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A CRITICAL REVIEW OF CHARACTERISTIC TECHNIQUES FOR IMPROVING THE CUTTING PERFORMANCE OF COATED TOOLS

The cutting performance of PVD coated tools can be significantly improved by applying optimized PVD processes, film architectures, as well as appropriate pre- and post- treatments of the substrates and coated surfaces respectively. Substrate pre-treatments aim, among others, at improving the coating adhesion. In this way, lower coating loads develop during cutting leading to a decelerated wear evolution. Furthermore, the effect of various PVD process parameters and film architectures such as of adhesive interlayers, Ar^+ ions bombardment, thickness distribution and multi-layer structure on the coated tool life is demonstrated. Finally, the potential to increase the wear resistance of coated tools via micro-blasting and to render sharp cutting edges mainly of small diameter tools more stable by rounding them via grinding is presented. Micro-blasting parameters such as of grain material, pressure, dry or wet etc., affect significantly the superficial coatings' hardness and brittleness and in this way their wear behaviour. To check the effectiveness of all these methods, innovative coating's characterization procedures providing information concerning the film and substrate properties as well as adhesion are applied, thus reducing the required experimentation time.

1. INTRODUCTION

The increasing manufacturing demands, being supported by the improved capabilities of modern machine tools, require the persistent evolution of superior materials and coatings for cutting tools [1-3]. For producing coated tools characterized by enhanced mechanical properties, the integration of various procedures before, during and after the coating deposition is necessary, as schematically shown in Fig. 1. In this context, the conduct of micro-blasting on cemented carbide substrates prior to the coating deposition has been showcased as an emerging technology capable to ensure sufficient film adhesion and prolonged coated tool life [1,4-5]. Macro-blasting on cemented carbide substrates has

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been also proved as an efficient method for reconditioning coated cemented carbide solid tools
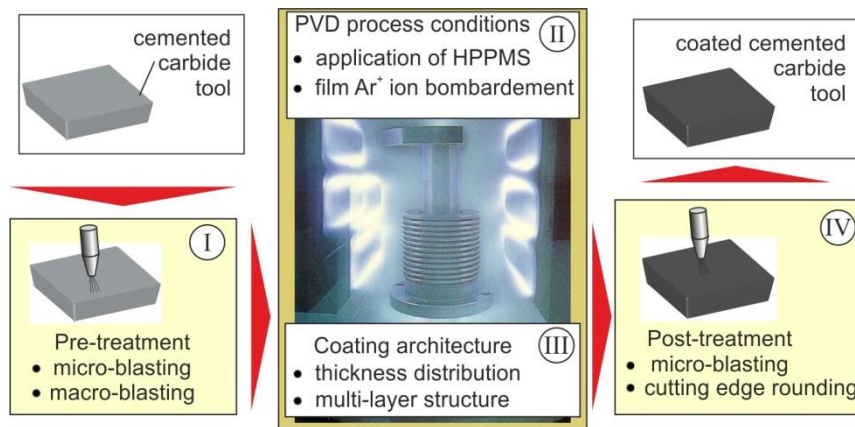

Fig. 1. Schematic presentation of the manufacturing chain to produce coated tools with improved properties

[1,6-7]. Furthermore, the continuously progress of the Physical Vapour Deposition (PVD) and especially the use of high power pulsed magnetron sputtering (HPPMS) has contributed to the production of coatings characterized by enhanced mechanical properties and uniform film thickness [1-2,5]. Moreover, the film bombardment by Ar^+ ions in the vacuum chamber during the PVD deposition process leads to denser film material structures and thus more wear resistant. Furthermore, by optimizing the coating architecture, as for example the film thickness distribution in the cutting edge region and the layer structure, the coating mechanical strength and thus, the coated tool life can be positively influenced [5,8-11]. The conduct of micro-blasting on the already coated surfaces has been documented as an efficient method for improving further the coated tool life [12-17]. Finally, the cuttings edges of coated tools with sharp cutting edges mainly of small diameter can be rounded after the film deposition via grinding. In this way, the cutting edges become more stable and they can be effectively used in cutting process if the applied cutting speed and chip lengths are appropriately adjusted [18]. In order to assess the effectiveness of all these methods, innovative coating's characterization procedures providing information concerning the film and substrate properties as well as adhesion are applied [1]. In Fig. 2 methods for determining material, dimensional and functional data of coated tools are displayed [1]. Combinations of these procedures jointly with FEM supported computations contribute to the explanation of the cutting tool films' failure mechanism.

2. SUBSTRATE'S PRE-TREATMENTS

2.1. MICRO-BLASTING FOR IMPROVING THE FILM ADHESION

The coating adhesion and subsequent the cutting performance of coated cemented carbide tools depends significantly on the applied mechanical pre-treatments. Micro-blasting of ground or polished substrates is an efficient method for improving film adhesion.

This can be explained considering the effect of micro-blasting on the surface morphology, as it is presented schematically in Fig. 3a. Superficial residual stresses are induced mainly due to the Co-binder deformation. Moreover, an increase of the micro-roughness occurs.

PROPERTIES		EDX	SEM	XRD	TEM	⋮	NI	⋮	NIT	IT	ITMFS	BC	WLS	IIT	S	NS	RC	DiF	OX	TRM
Material	Structure	✓	✓	✓	✓															
	Residual stresses			✓																
	Mechanical properties						✓													
	Hardness						✓													
	Britlleness								✓											
	Fatigue									✓										
	Fatigue at high strain rates										✓									
Dimensional	Thickness											✓								
	Thickness distribution on the cutting edge												✓							
Functional	Friction																			✓
	Adhesion													✓	✓	✓	✓			
	Diffusion																	✓		
	Chemical stability																		✓	

EDX: Energy-dispersive X-ray spectroscopy

SEM: Scanning Electron Microscope

XRD: X-ray Diffraction

TEM: Transmission Electron Microscopy

NI: NanoIndentations

NIT: Nano-Impact Test

IT: Impact Test

ITMFS: Impact Test with Modulated Force Signal

BC: Ball Cratering Test

WLS: White light scanning 3D measurements

IIT: Inclined Impact Test

S: Scratch test

NS: Nano-scratch test

RC: Rockwell C

DiF: DiFfusion test

OX: Oxidation test

TRM: TRiboMeter

Fig. 2. Characteristic methods for determining coating material, dimensional and functional properties

The individual carbides are revealed through the Co-binder removal from the cemented carbide surfaces. In this way it can be assumed that during the film deposition the nucleation rate of potentially formed transient junctions such as TiAlCN on the cobalt free WC-carbide surfaces is increased. Hence, an adhesion improvement between the substrate and the PVD film occurs, since, additionally, the less adhesive Co-regions on the substrate surface decrease [4]. After polishing by disc lapping, the carbides are rounded, the Co free WC-surfaces restricted and the Co-regions increased, thus deteriorating the film adhesion. Through micro-blasting of the polished insert surfaces, the described advantages of micro-blasting can be re-obtained. In addition, the WC carbides are now better embedded in the Co binder, due to the lower Rt micro-roughness in comparison to ground substrates.
The coating's adhesion of variously treated substrates was evaluated with the aid of the inclined impact test [19]. During this test, significant shear stresses are developed in the film-substrate interface. If these stresses exceed the interfacial toughness, a film overstressing occurs leading to its failure and rapid removal. Fig. 3b demonstrates the coating failed region versus the number of impacts, during this test. Ground, polished and micro-blasted substrates were investigated, all coated with the same PVD film. The coated inserts, subjected to substrate micro-blasting, withstand more effective

the applied loads and have a slower coating failed area ratio FR increase. Moreover, the removal of a poor-adherent coating on a polished insert possesses the most intense fracture propagation due to restricted film substrate mechanical interlocking. The highest wear resistance exhibits the coated insert with micro-blasted and polished substrate. These results are mirrored in the SEM micrographs, in the lower part of Fig. 3b and can be easily interpreted considering the dependencies described in Fig. 3a.
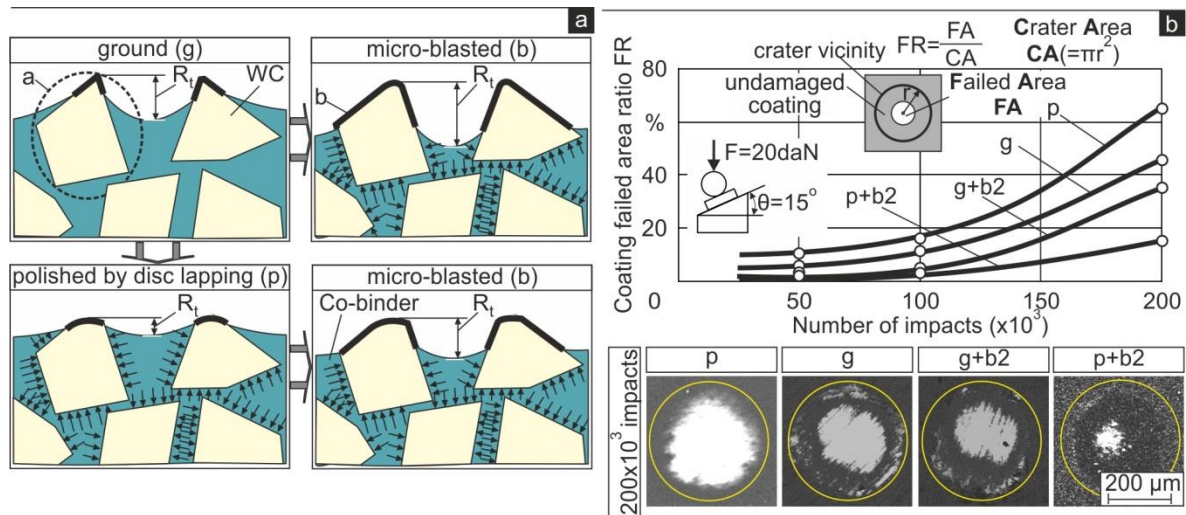
Fig. 3. (a) Micro-blasting and lapping effects on cemented carbide superficial structure. (b) Coating failed area ratio FR propagation in the inclined impact test

The coating adhesion improvement leads to a significant cutting performance increase, as exhibited in Fig. 4a. These results were achieved through milling investigations. The coated inserts with ground and micro-blasted substrates reach a tool life of approximately 55×10^3 cuts, at a flank wear width of 0.2 mm. Moreover, the results exhibit a further increase in wear resistance, by means of polishing and subsequent micro-blasting of the substrate. On the other hand, inserts with polished or ground substrates managed to cut only ca. 28×10^3 and 35×10^3, respectively, up to the same flank wear width. Moreover, based on a developed FEM model to simulate the coating–substrate interface adhesion strength by means of appropriate contact elements, the quantification of the film's adhesion properties was enabled via the contact stiffness ratio CSR [19]. In this way, the contribution of various substrate treatments to the film adhesion can be captured. In Fig. 4b, the remaining area ratio (1-FR) after 200×10^3 impacts and the contact stiffness ratio CSR in each substrate treatment case are presented.

2.2. APPLICATION OF MACRO-BLASTING DURING RECONDITIONING CEMENTED CARBIDE SUBSTRATES

In contrast to simple cutting inserts solid tools like milling cutters, gear hobs and gear shaping wheel cutters, broaching tools, etc., have to be reconditioned after achieving

the wear limit, due to their elevated cost compared to cutting inserts. The potential of reconditioning worn coated cemented carbide and high speed steel tools through sequential electro-chemical coating removal, tooth rake regrinding, micro-blasting and PVD recoating has a wide industrial importance [6]. However, the effect of all these sequential procedures on the mechanical properties, the cutting-edge sharpness and cutting performance, especially when recoated cemented carbide tools are employed, has to be considered. More specifically, the HM substrates mechanical properties diminishing due to material annealing could be significant after the film re-deposition. In this way, an impairment of carbide
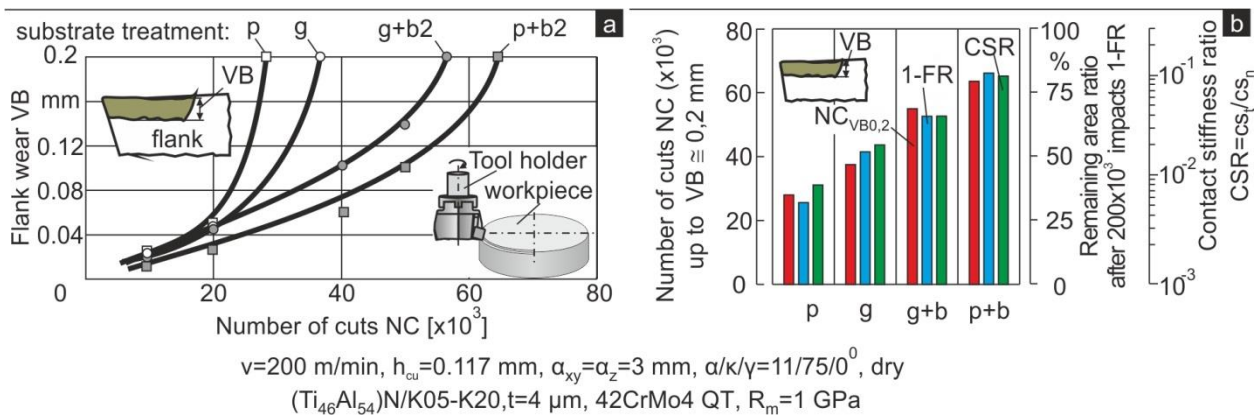
Fig. 4. (a) Flank wear development at various cutting edge pre-treatments, (b) Micro-blasting and pre-treatments effects on the film adhesion and coated tool life

grains holding by cobalt binder develops and cutting edge chippings may appear during grinding, as it is schematically demonstrated in Fig. 5a [20]. This mechanism may decrease the cutting performance of a recoated tool and thus the process reliability as well. To overcome this problem, macro-blasting is applied with large grains in comparison to the cemented carbide material grain size. The blasting conditions are appropriately adjusted to impose substrate material strengthening at the tooth flank too. In this way, enhanced cutting edge sharpness can be achieved after grinding (see Fig. 5b).

The appropriate conduct of procedures such as macro- and micro-blasting enhances the cutting performance after the tool reconditioning and improves the productivity, when using cemented carbide tools [6-7]. The wear behaviour of reconditioned in various ways cemented carbide hobs, macro-blasted with different grain sizes and shapes to strengthen them superficially and furthermore micro-blasted to increase the coating adhesion, is exhibited in Fig. 6. The micro-blasted substrates with small grain size possess, on one hand, a good adhesion with the film. On the other hand, a poor cutting performance is attained due to the development of cutting edge damages after regrinding, occurred by the reduced carbides' holding. The combination of substrate macro-blasting with large grains to impose superficial strengthening and a better WC-grains embedment before grinding and moreover, micro-blasting with small grain size to increase the film adhesion leads to a significant enhancement of the tool cutting performance.

3. PVD-PROCESS CONDUCT

3.1. APPLICATION OF HIGH POWER PULSED MAGNETRON SPUTTERING (HPPMS)

High power pulsed magnetron sputtering (HPPMS) has been used in industry as a very promising technology for producing well-adherent, dense, hard and nanostructured coatings, which contribute to enhanced cutting performance of coated tools [1,5,21]. The goal of HPPMS technology is to achieve a plasma density exceeding conventional ones by roughly three orders of magnitude. Normal sputtering leads to a plasma density of 10^{16} m^{-3}, while HPPMS reaches 10^{19} m^{-3} [21].
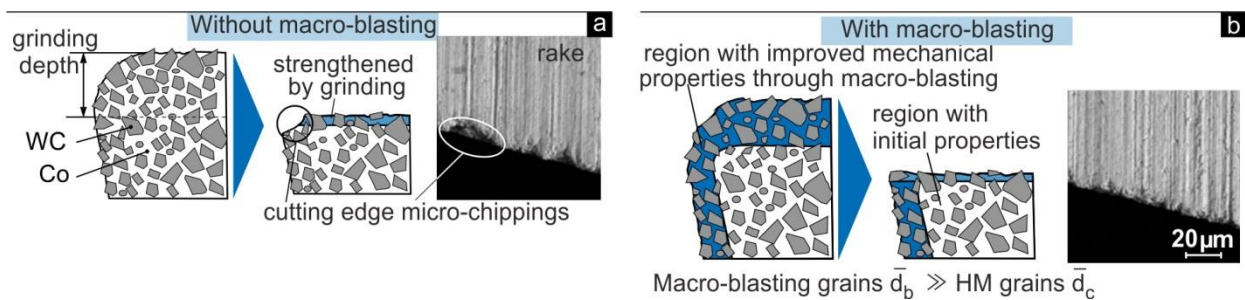
Fig. 5. Effect of macro-blasting and regrinding of the hob tooth rakes on the cutting edge sharpness
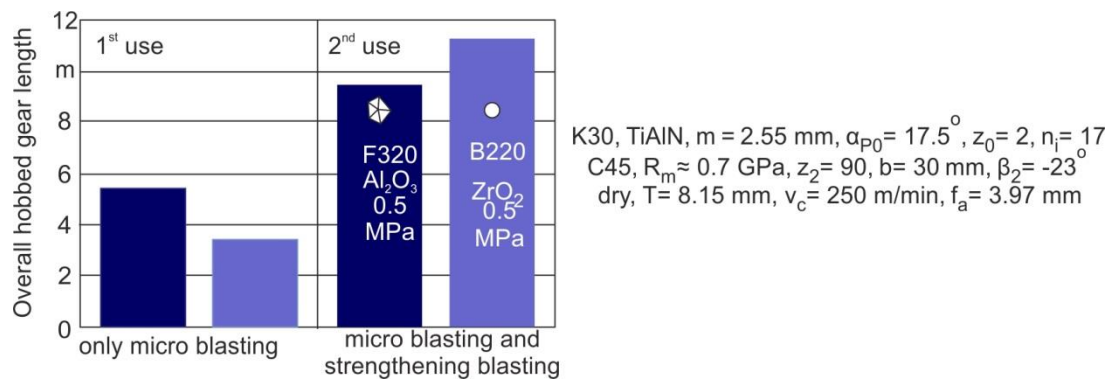
Fig. 6. Cutting performance of coated micro-blasted HM hobs, with various grain sizes and shapes

This is done by pulsing the power to the source with average amplitude of approximately 1 kW and peak power densities of about 0.4–0.5 MW per pulse, but at a low duty cycle of about 1–20 ms (see Fig. 7). In the developed hot and dense plasma area, the metallic atoms are highly ionized and subsequently deposited on the specimen surfaces with elevated kinetic energy. However, the effectiveness of coating deposited by High Power Pulsed Magnetron Sputtering (HPPMS) depends on the selection of an appropriate adhesive nano-interlayer, which immobilizes the WC carbides in reacting with high energy ions of the film material during their deposition on the substrate [1,5].

Recent investigations revealed that a HPPMS Cr-adhesive nanolayer leads to improved cutting performance resistance, compared to the performance of coated tools with W or Ti

adhesive interlayers [21]. Moreover, the potential to improve the film adhesion and thus the wear behaviour of HPPMS coated tools by using a Cr-adhesive interlayer depends on the substrate surface's roughness and on the layer thickness [5]. In this context, Rockwell HRC indentations were conducted for testing the effect of a HPPMS graded Cr/CrN-interlayer thickness on the adhesion of a TiAlN film [22].
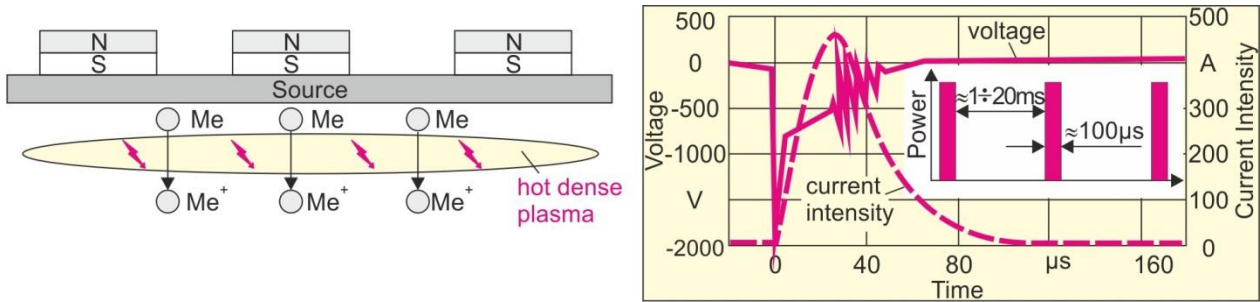

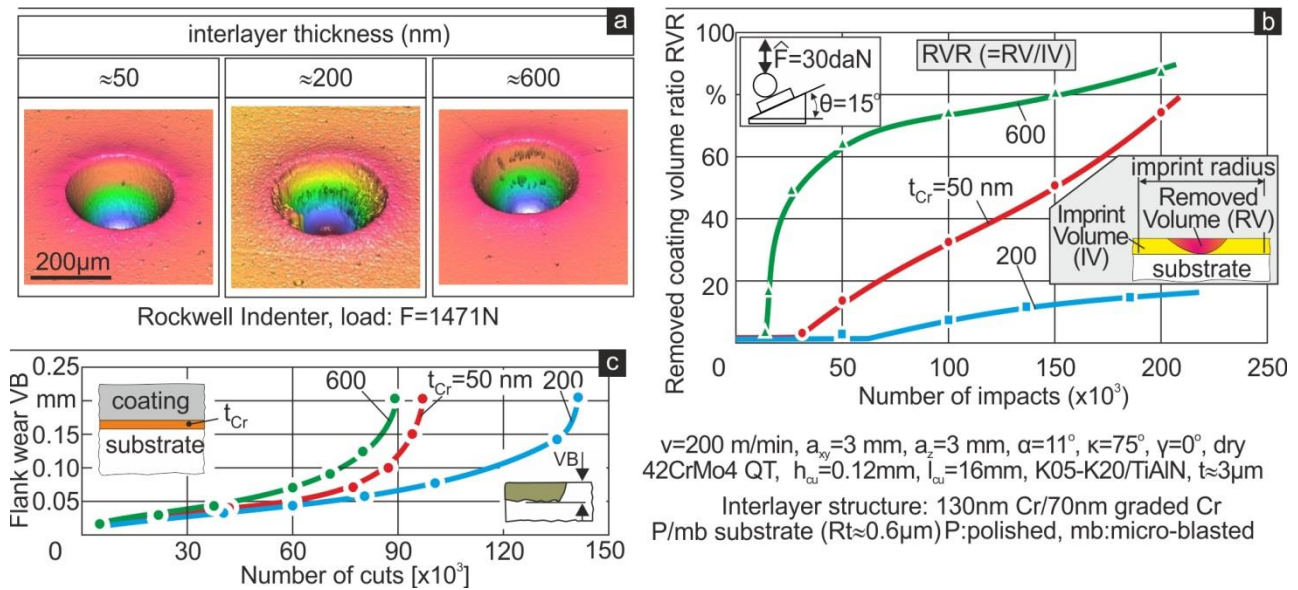Fig. 7. Plasma energy increase by HPPMS during PVD processes

Fig. 8. (a) Rockwell C indentation imprints on the coated inserts with various HPPMS Cr/CrN deposited adhesive interlayers' thicknesses. (b) Effect of HPPMS interlayers' thickness on the removed coating volume during the inclined impact test of coated inserts (c) Flank wear development versus the number of cuts of coated tools with different interlayer thickness

The Rockwell imprints were captured by confocal measurements and are displayed in Fig. 8a. No cracks or detachments appeared in the imprints vicinity of the coated inserts. According to these results, the adhesion may be characterized as good, in all coating cases. By inclined impact tests [19], significant adhesion quality differences were detected. The removed film volume ratios (RVR) versus the number of impacts on the examined inserts with various interlayers thicknesses by inclined impact tests determined, are exhibited in Fig. 8b. The TiAlN coated inserts with graded Cr/CrN-interlayers of 200 nm

withstand more effectively the repetitive oblique impact loads compared to the corresponding interlayers of 50 and 600 nm thicknesses. This can be explained considering that due to the perpendicular loading direction during the Rockwell indentation, the thin layers are pressed against the substrate, i.e. no shear loads within the interlayer occur, which can lead to shear fracture and subsequent film removal. In this way, no detachments or cracks develop, i.e. a good adhesion is concluded. On the other hand, the oblique loading direction during the inclined impact test induces shear stresses into the film, which in the case of a poor adhesion leads to coating material overloading and to its accelerated failure.

Furthermore, for correlating these results to the cutting performance of coated tools, the wear resistance of HPPMS TiAlN coated inserts with graded Cr/CrN-interlayer of various thicknesses was tested in dry milling (see Fig. 8c). The coated inserts with graded Cr/CrN nano-interlayer thickness of 200 nm exhibit the best wear resistance, reaching a tool life of approximately 140,000 cuts, at a flank wear VB of 0.2 mm. Moreover, coated inserts with 50 nm and 600 nm nano-interlayer managed to cut only ca. 100,000 and 90,000 times respectively, up to the flank wear of 0.2 mm. Thus, the cutting performance can be effectively correlated to the oblique impact resistance during the inclined impact tests.
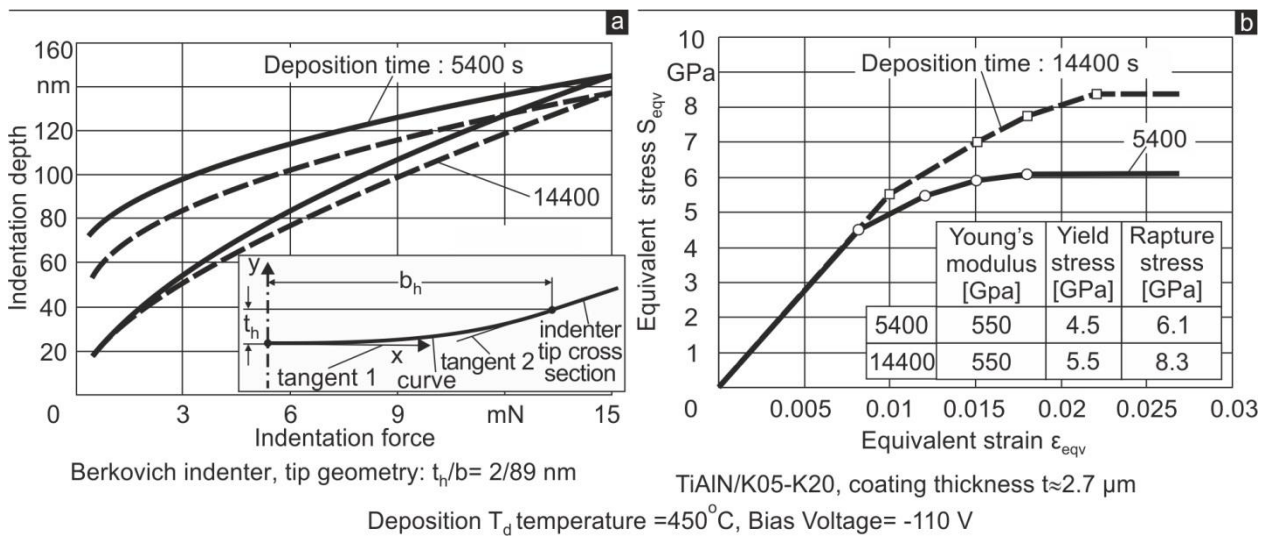

Fig. 9 (a) Nanoindentation curves and (b) stress–strain laws of the examined coating produced at various durations

3.2. BOMBARDMENT OF THE GROWING FILM BY AR$^+$ IONS

The ion bombardment during the PVD process affects significantly the film mechanical properties and consequently the coated tool life. Through the ion bombardment a denser film structure, as well as a finer and purer overall structure can be achieved due to a sputter cleaning effect [8]. To investigate the effect of intensive ion bombardment on the densification of the growing film and thus on the film properties modifications, the experimental setup in the vacuum chamber was modified from a standard three-fold rotation to a fourfold rotation, using instead of three, four rotating fixtures (planets) [8].

In this way, the shadowing effect leads to a decreased deposition rate per table revolution. Moreover, a further magnification of the shadowing effect was achieved by increasing the fold's diameter. The deposition time was adjusted accordingly to obtain the same overall coating thickness as the standard reference coating, in every film cases. As the deposition is line of sight, the bombardment with Ar^+ ions is statistically distributed and more random. Therefore, the growing film is exposed much higher to Ar^+ ions impacts related to deposited particles per table revolution.

The mechanical properties of the produced coatings at various overall PVD process durations were thoroughly investigated through nanoindentations. As the resulted load-displacement diagrams of Fig. 9a show, the achieved maximum indentation depth in case of the TiAlN coating, produced after 14,400 s, is lower than the corresponding one, deposited after 5,400 s. This trend can be attributed to a densification of the growing film due to the achieved longer ion bombardment during the PVD process at the increased overall deposition duration. In order to define the coatings' stress-strain laws, the nanoindentation results were evaluated with the aid of experimental and computational methods described in [1]. According to the obtained results, exhibited in Fig. 9, the coating Young's modulus remains practically stable to 550 GPa, while the yield and rapture strength depend on the deposition duration, increasing from 4.5 to 5.5 GPa and from 6.1 to 8.3 GPa for deposition durations of 5400 and 14,400 s respectively.
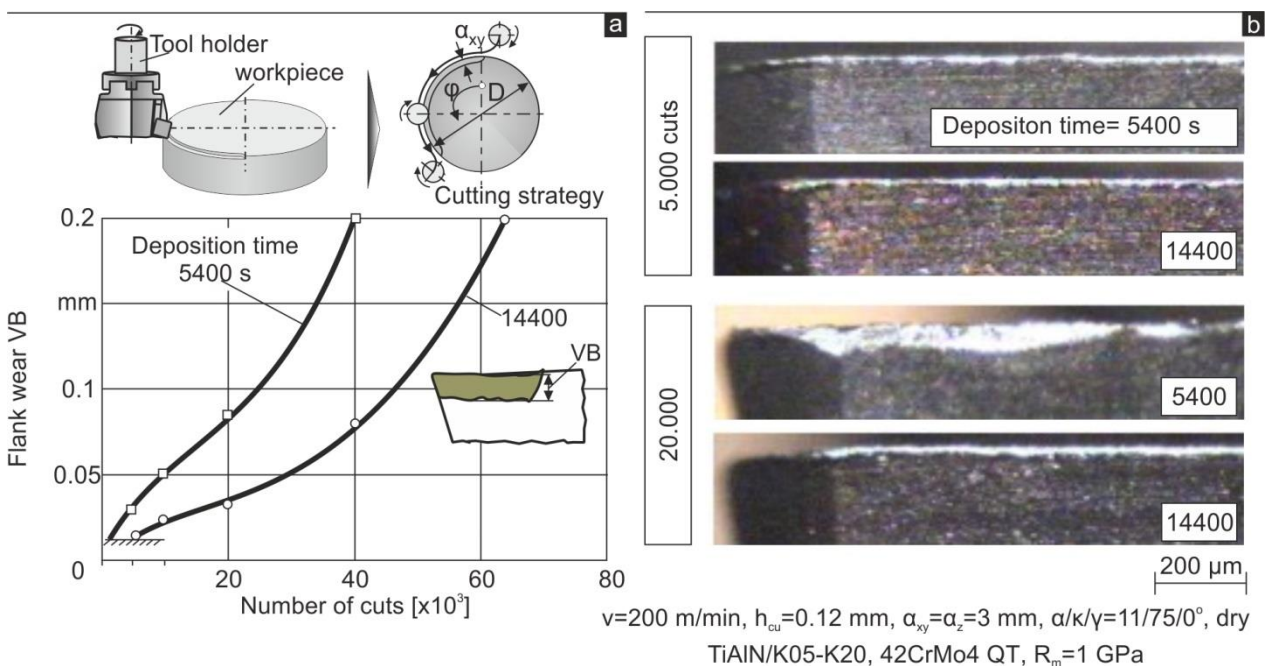

Fig. 10. (a) Flank wear behaviour versus the number of cuts and (b) corresponding wear micrographs of the examined coating produced at various deposition durations

The flank wear behaviour of the examined coated cemented carbide inserts in milling, produced at various deposition durations, is demonstrated in Fig. 10a. The investigations were performed using a 3-axis numerically controlled milling centre by programmed circular paths around the cylindrical workpiece material. The coated insert with deposition

duration of 14,400 s exhibits a better cutting performance, reaching a tool life of 65×10^3 cuts at a flank wear width of approximately 0.2 mm. On the other hand, the coated insert with shorter deposition duration attained only 40×10^3 cuts up to the same flank wear width. The flank wear after 5×10^3 and 20×10^3 for both film cases are illustrated in the micrographs of Fig. 10b. The wear resistance improvement is evident, when longer deposition duration is used to obtain the same film thickness.

4. COATING ARCHITECTURE

4.1. FILM THICKNESS DISTRIBUTION IN THE CUTTING-EDGE REGION

The coating thickness distribution on the tool rake and flank, depending on the tool fixturing geometry and kinematics in the vacuum chamber during the film deposition, might significantly affect the cutting tool performance [9]. The plasma flux during the PVD procedure in the vacuum chamber is guided from the targets to the fixtures, in which the specimens to be coated are placed. In the left part of Fig. 11, a characteristic arrangement of the targets and a specimen fixture is shown. In general, in order to achieve a uniformly distributed coating on all insert surfaces, three kinds of rotational motions are applied, the rotation of the basic plate ω_P, of each satellite station ω_S and of each specimen fixture ω_f. Moreover, the orientation of a cutting insert in relation to the plasma fluxes plays an important role in the distribution of the coating thickness in the cutting wedge region.
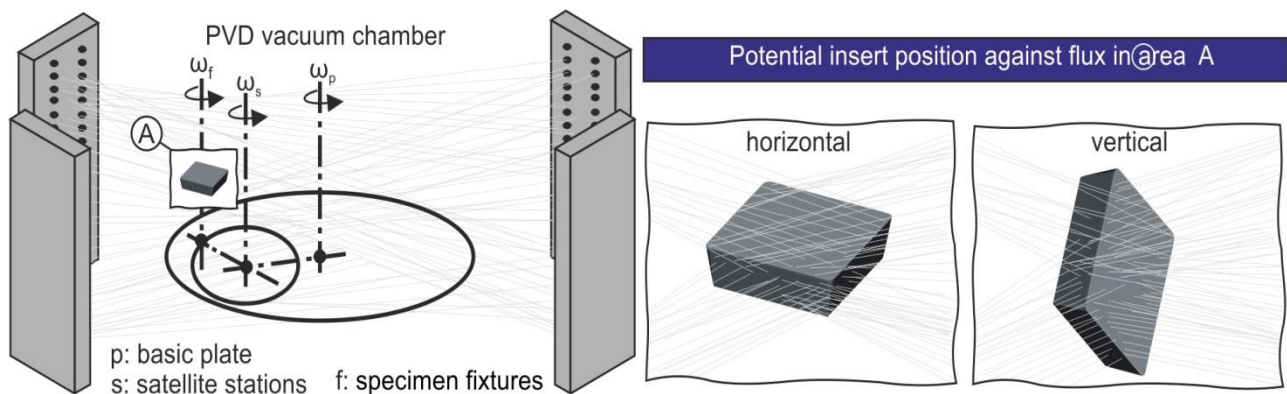

Fig. 11. Potential cutting insert positions and fixtures kinematics during physical vapour deposition (PVD) of coatings

In the bottom part of the figure, two potential insert positions against the plasma flux are illustrated. If the plasma flux is quasi parallel to the insert rake, a formation of a thicker coating on the flank in comparison to the corresponding one on the rake is expected. Keeping the magnetic field constant and placing the specimen rake vertically to the plasma flux, a coating with reverse thickness characteristics on the tool rake and flank in relation to the previous case can be obtained. In this way, cutting inserts can be coated with variable film thickness on the rake and flank depending on the incidence directions of the plasma flux to the insert rake. In order to investigate the effect of the coating thickness distribution

in cutting wedge regions on cutting performance, milling tests were carried out [9]. Three different groups were employed.

The first group is characterized as "symmetric", consisting of specimens with almost equal coating thickness on rake and flank. The second group is "rake" type, having an increased coating thickness on the rake in comparison to the flank. The third group is "flank" type. In this group, the coating thickness on the flank was always thicker than the corresponding one on the rake. An overview of the observed wear behaviour in all investigated insert type cases is shown in Fig. 12a. The number of cuts up to various flank wear widths versus the applied insert types are demonstrated. The decreasing of the coating thickness on the flank in the case of a "rake" type insert leads to a worse wear behaviour. This deterioration is more significant in the case of the "flank" type inserts, if the coating thickness on the rake decreases. The best cutting performance was obtained in the case of the "symmetric" inserts.

For explaining the aforementioned wear behaviour, FEM simulations of the cutting process were conducted [9]. The calculated ratio of the maximum von Mises stresses $S_{eqv,max}$ in the cutting wedge region to the film yield strength SY are presented in Fig. 12b. In the "symmetric" coating inserts, this ratio is comparatively lower. Herewith, the film stresses reduce and the number of cuts increase (see Fig. 12a). Furthermore, at approximately equal thickness ratio in the "flank" or "rake" insert types, the related stress ratios are approximately equal. However, in the case of the "flank" type inserts, an overstressed area is formed over a significantly larger area on the transient region between flank and rake (see Fig. 12c), hence contributing to an intensive wear evolution.
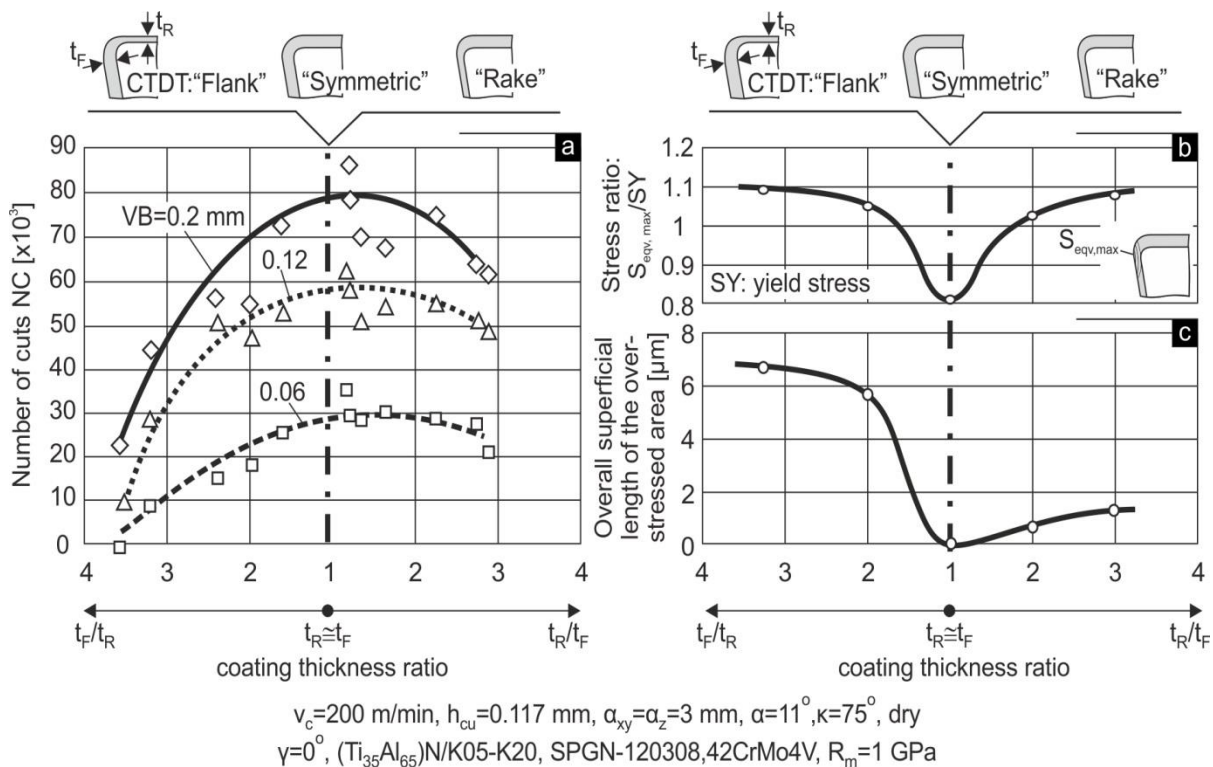

Fig. 12. Wear development and film stress characteristic data in various coating thickness distributions in the cutting edge region

4.2. MONO-AND MULTI-LAYER PVD FILMS

The deposition of multilayer PVD (TiAl)N coating systems instead of monolayer ones has been approved as a very effective method for prolonging coated tool life [10,23]. Especially in milling, multilayer coatings deposited on cemented carbide tools act as an inhibitor to the propagation of developed cracks under the exerted loads during repetitive cutting impacts [10,24]. Novel methods such as nano- and macro- impact tests with modulated force signals have to be applied for characterizing the fatigue and the brittleness of mono- and multi-layer PVD films. These properties are crucial in milling operations, since they influence the development of fatigue cracks and their propagation as well.

PVD TiAlN films, with an Al/Ti ratio of 54/46 were deposited by a CEMECON C900 coating machine [10] on cemented carbide inserts of HW-K05/K20 ISO quality. The overall film thickness was approximately 8 μm. The film structure consists of one, two and four layers. The layers of these coatings possess a columnar micro-structure. Moreover, nanocomposite PVD films of the same overall thickness of 8 μm were deposited on the same substrate, consisting of successive TiAlN and TiN layers. The thicknesses of the individual TiAlN and TiN layers amount to roughly 24 nm and 3 nm respectively. In this way, the resulting film structure is the sum of around three hundred TiAlN layers and a further three hundred TiN ones. No TiN interlayers were employed in the case of the monolayer coating as well as of the two and four multilayer films. Characteristic results attained by ball cratering tests are presented in Fig. 13. The superficial average grain size of each film structure is also displayed. In the case of coatings with columnar micro − structure, the grain growth mechanisms during PVD process are disrupted with a frequency dependent on the number of deposited layers. In this way, the average grain size and roughness diminish along with the layers' thickness reduction, as shown in Fig. 13. In the case of nanocomposite films, due to the restricted grain size, the surface integrity of the coated tools is almost equal to that of the uncoated ones.
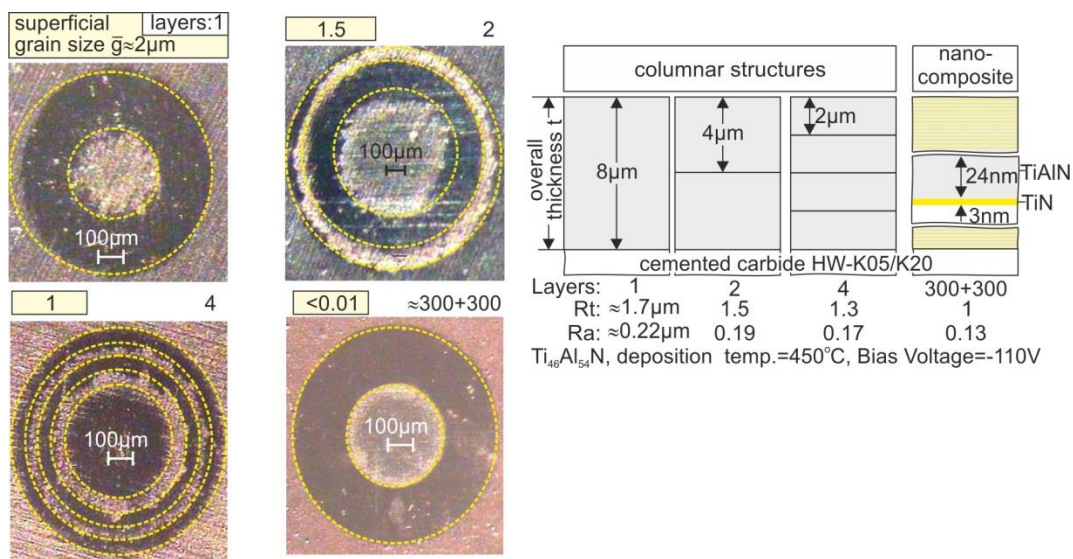

Fig. 13. Ball cratering tests on the investigated film structures

A correlation among brittleness, film fatigue strength and the accumulated tool life of the investigated films is shown in Fig. 14a, 14b and 14c respectively. This correlation is presented at short and long entry impact durations t_{ce} [10]. According to the attained results, an increased number of film's layers is associated with a cutting performance growth. Thus, due to the enlarged fatigue strength and lower film brittleness, the cracking initiation requires higher stress concentrations. Moreover, after the cracking initiation, multi-layer film structures prevent the cracks propagating straight down to the substrate. The enhancement of the cutting performance of coated tools by applying multi-layer PVD film structures can be quantified at various cutting edge entry impact durations, as displayed in Fig. 14d.
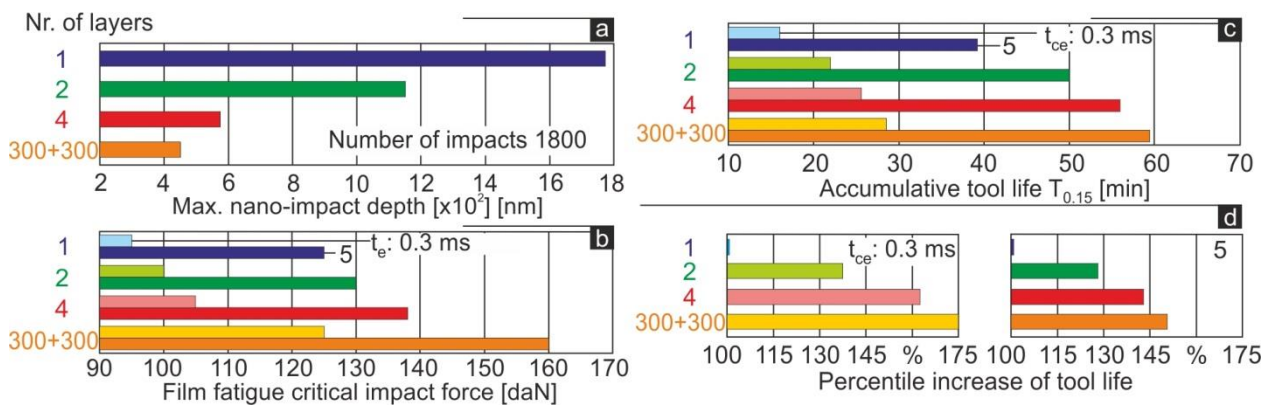

Fig. 14. Correlation among (a) brittleness, (b) film fatigue strength and (c) the accumulated tool life coated tool life in milling. (d) Percentile increase of tool life, when multi-layered PVD films are employed at various t_{ce}
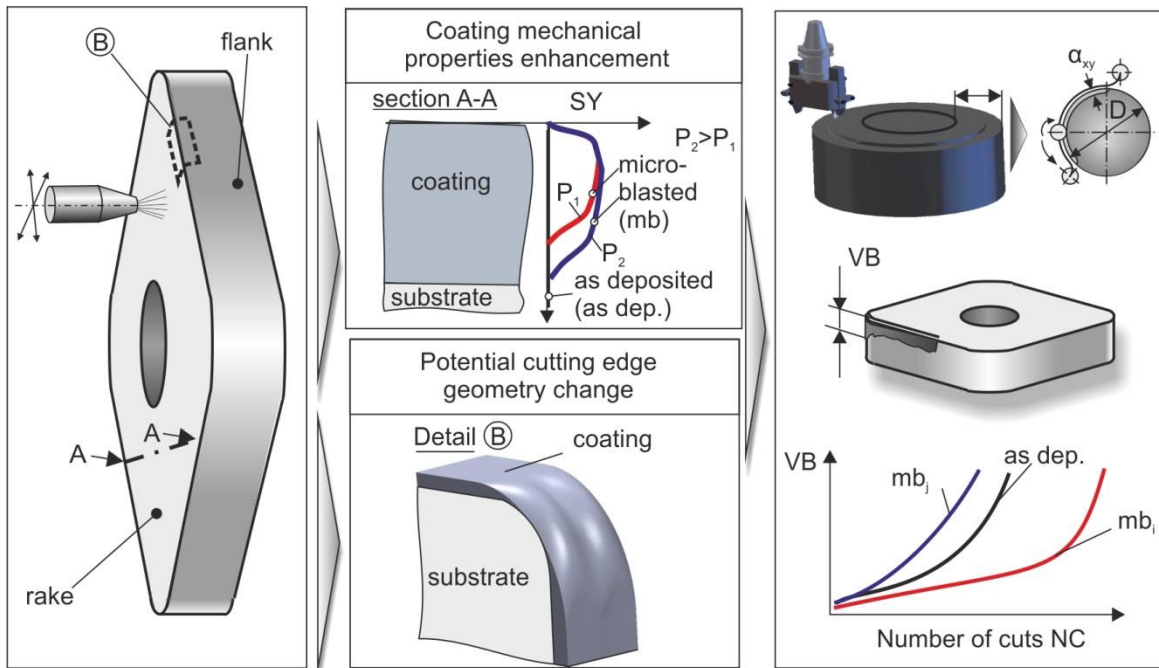

Fig. 15. Micro-blasting effects on coating's strength properties, topomorphy and tool life of coated tools

At a low t_{ce} of 0.3 ms, through the employment of multi-layer films, a tool life increase up to 75% can be achieved. This improvement is lower ($\approx$50%) at a longer t_{ce} of 5 ms. It is worth mentioning that in the latter t_{ce} case the attained tool lives are significantly higher compared to the obtained ones at $t_{ce}\approx$0.3 ms (see Fig. 14c).

5. COATED TOOL'S POST TREATMENTS

5.1. MICRO-BLASTING ON PVD FILMS

By micro-blasting on the coated tool surfaces, residual compressive stresses are induced into the film structure, thus increasing the coating hardness, but its brittleness too. Simultaneously, abrasion phenomena are activated, which may lead to roughness augmentation, film thickness decrease and substrate revelation. These potential effects of micro-blasting are schematically demonstrated in Fig. 15 and have to be taken into account for optimising the coated tools cutting performance. Micro-blasting parameters such as pressure, time as well as blasting grains' size and shape have a pivotal effect on the film strength properties and thus on the coated tools' cutting performance [12-14].
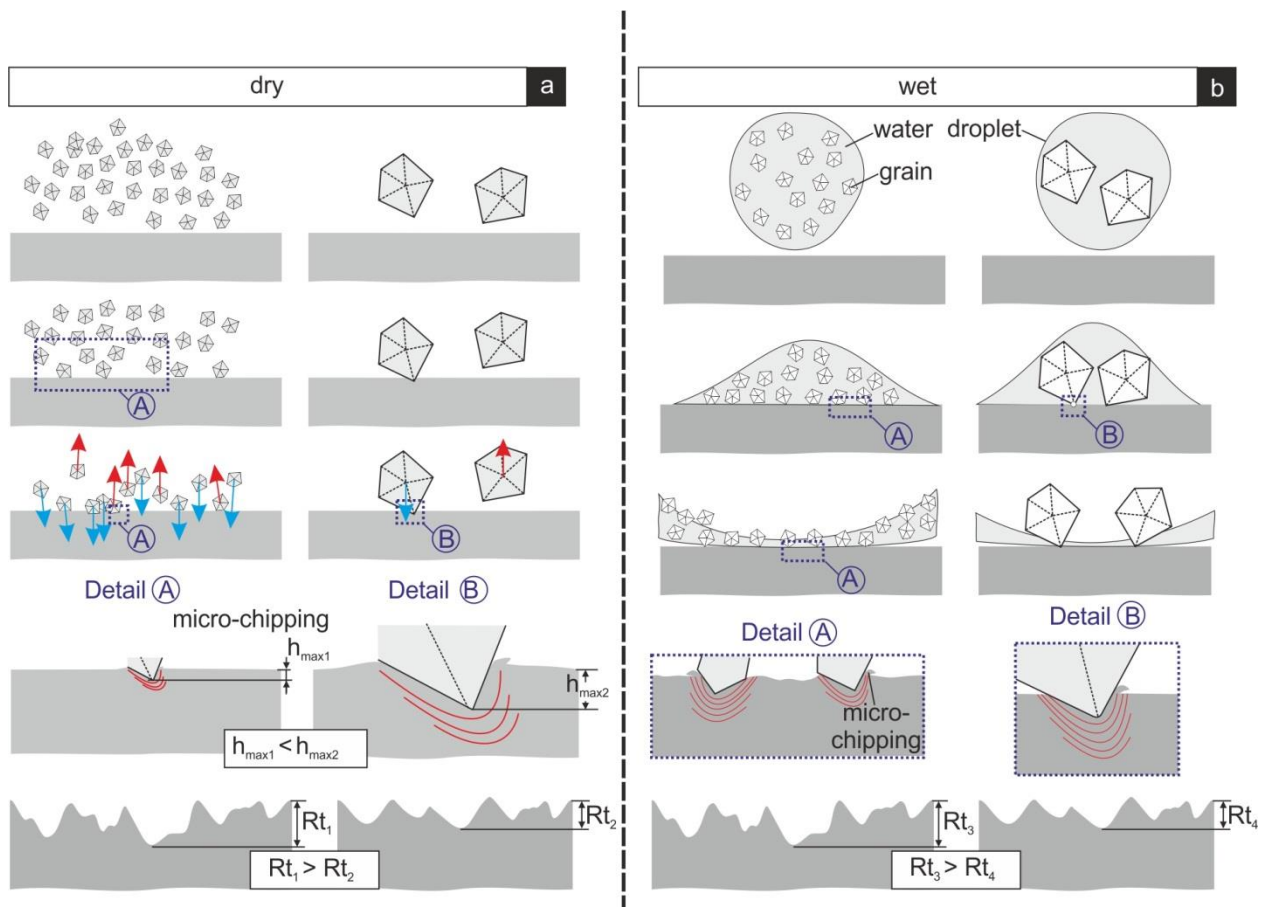

Fig. 16. Effect of abrasive grains' size and their transport medium on the surface roughness in: a) dry b) wet micro-blasting process

Figure 16 explains schematically the effect of dry or wet micro-blasting by fine Al_2O_3 grains of an average diameter of approximately 10 μm and by ten times larger in diameter as well, on the coated tools' surface integrity. In dry micro-blasting process (see Fig. 16a), a larger roughness Rt develops, if fine grains are employed. This can be explained by the repeated micro-chippings of the film's surface considering the large concentration of the fine particles, as it is schematically shown in this figure. Hence, due to the intense coating material removal, a smaller portion of the initial grain kinetic energy of the fine grains is consumed to deform plastically the coating, compared to the corresponding one by the coarser grains. In this way, coatings subjected to dry micro-blasting by Al_2O_3 grains of an average diameter of approximately 10 μm are expected to possess higher roughness and smaller nanohardness compared to micro-blasting by Al_2O_3 grains of ca. 100 μm average diameter, under the same conditions.

Related mechanisms appear in the case of wet micro-blasting, as it is illustrated in Fig. 16b. Numerous fine abrasive grains are guided by water droplets at high density on the coated surface. These can cause more intense coating material removal through micro-chippings, for the same treatment duration compared to micro-blasting by coarse and less numerous grains per water droplet. On one hand, this happens, since the numerous small grains are dragged easier by the flowing water along the film surface, thus intensively deteriorating its roughness. On the other hand, the coarse grains are less affected by the flowing water and mainly deform the coating material. In this way, a larger portion of the initial grain kinetic energy of the coarse grains is consumed to deform plastically the coating, compared to the small ones. Thus, coatings subjected to wet micro-blasting by fine Al_2O_3 grains are expected to possess higher roughness and smaller nano-hardness, compared to the corresponding ones, micro-blasted by coarser grains under the same conditions.
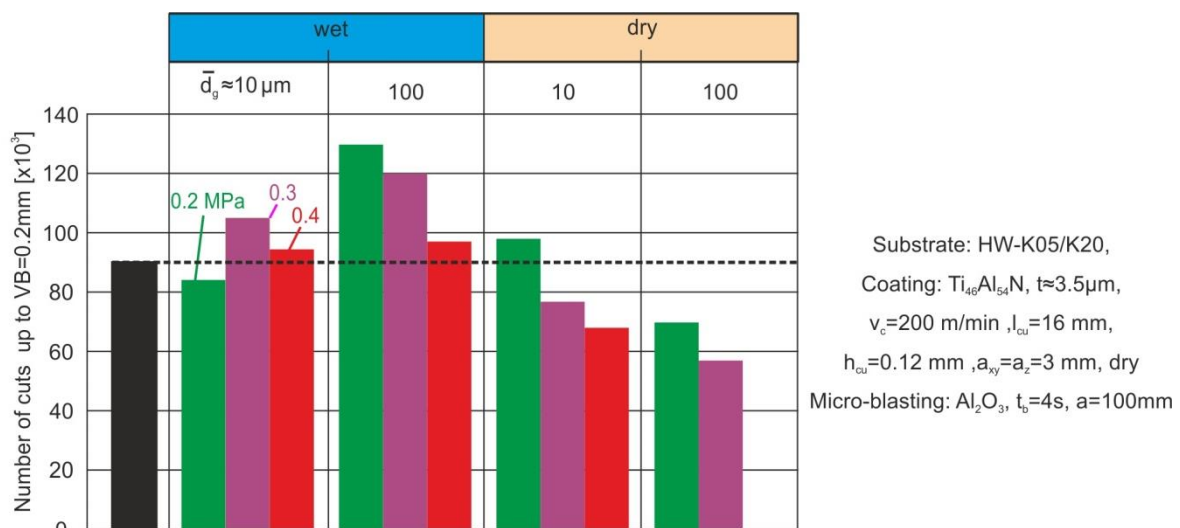

Fig. 17. Comparison of flank wear development of coated tools subjected to wet or dry micro-blasting by fine or coarse grains at different pressures

The abrasive effect exerted by dry blasting using Al_2O_3 particles is expected to be less intense for both, fine and coarse grain sizes compared to the corresponding one when a wet

process is applied. In dry micro-blasting, the grains bounce from the coated surface after the impact almost perpendicular (see Fig. 16), thus affecting the film integrity slightly. This effect results in larger coatings' nano-hardness compared to wet micro-blasting, where the grains are dragged along the coating surface. In dry micro-basting process, the particles kinetic energy is mainly consumed to plastically deform the coating, while in the case of wet blasting, a portion of this energy is allocated to the described abrasive phenomena.

The achieved number of cuts up to a flank wear width of ca. 0.2 mm of coated tools subjected to micro-blasting by fine or coarse sharp-edged Al_2O_3 grains, employing different micro-blasting grain transport media is illustrated in Fig. 17. According to these results, wet micro-blasting, when coarse grains are used, contributes to coated tool cutting performance improvement. This enhancement depends on the applied micro-blasting pressure. Moreover, in the investigated cases, dry micro-blasting leads to tool wear behaviour improvement, only at low pressures and by fine grains.

5.2. GRINDING OF COATED CUTTING EDGES

Rounding sharp cutting edges mainly of small diameter tools by grinding is a practice often encountered in industry. In this way, the tool edges become more stable and the cutting performance can be improved. The investigation of the related wear phenomena is pivotal in explaining the tool failure and adjusting the coating roundness and the cutting conditions according to films and substrate material properties.

For investigating such an issue, coated cemented carbide (HM) inserts at three stages of cutting edge roundness have been applied [18]. On one hand, as the cutting-edge region becomes more round, i.e. less sharp, the stresses developed during cutting are evenly distributed in the transient area between flank and rake, thus reducing local overstresses and consequently lead to a more stable material removal process [25-26].
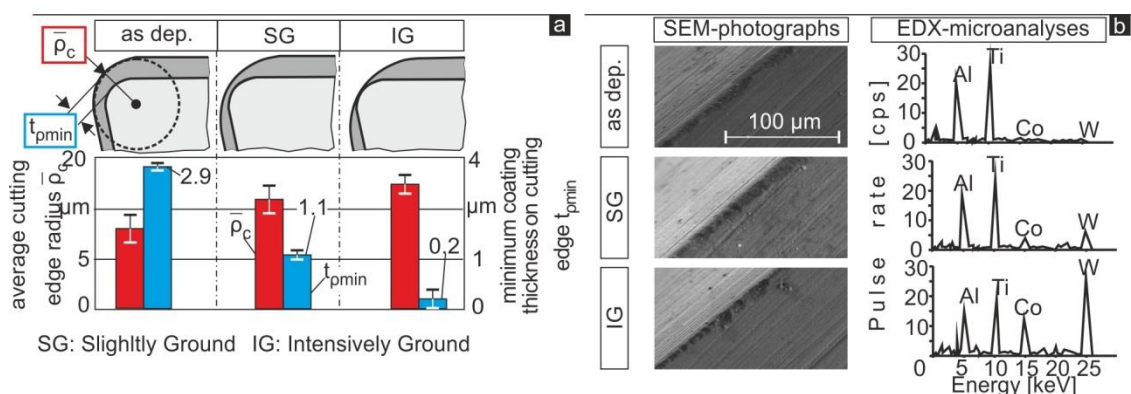

Fig. 18. SEM micrographs of the cutting edge shape and EDX microanalyses of the used coated HM cutting inserts

On the other hand, the cutting-edge radius increase, by grinding the coating in the cutting edge transient region, leads to a heat flux growth into the substrate, which might deteriorate the tool performance, especially at high cutting speeds. To clarify such

mechanisms coated cemented carbide, (HM) inserts with an AlTiN PVD film were variously rounded after the film deposition. Appropriate procedures were conducted for determining the film thicknesses on the flank and rake as well as the average cutting edge radius of the uncoated HM inserts and of deposited and variously ground coated tools [18]. Taking into account these magnitudes, the film distribution in the transient cutting edge region can be determined as exhibited in Fig. 18a. The film surfaces are tangents to a circle with the average radius ρ_c. In this way, a minimum film thickness t_{rmin} develops in the transient cutting edge region, as shown in the diagram at the lower part of Fig. 18a. Since the cutting-edge radius increases with a growing grinding intensity, the minimum coating thickness t_{rmin} drastically decreases. In Fig. 18b, SEM photographs and characteristic EDX microanalyses on cutting edges of the coated cemented carbide inserts are shown. These results were obtained by a Joel JSM-840 Scanning Electron Microscope, with Energy Dispersive X-ray analysis facilities. The increase of cutting edge radius reduces the coating thickness close to the cutting edge, thus leading to a substrate revelation. This explains the fact that characteristic substrate's chemical elements, such as of Co and W, were detected on the cutting edge, as it is displayed in Fig. 18b.

The cutting investigations were conducted using a numerically controlled 3D milling center, by programming circular paths around cylindrical workpieces, as presented at the top of Fig. 19a. An overview of the achieved results in the investigated cutting edge roundness cases is displayed in the diagram at the bottom part of this figure. The overall best cutting performance was achieved in the as deposited coated tool case, reaching approximately 75,000 cuts up to a width of the flank wear land of 0.2 mm.
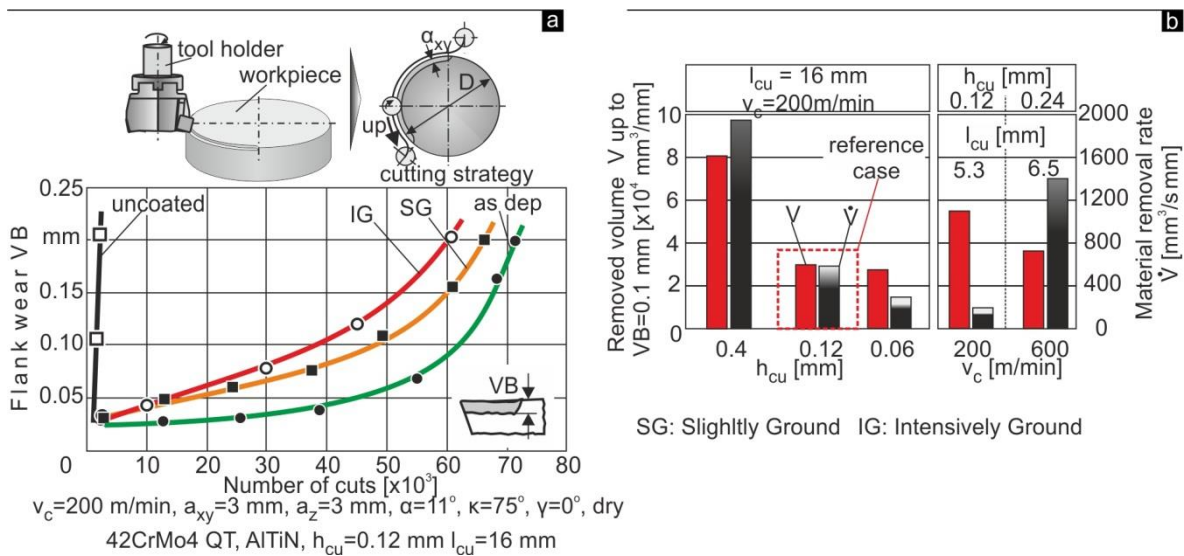

Fig. 19. (a) Flank wear development versus the number of cuts in milling with variously ground cutting edges (b) Achieved removed material volumes and material removal rates at various cutting conditions in milling with IG cutting edges

The cutting-edge rounding deteriorates the tool cutting performance. Up to the same flank wear, only approximately 64,000 and 58,000 cuts were obtained in the slightly ground (SG) and intensively ground (IG) cutting edge treatment cases respectively. However, even

in the worst IG tool case the flank wear development versus the number of cuts is much slower compared to the corresponding one of the uncoated HM insert. To adjust the cutting conditions according to the IG cutting edge data, it was necessary to detect the reasons for the tool premature failure, compared to the as deposited cutting edge case. Based on appropriate FEM calculations, it was revealed that coating stress reduction occurs by increasing cutting edge radius in the IG insert case compared to the as deposited tools. On the other hand, the substrate is more intensely mechanically loaded if the cutting edge is intensively ground. In this way, the substrate is loaded over its yield strength in its transient region of the IG inserts, and the overall tool life is reduced compared to milling with as deposited coated tools intensively ground.

To overcome this problem, additional investigations were focused on reducing the cutting mechanical stresses, in order to facilitate the effective application of tools with intensively ground coated cutting edges. To achieve this target two potential research directions were considered:

- The decreasing of the undeformed chip thickness h_{cu},
- The change of the undeformed chip geometry and especially of the undeformed chip length l_{cu}.

Considering as reference data, the removed material volume V and the related material removal rate $\dot{V}$ up to a width of the flank wear land of 0.1 mm at cutting speed of 200 m/min (Fig. 19b), a comparison among the cutting conditions concerning an effective application of IG milling cutters can be conducted. As shown in Fig. 19b, a decrease of the undeformed chip thickness h_{cu}, leads to a reduction of the material removal rate $\dot{V}$ without affecting the removed material volume V. The enlargement of h_{cu} up to 0.4 mm, causes significant V and $\dot{V}$ increases, while on the other side it also causes cutting force growth, which might lead to dynamic problems during milling, especially with small diameter tools. A decrease of the undeformed chip thickness from 0.12 to 0.06 mm does not significantly lower the removed material volume V. The decrease of the undeformed chip length l_{cu} to 5.3 mm at a cutting speed of 200 m/min is associated with an augmentation of V and a reduction of $\dot{V}$. To overcome this disadvantage, the cutting speed and the undeformed chip thickness can be increased up to 600 m/min and 0.24 mm respectively, herewith achieving sufficient larger V and $\dot{V}$ values compared to the corresponding ones in the reference case. The cutting force increase in this case is not so intensive compared to milling at h_{cu} of 0.4 mm. The appropriate adjustment of the cutting conditions facilitates an effective application of IG milling cutters.

6. CONCLUSIONS

In this paper procedures for producing coated cemented carbide tools with enhanced cutting performance were presented. The introduced processes include the conduct of micro-blasting or the deposition of an adhesive interlayer prior to the coating deposition for improving the film adhesion. Moreover, the conduct of macro-blasting on hardmetal substrates is recommended as a procedure for reconditioning worn coated solid cemented carbide cutting tools. Various parameters in the vacuum chamber and the coating

architecture have to be appropriately adjusted for improving the film properties and thus the coated tools cutting performance. Finally, PVD coated inserts subjected to micro-blasting or grinding can exhibit an impressive wear resistance improvement if the related process parameters and cutting conditions are appropriately selected.

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