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Use of laser ablation for formation of discontinuous (discrete) wear-resistant coatings formed on solid carbide cutting tool by electron beam alloying and vacuum-arc deposition

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Abstract – A technological process of solid carbide cutting tool surface treatment by selective laser ablation of wear-resistant coating is described. Discontinuous coating is achieved by laser ablation of pre-deposited complex coating, formed by NbHfTi electron beam alloying with subsequent vacuum arc (TiAl)N coating. It is shown that this treatment helps to slow down the wearing process of cutting inserts on their rake and flank surfaces, thus increasing the tool lifetime.

Key words: Tungsten carbide / laser ablation / discontinuous (discrete) wear resistant coatings / electron beam alloying / vacuum arc coating

1 Introduction

The main performance data of tungsten carbide cutting tools are subject to strict standards [1–3]. However, even for the cutting tool produced by the same manufacturer and having the same dimension, the corner radius r may vary significantly [4, 5]. As it is known from the metal cutting theory, the corner radius strongly influences cutting process, especially with low cutting depth, by modifying the rake angle of cutting tool and affecting cutting forces, tool lifetime, cutting power and machined surface roughness [6].

The presence of corner radius and its optimal values range is still the point of discussion [7–9]. Traditionally it is considered that for the cutting tool made of high-speed steel, the optimal corner radius is within the range of $8-12$ μm while for the tungsten carbide inserts it is equal to $10-20$ μm. The most widespread current technologies for the wear resistant coatings deposition also affect the corner radius, usually increasing it. Many cutting tools manufacturers perform series of additional operation steps after the coating deposition in order to optimize the corner radius [10].

Nowadays, the laser ablation surface treatment achieved the high level of the technical development and technological application [11–14], when the known method is not spread for solution of the current problem of machine time prolongation of cutting inserts. Hence, the scientific problematic question of corner radius and its optimal values range for cutting inserts and the research in field wear-resistant coating formation and its exploitation by innovative methods of complex coatings and its laser ablation surface treatment of inserts' cutting edge are actual today.

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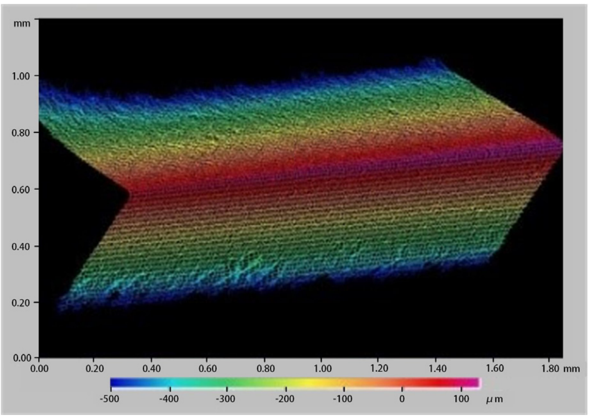
2 Experimental setup

The specialized GFM MicroCAD Light 3D microscope with the accuracy of 1 μm was used to evaluate actual values of corner radius and to measure it. The measurement was performed at the cutting insert tip and at the cutting edge adjacent to it. In the experimental research, the H13A (Sandvik Coromant) cutting inserts were used as the cutting tool.

The uncoated cutting inserts have corner radius of $15-35$ μm, while after the ion-plasma coating deposition it increases to $30-55$ μm (Fig. 1).

Such increase of initial corner radius value will strongly affect the allowable cutting depth, which is critical when the cutting data for finishing cutting is selected. If the assumed cutting depth is equal or comparable to the corner radius, the cutter will not cut the work piece but crease it. Concurrently, there is a high probability of chattering and deteriorating the machined surface roughness. The cutting tool will intensively wear because of heating, thus neutralizing many useful properties of the wear-resistant coating.



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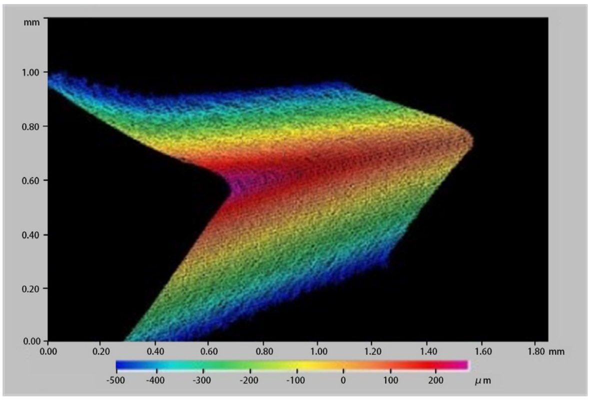

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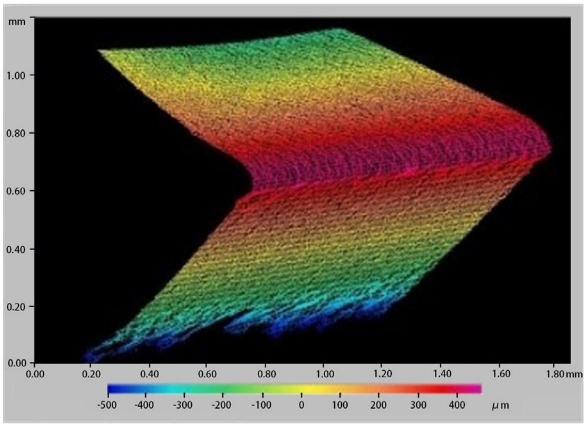


(c)

Fig. 1. 3D-images of corner radii of carbide inserts (as received) with no coating (a, b) and with coating (c): a) 21 μm; b) 32 μm; c) 55 μm, obtained by GFM MicroCAD Light 3D microscope.

It is known, the corner radius can be changed using, for example, the mechanical impact to the cutting tool surface. With this treatment, it is possible to form chamfers, steps and other irregularities on the surface, among them ones formed by stripping along the cutting edge. However, the spot stripping is quite difficult to perform, especially considering small size of chamfer and its precise positioning with respect to the cutting edge. In present paper, an approach for selective laser coating removal (stripping) from the defined part of cutting tool surface is considered, i.e. formation of the discontinuous (discrete) coating on the rake surface or, as a special case, its complete removal.

Currently, the main used architecture of discrete coating is one in the form of frame (grid) [15]. In addition, there is an approach for discontinuous coating formation in a vacuum-arc discharge using single or multicomponent electrodes [16].

The discrete coating allows decreasing stresses in the surface layer of the cutting insert substrate and shifting the maximum of shear stress away from the “substrate – coating” adhesion contact surface into the depth of the material. The coating in the isolated area is stiffer than the continuous coating and the crack formation is limited by this area without spreading to the adjacent area. Besides that, the discontinuous coatings capture the solid wear particles in the regular cavities and keep the cutting coolant inside them.

A distinction is made between the discrete and framed coating. From tribotechnical data, the framed coatings have a wear resistance up to 30% higher than one of the discrete coatings with both dry friction and lubricated friction [17].

As for the formation of discrete coatings using laser treatment, the process parameters should be selected so that the coating will be removed from the working area with minimal impact to the substrate and cutting part of the cutting tool. As the previous research has shown, maximum allowed laser power density is 0.25 J/cm^2 [9,17]. If this value is exceeded, the cracks formation or the surface fusion in the working area is observed [18]. For that reason, special equipment allowing permanent control of the cutting tool position in relation to the laser beam needs to be used. The up-to-date multicoordinate laser machining centers may serve as an example [19].

For the current experimental research, H13A inserts were selected as the substrate material for the formation of discontinuous coatings on the tungsten carbide cutting tools. Before the coating deposition, they were treated on the RITM technological unit [8,15], where thin NbHfTi film with the thickness of 150−250 nm was deposited by magnetron source in order to create an alloyed layer consisting of wear-resistant nonstoichiometric carbides. Then, the samples were treated with the series of wide-aperture low-energy high current electron beam in the same chamber avoiding the air contact. The electron beam heats the surface to the high temperature and initiates a chemical reaction of solid- and liquid-phase carbides formation between thin metal film and carbon present in the substrate in free or bound state. Available data shows that the cutting tools subjected to such treatment with the consequent vacuum-arc coating deposition satisfy the strict requirements for quality, durability and productivity [18,19]. After that, the gradient (TiAl)N coating with the thickness of 5−7 μm was deposed onto

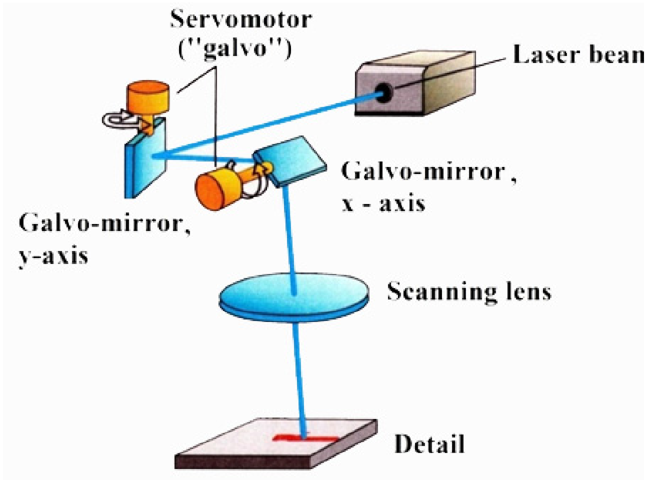


Fig. 2. Elementary diagram of laser ablation process performed using Laser 600 unit.

the a tool surface with the alloyed layer using the Platit π80 coating unit.

The laser ablation of the coatings was performed using the laser-machining center equipped with the solid-state pulsed optical fiber Laser 600 GF by Agie Charmilles with the output power of 50 W and the pulse length of 90 ns [20–22].

The elementary diagram of laser ablation process used for the cutting tool treatment is shown in Figure 2.

3 Results and discussion

At the first stage, the process parameters for the coating stripping with the minimal impact to the substrate were searched for. The pulsed laser beam with the step of 20 μm, which equals to the spot half width, was applied to the selected area of the cutting insert with wear-resistant (TiAl)N coating. The optimal parameters for the process, when the coating was stripped uniformly from all treated areas with no crack formation to the underlying material and minimal surface layer morphology changes, were empirically found. The Laser 600 unit was shown to be able to strip the coating during one pass with the output power set to 40 W, pulse frequency to 150 kHz and scanning speed 1 m/sec (Fig. 3). The area of laser treatment on the cutting insert H13A is presented in Figure 4. The images obtained by optical microscope AxioCam MRc 5 and SEM VEGA 3 LMH TESCAN.

The above-described operating modes allow the cutting edge surface treatment, in which a chamfer of 100 μm width, running parallel to the cutting edge, is produced. Discontinuities in the wear-resistant coating act to reduce direct stress to the cutter face and eliminate edge effect in the volumes of coating material localized on the radial tool surfaces. Treated area roughness R_a was measured to be no more than 2.0 μm after stripping. Wear-resistant coating is stripped almost completely in the treatment areas, and surface fusion is only marginal. Crack formation

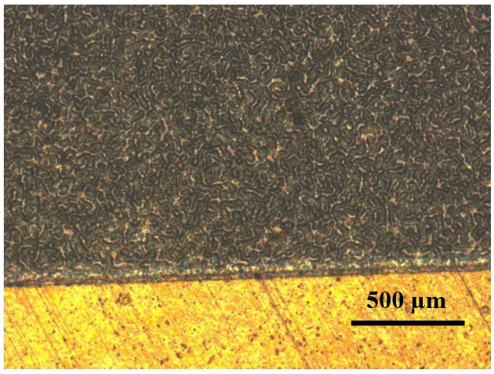
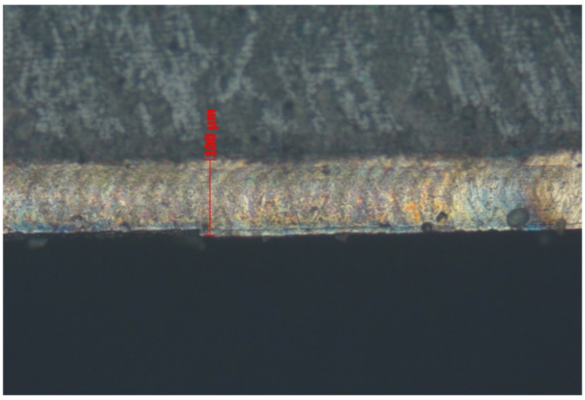


Fig. 3. Surface of cutting insert H13A, obtained in the zone of laser treatment with laser power 40 W (optical microscopy by AxioCam MRc 5 with the resolution 500×).



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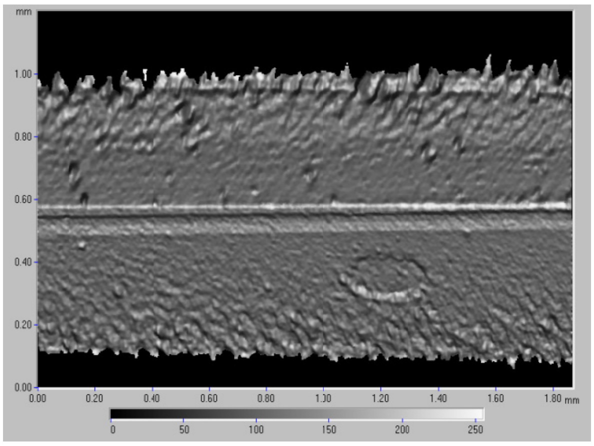


(b)

Fig. 4. Results of laser treatment on surface of cutting insert H13A, where (a) view on the produced track, obtained by optical microscope, (b) SEM-image of the track.

was not observed in the treatment area, and importantly, there was no chipping along the cutting edge. The cutting edge corner radius is decreased by more than 5 μm.

The chamfer produced by laser ablation surface treatment and its graphic presentation by 3D microscope is presented in Figures 5a and 5b, correspondingly. Figure 5c presents the results of discontinuous (discrete) (TiAl)N

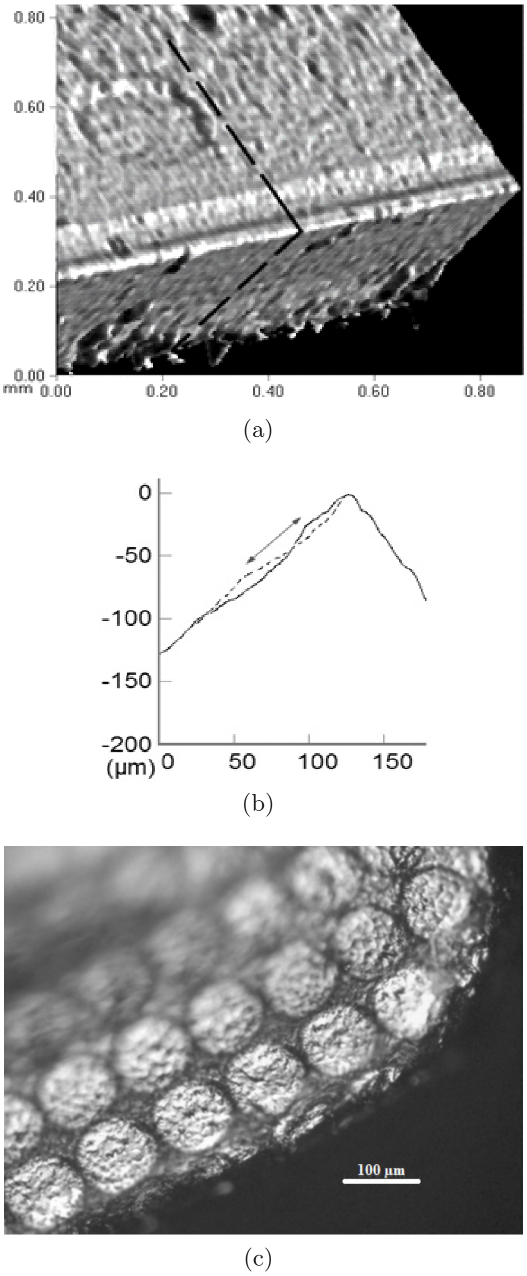


Fig. 5. Chamfer formed on the cutting edge of carbide insert after stripping (a), cutting edge profile produced by 3D microscope (b), discontinuous (discrete) (TiAl)N coating deposited to H13A tungsten carbide insert (c).

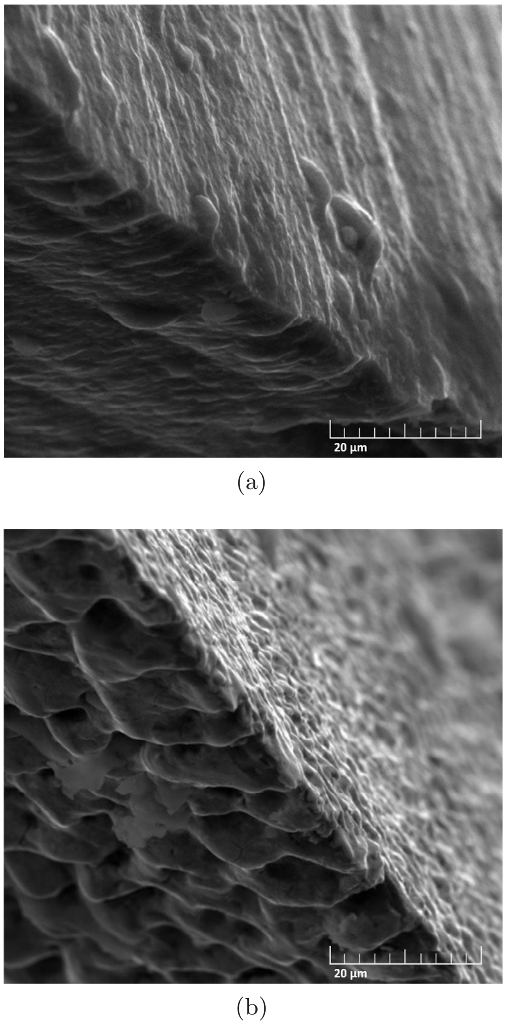


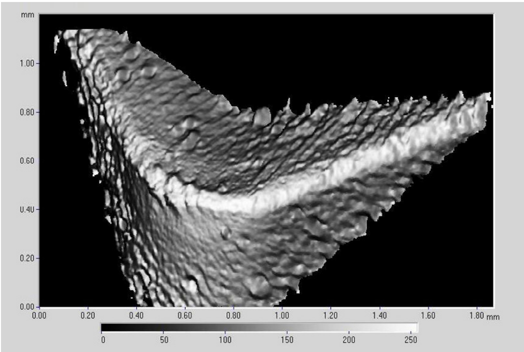
Fig. 6. SEM images of cutting edges of tungsten carbide indexable inserts after surface treatment (a) and after laser ablation (b).

coating, formed after laser ablation surface treatment, deposited to H13A tungsten carbide cutting insert, obtained by optical microscope Olympus BX51M.

SEM images obtained on VEGA 3 LMH TESCAN electron microscope demonstrate surface modification by the treatment of the cutting edges of NbHfTi-alloyed and (TiAl)N-coated carbide inserts. Micrographs show the cutting edge before (a) and after (b) laser ablation selective coating stripping (Fig. 6)

Further experiments on 100Cr6 (DIN) steel test samples turning (hardness 43−47 HRC) have shown that ablation-formed discontinuous coating can control crater formation on the rake surface during machining. The best improvements were observed in the finishing operation, and if the coating is completely stripped on all areas more than 200 μm away from the cutting edge.

Selective laser ablation or the complete removal of coating on the rake surface significantly influences the corner radius of cutting edge and changes the wear pattern. The cutting insert tip 3D micrograph with discontinuous coating formed by selective laser ablation is shown in Figure 7a (initial corner radius of this test sample was 50 μm). In Figures 7b−7d, SEM images of the same tool tip after 4, 10 and 26 minutes of turning operation are shown (finishing cutting data: $t = 0.25$ mm, $s = 0.1$ mm/rev, $v = 200$ m/min). Measured radii of cutting insert tip with discontinuous coating deposited by the laser ablation surface treatment are showed in Figure 8, correspondingly.



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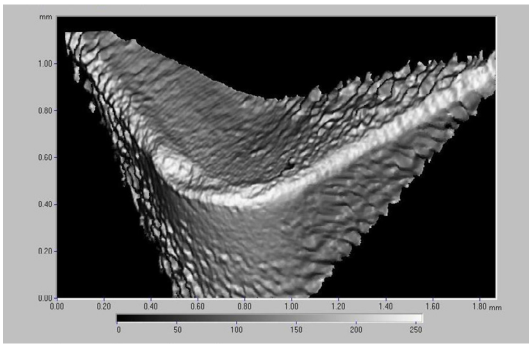

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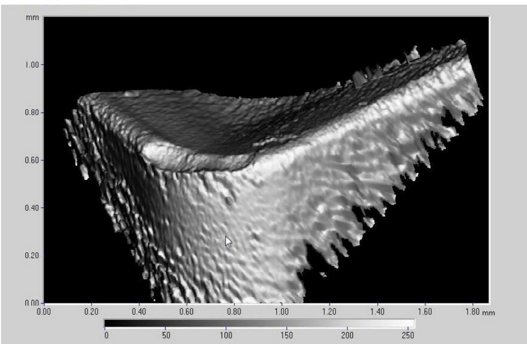

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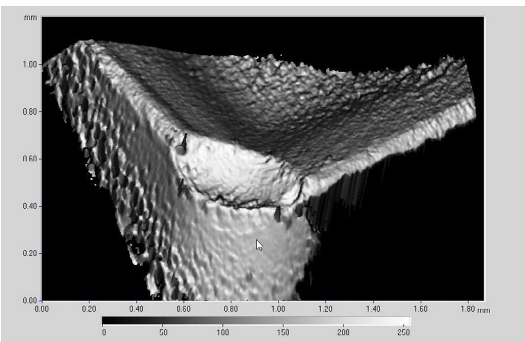
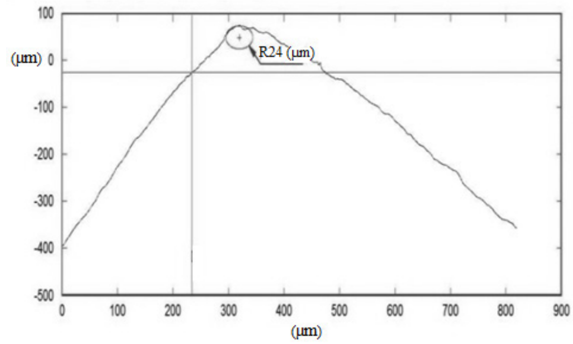


(d)

Fig. 7. 3D-images of cutting insert tip with discontinuous coating deposited by the laser ablation: as received (a), after 4 min (b), 10 min (c) and 26 min (d) of cutting obtained by GFM MicroCAD Light 3D microscope.



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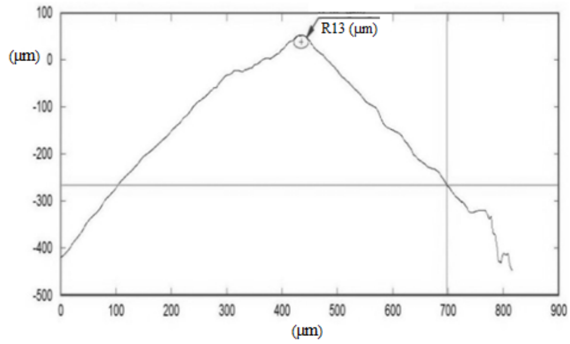

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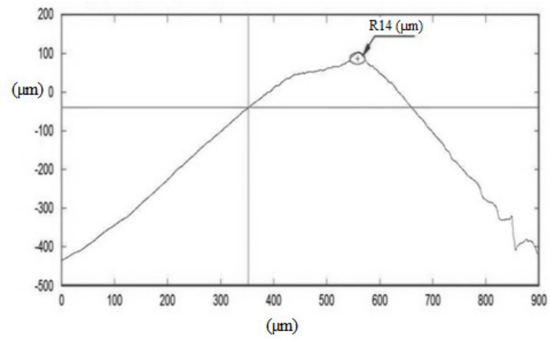

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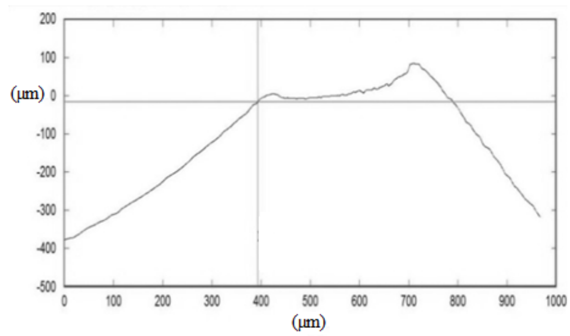

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Fig. 8. Measured radii of cutting insert tip with discontinuous coating deposited by the laser ablation as received (a), after 4 min (b), 10 min (c) and 26 min (d) of cutting process.

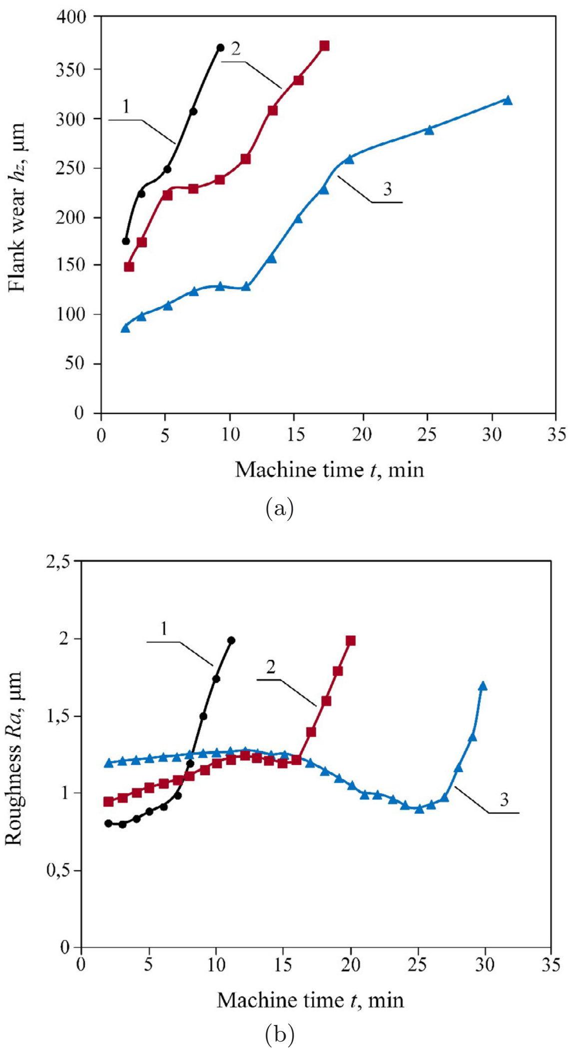

Fig. 9. Flank wear (a) and machined surface roughness (b) depending on cutting time: 1 – cutting insert with vacuum arc (TiAl)N coating; 2 – with complex surface treatment (electron beam alloying with NbHfTi and deposing of (TiAl)N) coating; 3 – after laser ablation of the rake surface of cutting tool having a complex surface treatment.

The influence of selective laser ablation surface treatment on wear resistance of the tool was assessed in the comparative tests. Cutting inserts with three different surface treatment types (vacuum-arc coating with (TiAl)N; complex surface treatment by electron beam NbHfTi alloying and (TiAl)N coating; selective laser ablation after complex surface treatment) were tested in the same cutting condition ($t = 0.25$ mm, $s = 0.1$ mm/rev, $v = 200$ m/min). The failure criteria used in the tests were 0.3 mm flank surface wear and 1.5 μm roughness of the machined surface; operating performance is considered lost, if these values are exceeded. Plots of measured wear vs. time of operation are shown in Figure 9. Experimental data indicate more than twofold increase of the complex-coated tool wear resistance after selective laser ablation treatment of the coating. Graphs show that laser ablation surface treatment increases significantly the machine time of cutting inserts: in comparing with cutting inserts with complex surface treatment in 1.5–2 times, and in comparing with traditional vacuum arc (TiAl)N coating in 3–4 times.

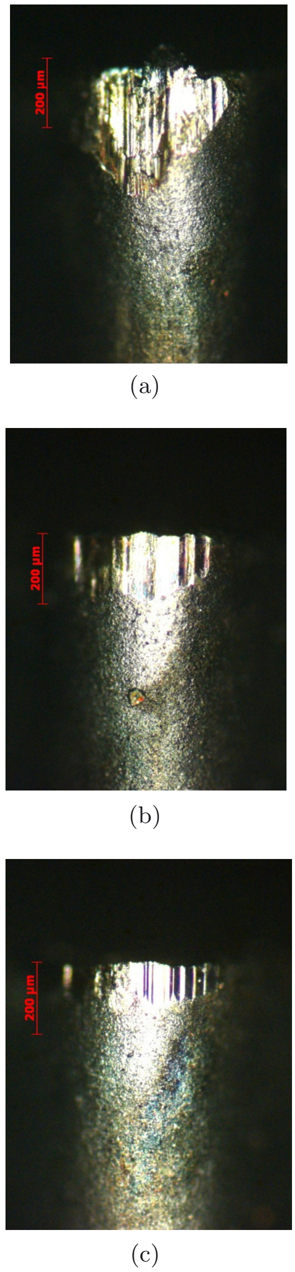

Fig. 10. Dimensions of flank wear spot of cutting tool made of the H13A solid carbide after longitudinal cutting of 100Cr6 steel (43–47 HRC) with cutting depth $t = 0{,}25$ mm; feed per revolution $s = 0{,}1$ mm; cutting speed $v = 200$ m/min after 10 min of cutting: a) cutting insert with vacuum arc (TiAl)N coating; b) with complex surface treatment (electron beam alloying with NbHfTi and deposing of (TiAl)N) coating; c) after laser ablation of the rake surface of cutting tool having a complex surface treatment.

Selective laser ablation of surface coating on the rake surface changes the tool wear pattern, which is demonstrated in Figure 10. Rake surface friction conditions are

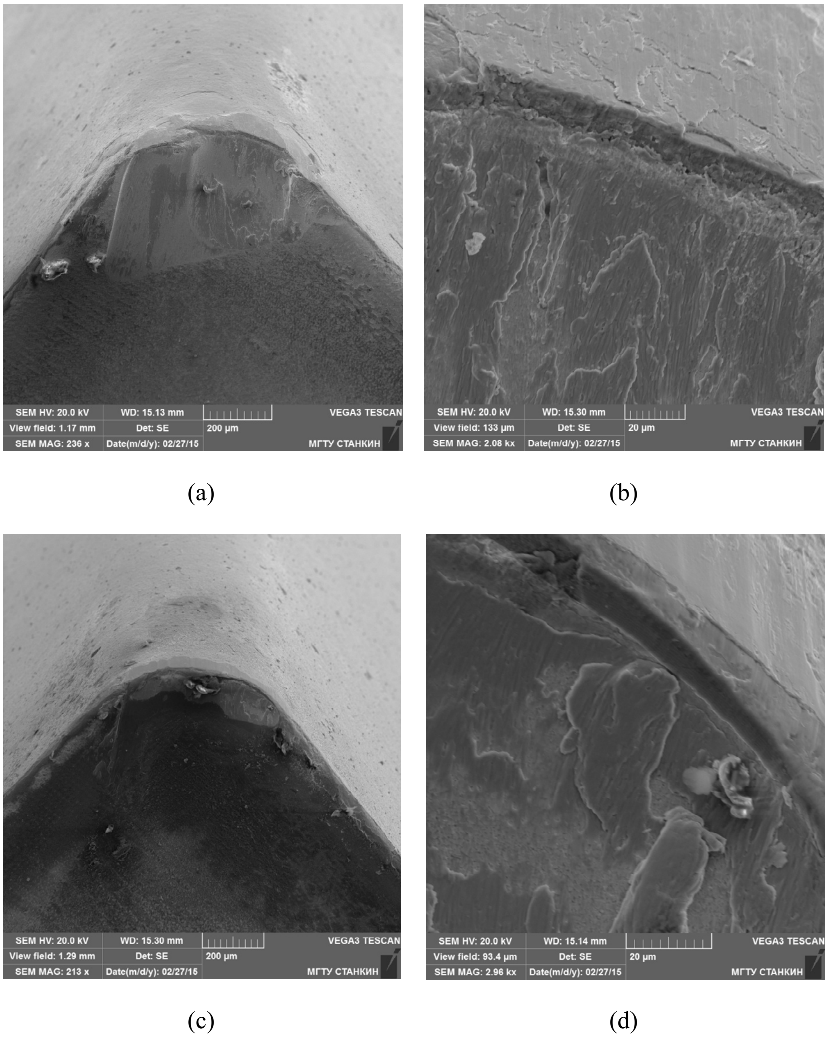

Fig. 11. SEM-images of cutting inserts' wear after remove of the coatings on the cutting edge, where (a) and (b) cutting insert with wear-resistant coating after 2 min of cutting process, (c) and (d) cutting insert with complex surface treatment after 4 min of cutting process.

changed by the selective coating removal, so that a crater with sharp cutting edge is formed on it during the first minute of operation. Material in this area has increased its toughness due to electron-beam alloying, so the insert is made self-sharpening during the operation. Flank surface wear quickly stabilizes at $0.1-0.15$ mm, and corner radius is keeping constant at 13–14 μm.

SEM-images, presented in Figure 11, demonstrate the cutting inserts' wear after remove of the coatings on the cutting edge after 2 min (a and b) and 4 min (c and d) of cutting process It shows obviously that cutting inserts with wear-resistant coating has a significant wear, when cutting insert with complex surface treatment has almost no visible wear and can be reused for further processing after recoating.

4 Conclusions

Wear spot size increases through the operation, but overall tool wear condition remains basically the same. Flank surface wear is significantly reduced, and metal buildup and outgrowth are minimized. Flank surface wear is significantly reduced, and metal buildup and outgrowth are minimized.

To summarize, a set of tests was conducted which show that the wear pattern and intensity can be controlled by selective laser ablation treatment of the predeposited complex coating on the surfaces of carbide cutting tools, and formation of discontinuous coating enables more intense cutting data.

To achieve best performance, a three-stage coating/surface treatment process is recommended, consisting of the following steps: NbHfTi alloying, applying of (TiAl)N gradient toughening coating of $5-7$ μm thickness, and the subsequent selective laser ablation surface treatment (50 W output, pulse duration 90 ns).

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