces in order to identify if similar wear mechanisms take place when machining Ni-based Inconel 718. Figure 7 presents the results of AFM taken on the tool crater and on the wear land. Prior AFM the tool was subjected to etching with Kallings #2 etchant affecting only matrix γ-phase of superalloy. On the contrary to the hard machining, topography of the crater proved to be very smooth and without appreciable damages. Severe grooving on the tool flank (see Figure 4) posed a limitation to the size of AFM image, see Figure 7.b. Behavior opposite to the one found on the crater surface and in typical cases of hard turning was observed. Figure 7.b clearly shows significant amount of protruding particles of tool material, thus making the assumption of dominance of adhesive wear mechanism not sustained.

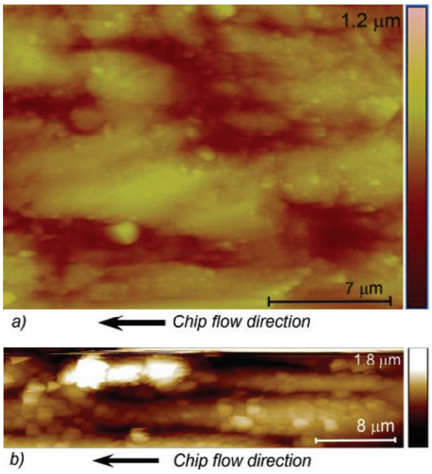

Fig. 7. AFM topography of (a) crater and (b) wear land on worn out UCBN tool (v_c=350 m/min, f=0.2 mm/rev)

It can be assumed that a combination of chemical and abrasive wear plays dominant role. High temperature developing on the crater leads to reaction of both cBN and binder with the workpiece material as well as their softening and a subsequent removal of reaction layer by abrasive particles of Inconel 718, thus smooth and uniform surface. According to Proskuryakov [4] temperature on the tool clearance is lower by 200-250 ºC than on the rake, which implies that intensity of chemical reactions is limited, if existent. Hot hardness of cBN in this temperature range is significantly higher than that of TiC-based binder. According to Ståhl [18] hardness of TiC at temperatures 850-950 ºC is only 520 HV. Based on the above results it is assumed that highly abrasive TiC and NbC carbides in the matrix of Inconel 718 tend to abrade the binder at higher rate than cBN, exposing the later (Figure 7.b).

3.4. Aspects of surface integrity

Apart from the surface roughness, shown in Figure 2, other aspects of surface integrity were analyzed: subsurface deformation and distribution of residual stresses into the machined surface. The test samples for both subsurface deformation and residual stress testing were generated with new tools. Subsurface deformation was studied on a cross-section of the samples after their polishing and subsequent etching, see Figure 8. When characterizing deformation it is possible to distinguish a zone of severe deformation, adjacent to the machined surface, having significant bending and elongation of grain boundaries and slip lines in the direction of cutting. This major deformation zone normally extends to 10-15 µm. Both, intensity of deformation in this zone and thickness of the zone increase with the cutting speed.

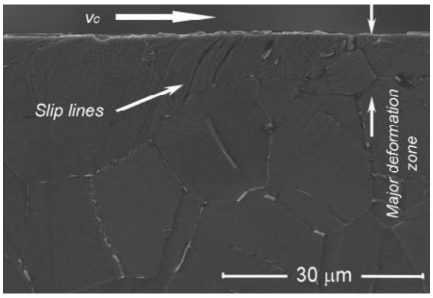

Fig. 8. SEM of subsurface deformation after machining with CCBN tool (v_c=250 m/min, f=0.1 mm/rev, new tool)

Application of coated PCBN tools resulted in more severe grain elongation, but thickness of this zone was affected to a lesser degree. These effects can be explained by the increase of the process temperature with increase in cutting speed and insulation effect of the coating. Rise of the temperature results in a loss of material strength and increase of its plasticity, allowing for more intensive deformation. Effect of higher edge radius of the coated tools additionally contributes to the ploughing action and mechanical constituent of subsurface damage.

When analyzing residual stresses after machining it was found that both axial and tangential stresses have exhibited a "hook" type profile (see Figure 9), which is typical for high speed machining with PCBN tools. Significant difference between reported data when machining with cemented carbide tools [15] and the current study was found for residual stresses on the surface. Surface residual stresses were found to be compressive for both PCBN tools, on the contrary to undesired tensile stresses for cemented carbide tools.

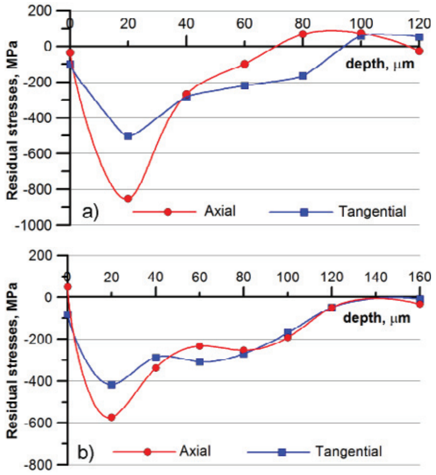

Fig. 9. Residual stresses profile for (a) uncoated and (b) coated PCBN tools (v_c=300 m/min, f=0.1 mm/rev, new tool)

The main factor responsible for the generation of surface compressive stresses in the workpiece is the tool geometry, large nose radius in particular. Round inserts with diameter of 12.7 mm were applied throughout the tests, which leads to a significant thinning of the chip area. This, in turn, results in considerable reduction of local cutting temperature in the surface formation region of the tool-workpiece interface [12]. This in turn reduces the thermally-related tensile component of residual stresses as a whole. On the other hand large nose radius leads to multiple deformation of the machined surface [19] thus increasing compressive mechanical-related stresses. Similar effect of nose radius on surface residual stresses was observed by Arunachalam et al. [8].

It can also be seen (Figure 9) that the residual stresses have significantly lesser values of compressive stresses for coated PCBN tools than for uncoated ones, this being related to lower thermal conductivity of CCBN tools and higher thermally-related contribution. Additionally, stress profile for CCBN tools has bigger depth (~ 120 μm) than UCBN tools (~ 100 μm), which, as for the case of subsurface deformation, is related to larger edge radius (r_β) of coated tools.

4. Conclusions

The article presents the results of experimental study of machinability of aged Inconel 718 during its high speed turning with coated and uncoated PCBN tools. The machinability was evaluated in terms of cutting forces, tool life, tool wear and generated surface integrity. The obtained results indicate that advantage of the coating on the PCBN tools has a cutting-speed-limited effect. With increase of speed to 300 m/min and above the coating provides no benefits in terms of tool life. Tool life was found to be highly sensitive to cutting speed, where it decreased by 250% with increase in speed from 250 m/min to 350 m/min. Findings of EDX analysis have shown that chemical wear mechanisms plays dominant role in this behavior. Atomic force microscopy has shown that abrasive wear also plays significant role in the wear of PCBN tools. Assessment of residual stress profiles for machined surface has shown generation of advantageous compressive surface stresses. Application of coated PCBN tools, as compared to uncoated ones, have shown a tendency of transition from compressive to tensile surface stresses.

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