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INVESTIGATION OF INITIAL WEAR PERIOD OF DIFFERENTLY COATED CARBIDE CUTTING TOOLS

In this paper the results of experimental studies concerning the phenomenon of initial period of the wear of differently coated sintered carbide tools when dry orthogonal cutting of an AISI 321 austenitic stainless steel are presented. The motivation for this study results from the lack of technological guides concerning the optimal choice of coated cutting tools for machining of corrosion resistant austenitic stainless steels. A number of cutting tool inserts with the plane rake face made of a fine H10F sintered carbide substrate with specially deposited TiN, including TiCN, TiAlN, AlTiN and AlCrN single layers were used in wear tests. Both rake and flank faces of the cutting inserts were examined by optical and confocal microscopy after controlled tool wear. The possible wear mechanisms in terms of changes of the tool-chip contact were investigated.

1. INTRODUCTION

Today, thin hard coatings are the main way of improving the performance of cemented carbide, ceramic and CBN tools in the machining of different workpiece materials, including difficult-to machine materials. It is well known that the new generation of complex multi-component and multilayer coatings ensures improved tool life and provides increased productivity under dry and hard machining conditions [2],[5],[14],[16].

The choice of layer sequence and total coating thickness can be tailored to meet particular manufacturers' requirements. It is reported [2] that more than 60% of cutting tool inserts currently used in the US and Western Europe are CVD-coated ones, which permits the use of higher machining speeds and increases the productivity. In particular, a new generation of PVD-TiCN and PVD-TiAlN coatings provides increased productivity in a broad range of machining operations and workpiece materials including austenitic stainless steels and aerospace materials. Visible improvements in the cutting tool performance are still achievable by new coating technologies applied not only to carbide, but also to cermet and ceramic substrates [1],[9],[15]. According to world-class manufacturers of cutting tool materials [9],[10] the future research will be based on tougher ceramics, PCD and PCBN based composites in the substrate of the tool or deposited coatings.

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Most of the prior research [4],[12],[15] showed that for a given combination of coatings and workpiece materials, as well as given rake face configurations, coatings influence the chip-formation mechanism and the tribological interaction at the chip-tool contact area. From a tribological point of view, the most important is the influence of the thermal properties of coating components and the coating structure on the behaviour of the tool-chip contact. In this aspect, it was found [7] that by optimizing the tribo-contact pairs the reduction of friction between the chip and the rake can cause a substantial decrease of the mechanical and thermal loads acting in the vicinity of the cutting edge.

The predominant wear mechanisms under metal cutting conditions are as follows [1],[6],[11]:

- adhesive wear,
- diffusive wear,
- mechanical wear (abrasion and plastic deformation),
- oxidation.

In this study, the tribological behaviour of several coatings deposited on sintered tungsten carbide inserts were examined in the orthogonal machining of an AISI 321 austenitic stainless steel. Experiments were focused on the identifications and quantifications of typical wear scars of coated cemented carbide inserts which occurred under different cutting conditions. The 3D visualization technique based on confocal microscopy was used to obtain a series of configurations of the tool wedge along the cutting edge. Special attention was paid to initial phase of wear of cutting tool faces which substantially influences tool wear evolution.

2. INVESTIGATION METHODOLOGY

In this investigation a number of cutting tests were performed under dry orthogonal conditions using an AISI 321 corrosion resistant stainless steel as the workpiece material and comparatively uncoated and coated cutting tool inserts with a H10F carbide substrate. The TNMA 160408 type cutting tool inserts with the plane rake face mounted in a PTNGR 2020-16 type tool holder were used. In the case of coated tools, five different thin layers including TiN, TiCN, TiAlN, AlTiN and AlCrN single and two-phase compositions were tested and compared in terms of tool wear evolution and wear mechanism occurring. All these coatings were specially deposited in Balzer's plant in Poland. The cutting tool angles and their values are specified in Table 1.

Table 1. Specification of tool angles of TNMA 160408 inserts

Cutting tool angle	Symbol	Value
Normal rake	γ_n	-5°
Normal clearance	α_n	5°
Major tool cutting edge	κ_r	90°
Inclination	λ_s	-6°

The machining trials were carried out using the following machining parameters:

- variable cutting speed of $v_c = 66.67, 86.33, 100.00, 116.67, 133.33, 150.00$ m/min,
- variable feed rate of $f = 0.10, 0.20, 0.28, 0.40$ mm/rev,
- constant depth of cut of $a_p = 2$ mm.

All investigations were divided into two steps. First, the measurements of basic cutting quantities including cutting forces, cutting temperature (equivalently the *emf* signals) and recording the thermographs of the cutting zone. In the next step performed in a post-process mode after cutting tests, the chip compression ratio, the tool-chip contact length, the wear indicators at the rake and flank faces were measured and the worn faces were examined using optical and confocal microscopy. A special set-up allowing the realization of these tasks was assembled. The machining trials were consequently carried out on a conventional lathe with a stepless control of the spindle using appropriate measuring sensors and devices as well as data acquisition system.

A special attention was paid on the measurements of wear effects concerning the wear scars and deterioration of the deposited coatings resulting from different wear mechanisms. The coating removal was examined on the rake face within the tool-chip contact length and on the flank face within its contact with the machined surface of the workpiece material. In particular, the average width of the flank wear VB_B was measured on the optical images recorded by means of LEICA MS 5 optical microscope and dedicated LEICA IM 1000 Image Manager software. Exemplarily, the measurement of the VB_B value visualized on the image of worn flank face coated with the AlTiN layer is shown in Fig. 1. It should be pointed out in Fig. 1 that the outer boundary of the removed coating is not sharp and consequently the measuring error ΔVB_B was determined.

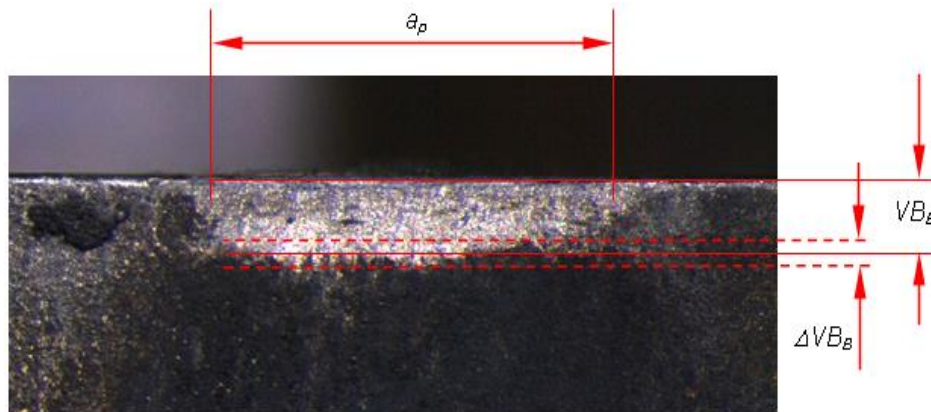


Fig. 1. Determination of average width of flank wear VB_B and measuring error ΔVB_B tool coated with AlTiN layer, Cutting parameters: $v_c=100$ m/min, $f=0.20$ mm/rev

Detailed data on the wear morphology of the rake faces of the tested inserts were gathered based on 3D isometric images recorded on a LEXT OLS 4000 Olympus confocal microscope, as exemplarily shown in Fig. 2. In particular, such visualization of the worn surfaces allows the extraction of individual profiles in the selected places and quantification of wear evolution using standardized wear indicators. These cross-sections were generated

using a Mountains Map Universal package. Some recorded profiles of the worn rake face are presented in Fig. 7.

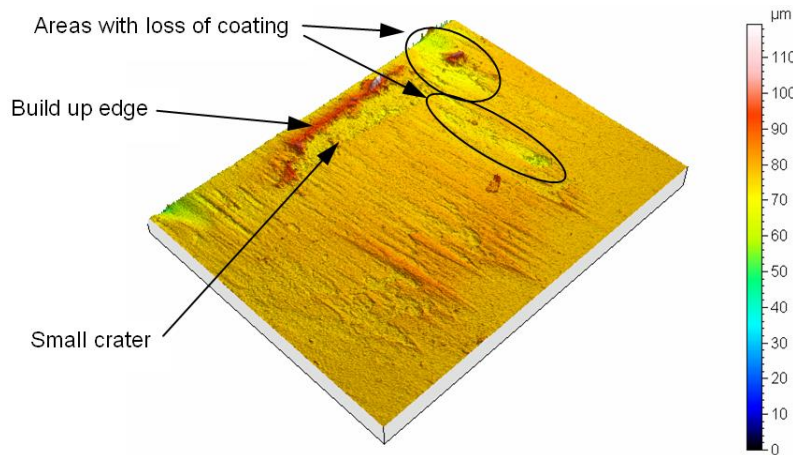


Fig. 2. Isometric image of the worn rake face of TiAlN coated insert using confocal microscopy. Cutting parameters: $v_c = 100$ m/min, $f = 0.20$ mm/rev, machining time $t = 4$ min

3. EXPERIMENTAL RESULTS AND THEIR ANALYSIS

In general, tool wear evolution depends on the mechanical and thermophysical properties of mating workpiece and cutting tool materials. Fig. 3 presents different wear effects observed on the flank faces of uncoated and coated cutting tools. In relation to the uncoated carbide cutting tool for which flank face wears uniformly (Fig. 3a) coatings deposited on cutting tools contribute to the decrease of tool wear and the values of VB_B indicator are visibly lower. For instance, for the TiAlN coated carbide tool the VB_B measured after a 4 min wear test is about 14% lower than for the uncoated tool. However, the additional visible wear effect is that the cutting edge radius decreases as shown in Fig. 3b. In general, the cutting edge radius decreases from about $60 \mu\text{m}$ to about $25 \mu\text{m}$ independently of the coating grade. The TiAlN coating was removed continuously and without local massive losses.

In the case of AlCrN shown in Fig. 3c the wear scars indicate some areas in which the coating was practically removed. In comparison to the TiAlN layer the increase of the cutting edge radius was not depicted. The average VB_B value was about 0.29 mm and about 18% less than for the uncoated H10F carbide insert. These differences in tribological behaviour of TiAlN and AlCrN coatings can be related to different hot hardness and wear resistance [8]. The VB_B values recorded after 1, 2 and 4 min wear tests are depicted in Table 2. and accordingly presented in Fig. 4.

It can be seen in Fig. 4 that in the first wear period of 1 min tool wear for all tested cutting tools is comparable and the VB_B is about 0.25 mm. When the tool wear progresses, coated tools, especially a group of coatings based on the aluminium nitride- TiAlN, AlTiN and AlCrN, wear less intensively. This fact is in accordance with the recommendations

of cutting tool's manufacturers [3],[8] who dedicate these coatings to the machining of difficult-to-machine materials such as titanium alloys, nickel-based alloys, stainless steels and hard materials up to 70 HRC hardness under dry conditions [13]. The decisive factors are lower friction coefficient, higher hot hardness and predominantly higher abrasive wear resistance [3],[8],[13].

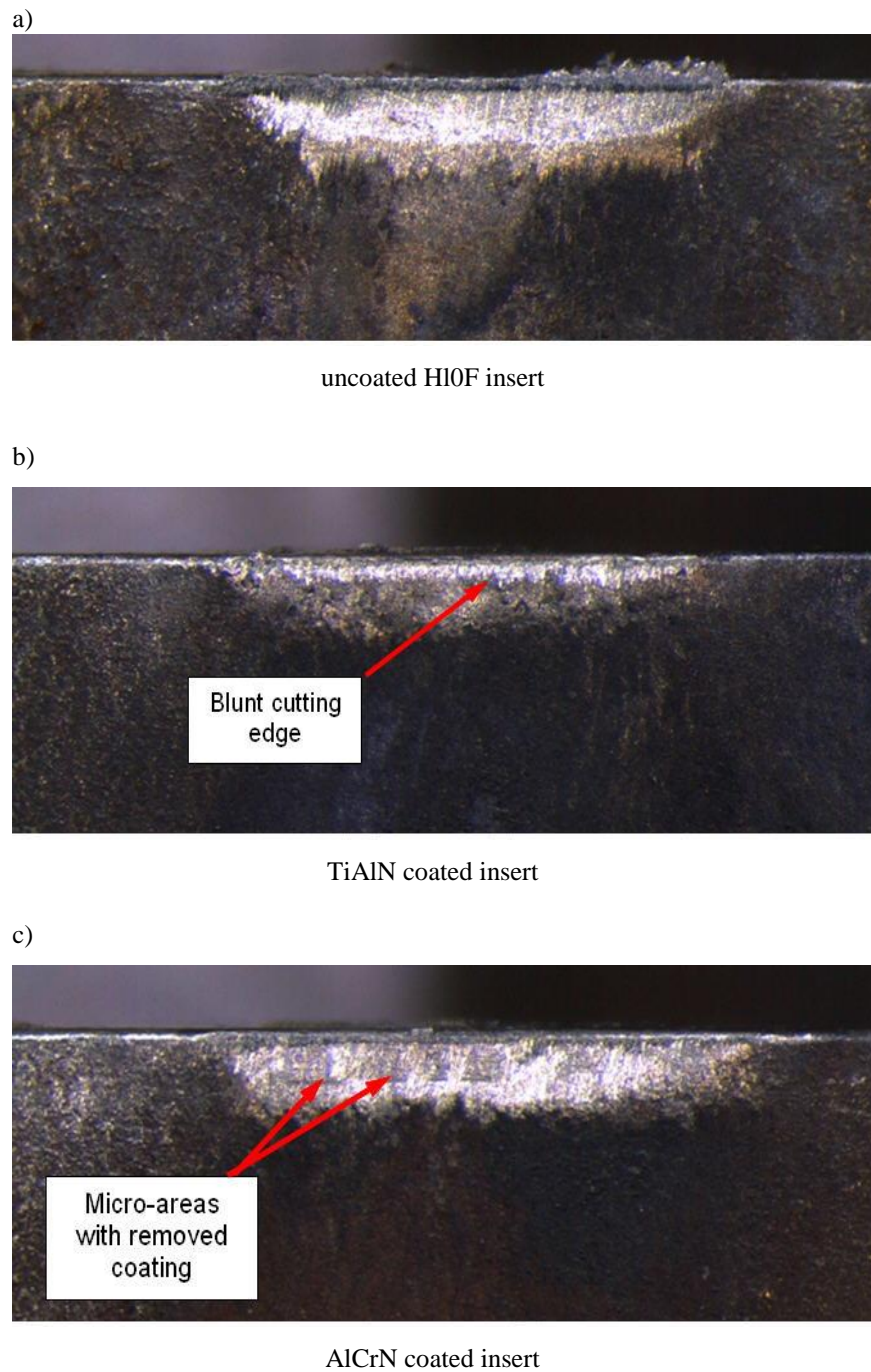
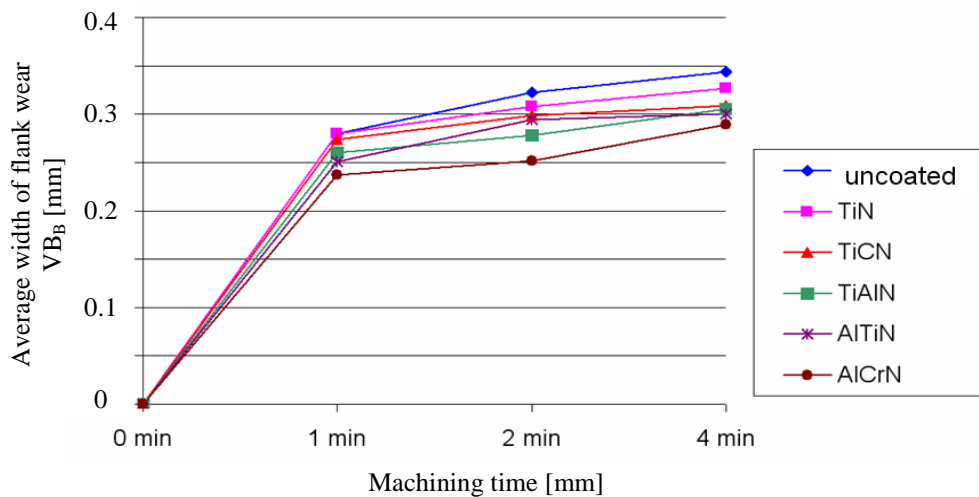
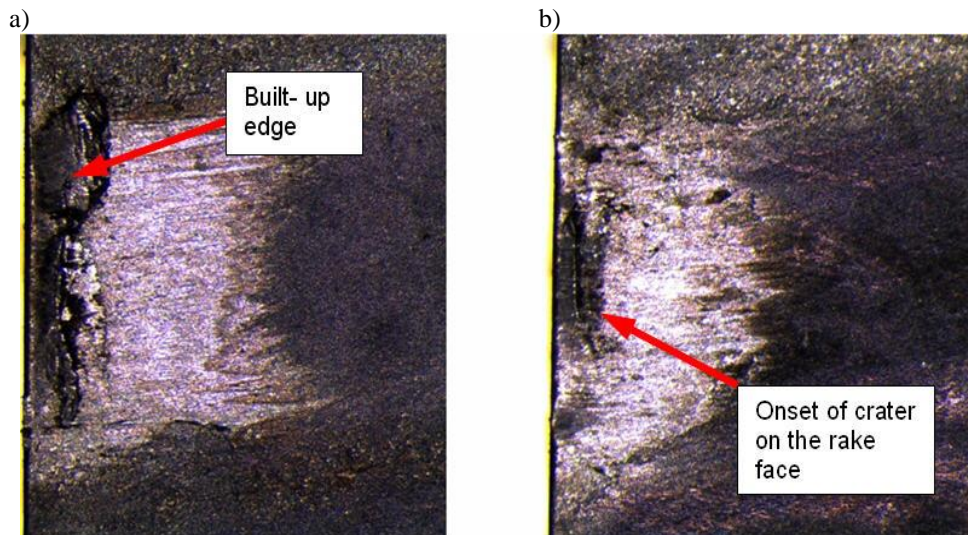


Fig. 3. Selected images of worn flank faces of uncoated (a) and coated (b and c) inserts obtained after 4 min, cutting parameters: $v_c=100$ m/min, $f= 0.20$ mm/rev

Table 2. Values of the average width of flank wear VB_B recorded after 1, 2 and 4 min respectively

Type of coating	Average width of flank wear VB_B , mm after		
	t = 1 min	t = 2 min	t = 4 min
uncoated	0.279	0.322	0.344
TiN	0.280	0.308	0.327
TiCN	0.274	0.299	0.309
TiAlN	0.260	0.278	0.305
AlTiN	0.251	0.294	0.300
AlCrN	0.237	0.252	0.289

Fig. 4. Comparison of evolution of the average width of flank wear VB_B for examined tools during 4 min testFig. 5. Images of worn rake face of TiAlN coated inserts after machining time of (a) 1 min and (b) 4 min; cutting parameters: $v_c=100$ m/min, $f=0.20$ mm/rev

The observations of the tool wear concern also the plane rake face due to formation of the groove in the tool-chip contact area. It was found, that the character and intensity

of the rake wear were similar for all coated tools regardless the chemical compositions and configurations of the deposited thin films. In particular, the built-up edge (BUE) was observed in the machining of AISI 321 corrosion resistant stainless steel as shown in Fig. 5a. The BUE was localized in the vicinity of the cutting edge (see also Fig. 2) causing the catastrophic failure. Moreover, Fig. 5 shows that besides the BUE which develops after 1st min the crater develops as well. In addition, the rake wear evolution was characterized by a series of profiles obtained by slicing the 3D isometric image shown in Fig. 2. For instance, Fig. 6 shows three cross-sections of the worn rake face with deposited TiAlN coating after a 4 min wear test.

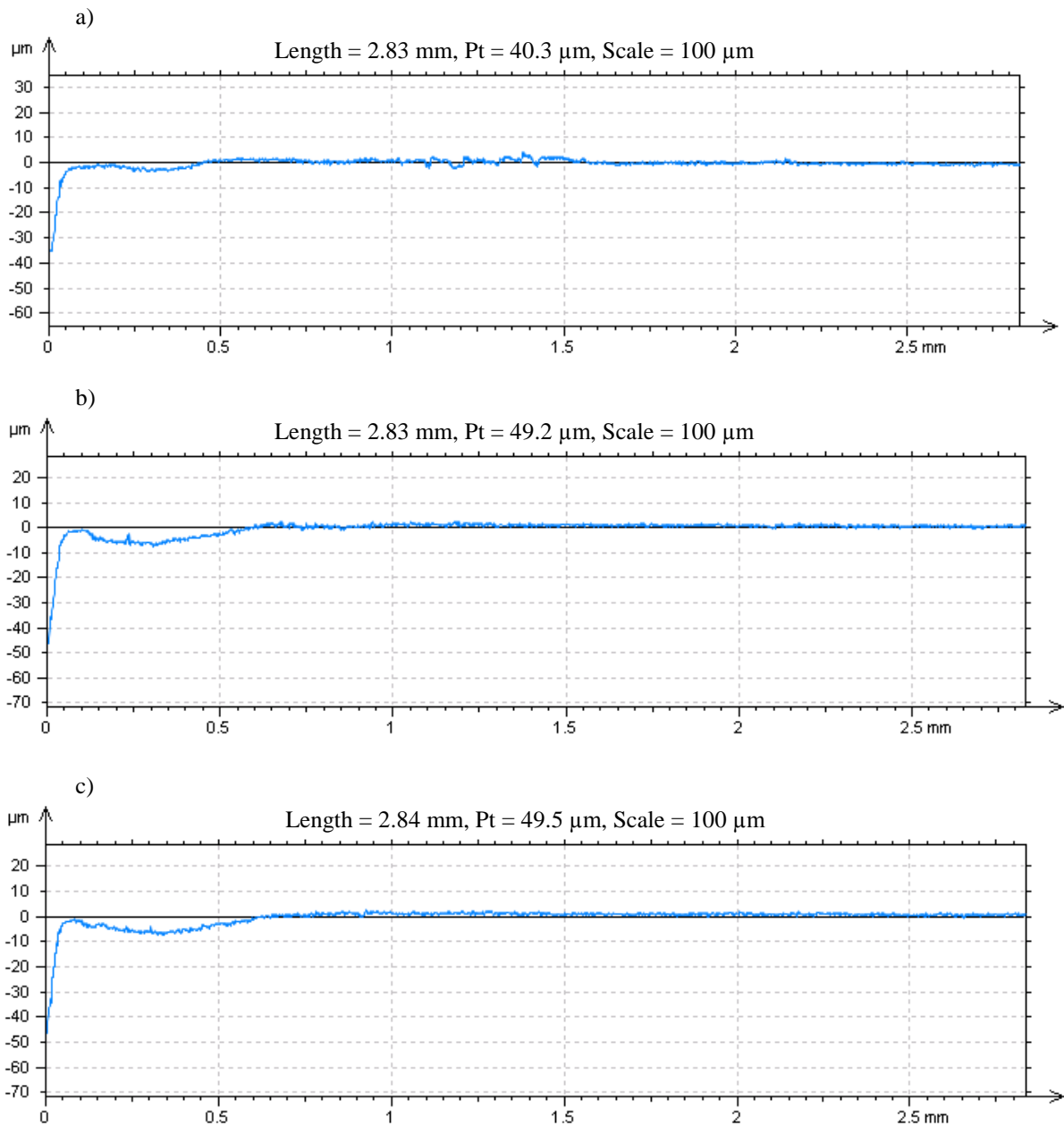


Fig. 6. Characteristic profiles of worn TiAlN coated rake face obtained after 4 min for different cross-sections; cutting parameters: $v_c=100$ m/min, $f=0.20$ mm/rev

As a result, three different profiles of the worn rake face with deposited TiAlN coatings and generated in the direction normal to the cutting edge can be compared. Fig. 6a presents the profile corresponding to the periphery of the tool-chip contact area whereas the next two profiles presented in Figs. 6b and 6c were generated in the middle part of the contact area. As a result, they are assumed to be representative profiles in this stage of tool wear and the initial configuration of the rake face when tool wear progresses further.

As can be seen in Fig. 6c, a groove was formed resulting from crater wear and in addition the cutting edge radius was reduced to about $25\ \mu\text{m}$. Based on this technique it is possible to record precisely the changes of all these artifacts. It should be noted in a sequence of profiles shown in Fig. 6 that the cutting edge radius changes depending on the localization of tool-chip contact area.

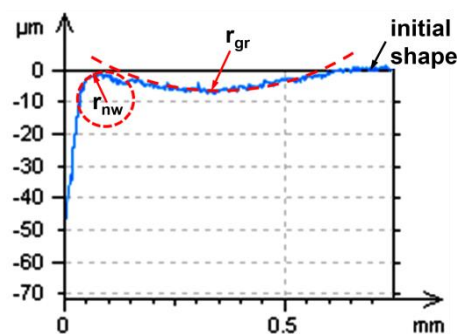


Fig. 7. Magnified part of profile of worn TiAlN coated rake face shown in Fig. 6c

Fig. 7 presents the magnified part of the worn cutting edge with a mask of the initial wedge shape. Both the groove radius r_{gr} and the cutting edge radius r_{nw} are marked. In this case study the cutting edge radius was changed from $58\ \mu\text{m}$ to $9\ \mu\text{m}$. In addition, a groove of the radius of $89\ \mu\text{m}$ was formed on the rake face. This information seems to be important with regard to the selection of cutting tools for the machining of an AISI 321 stainless steel.

4. CONCLUSIONS

The following conclusions can be drawn from this study:

1. In the first stadium of tool wear the flank wear causes a displacement of the cutting edge and further when the wear is being continued the modifications of both the cutting edge and the rake face occur.
2. In this investigation the cutting edge is reduced from initial $56\text{--}59\ \mu\text{m}$ to $22\text{--}25\ \mu\text{m}$ independently of the coating deposited. Moreover, a characteristic groove is formed similarly to commercial grooved cutting tool inserts.
3. It was documented that abrasion and adhesion are the two dominant wear mechanisms. The flank wear mainly results from abrasion, whereas the crater on the rake face is the joint effect of both abrasion and adhesion.

4. The machined stainless steel reveals the strong tendency to strain-hardening and BUE formation. In particular, the adhesive joints cause local removal of coatings due to chemical affinity to titanium nitride. At cutting temperatures higher than 800 – 850°C, also the diffusion can accelerate the coating degradation and substrate wear as well.
5. A practical value of this study concerns the 3D configurations of both grooved rake face and the rounded cutting edge. In particular, they can support the modifications of commercial cutting tool inserts recommended for austenitic corrosion resistant steels.
6. The theoretical value of the experimental results is mainly based on the interrelationships between an optimal shape of the cutting edge and the grooved rake face and the tool wear behaviour. It also concerns the so-called self-organization of the tribo-systems. This study will be continued taking into account all these findings.

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