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Performance and wear mechanisms of whisker reinforced alumina, coated and uncoated PCBN tools when high speed turning aged Inconel 718

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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 a study of superalloy machinability with whisker reinforced alumina, uncoated and coated PCBN tools. Turning of age hardened Inconel 718 (45 HRC) was done under high speed machining conditions (v_c=250…350 m/min). Aspects of tool life, tool wear and generated surface quality were studied. Application of uncoated PCBN tools resulted in surface quality and force level superior to other tool materials. Considerable side-flow of workpiece material was found to affect surface quality, especially for coated PCBN and ceramic tools. It was found that protective function of the coating, which increases the tool life up to 20%, is limited only to low cutting speed range. EDX and AFM analyses suggested dominance of chemical and abrasive wear mechanisms. EDX mapping of worn tools pointed absence of diffusional wear for PCBN tools and intensive degradation of whisker reinforcement in ceramic tools due to diffusion of Ni, Fe and Cr.

Keywords: *Inconel 718, PCBN, whisker reinforced alumina, high speed machining, diffusion*

1 Introduction

Spread and utilization of efficient and sustainable equipment for energy sector depends on the materials selected for its 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]. These beneficial properties make it a primary choice material for power generation, aerospace, nuclear and other critical industries however these same properties introduce difficulties during its machining. Its low thermal conductivity and high strength lead to development of high cutting temperature which, combined with its tendency to work-hardening, shorten the tool life dramatically. For cemented carbide tools a reasonable tool life is achieved at cutting speed v_c=30-50 m/min. This low-efficiency process can be improved through employment of coatings (v_c=60-90 m/min) or by the use of ceramic tools (v_c=150-250 m/min) [2]. Whisker reinforced alumina (WRA) tools are preferable for machining superalloys [3] due to their high mechanical properties which result from reinforcement of Al_2O_3 matrix by silicon carbide whiskers. In industry the WRA tools are mostly limited to semi-finishing and roughing operations due to their spontaneous failure and less predictable tool life and therefore due to the risk of rejection of the being manufactured component [4]. Another approach includes use of polycrystalline cubic boron nitride (PCBN) tools. Attempts on application of PCBN tools has been made in 1990-th but available PCBN material had high cBN content (90-95%) with metallic or ceramic (AlN, AlB_2) binder and the cutting speed for such tools was limited to 90-120 m/min [5]. Recent developments in the PCBN materials related to optimization of cBN content and a type of binder have led to extension of cutting speed range to 200-300 m/min for turning Inconel 718 [6, 7]. Performance of PCBN tools when machining other Ni-based superalloys has also been subjected to study [8, 9]. It was found that content and type of alloying elements in the workpiece material have a crucial influence on tool life. Diffusion and chemical reactions of cBN with alloying elements (Fe, Cr, Ni, Ti, Nb, etc.), stemmed from high cutting temperature, were found to govern the wear rate of the tools [8]. Application of ceramic binder of TiN, TiC, Ti(C,N), AlN, AlB_2, etc., reduces the amount and exposure of cBN particles to the chemical wear [7] as well as facilitates in formation of built-up-layer which acts as a diffusion barrier [5, 10]. Application of coatings on PCBN tools is expected to act as an additional diffusion barrier [11] and therefore facilitate suppression of chemical wear.

The aim of the study is to evaluate and compare the performance of ceramic, uncoated and coated PCBN tools when high speed turning aged Inconel 718. The following aspects of the process are addressed: cutting forces, surface quality, tool life and wear mechanisms of the tools.

2 Experimental details

Continuous longitudinal turning was selected as the machining operation. Workpiece material was the heat-resistant superalloy Inconel 718 in solution annealed and aged state (~ 45 HRC). A bar 70 mm in diameter and 250 mm in length was machined with PCBN and whisker reinforced alumina (WRA) tools. PCBN tools were selected in uncoated (UCBN) and titanium nitride coated (CCBN) state. PCBN grade with low content of cBN (approx. 50% vol.) 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 employed (Fig. 1a). Thickness of the titanium nitride coating was 2 microns. RNGN120300E25 inserts with honed edge radius were used throughout the tests, which in combination with with corresponding toolholder provided 6° inclination and -6° rake angles. Whisker reinforced alumina inserts (Fig. 1b) were of RNGN120700T01020 type, providing 0.1×20° chamfer along with edge hone. Cutting conditions were selected to cover finishing operations with data being equal and larger than those recommended by tool manufacturers. 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. Machining was done with use of 8% semi-synthetic coolant (Sitala D 201-03 Shell) 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 registration of cutting forces. Optical stereomicroscope *Leica MZ16* was used for measurement of tool wear. Scanning electron microscope *HRSEM FEI Nova NanoLab 600* was used for inspection of wear morphology and Focused Ion Beam milling of worn-out tools. XRD analysis of all tool materials was done with Cu

Kα source on *DRON-3M* diffractometer. Energy dispersive X-ray analysis and mapping 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* optical fringe projection system was used for characterization of edge radius for new and worn tools.

SEM analysis of worn tools has revealed that PCBN tools have limited-to-moderate adhesion of workpiece material while WRA tools have significant adhesion on the flank wear land and thus the tools were etched prior to AFM and 3-D optical microscopy. Kallings #2 etchant, which removes only the matrix γ-phase of Inconel 718, was applied in ultrasonic-assisted regime.

3 Results and discussion

3.1 Performance of tool materials

Figure 2 shows cutting forces registered for different tools in their unworn state. General tendency is that coated and uncoated PCBN tools give similar forces yet coated tools have force level about 10 % higher, especially for cutting (F_c) and radial (F_r) components. Much stronger difference, reaching up to 40 %, was observed for the case of WRA tools. For the case of PCBN tools it is expected that coated tools should exhibit lower force level due to lower friction coefficient and higher cutting temperatures. But in this study the observed differences can mostly be attributed to variations in tool microgeometry. Measurements of tool microgeometry with 3-D optical microscope has revealed that uncoated tools (UCBN) have edge radius r_β=15-18 μm, while for coated tools (CCBN) r_β=20-22 μm. WRA tools, besides having the chamfer, also have a honned edge with r_β=25-28 μm.

Similar effect of tool microgeometry was observed when studying quality of the machined surface. Figure 3a shows that for indentical cutting conditions surface roughness increases with the increase of the edge radius, with lowest for UCBN tools. This effect is normally associated with the phenomena of minimum chip thickness h_{1min}, when the tool ceases to remove material below a certain uncut chip thickness h_1 value leading to its plastic deformation [12]. Figure 4 gives the scheme associated with identification of h_{1min} and its location on the edge for round tools and tools with large nouse radius. For this type of tools the h_{1min} effect on the surface roughness is especially strong because h_{1min} region falls on surface-generating part of the edge.

$$h_1 = f \cdot \sin(\delta) + R - \sqrt{f^2 \cdot \sin(\delta)^2 + R^2 - f^2} \tag{1}$$

Equation 1 describes the influence of feed (*f*) and nose radius (*R*) on the theoretical chip thickness (h_1) for any given position on the cutting edge corresponding to the angle δ. Figure 3b gives the results of calculations based on Eq. 1 for the area of uncut material. Calculations are also based on the representation given in Fig. 4 and the following assumption: $h_{1min}=0.1 \cdot r_\beta$ [13].

The uncut material is distributed over the machined surface and is ploughed towards the minor cutting edge in the form of side-flow [14, 15], which increases the roughness. As expected from the calculation data (Fig. 3b) WRA tools resulted in the highest degree of side-flow, Figure 5a. The most frequent occurrence of side flow was recorded for lower feeds and for WRA tools (Fig. 5a), which closely follows the results of calculations (Fig. 3b). When machining with coated PCBN tools spontaneous and irregular formation of severe side-flow was observed as well (Fig. 5b), which leads to a dramatic increase in roughness (Fig. 3a). This can be attributed to workpiece material softening due to low thermal conductivity of TiN coating (28 W/m·K) [16] and consequent flow towards the minor cutting edge. For larger feeds roughness increases as expected from the viewpoint of process kinematics.

Relatively low performance of coated PCBN tools in terms of roughness is partly countered by their higher tool life. Figure 6 presents the tool life comparison between all tool materials for all test conditions at wear criterion of VB_{max}=0.3 mm. Tool life for WRA tools proved to be independent of feed rate while PCBN tool have shown a slight reduction in tool life (approx. 15%) with increase in feed. This can be explained by the simultaneous action of mechanical and thermal loads. According to Proskuriakov [9], 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 [11] while WRA tools are not prone to chemical wear at these temperatures.

It can also be seen (Fig. 6a) 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 [17] that titanium nitride begins to oxidize with formation of rutile (TiO_2) even at 650 °C but the reaction achieves significant intensity at temperature above 1000 °C. Cutting temperature reaches this level at speed around 240–270 m/min for PCBN tools with high cBN content [9]. Low cBN tools used in the current tests, possessing lower thermal conductivity than the high-cBN grades, are expected to reach even higher process temperatures. The same thermal effect is attributed to the significant decrease in tool life with the increase in cutting speed (Fig. 6). Increase in speed from 250 m/min to 350 m/min leads to the drop in tool life of PCBN tools by more than 250%. At these temperatures chemical wear due to reactions of cBN with alloying elements (Cr, Fe, Ni, Nb, Mo, etc.) is believed to be one of the main wear mechanisms when machining Ni-based superalloys [8]. At the same time WRA tools have shown smaller sensitivity to the effects of cutting speed. Only 35% decrease of tool life was observed for speed 350 m/min.

3.2. Morphology of tool wear

Appearance of intensive rake cratering and grooving on the tool clearance observed for PCBN tools (Fig. 7a) is normally attributed to chemical wear when machining superalloys [2]. It can be seen that grooving has varying intensity along the edge line. Closer to the 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 [18]. It was found that intensity of grooving depends on the cutting speed and tool type. Increase in the cutting speed and application of coating leads to extension of grooving to the minor cutting edge and increase in its depth. Additionally to grooving, deposits of wear products were found on the rake face of PCBN tools, their intensity increasing with cutting speed. The above wear features are an indirect indication of chemical wear mechanism for the PCBN tools. Apart from the above defects, both WRA and PCBN tools have experienced fracture beneath the wear land, Fig. 4. Moreover, WRA tools exhibited flaking of the rake surface. For both uncoated and coated PCBN 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 but severe fracture was observed under v_c=350 m/min and $f \geq 0.15$ mm/rev for PCBN. Fracture of WRA tools was observed under similar test conditions. Flaking of the WRA rake has more intensive character than fracture. It was observed for all tests with speed $v_c \geq 300$ m/min. This can be attributed to the change of the tool geometry due to intensive cratering observed for higher cutting speeds and therefore change of the stress state.

Several other deterioration mechanisms were observed: thermal cracking for both WRA and PCBN and delamination of coating for CCBN tools, but their influence on the tool life was limited. For WRA tools cracking was restricted only to the far end of the crater while for PCBN tools the cracks have significant length and stretch outside crater and flank wear land. Focused Ion Beam (FIB) milling of the PCBN crater (Fig. 8) has revealed that cracks are not superficial and extend deep into the tool bulk. FIB milling of WRA tools have shown that cracks extend only up to 5-10 μm into the tool bulk which are expected to originate during tool cooling at its disengagement [19].

SEM observations have prompted that the cutting edge for all tool materials has not become blunted during the wear process. 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 PCBN tool types (Fig. 9a, b). Closer to the minor cutting edge, where wear land becomes uniform and absent of grooving, edge radius increases up to r_{β}=25 μm. Worn WRA tools maintained the edge radius close to original size r_{β}=25-28 μm but in the minor cutting edge region failure of the crater formation was observed. Figure 9c depicts absence of crater in this region and significant bluntness of the edge: r_{β}=40-80 μm. This is expected to dramatically increase the size of h_{1min} for worn tools and therefore lead to deterioration of surface quality, intensification of side-flow and to an increase of subsurface deformation.

3-D characterization has also indicated that the shape of cutting edge for WRA tools was a waterfall (oval) rather than the radius type. Cross sectioning of the worn tools was done in order to clarify this special behavior of wear of WRA tools. Figure 10 presents the cross sections of PCBN and WRA tools. While the wear land for PCBN tools is flat and has zero clearance angle (Fig. 10a) WRA tools exhibit oval-type wear land with negative clearance angle (– 1,5…2 deg.). Detailed examination of WRA cross section (Fig. 10b) indicates formation of an additionally more negative (– 3…4 deg.) wear land closer to the edge. It was pointed by Brandt et al. [19] that diffusion of Ni, Cr and Fe into the tool takes place during machining Inconel 718, which leads to degradation of whisker reinforcement. The diffusion rate in the vicinity of the cutting edge is highest since the temperature in the region is highest as well [20]. Modification of SiC whisker reinforcement due to diffusion is expected to reduce the abrasive resistance of the tool material and therefore to intensify its wear in the cutting edge vicinity.

3.3. Wear mechanisms of PCBN tools

Presence of a deposit of wear products on the rake face was observed for all tool materials but its intensity was substantially higher for both PCBN tool types. For machining with PCBN, its formation 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. [21], or both. Since the tool material is a composite with cBN and binder phases, chemical reactions and eutectics with both can be a decisive wear mechanism. Indeed, Klimenko et al. [21] have shown formation of Fe-Fe_2B eutectics with cBN, while Gimenez et al. [22] found formation of Fe-C perlite-like structures of as a result of interaction of pure iron with TiC binder. Other reactions of cBN with Ni (Ni_3N), Mo (Mo_2N), Cr (CrB, Cr_2B), etc. in machining superalloys are possible at temperatures developing in the cutting zone [8]. Figure 11 presents a 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 which consists of bound individual particles. According to conclusions of Klimenko et al. [21] such structure can be a result of ejection of eutectic melt from the cutting zone in the shape of droplets and their subsequent 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 aluminum and titanium come from the binder of tool material consisting of TiC, TiB_2 and small concentrations of Al_2O_3 and AlN, see Fig. 1b. Apparent presence of magnesium, calcium and fluorine 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 [23, 24] 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 12 presents the results of AFM taken on the tool crater and on the wear land of UCBN tool. 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 (Fig. 7) posed a limitation to the size of AFM image, see Fig. 12b. Behavior opposite to the one found on the crater surface and to the typical cases of hard turning was observed. Figure 12b clearly shows significant amount of protruding particles of tool material, thus making the assumption of dominance of adhesive wear mechanism not sustained. It can be assumed that a combination of chemical and abrasive wear plays dominant role. High temperature of 1100-1200° C [9] developing on the crater leads to reaction of both cBN and binder with the workpiece material as well as their softening and a subsequent uniform removal of reaction layer by abrasive particles of Inconel 718. According to Proskuryakov [9] 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 (≈2400 HK [25]) is significantly higher than that of TiC-based binder. According to Ståhl [26] 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 (Fig. 12b).

Diffusion, alongside with chemical wear, is viewed as dominant wear mechanism during machining with PCBN tools at high cutting speeds [5]. Costes et al. [7], when performing EDX line scan on the fracture surface of worn PCBN tools used in turning Inconel 718, have shown presence of diffused Ni, Cr, Fe and Nb in superficial layer of the tool crater. On the other hand, Angseryd et al. [27] have emphasized the need for careful sample preparation, which, if not followed, can result in considerable scatter of results. The authors [27] used Ga^+ ion beam milling for extraction of PCBN sample from a worn tool used in turning hardened steel. Application of several analytical techniques has indicated absence of workpiece material diffusion into the tool and some indications on the carbon diffusion from the TiC binder into the chips.

Figure 13 depicts the lamellas removed from the rake of the worn PCBN and WRA tools with the help of Focused Ion Beam milling. Upon removal the lamellas were mounted on a TEM grid for handling, finish milled and subjected to energy dispersive X-ray analysis in order to detect the diffusion. The EDX mapping performed on PCBN tool (Fig. 13a) have revealed an adhered layer of Inconel 718 on the tool surface, marked with an arrow. It can be seen that workpiece elements do not propagate into the tool bulk and are limited to the adhered Inconel 718 layer, which sustains the finding of Angseryd et al. [27] about absence of diffusion wear of PCBN tool materials.

EDX mapping of the WRA tool (Fig. 13b), on the contrary, has shown a significant ingress of workpiece elements, particularly Ni, Cr and Fe, into the tool bulk. It can be seen that replacement of silicon in the SiC whiskers by Ni, Cr and Fe occurs, while no diffusional attack on Al_2O_3 was evident. EDX point analysis for the areas of interest has shown dominance of Ni ingress followed by Fe and Cr, respectively. It is also noted that Ni and Fe diffuse markedly deeper than Cr due to an ease of formation of chromium carbide with free carbon left in the whiskers after replacement of Si. Intensive carbide-forming tendency of niobium can be attributed to its diffusion being limited only to the near-surface region. Previously reported [28] diffusion of additionally Mo and Co was not observed. It can be concluded that diffusional stability of PCBN tool material can be attributed to its tool life being longer than for WRA tools. This effect is especially pronounced at moderate cutting speeds when the mechanism of chemical wear of PCBN is least intensive.

4 Conclusions

The article presents the results of experimental study of machinability of aged Inconel 718 during its high speed turning with SiC whisker reinforced alumina, coated and uncoated PCBN tools. The machinability was evaluated in terms of cutting forces, tool life, tool wear and generated surface finish. Uncoated PCBN tools provided superior surface quality and advantageous force level than other tools. Degradation of surface quality was attributed to intensive side-flow for WRA tools and spontaneous severe side-flow for coated PCBN tools. The obtained tool life 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 for PCBN 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. WRA tools have minor sensitivity to variation of cutting speed which provides the potential for their application at very high cutting speeds. Findings of EDX analysis have shown that chemical wear mechanisms plays dominant role in this behavior. EDX analysis of diffusional wear indicates absence of workpiece diffusion into PCBN, while intensive replacement silicon in SiC whiskers by Ni, Cr and Fe was observed for WRA tools. Atomic force microscopy has shown that abrasive wear also plays significant role in the wear of PCBN tools.

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Figures

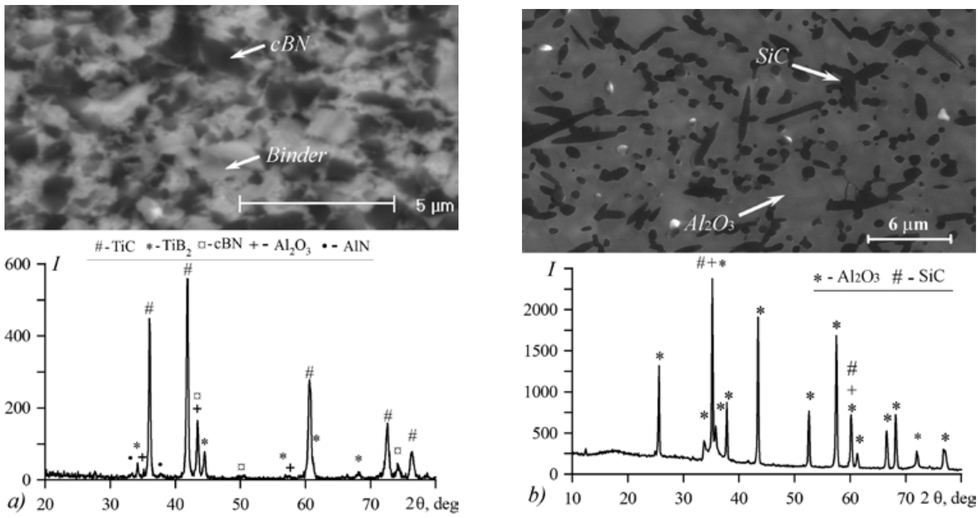

Fig. 1 Microstructure and XRD phase analysis of **(a)** PCBN and **(b)** WRA tool materials

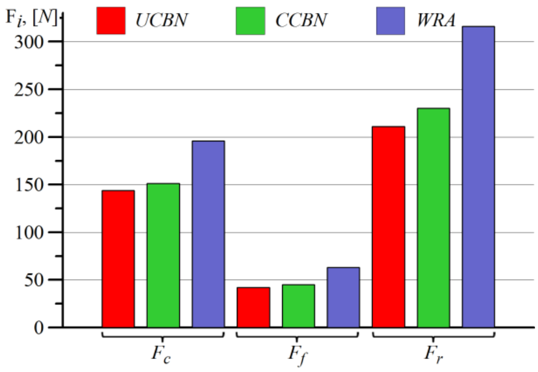

Fig. 2 Comparison of force components (v_c=300 m/min, f=0.1 mm/rev)

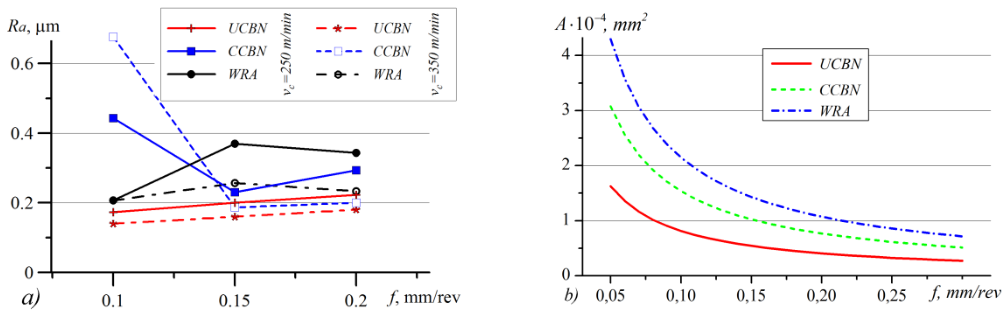

Fig. 3 **(a)** Surface roughness under variation of feed and **(b)** Area of uncut material under assumption h_{1min}=0.1·$r_β$

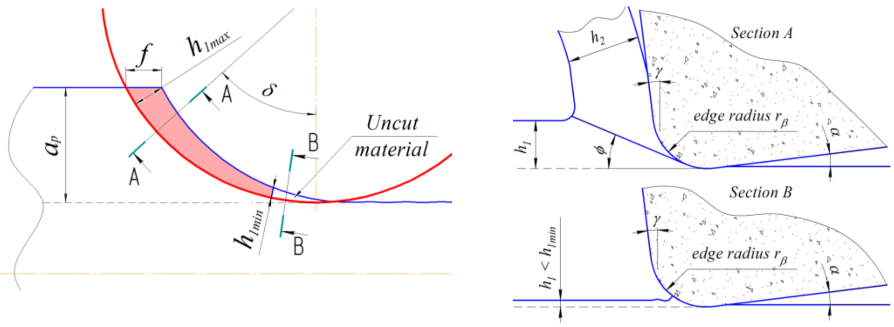

Fig. 4 Scheme of location of minimum chip thickness (h_{1min}) for round cutting tools

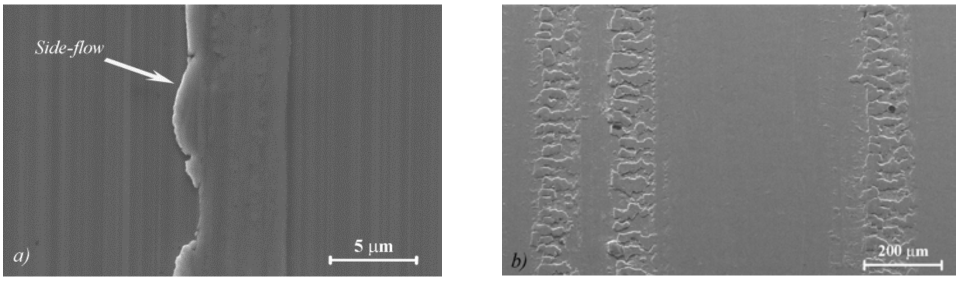

Fig. 5 (a) Side-flow on the WRA machined surface (v_c=350 m/min, f=0.15 mm/rev) and **(b)** Severe side-flow on the surface machined with CCBN tool (v_c=250 m/min, f=0.1 mm/rev)

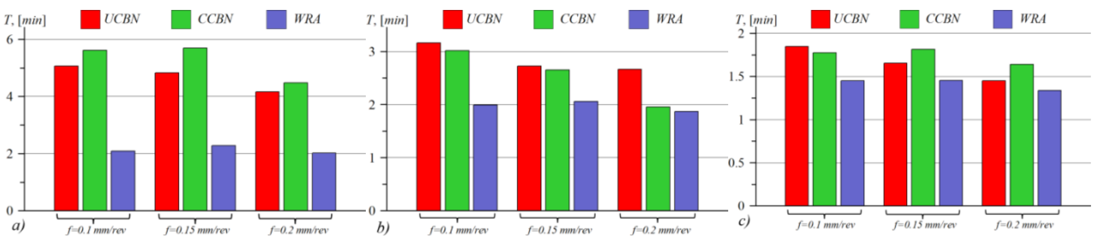

Fig. 6 Comparison of tool life for tool materials under variation of speed: **(a)** v_c=250 m/min, **(b)** v_c=300 m/min, **(c)** v_c=350 m/min

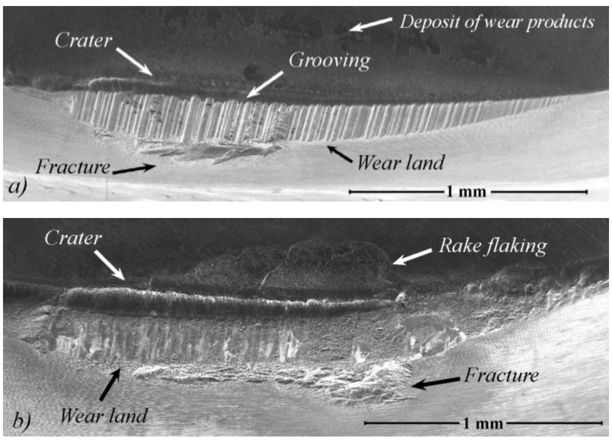

Fig. 7 SEM of worn out **(a)** CCBN (v_c=350 m/min, f=0.1 mm/rev) and **(b)** WRA (v_c=350 m/min, f=0.1 mm/rev) tools

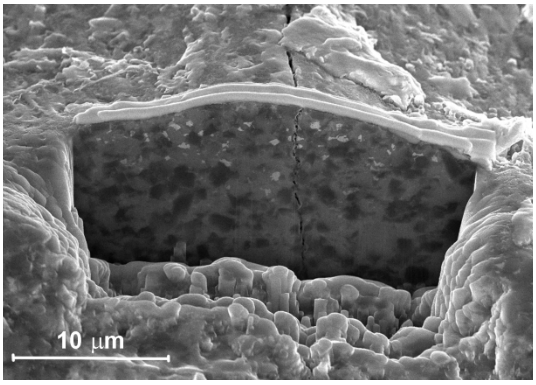

Fig. 8 FIB milling of the crack on the crater of UCBN tool (v_c=300 m/min, f=0.2 mm/rev)

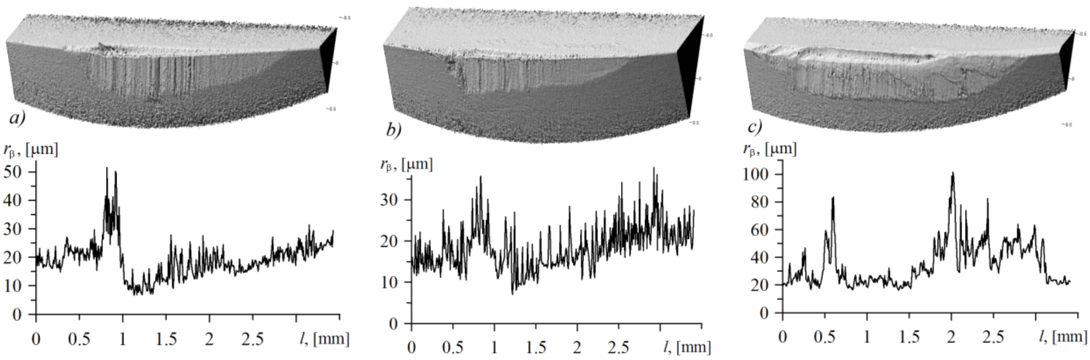

Fig. 9 3-D optical characterization of worn-out tools and variation of edge bluntness (r_β) along the edge line: **(a)** UCBN, **(b)** CCBN, **(c)** WRA at v_c=300 m/min, f=0.15 mm/rev

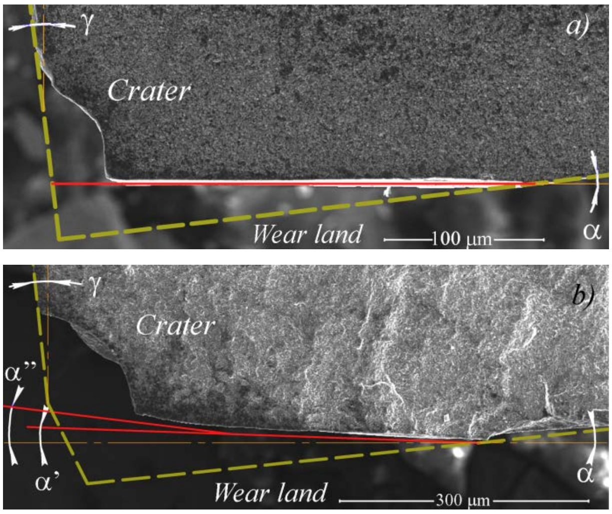

Fig. 10 Cross-section of worn out tools: **(a)** CCBN (v_c=250 m/min, f=0.2 mm/rev), **(b)** WRA (v_c=350 m/min, f=0.2 mm/rev)

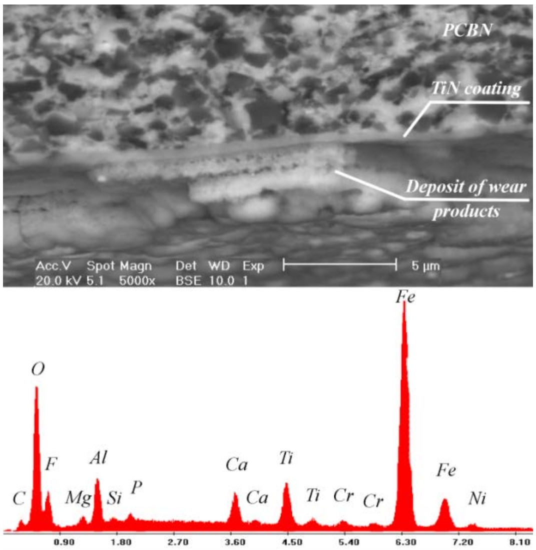

Fig. 11 SEM and EDX analysis of deposit of wear products on CCBN rake (v_c=250 m/min, f=0.15 mm/rev)

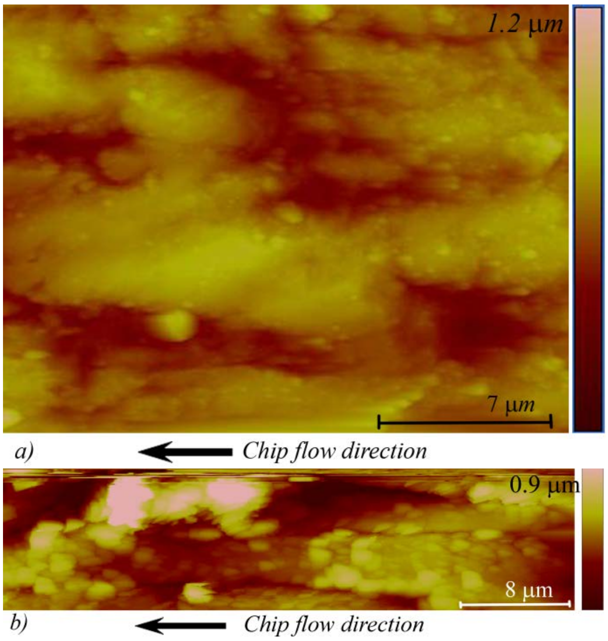

Fig. 12 AFM topography of **(a)** crater and **(b)** wear land of worn out UCBN insert (v_c=350 m/min, f=0.2 mm/rev)

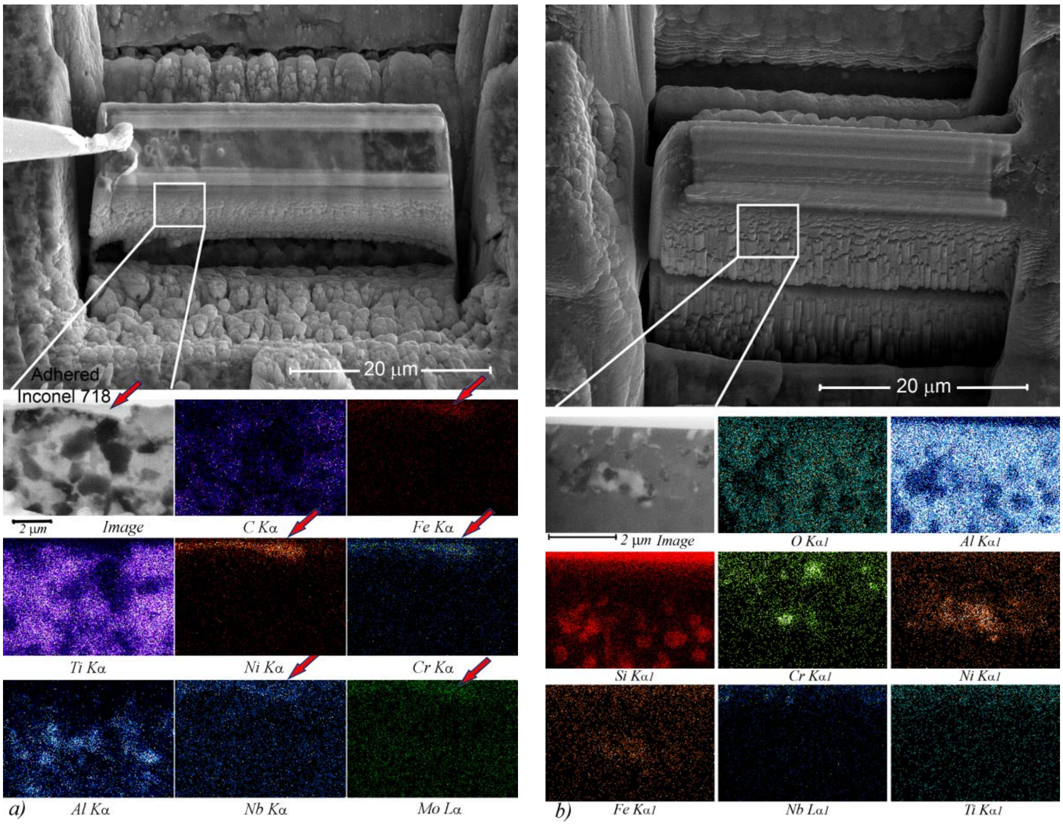

Fig. 13 EDX mapping of FIB milled lamella from **(a)** the crater of UCBN tool (v_c=300 m/min, f=0.2 mm/rev) and **(b)** the crater of WRA tool (v_c=250 m/min, f=0.2 mm/rev)