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Effect of PVD films wet micro-blasting by various Al_2O_3 grain sizes on the wear behaviour of coated tools

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A B S T R A C T

Micro-blasting on PVD films has been documented, among others, as an efficient method for inducing compressive stresses, thus for increasing the coating hardness and potentially tool life of coated tools. Since contradictory results have been registered concerning the efficiency of wet micro-blasting on coated tools for improving the wear behaviour, the paper aims at explaining how this process can be successfully applied for post-treatment of PVD films. In this context, the employed conditions such as pressure and grain size affect significantly the wear resistance of the micro-blasted coated tools.

In the described investigations, TiAlN coatings were post-treated through wet micro-blasting by Al_2O_3 abrasives of various grains' diameter. Abrasion mechanisms after micro-blasting were investigated by roughness measurements. Nanoindentations on micro-blasted film surfaces at various pressures revealed the influence of this process on coating superficial hardness. The related residual stress changes were estimated considering the film yield stress alterations, which were analytically determined, based on nanoindentation results. Nano-impact tests were conducted for investigating the effect of the developed film compressive stresses at certain micro-blasting pressures and grain sizes on the film's brittleness. To monitor film thickness and cutting edge radius changes of coatings subjected to micro-blasting, ball cratering tests and white light scans were carried out respectively. In this way, micro-blasting conditions for improving the film hardness, without revealing the substrate in the cutting edge region, were detected. Finally, the wear behaviour of coated and variously wet micro-blasted tools was investigated in milling of hardened steel.

1. Introduction

The post-treatment of PVD coated tools by micro-blasting is applied in the industry, as an efficient method for improving the performance of coated tools and machine elements [1–5]. By this process, among others, coating surfaces with enhanced tribological characteristics can be attained [5]. Moreover, residual compressive stresses are induced into the film structure, thus leading to coating hardness and strength properties improvement [6–8]. Micro-blasting parameters such as pressure and time have a pivotal effect on the coated tool cutting performance [2,3].

The present paper investigates the potential for increasing the wear resistance of PVD TiAlN coated cemented carbide tools through wet micro-blasting by Al_2O_3 abrasive grains of different diameters. The grain size is pivotal for the developed hardness and residual stresses close to the film surface and for the cutting edge integrity as well. Herewith, the wear resistance of coated tools can be significantly improved.

2. Experimental details

Fig. 1 illustrates the working principle of the applied water micro-blasting procedure. In this operation, water with abrasive grains is guided into the blasting nozzle, where an incoming air flow of adjustable pressure, accelerates the mixture and generates the water jet. In the described investigations sharp-edged Al_2O_3 abrasives with average grain diameters of 10 μm and of 100 μm were used for conducting wet micro-blasting on TiAlN films. The water micro-blasting treatments were conducted by a NP10 machine of WIWOX GmbH Surface Systems. The Al_2O_3 material concentration was approximately 10 gr/L and 6 gr/L in the cases of 10 μm and of 100 μm grains' diameter respectively. These values correspond to water Al_2O_3-grains mixtures, streaming out from the blasting nozzle at a pressure of 0.3 MPa. Considering previous micro-blasting investigations published in Refs. [2–4], the distance between the nozzle and substrate was set to 100 mm and the process duration at 4 s. The air pressure was varied from 0.2 MPa up to 0.4 MPa, in steps of 0.1 MPa. The tool rake and flank were treated in separate micro-blasting procedures.

TiAlN films, with an Al/Ti ratio of 54/46 were deposited by a CEMECON C900 coating machine [9] on SPGN120308 cemented carbide inserts of

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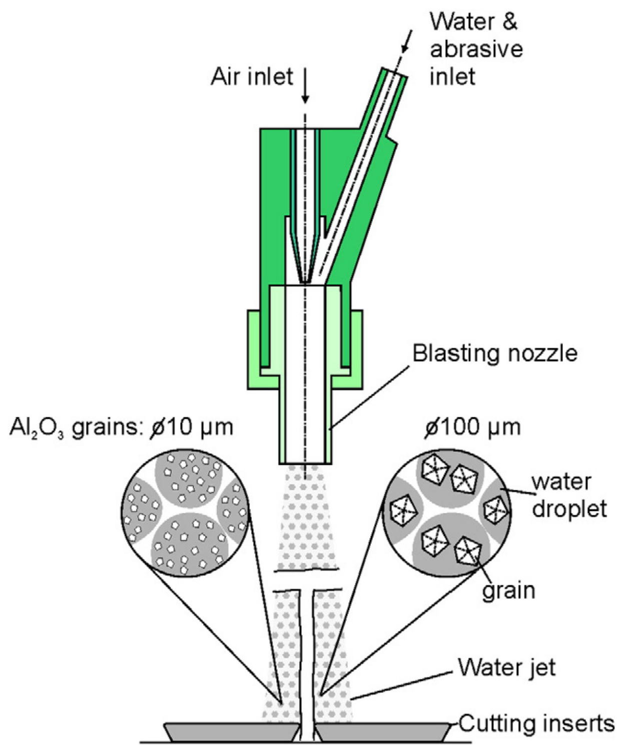

Fig. 1. Working principle of water micro-blasting.

HW-K05/K20 ISO specifications. The film thickness on the tool rake was approximately 3.5 µm. A PVD process technology with high ionization sputtering and pulsing (HIS and HIP) was applied, leading to nano-structured, nano-laminated and nano-dispersed coating systems [9]. The deposition temperature was 450 °C, the total gas pressure 570 mPa and the Ar and N_2 partial pressure amounted to 450 mPa and 120 mPa respectively. The developed residual stress in the films at an information depth of 1 µm, in both of parallel and perpendicular directions to the cutting edge, are less than 1 GPa, according to X-ray diffraction measurements by the $\sin^2\psi$ method [10]. The used device was a SEIFERT XRD 3000 unit, equipped with a 4-circle goniometer [3]. The residual stress changes after micro-blasting were estimated, taking into account, that the coating yield stress changes after micro-blasting correspond to the equivalent residual stress alterations, as described in Ref. [11].

The nanoindentations were carried out by a FISCHERSCOPE H100 device. The roughness R_t of the coated specimens amounted approximately to 0.5 µm. For excluding the specimen roughness effect on the nanoindentation results accuracy, 30 measurements per nanoindentation were conducted for stabilizing the moving average of the indentation depth versus the indentation force [12]. To capture cutting edge radius and coating thickness distributions, white light scanning by a 3D confocal system µSURF of NANOFOCUS AG was employed. The nano-impact tests were conducted via a Micro Materials Ltd device at loads of 10, 20 and 30 mN, at a frequency of 1 Hz [13]. The milling investigations were carried out by a three-axis numerically controlled milling centre using the steel 42CrMo4 QT, hardened at approximately 300 HV (≈30 HRC).

3. Results and discussion

3.1. Abrasion mechanisms in wet micro-blasting and developed film hardness and residual stress changes

Fig. 2 explains schematically the effect of wet blasting by fine Al_2O_3 grains of an average diameter of approximately 10 µm and by ten times larger in diameter Al_2O_3 grains as well, on the coated tools' surface integrity. Numerous fine abrasive grains are guided by the water droplets at high density on small areas of the coated tool's surface. These can cause for the same treatment duration, more intense coating material removal through micro-chippings, 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 deteriorating intensively 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 nanohardness, compared to the corresponding ones, micro-blasted by coarser grains under the same conditions.

The aforementioned assumptions can be validated taking into account the demonstrated results in Fig. 3. The more intense abrasion in wet micro-blasting, when fine Al_2O_3 grains instead of coarse ones are applied, leads to increased roughness on the tool surface (see Fig. 3a) as well as near the cutting edge. This is clearly visible in the displayed surface topomorphies before and after micro-blasting by various grain sizes at 0.4 MPa. In this way, it can be concluded that although the average coating's thickness remains practically invariable by blasting procedures at low pressures and process durations [2], the actual film thickness in individual micro-regions on rake and flank depends strongly on the developed integrity after micro-blasting. Thus, the augmentation of micro-blasting pressure and duration may result in significant local coating thickness reductions, which may affect the micro-blasted coated tool's cutting performance.

Nanoindentations at a maximum load of 15 mN were conducted on coated inserts, wet micro-blasted by fine ($\overline{d}_g \approx 10$ µm), or coarse ($\overline{d}_g \approx 100$ µm) Al_2O_3 grains at various pressures. The corresponding courses of the maximum indentation depth versus the micro-blasting pressure are presented in Fig. 3b. By increasing the micro-blasting pressure in the case of coarse Al_2O_3 grains, a diminution of the maximum indentation depth develops, thus improving the film hardness. Similar

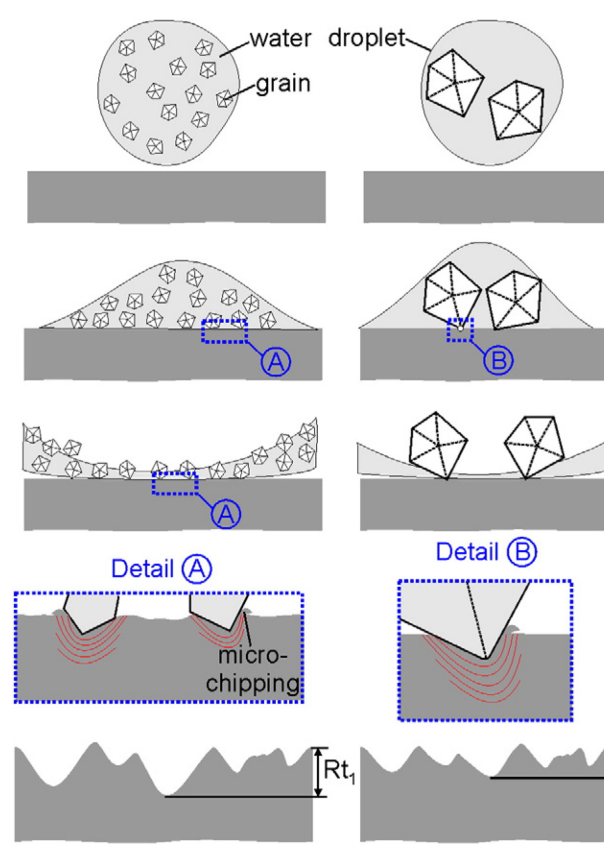

Fig. 2. Effect of abrasive grains' size on the surface roughness in wet micro-blasting.

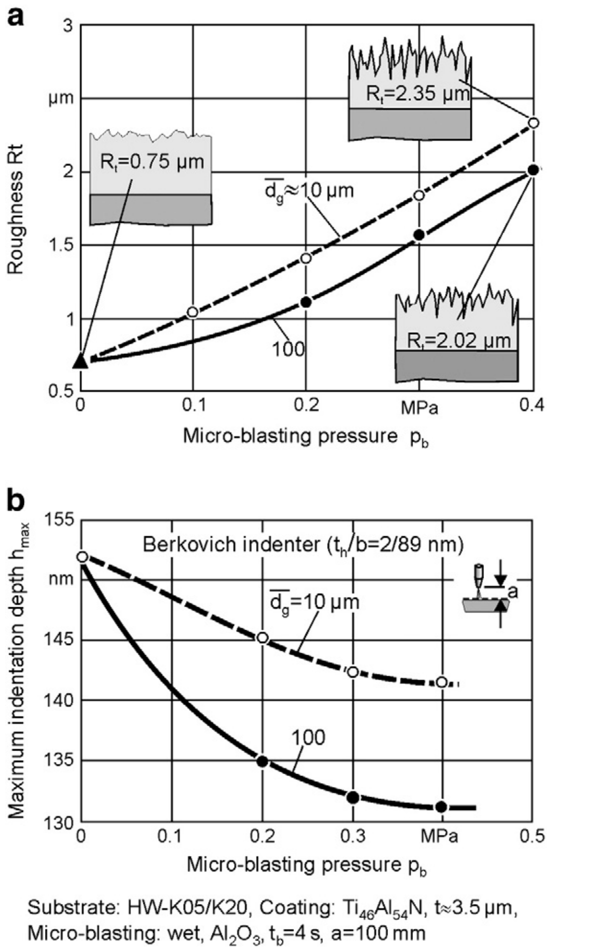

Fig. 3. a) Roughness and b) nanoindentation results on post-treated coatings by wet micro-blasting with Al_2O_3 grains, at various pressures.

effects can be observed after micro-blasting by fine Al_2O_3 grains. A comparison of the achieved maximum indentation depths at various pressures confirms the hypothesis, that the more intense superficial coating deformation during wet micro-blasting by coarse Al_2O_3 grains leads to a larger hardness improvement, compared to the attained one by fine Al_2O_3 grains.

The nanoindentation results in the “as deposited” film case and in the micro-blasted ones were evaluated by the “SSCUBONI” algorithm [12]. The related coatings' yield stresses were determined and they are exhibited in Fig. 4. A gradation of the yield stress versus the film thickness develops after micro-blasting [7]. In the described investigations, for simplifying the related calculations, it was assumed that a unique yield stress distribution versus the coating thickness, up to a depth of 1.5 μm from the film surface occurs. According to the obtained results, the coating material deformation induced by the coarse Al_2O_3 grains and the corresponding yield stress increases versus the pressure are larger compared to the fine Al_2O_3 grains under the same conditions. The determined yield stresses in both examined grain sizes remain practically unaffected at a pressure over 0.4 MPa. Furthermore, the induced equivalent residual stress changes in the coatings after micro-blasting at various pressures are shown in the bottom part of Fig. 4. The increase of the equivalent residual stresses, according to the literature [11], is equal to the yield stress differences. As it can be observed, micro-blasting by coarse Al_2O_3 grains contributes to a significant increase of the residual stresses up to a pressure of 0.3 MPa. At higher micro-blasting pressures, the equivalent residual stresses remain practically invariable and they are extended deeper from the coating surface [7]. Similar, but less intense mechanisms take place in wet micro-blasting by

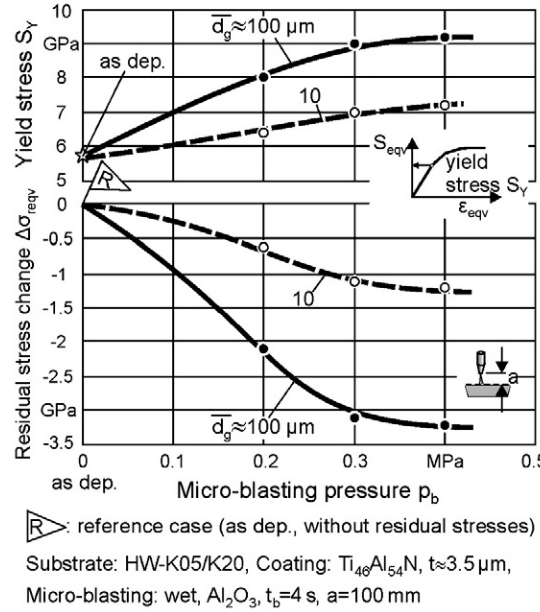

Fig. 4. Yield stresses and residual stress changes of post-treated coatings by wet micro-blasting with Al_2O_3 grains of different sizes, at various pressures.

fine Al_2O_3 grains ($\overline{d_g} \approx 10$ μm), considering the related curves, displayed in the diagrams of Fig. 4.

The described compressive stresses increase in the film structure deteriorates the film ductility [7] and thus increases the coating's brittleness. The nano-impact test was employed to investigate the film brittleness at various micro-blasting conditions [13]. In the diagram of Fig. 5, the courses of the maximum attained impact depths at various impact loads versus the micro-blasting pressure, when coarse Al_2O_3 grains are employed, are monitored. Although up to a repetitive impact load of 20 mN, the higher micro-blasting pressure of 0.3 MPa seems to improve the film failure behaviour, at 30 mN, the increased coating brittleness leads to a larger film failure. This effect has to be considered for explaining the cutting performance of coated and micro-blasted tools, as it will be described in a next section.

3.2. Effect of abrasive grains' size on the coated cutting edge geometry

For investigating the micro-blasting grains' effects on the cutting edge roundness, white light scans along the cutting edges of variously wet micro-blasted cutting inserts were conducted. In this way, successive cross sections of the cutting edges can be monitored and with their aid, the corresponding tool wedge radii as well as the average value and the

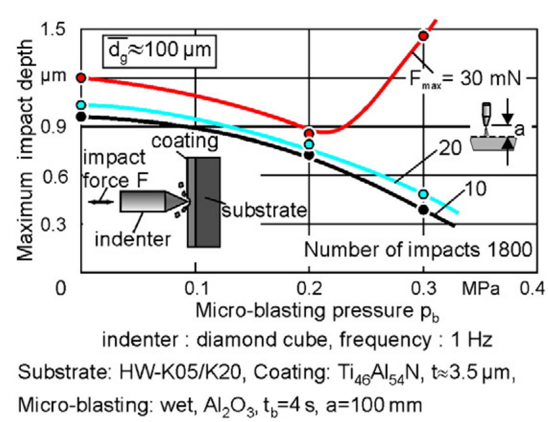

Fig. 5. Nano-impact results at different impact forces on wet micro-blasted coatings at various pressures.

fluctuations of the cutting edge roundness, before and after wet micro-blasting at various pressures can be estimated. A characteristic example, for the "as deposited" coating case is demonstrated in the left part of Fig. 6a. Moreover, the course of cutting edge radius versus the micro-blasting pressure, when fine or coarse Al_2O_3 grains are used, is shown at the right of Fig. 6a. These results reveal that by increasing the micro-blasting pressure, when fine or coarse Al_2O_3 grains are used, an enlargement of the cutting edge radius develops. This growth is visible at micro-blasting pressures over 0.2 MPa and it is more intense, when coarse Al_2O_3 grains are employed. On one hand, considering results introduced in Ref. [14], a cutting edge radius enlargement, of less than 5 μm at maximum, does not affect significantly the developed stress field in the transient area between the tool flank and rake and thus the tool wear. On the other hand, the substrate thermal and mechanical loads grow and the coated tool cutting performance can be deteriorated [14].

Taking into account the previous results, the coating thickness distributions along the cutting edge, after wet micro-blasting at various pressures, were analytically determined. The calculated coated cutting edge cross section geometries at pressures of 0.2 and 0.4 MPa are monitored in the upper part of Fig. 6b. At a micro-blasting pressure of 0.2 MPa, no significant difference can be observed, when fine or coarse Al_2O_3 grains are used. On the other hand, the coating thickness $t_{\rho min}$ may diminish to zero at 0.4 MPa, when coarse Al_2O_3 grains are applied. Thus, substrate revelations may develop, as it is also indicated in the diagram at the bottom of Fig. 6b. When fine Al_2O_3 grains at a micro-blasting pressure of 0.4 MPa are employed, even though the minimum coating thickness at the cutting wedge $t_{\rho min}$ amounts to approximately 1.1 μm, substrate revelations may occur at the cutting wedge, taking into account local film thickness decrease, due to the coating roughness augmentation. However, the risk of local significant coating thickness decreases and even more of a substrate revelation is more relevant in the case of coarse Al_2O_3 grains, compared to fine ones, at micro-blasting pressures over 0.3 MPa.

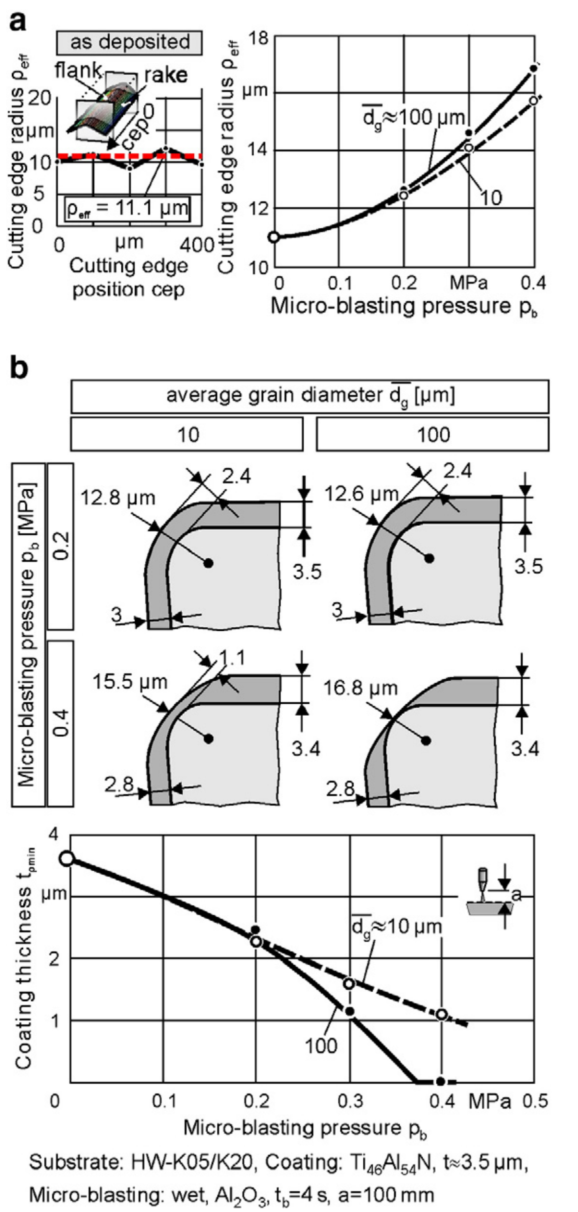

Fig. 6. a) Cutting edge radius ρ_{eff} and b) cutting edge geometries after wet micro-blasting by various grain sizes at different pressures.

3.3. Wear behaviour of coated tools with wet micro-blasted films in milling

As it has been previously described, on one hand, increased micro-blasting pressure results in enhanced film hardness. This improvement is more intense in the case of coarser Al_2O_3 grains and is restricted over a certain pressure (see Fig. 3b). On the other hand, an increased micro-blasting pressure leads to an augmentation of the film brittleness as well as of the cutting edge radius and to a simultaneous film thickness decrease on the cutting wedge. This film thickness decrease is aggravated by the produced rough topomorphy of the micro-blasted surface, especially when coarser Al_2O_3 grains are applied. Hence, wet micro-blasting on PVD films can be considered as an efficient method if the balance between the described effects leads to improved tool life.

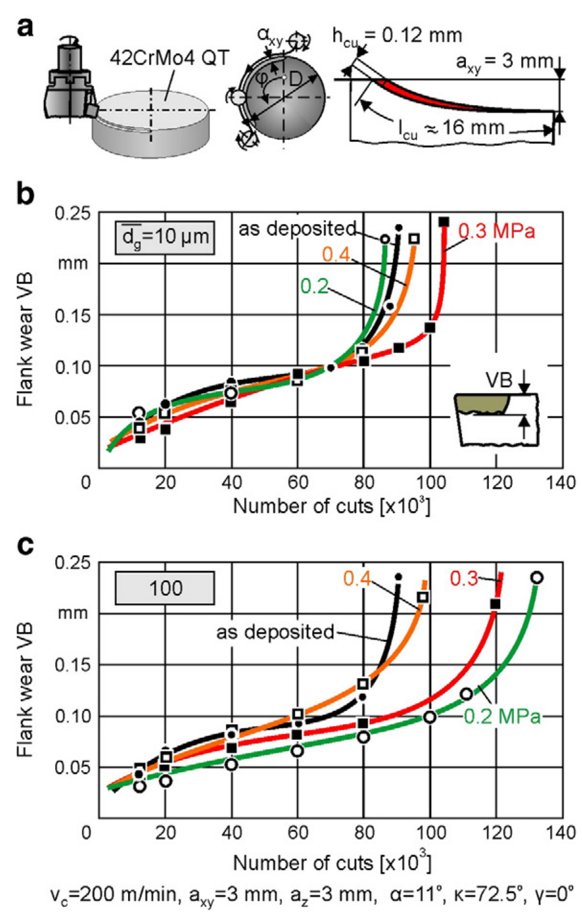

Fig. 7. Flank wear development versus the number of cuts of wet micro-blasted coated inserts at various conditions.

To determine the effect of wet micro-blasting conditions on the cutting performance of coated tools, milling investigations were conducted by a three-axis numerically controlled milling centre. The applied tool-workpiece system and the main characteristics of the undeformed chip geometry are illustrated in Fig. 7a. The flank wear development on coated inserts, which were wet micro-blasted by Al_2O_3 grains of average diameters of ca. 10 μm and 100 μm at various pressures, is demonstrated in Fig. 7b and c respectively. Cutting inserts wet micro-blasted with fine Al_2O_3 grains at 0.2 MPa show a similar cutting performance with the as deposited coated tool, reaching a tool life of ca. 90 000 cuts up to a flank wear width of 0.2 mm. A cutting performance improvement of 105 000 cuts up to the same flank wear width is achieved after wet micro-blasting at a pressure of 0.3 MPa because of the enhanced film hardness (see Fig. 4). At the higher micro-blasting pressure of 0.4 MPa, local coating removals and substrate revelations as well as the increased film brittleness, despite the improved film hardness, reduce the tool life.

In the case of the coarse Al_2O_3 grains (see Fig. 7c), the micro-blasted tools at a pressure of 0.2 MPa exhibited the best cutting performance, reaching a tool life of approximately 130 000 cuts up to a flank wear width of 0.2 mm. A slight tool life reduction at 120 000 cuts up to the same flank wear of 0.2 mm was encountered at a pressure of 0.3 MPa. The treated tool at 0.4 MPa appears practically the same cutting performance, compared to milling with untreated inserts. Due to local coating removals, film brittleness augmentation and substrate revelations after wet micro-blasting at this pressure, the thermal barrier at the cutting edge roundness is locally damaged. Herewith, the substrate thermal and mechanical loads increase, thus contributing to cutting performance deterioration.

4. Conclusions

In the present paper, the effect of wet micro-blasting by Al_2O_3 abrasive grains of various diameters on PVD films' hardness and brittleness, tool wedge geometry and cutting performance is introduced. Due to the more intense micro-chipping mechanisms on coating surface during wet micro-blasting by fine Al_2O_3 grains, compared to coarse ones, higher roughness values are registered. Although an increased wet micro-blasting pressure is beneficial for enhancing the coating hardness, this can cause substrate revelations as well as increased film brittleness, affecting the tool life. Thus, the applied conditions during wet micro-blasting have to be selected with respect to the size of the used abrasive grains. Micro-blasted inserts by coarse Al_2O_3 grains of an average diameter of 100 μm, at the low pressure of 0.2 MPa, led to a significant tool life improvement.

References

[1] P.W. Gold, J. Loos, Wear 253 (2002) 465.
[2] K.-D. Bouzakis, S. Gerardis, G. Skordaris, G. Katirtzoglou, S. Makrimallakis, F. Klocke, E. Bouzakis, Surf. Coat. Technol. 204 (2009) 1081.
[3] E. Bouzakis, Steigerung der Leistungsfähigkeit PVD-beschichteter Hartmetallwerkzeuge durch Strahlbehandlung. Dissertation, RWTH Aachen, 2008.
[4] F. Klocke, T. Schroeder, E. Bouzakis, A. Klein, Surf. Coat. Technol. 202 (2007) 1194.
[5] D.M. Kennedy, J. Vahey, D. Hanney, Mater. Des. 26 (2005) 203.
[6] M. Klaus, Ch. Genzel, H. Holzschuh, Thin Solid Films 517 (2008) 1172.
[7] K.-D. Bouzakis, G. Skordaris, F. Klocke, E. Bouzakis, Surf. Coat. Technol. 203 (2009) 2946.
[8] C. Barbatti, J. Garcia, R. Pitonak, H. Pinto, A. Kostka, A. Di Prinzio, M.H. Staia, A.R. Pyzalla, Surf. Coat. Technol. 203 (2009) 3708.
[9] A.G. CemeCon, Website, www.cemecon.de/index_eng.html 2010.
[10] Ch. Genzel, Adv. X-Ray Anal. 44 (2001) 247.
[11] K.-D. Bouzakis, G. Skordaris, I. Mirisidis, S. Hadjiyiannis, J. Anastopoulos, N. Michailidis, G. Erkens, R. Cremer, Surf. Coat. Technol. 174–175 (2003) 487.
[12] K.-D. Bouzakis, N. Michailidis, S. Hadjiyiannis, G. Skordaris, G. Erkens, Mater. Charact. 49 (2003) 149.
[13] B.D. Beake, G.S. Fox-Rabinovich, S.C. Veldhuis, S.R. Goodes, Surf. Coat. Technol. 203 (2009) 1919.
[14] K.-D. Bouzakis, S. Gerardis, G. Katirtzoglou, S. Makrimallakis, A. Bouzakis, R. Cremer, H.-G. Fuss, CIRP Ann. Manuf. Technol. 58 (2009) 61.