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RESEARCH

Optimization of Wet or Dry Micro-blasting on PVD Films by Various Al_2O_3 Grain Sizes for Improving the Coated Tools' Cutting Performance

Micro-blasting on PVD coated tools is an effective technology for improving their cutting performance. Through micro-blasting, compressive stresses are induced into the film, 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. In this way, for a successful process conduct, it is pivotal to adapt, among others, the applied micro-blasting pressure to the employed medium, air or water. The paper deals with the optimization of wet or dry micro-blasting pressure by various Al_2O_3 grain sizes for improving the coated tool's wear resistance. The wear behaviour of coated and variously dry or wet micro-blasted tools was investigated in milling. Considering the grains' penetration kinematics into the coated tool surface and the film deformation mechanisms during dry or wet micro-blasting by fine or coarse sharp–edged Al_2O_3 grains, optimum process pressures can be determined.

Keywords: *PVD coatings, Micro-blasting, Mechanical properties, Brittleness, Cutting edge radius, Wear.*

1. INTRODUCTION

Micro-blasting on PVD films is applied in the industry, as an efficient method for improving the performance of coated tools and machine elements [1,2,3,4,5,6,7]. By this process, residual compressive stresses are induced into the film structure, thus leading to coating hardness and strength properties improvement [8,9,10]. Micro-blasting parameters such as pressure and time have a pivotal effect on the coated tool cutting performance [2,6,7].The present paper introduces the potential for increasing the wear resistance of PVD TiAlN coated cemented carbide tools through dry or wet micro-blasting by Al_2O_3 abrasive grains of different diameters.

2. EXPERIMENTAL DETAILS

TiAlN films, with an Al/Ti ratio of 54/46 were deposited by a CEMECON C900 coating machine [11] on SPGN 120308 cemented carbide inserts of 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 [11]. The deposition temperature was 450°C, the total gas pressure 570 mPa and the Ar and N_2 partial pressure amounted 450 mPa and 120 mPa respectively. The stress-strain curves were determined by analytical evaluation of related nanoindentation results, employing methods introduced in the literature [12].

Sharp-edged Al_2O_3 abrasives with average grain diameters of 10 μm and of 100 μm were used for

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conducting dry or wet micro-blasting on TiAlN films. Dry and water micro-blasting treatments were conducted by a DI12 machine and a NP10 one of WIWOX GmbH Surface Systems respectively. The working principle of the applied water micro- blasting procedure is described in the literature [6]. Considering previous micro-blasting investigations published in [2,6,7], the distance between the nozzle and substrate was set to 100 mm and the process duration at 4 seconds. 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.

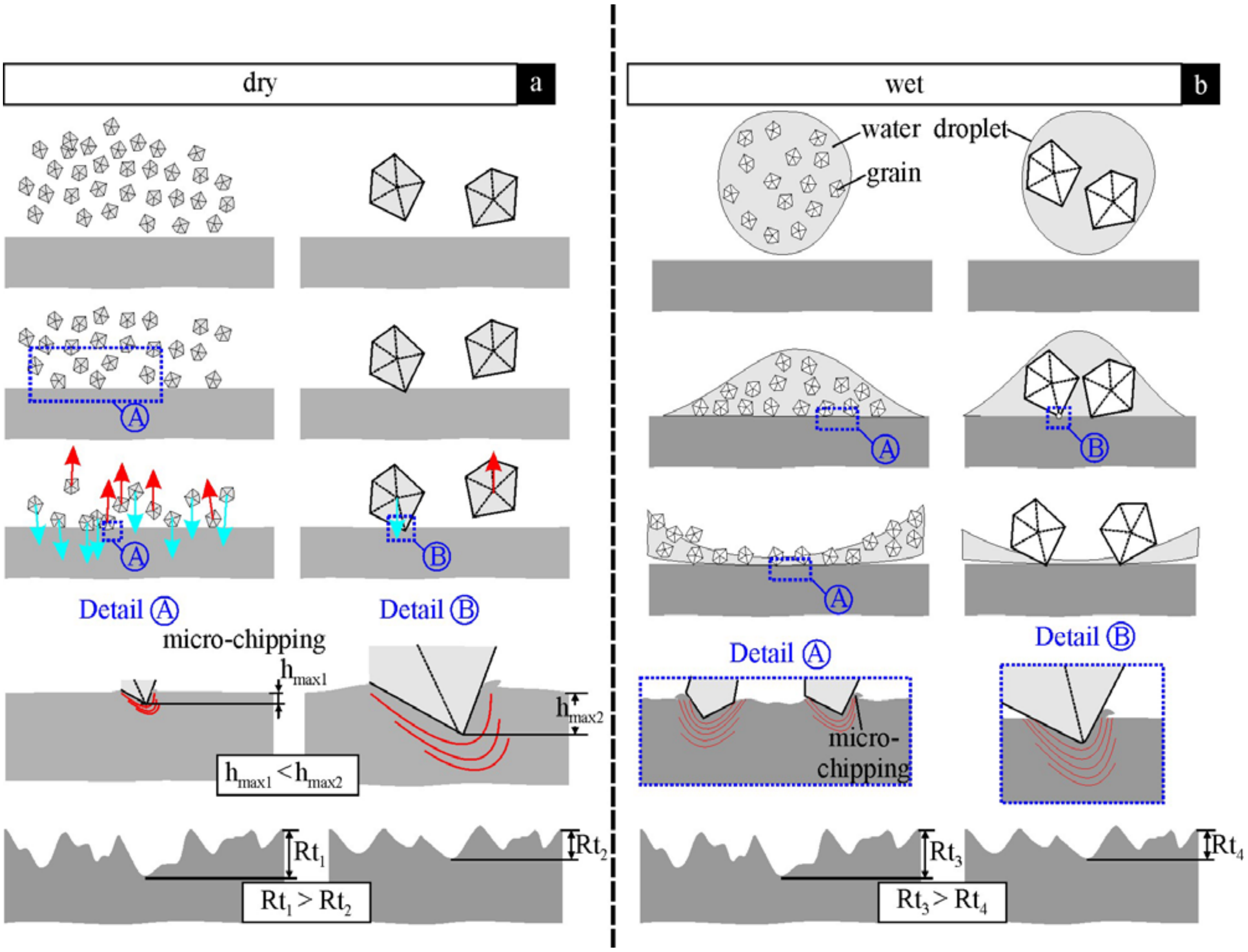


Figure 1. Effect of abrasive grains' size and their transport medium on the surface roughness in a) dry b) wet micro-blasting process

The nanoindentations were carried out by a FISCHERSCOPE H100 device. The roughness Rt 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 milling investigations were carried out by a three-axis numerically controlled milling centre using the steel 42CrMo4 QT, hardened at approximately 300 HV.

3. RESULTS AND DISCUSSION

3.1 Abrasion mechanisms in wet and dry micro-blasting and developed film hardness

Figure 1. 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 figure 1a), 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.

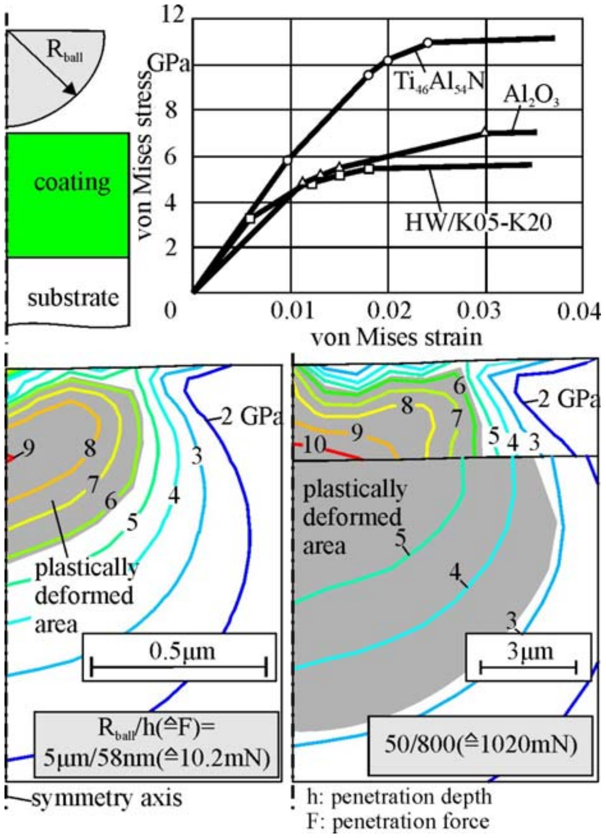
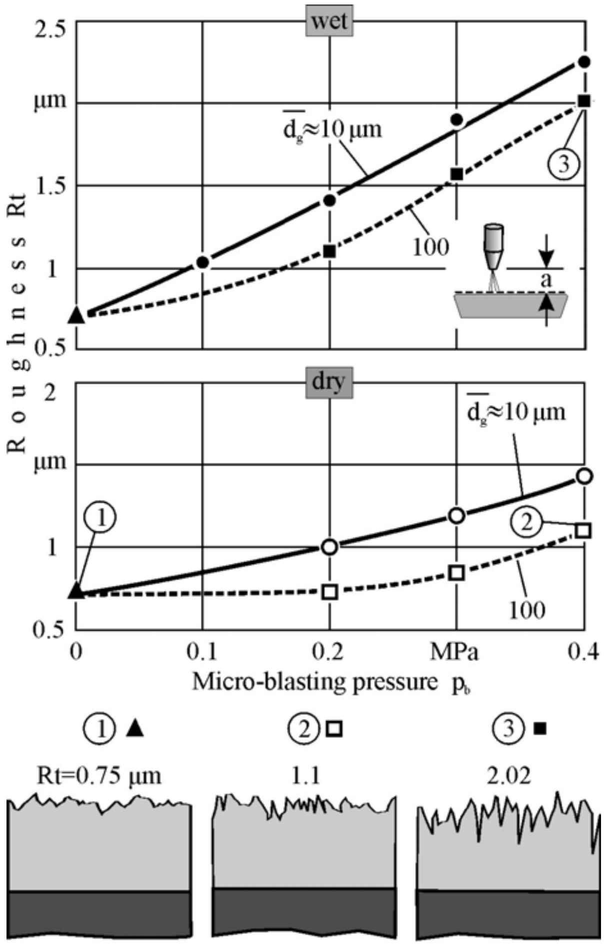


Figure 2. Developed von Mises stress fields during micro-blasting by different grain sizes

Related mechanisms appear in the case of wet micro-blasting, as it is illustrated in figure 1b [6]. 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 nanohardness, compared to the corresponding ones, micro-blasted by coarser grains under the same conditions.

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 figure 1), thus affecting the film integrity slightly.



Substrate: HW-K05/K20, Coating: $Ti_{46}Al_{54}N$, t≈3.5µm, Micro-blasting: Al_2O_3, t_b=4s, a=100mm

Figure 3. Roughness results on post-treated coatings by wet or dry micro-blasting via Al_2O_3 grains of different diameters, at various pressures

This effect results in larger coatings' nanohardness 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.

Insight into the coating and substrate deformation in micro-blasting by various grain sizes provides figure 2. The developed stress fields were calculated based on an already introduced FFM model [9], which simulates Al_2O_3 grains of 10 µm and 100 µm diameter. In the fine micro-blasting grain case, the penetration depth was only 58 nm corresponding to a maximum impact force of approximately 10.2 mN. If Al_2O_3 grains of an average diameter of 100 µm are employed, considering their mass relation to the 10 µm particles, over hundred times larger forces are expected. At such impact force levels, the penetration depth corresponds to much higher imprint depth.

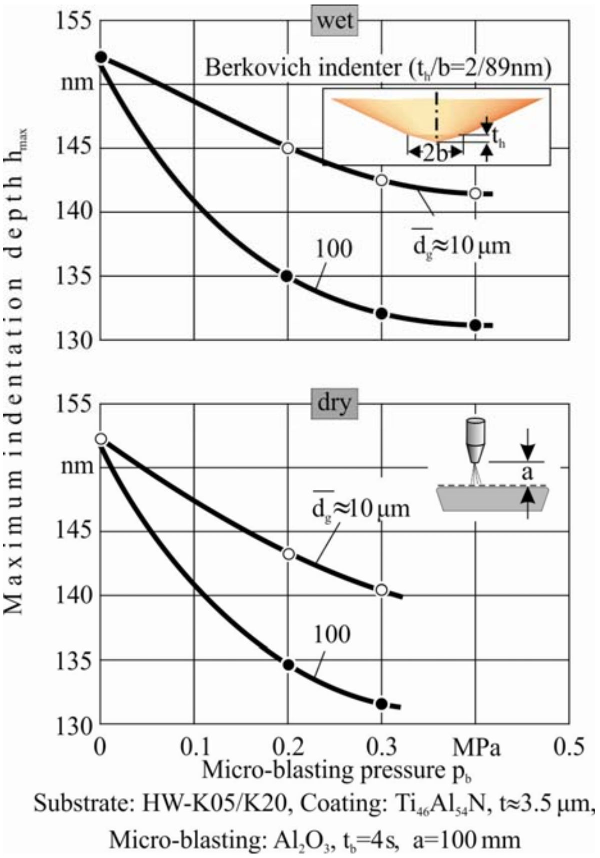


Figure 4. Nanoindentation results on post-treated coatings by wet or dry micro-blasting via Al_2O_3 grains of different diameters, at various pressures

In the demonstrated case, a grain of 100 µm diameter penetrates 800 nm into the film at an indentation force of 1020 mN. According to the FEM results, the coating is deformed plastically in both grain size cases. In the case of micro-blasting by the 10 µm grains, the substrate remains unaffected by the grain penetration. Moreover, at the larger grain size of 100 µm diameter, an extent region of the coating and the substrate is intensively deformed. Thus, the risk of a brittle coating failure and in this way substrate revelation after micro-blasting is higher, if coarser micro-blasting grains are used.

These assumptions can be validated considering the demonstrated results in figure 3. In both cases of wet and dry micro-blasting, when fine Al_2O_3 grains instead of coarse ones are used, a roughness increase develops on the film surface. Characteristic surface topomorphies before and after dry or wet micro-blasting at 0.4 MPa are displayed at the bottom figure part. 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.

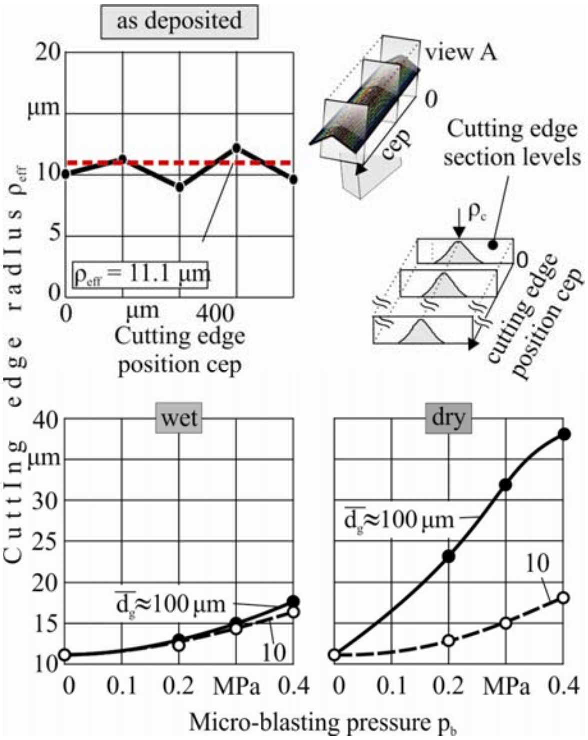
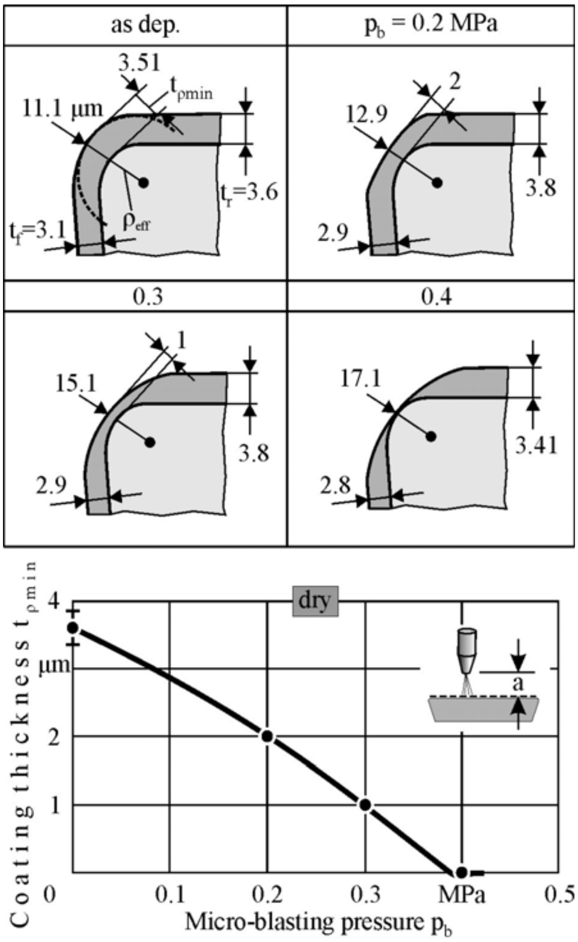


Figure 5. Cutting edge radius ρeff after wet or dry micro-blasting by various grain sizes at different pressures

Nanoindentations at a maximum load of 15 mN were conducted on coated inserts, subjected to wet or dry micro-blasting by fine (dg≈10 µm), or coarse (dg≈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 figure 4. In both wet and dry blasting processes, 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 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. Moreover, this phenomenon is even more intense in the case of dry blasted inserts.

It has to be pointed out that in the case of dry blasting at micro-blasting pressures over 0.3 MPa, coating damage and substrate revelation may take place, as it will be described in the next section.

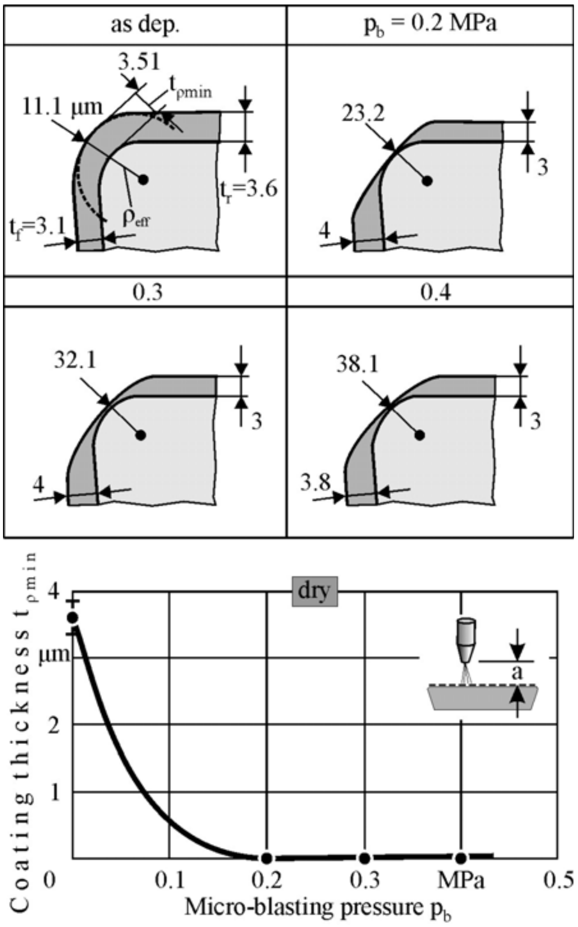


Substrate: K05-K20, Coating: $Ti_{46}Al_{54}N$, t≈3.5µm,
Micro-blasting: Al_2O_3, t_b=4s, ⌀ 10 µm, a=100mm

Figure 6. Cutting edge geometries and minimum coating thickness $t\rho_{min}$ after dry micro-blasting by fine grains at different pressures

3.2 Effect of abrasive grains' size and blasting medium on the coated cutting edge geometry

For investigating the micro-blasting medium and grains' effects on the cutting edge roundness, confocal measurements along the cutting edges of variously wet and dry 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 fluctuations of the cutting edge roundness, before and after micro-blasting at various pressures can be estimated. A characteristic example, for the as deposited coating case is demonstrated in the upper part of figure 5. 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 bottom part of figure 5, for both, wet and dry blasting conditions.



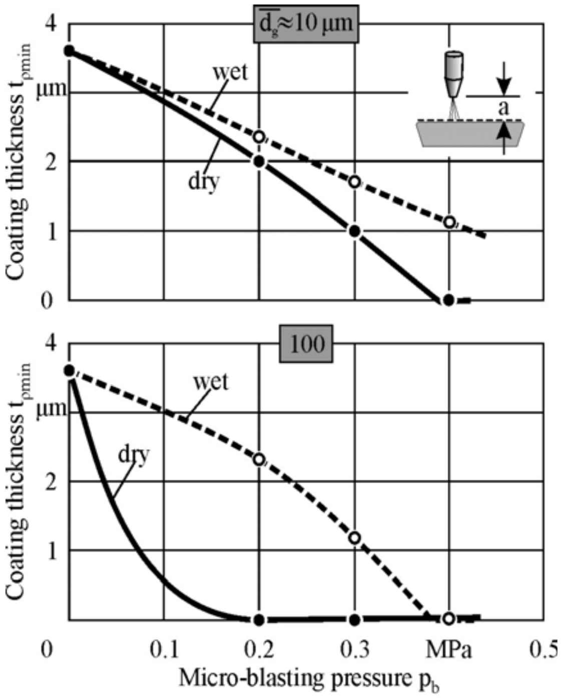
Substrate: K05-K20, Coating: $Ti_{46}Al_{54}N$, t≈3.5µm,
Micro-blasting: Al_2O_3, t_b=4s, ⌀ 100 µm, a=100mm

Figure 7. Cutting edge geometries and minimum coating thickness $t_{\rho min}$ after dry micro-blasting by coarse grains at different pressures

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. The cutting edge radius growth is visible at micro-blasting pressures over 0.2 MPa and it is more intense, when coarse Al_2O_3 grains are employed. This phenomenon amplifies even more in the case of dry blasting.

Taking into account the previous results, the coating thickness distributions along the cutting edge after dry micro-blasting at various pressures, were analytically determined. The calculated coated cutting edge cross section geometries after dry micro-blasting by fine and coarse grains at pressures of 0.2, 0.3 and 0.4MPa are monitored in figures 6 and 7 respectively. When fine grains are employed, the coating thickness t_{pmin} may diminish up to zero at approximately 0.4MPa. Thus, substrate revelations may develop. However, the application of coarse grains results in extent film damage near the cutting edges already at low micro-blasting pressure.

In figure 8, the effect of micro-blasting grain's transport medium on coating thickness distributions along the cutting edge is exhibited.



Substrate: K05-K20, Coating: $Ti_{46}Al_{54}N$, t≈3.5µm,
Micro-blasting: Al_2O_3, t_b=4s, a=100mm

Figure 8. Minimum coating thickness t_{pmin} after wet or dry micro-blasting by fine or coarse grains at different pressures.

When fine grains are used, the risk of coating thickness decrease and even more of a substrate revelation is more relevant in the case of dry micro-blasting compared to wet one at micro-blasting pressures over 0.3MPa. In the coarse grain case, the negative contribution of the dry micro-blasting on the coating thickness diminution along the cutting edge is visible. This was verified by SEM measurements for both Al_2O_3 grain sizes at pressures of 0.3 and 0.4MPa, as it is illustrated in figure 9.

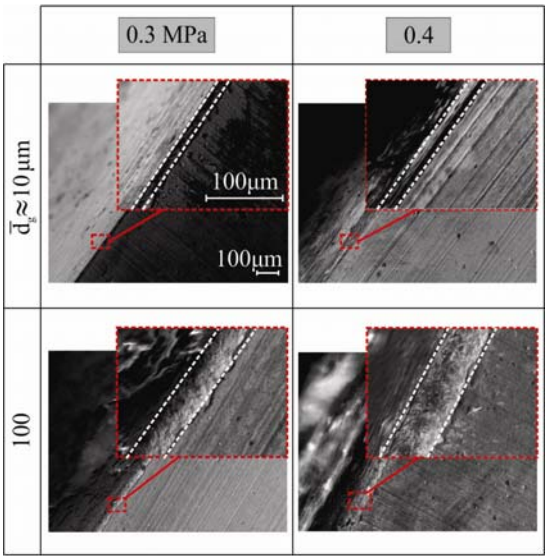
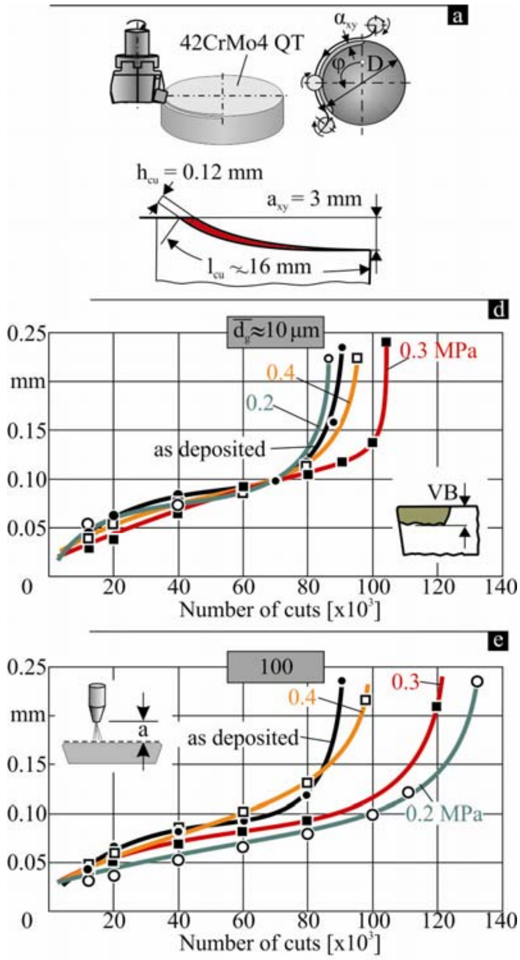


Figure 9. SEM micrographs of coated cutting edges after dry micro-blasting by fine or coarse grains at different pressures



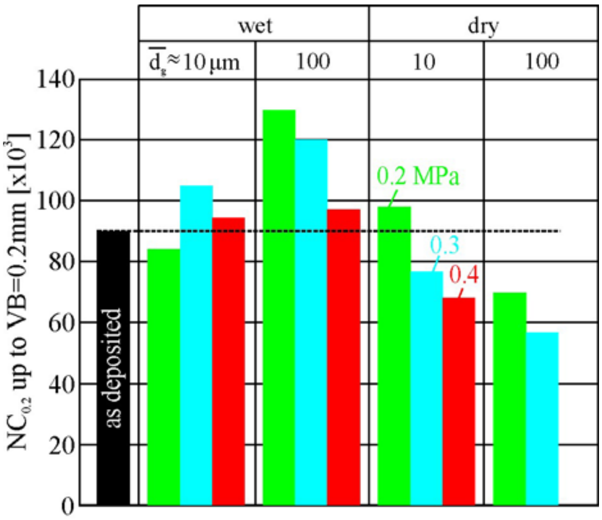
Substrate: HW-K05/K20, Coating: $Ti_{46}Al_{54}N$, t≈3.5µm,
v_c=200 m/min,l_{cu}=16 mm, h_{cu}=0.12 mm,a_{xy}=a_z=3 mm
Micro-blasting: Al_2O_3, t_b=4s, a=100mm

Figure 10. Flank wear development versus the number of cuts of wet micro-blasted coated inserts at various conditions.

It is evident that an increase of pressure results in a wider substrate exposure, especially when coarser grains are used.

3.3 Wear behaviour of coated tools with 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 figure 4). On the other hand, an increased micro-blasting pressure leads to an augmentation of the film brittleness [6,7].



Substrate: HW-K05/K20, Coating: $Ti_{46}Al_{54}N$, t≈3.5µm, v_c=200 m/min,l_{cu}=16 mm, h_{cu}=0.12 mm,a_{xy}=a_z=3 mm
Micro-blasting: Al_2O_3, t_b=4s, a=100mm

Figure 11. Comparison of flank wear development of coated tools subjected to wet or dry micro-blasting by fine or coarse grains at different pressures.

Furthermore, higher micro-blasting pressures resulted in increased cutting edge radius and simultaneously to a film thickness decrease on the cutting wedge, especially when dry blasting conditions are applied. This film thickness decrease is aggravated by the produced rough topomorphy of the micro-blasted surface, in particular when coarser Al_2O_3 grains are employed. Hence, micro-blasting on PVD films can be considered as an efficient method, if the balance between the described effects leads to improved tool life.

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 figure 10a. 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 figure 10b and 10c respectively. Cutting inserts wet micro-blasted with fine Al_2O_3 grains at 0.2MPa 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 0.3MPa because of the enhanced film hardness (see figure 4). At the higher micro-blasting pressure of 0.4MPa, 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 figure 10c), 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.

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 figure 11. 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.

4. CONCLUSION

In the present paper, the effect of wet and dry micro-blasting by Al_2O_3 abrasive grains of various diameters on PVD films' hardness, tool wedge geometry and cutting performance is introduced. Wet micro-blasting with coarse sharp-edged Al_20_3 grains may lead to a significant coated tool life increase. The applied micro-blasting pressure has to be adjusted with respect to the size of the used abrasive grains. Wet micro-blasting is a more efficient post treatment for enhancing the cutting performance of coated tools, compared to dry micro-blasting.

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