CIRP Annals - Manufacturing Technology 60 (2011) 587–590

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Optimization of wet micro-blasting on PVD films with various grain materials for improving the coated tools' cutting performance

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ARTICLE INFO

Keywords:
Coating
Wear
Micro-blasting

ABSTRACT

The applied grains' material in micro-blasting of Physical Vapour Deposition (PVD) films and the process conditions affect significantly the coated tools' 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. The paper deals with the optimization of wet micro-blasting conditions for improving the coated tool's wear resistance. The explanation of the grains' penetration into the coated tool surface and of the film deformation mechanisms renders the achievement of this target possible.

1. Introduction

Micro-blasting on PVD films is a very promising technology to improve the cutting performance of coated tools [1–5]. However, for a successful process conduct, especially in the case of wet micro-blasting, it is pivotal to adapt the blasting pressure to the employed grains' properties.

In the present paper, PVD coated tools were subjected to wet micro-blasting by sharp-edged Al_2O_3 abrasive grains and spherical ZrO_2 ones, with smooth surfaces and average diameter of approximately 100 μm. The different micro-blasting grain materials at various process pressures affect variously the film's surface characteristics such as roughness, hardness and brittleness as well as the cutting edge geometry and hence the coated tools wear behaviour. The explanation of the corresponding mechanisms renders possible, among others, a targeted optimization of micro-blasting pressure.

2. Experimental details

TiAlN films, with an Al/Ti ratio of 54/46 were deposited by a CEMECON C900 coating machine [6] on cemented carbide inserts of K05-K20 ISO quality. The film thickness on the tool rake was approximately 3.5 μm. A PVD process technology with a high ionization sputtering and pulsing (HIS and HIP) was applied, leading to a nano-structured, nano-laminated and nano-dispersed coating system. The developed residual stresses in the films at an information depth of 1 μm, in both directions parallel and perpendicular to the cutting edge, are less than 1 GPa, according to X-ray diffraction measurements by the $\sin^2 \psi$ method [7]. The used device was a SEIFERT XRD 3000 unit, equipped with a 4-circle goniometer [3]. The water micro-blasting treatments were conducted via a NP10 machine of WIWOX GmbH Surface Systems. The equivalent 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 [8].

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 [9]. To capture cutting edge radius and coating thickness distributions, white light scanning by a 3D confocal system μSURF of NANOFOCUS AG was employed. Nano-scratch and nano-impact tests were conducted by a diamond cube indenter of a Micro Materials Ltd device [10]. The milling investigations were carried out in a three-axis numerically controlled milling centre using the steel 42CrMo4 QT, hardened at approximately 300 HV.

3. Results and discussion

3.1. Effect of the employed grain material on the film hardness and brittleness

Fig. 1 explains how the kinematics of different grains' shape in wet micro-blasting affects the film material deformation and the surface integrity. In the case of wet micro-blasting by Al_2O_3 grains, on one hand, due to the grains' sharp shape compared to the spherical ZrO_2 ones, a deeper and less wide penetration into the

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0007-8506/$ – see front matter © 2011 CIRP.
doi:10.1016/j.cirp.2011.03.012

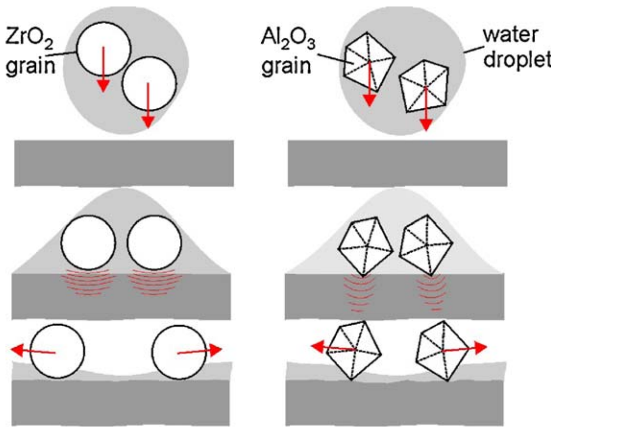

Fig. 1. Effect of grains' materials on the film surface deformation and roughness in wet micro-blasting.

coating material takes place and thus, the film is locally more deformed. On the other hand, the Al_2O_3 grains are guided along the film surface, at high friction, by the flowing water and cause at the same treatment duration and pressure, more intense coating material removal through micro-chippings, compared to the smooth spherical ZrO_2 grains. In this way, coatings subjected to micro-blasting by sharp-edged Al_2O_3 grains are expected to possess higher nanohardness and roughness compared to micro-blasting by ZrO_2 grains, under the same process conditions.

The previous assumptions can be validated considering the results exhibited in Fig. 2. In Fig. 2a, the attained maximum indentation depth after wet micro-blasting at various pressures by smooth spherical ZrO_2 grains and by sharp-edged Al_2O_3 ones is displayed. The maximum indentation load amounted to 15 mN. By increasing the micro-blasting pressure in both grain material cases, a diminution of the maximum indentation depth and hence a hardness augmentation appears. This can be attributed to the induced residual compressive stresses into the film structure due to its deformation by the individual grains [11–13]. A comparison of the achieved maximum indentation depth by various grain materials versus the micro-blasting pressure reveals that, as it was expected, the more intense coating deformation induced by Al_2O_3 grains compared to ZrO_2 ones, leads to larger hardness. Furthermore, according to the results monitored in Fig. 2b, the more intense abrasion in wet micro-blasting, when Al_2O_3 grains are used, instead of ZrO_2 ones, causes a roughness increase at the same micro-blasting pressure. The augmentation of micro-blasting pressure and duration may result in significant local coating

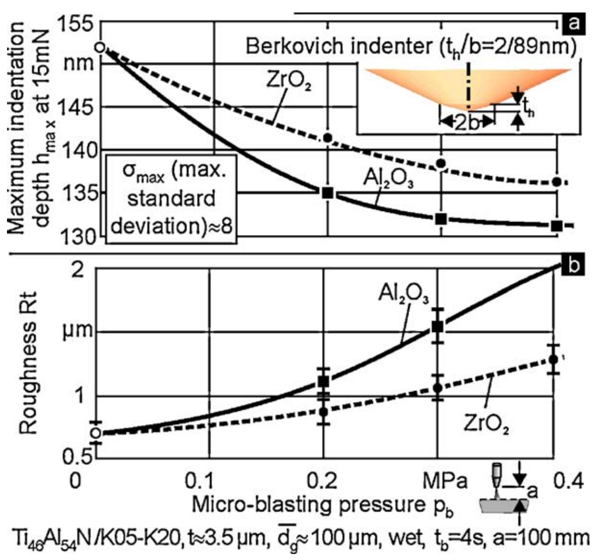

Fig. 2. (a) Nanoindentation and (b) roughness results on post-treated coatings by wet micro-blasting with Al_2O_3 and ZrO_2 grains.

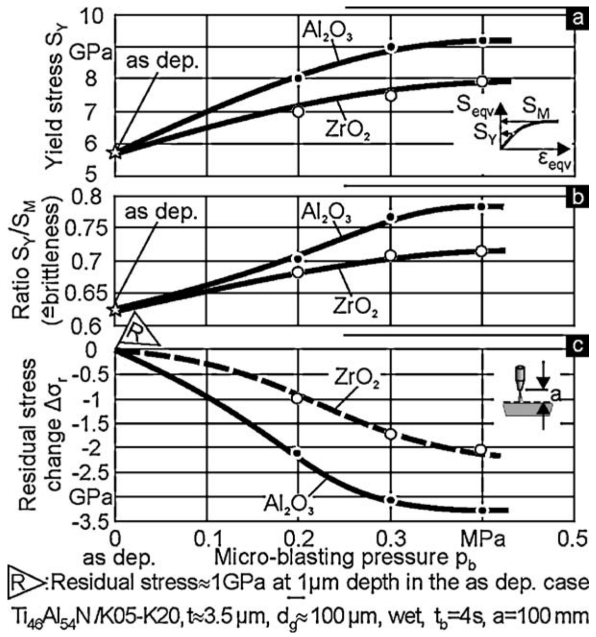

Fig. 3. (a) Yield stresses, (b) S_Y/S_M ratio and (c) residual stress changes of post-treated coatings by wet micro-blasting with Al_2O_3 and ZrO_2 grains.

thickness reductions especially in the cutting edge region in both grains' material cases. In this way, the micro-blasted coated tool's cutting performance may be deteriorated. This effect, when Al_2O_3 grains instead of ZrO_2 ones are used, is expected to appear at comparable lower micro-blasting pressures, because of the mechanisms described in Fig. 1.

The coatings' yield stresses were determined by the "SSCU-BONI" algorithm [9]. In generally, a gradation of the yield stress versus the film thickness develops after micro-blasting [12]. In the described investigations, for simplifying the related calculations, it was assumed that an evenly distributed yield stress versus the coating thickness, up to a depth of 1.5 μm from the film surface occurs. Due to the larger coating material deformation, induced by the Al_2O_3 grains, the yield stress increase versus the pressure is higher compared to the corresponding one, when ZrO_2 grains at the same process conditions are applied (see Fig. 3a). The determined yield stresses in both grain material cases remain practically unaffected over a pressure of 0.4 MPa.

Moreover, Fig. 3b exhibits the yield to rupture stress ratio (S_Y/S_M) course versus the micro-blasting pressure. An increase of this ratio indicates a simultaneous film brittleness growth i.e. fracture at less plastic deformation. The augmentation of the equivalent residual stresses is equal to the yield stress differences [8]. Considering this dependency, the equivalent residual stress changes in the coatings after micro-blasting at various pressures were calculated and they are displayed in Fig. 3c. Micro-blasting by Al_2O_3 grains contributes to a significant increase of the residual stresses up to 0.4 MPa. At larger pressures, the residual stresses remain practically invariable and are extended deeper in the coating thickness [12]. Because of the comparable lower film deformation in wet micro-blasting by ZrO_2 grains, the residual stress change is less intense, as the related curves in Fig. 3c show.

For investigating the effect of the PVD film nano-hardness changes, induced by micro-blasting, on the wear resistance of coated tools, repetitive nano-scratch tests were conducted up to a maximum load of 500 mN. Fig. 4a demonstrates the course of the developed depth during loading and of the remaining one, due to the film elastic relaxation, versus the indenter displacement, after five repetitive scratch tests. The applied films were micro-blasted by Al_2O_3 grains at a pressure of 0.2 MPa. The achieved maximum depths, shown in Fig. 4b, are almost equal in both investigated Al_2O_3 and ZrO_2 grain cases at 0.2 and 0.4 MPa, respectively, and the nanohardness and residual stress changes as well (see Fig. 3c).

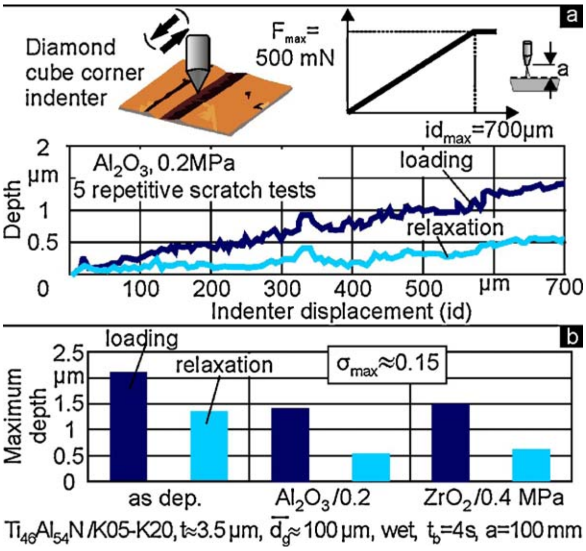

Fig. 4. Repetitive nano-scratch tests on variously wet micro-blasted coatings.

Moreover, the micro-blasted films have an improved wear resistance compared to the as deposited one.

Nano-impact tests were carried out on the variously micro-blasted coated inserts by a sharp cube corner diamond indenter. In nano-impact test, a solenoid is used to pull the indenter off the surface and to re-accelerate it from a small distance against the film [10]. An appropriate automation enables repetitive impacts at the same position on the sample surface at a set frequency. The evolution of the indentation depth, due to the progressing film damage during the repetitive impacts, is continuously monitored. Fig. 5a displays related test results at various impact loads on coating subjected to micro-blasting by spherical ZrO_2 grains at a pressure of 0.4 MPa. The impact load increase up to 30 mN is associated with a continuous depth growth. At the impact load of 40 mN, a comparable steeper depth augmentation occurs, caused by the coating overloading and brittleness increase at high pressures (see Fig. 3b). In Fig. 5b, the attained maximum depth at various impact loads is exhibited versus the micro-blasting pressure, when Al_2O_3 or ZrO_2 grains are employed. In the as deposited film case, a continuous depth augmentation with

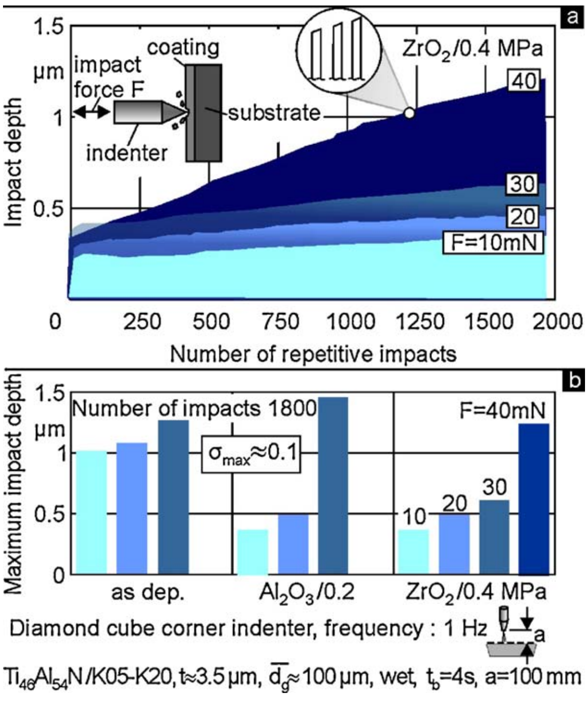

Fig. 5. Nano-impact results on wet micro-blasted coatings (a) by ZrO_2 grains at 0.4 MPa (b) by different grains' materials at various pressures.

growing impact load develops. The attained depths up to an impact load of 20 mN in the case of Al_2O_3 grains and up to 30 mN, when ZrO_2 materials are applied, are significant lower compared to the as deposited film case. Over these impact loads and at higher S_Y/S_M ratios than 0.7 (see Fig. 3b), a film brittle fracture develops and the impact depths are comparable to those, of the as deposited coatings.

3.2. Effect of the employed grain material on the edge integrity and coated tools cutting performance

For investigating the micro-blasting grains' material effect on the cutting edge roundness, white light scans along the tool edge of variously wet micro-blasted cutting inserts were conducted. Successive cross sections of the cutting edges were monitored, as it is shown in Fig. 6a. With their aid, the corresponding radii as well as the average and the fluctuations of the cutting edge roundness, before and after wet micro-blasting at various pressures, were estimated. A characteristic example for the as deposited coating case is demonstrated in Fig. 6b. The course of cutting edge radius versus the micro-blasting pressure is illustrated in micro-blasting with Al_2O_3 and ZrO_2 grains. By increasing the micro-blasting pressure in both grains' material cases, an enlargement of the cutting edge radius develops. This growth is more intense at micro-blasting pressures over 0.2 MPa and comparably larger, when Al_2O_3 grains are employed.

Taking into account these 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 sections at pressures of 0.2 and 0.4 MPa, when various abrasive grains are employed, are monitored in Fig. 6c. Based on these geometries, the coating thickness $t_{\rho\,\min}$ can be determined versus the micro-blasting pressure (see Fig. 6d). This parameter diminishes to zero at a comparable lower pressure, if Al_2O_3 grains are used, instead of ZrO_2 ones. Thus, substrate

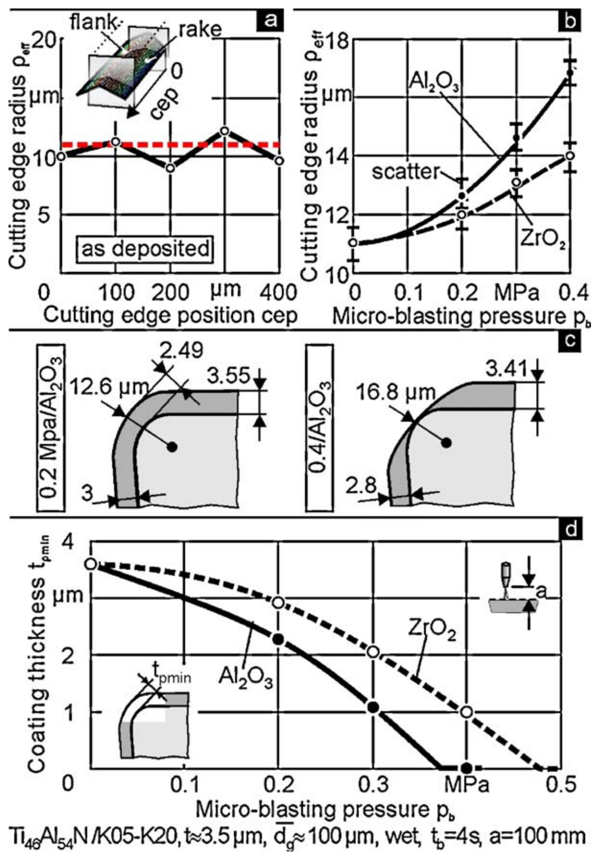

Fig. 6. (a) White light scans along the cutting edge in the as deposited case, (b) cutting edge radius ρ_{eff}, (c) cutting edge geometries and (d) minimum coating thickness $t_{\rho\,\min}$ after wet micro-blasting by different grain's materials.

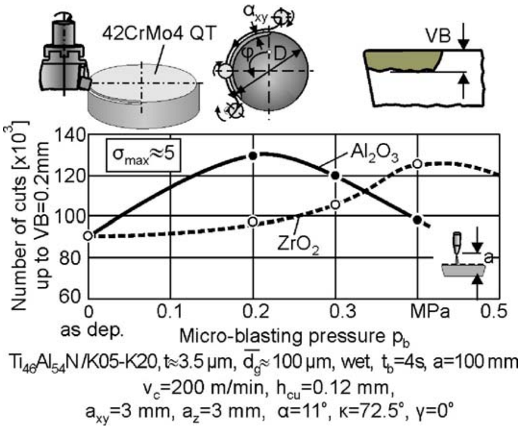

Fig. 7. Flank wear development versus the number of cuts of wet micro-blasted coated inserts at various conditions.

revelations may develop, when Al_2O_3 grains are employed at a micro-blasting pressure of ca. 0.35 MPa, whereas in the case of ZrO_2 grains, at a pressure of approximately 0.5 MPa.

A coating thickness $t_{\rho\ \min}$ diminution leads to substrate thermal and mechanical loads growth and thus, the coated tool cutting performance may be deteriorated [14]. To capture the effect of the applied micro-blasting grains on the cutting performance of coated cemented carbide inserts, milling investigations were conducted. The applied tool-workpiece system is illustrated at the top of Fig. 7. In this figure, the achieved numbers of cuts, up to a flank wear land width of 0.2 mm are displayed. The employed coated cutting inserts were micro-blasted at various pressures by Al_2O_3 or ZrO_2 grains. The cutting performance of coated micro-blasted tools at a pressure of 0.2 MPa by Al_2O_3 grains is significantly improved compared to the corresponding performance of the untreated (as dep.) coated inserts or micro-blasted at higher than 0.2 MPa pressures. In the case of ZrO_2 grains, the coated tool life has a maximum at a pressure of approximately equal to 0.4 MPa, because of the different film deformation and grain's kinematics during micro-blasting, compared to Al_2O_3 grains.

4. Conclusions

In the paper, the effect of sharp-edged Al_2O_3 micro-blasting grains and smooth spherical ZrO_2 ones on coating mechanical properties, brittleness, tool wedge geometry and cutting performance is introduced. Due to the smooth spherical ZrO_2 surfaces, the abrasion during micro-blasting is less intense and the coating material deformation lower, compared to treatment by Al_2O_3 grains of the same diameter and conditions. Although micro-blasting pressure augmentation is beneficial for enhancing coating mechanical properties, this may increase the film brittleness and cause local substrate revelations. In the conducted wet micro-blasting investigations by employing Al_2O_3 and ZrO_2 grains of an average diameter of 100 μm, pressures of 0.2 and 0.4 MPa, respectively, led to a cutting performance maximum.

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