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Bias voltage effect on the mechanical properties, adhesion and milling performance of PVD films on cemented carbide inserts

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ABSTRACT

The potential of coated cutting inserts to withstand effectively cutting loads depends among others on the coating's mechanical properties and adhesion. These data are strongly affected by the applied PVD process parameters, even if the coatings comprise the same chemical composition. Hereupon, one significant parameter is the bias voltage during the film deposition. For detecting its effect on the occurring film mechanical properties, adhesion and wear behavior, PVD TiAlN coatings were deposited on cemented carbide inserts at diverse bias voltages. The properties of the manufactured coatings were determined via FEM-supported results evaluation of nanoindentations, perpendicular and inclined impact tests. Coatings produced at elevated bias voltage possess comparably increased mechanical properties and fatigue endurance. However, their adhesion deteriorates, thus reducing the coated inserts cutting performance especially when a good adhesion during a material removal process as in milling hardened steel is required. Relevant FEM calculations of this process were employed to explain the wear evolution on the flank and rake of the used coated tools considering their cutting edge geometry and their actual film's mechanical properties and adhesion dependent upon the applied bias voltage during the coating deposition.

1. Introduction

The potential of PVD-coatings to withstand mechanical and thermal loads in cutting procedures depends among others on their mechanical properties and adhesion [1–3]. Coatings with poor adhesion are loaded more intensely compared to well-adherent ones, when high loads are exercised tangentially on the film–substrate interface [3–5]. As a result, an increased wear on the tool flank and rake may appear deteriorating the tool life.

Coatings comprising the same chemical composition possess diverse mechanical properties and adhesion dependent on the applied conditions during the PVD process. Hereupon, elevated film residual stresses result when the bias-voltage grows up to a certain stage and the mechanical properties of the deposited PVD coatings increase [6–13]. However, the coating adhesion may be deteriorated. More specifically, the adhesion worsens over a critical level of residual stresses, thus diminishing the coated tool life in cutting [14–16].

The paper aims at presenting the effect of the bias voltage on the film's mechanical properties, adhesion, flank and rake wear of coated cemented carbide tools in milling. In this context, cemented carbide inserts were coated by applying different bias voltages of constant or variable magnitudes during the PVD process. The film mechanical properties were determined via FEM-supported results' evaluation of nanoindentations [3,17]. The coating's fatigue endurance was described with the aid of Smith- and Woehler-like diagrams created via appropriate FEM-calculations for evaluating perpendicular impact test's results [18]. For quantifying the films' adhesion, the corresponding film Contact Stiffness Ratios (CSR) were defined, based on inclined impact test results on coated cemented carbide inserts and a FEM supported analysis [5]. Furthermore, the coated inserts were used in milling hardened steel for assessing their cutting performance. The stress fields developed in the coated cutting wedge region were calculated by means of a FEM simulation of the cutting process considering the actual cutting edge geometry and the determined CSRs. In this way, it was possible to explain the coating wear evolution on the tool flank and rake dependent on the film mechanical properties and adhesion.

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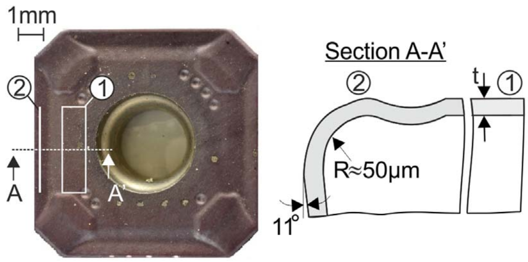

Substrate
Geometry: Sandvik R245-12 T3
Material ISO: HW-K05
Roughness: Rt/Ra=1.6/0.25 [μm]
Coating
PVD $Ti_{60}Al_{40}N$, thickness t≈3μm

Indicative regions for conducting impact tests:
① Perpendicular and inclined /② Inclined

Material:	Hardness HV30	Mechanical properties $E/S_Y/S_M$ [GPa]
42CrMo4 QT (AISI 4140)	300	210/0.7/1
HW-K05	1800	580/3.3/5.8

E: elasticity modulus, S_Y: yield stress, S_M: rupture stress

Fig. 1. Geometrical and technological data of the applied coated cemented carbide inserts and workpiece material.

2. Experimental-computational details

2.1. The used coated cemented carbide inserts

The geometry and significant data of the applied cemented carbide cutting inserts and workpiece material are exhibited in Fig. 1. The inserts were manufactured by Sandvik according to R245-12 T3 specifications of this company. The cemented carbide can be classified as ISO K05 by its Co-content of approximately 5%. The cutting edge radius amounts to roughly 50 μm whereas the rake is appropriately shaped for facilitating the chip flow, as shown in section A-A′ of Fig. 1. Moreover, main strength properties of these inserts as well as main material data of the used workpieces in milling investigations are also displayed. The inserts' strength properties were obtained via the experimental-mathematical procedures described in the next section. The hardness of the quenched and tempered steel 42CrMo4 QT amounts to 300 HV30. All these geometrical details and material data were taken into account in the FEM model of the cutting edge, as introduced in a next section.

The cemented carbide inserts were coated with a $Ti_{60}Al_{40}N$ PVD film of about 3 μm thickness. Hereupon, three individual PVD processes at various substrate bias voltages were carried out. More specifically, three groups of coated inserts were prepared at a low (−30 V), medium (−50 V) and multi (−30 V and −90 V) bias voltage (see Fig. 2). In the first two cases, the bias voltage was kept constant throughout the PVD process resulting in the formation of film structures with almost uniform properties (Fig. 2a). In the third case, the bias voltage was changed few times from −30 V up to −90 V during the coating deposition. As a consequence, coating regions with variable properties were formed, as in Fig. 2b schematically illustrated.

2.2. Determination of coating's stress-strain curves

The coating and substrate mechanical properties were determined by a FEM-supported evaluation of nanoindentation's results. The nanoindentations were performed using a FISCHERSCOPE H100 device. The tip deviations of the applied diamond indenter from the ideal Vickers pyramid geometry due to manufacturing inaccuracies was mathematically described considering among others the parameters b and t_h depicted in Fig. 3. The latter parameters were experimentally-theoretically determined, as explained in the publication [19]. For excluding the effect of the inserts' roughness causing a scatter of the indentation depths measured versus the increasing indentation load, a sufficient number of nanoindentations was conducted [20]. After a certain number of measurements which depends on the surface roughness magnitude, the moving average of the indentation depth versus the indentation load is stabilized. To determine the coating and substrate stress–strain curves based on the stabilized moving average of the nanoindentation curves and on the indenter tip actual geometry, the 'SSCUBONI' algorithm was applied. 'SSCUBONI' simulates continuously the indenter penetration into the tested material and calculates the developed reaction force F_y versus the penetration depth. The elasticity modulus and the stress-strain curve of the tested material is defined by comparing the course of the reaction force F_y versus the penetration depth to the measured one of the indentation load versus the indentation depth. The curved area of the stress-strain graph associated with the film plastic deformation is approached stepwise by successive linear intervals (see Fig. 3). The accuracy of the described experimental-analytical procedures was verified by determining the elasticity modulus of reference materials. The attained data were within properties deviations of the tested materials amounting to roughly ± 1.2% [17]. A stress-strain curve provides material data concerning the elasticity modulus E as well as the equivalent yield S_Y and rupture stress S_M. The determined stress-strain curves of the used substrates and coatings deposited at various bias voltages were taken into account in the FEM calculations introduced in the following sections.

2.3. Determination of the coating's contact stiffness ratio (CSR) via a FEM supported evaluation of impact test's results

The coating's adhesion can be graded by means of the Contact Stiffness Ratio (CSR) [5]. CSR is defined as the ratio of the tangential to the normal stiffness of the employed contact elements for simulating the coating-substrate interface adhesion strength. CSR equal to 1 means, that the film adhesion is ideal.

The individual experimental-computational procedures for determining the CSRs of the coatings deposited at various bias voltages are explained in Fig. 4. These procedures are classified in three stages. In the first stage, perpendicular impact tests are conducted at different force amplitudes for one million repetitive impacts. These tests aim at detecting the maximum impact force F_{max} (fatigue threshold force) which the coating can withstand without failure. With the aid of a FEM simulation of the impact test, the maximum equivalent stress developed in the coating at the fatigue threshold force F_{max} during its loading and the remaining one due to the substrate plastic deformation is calculated. Based on these data, the Smith-like diagram illustrated in Fig. 4 is established [18]. Via this diagram, the coating fatigue endurance stress S_D for repetitive loads from zero up to a certain maximum value is determined. Considering S_D, the Woehler-like diagram demonstrated in the middle of Fig. 4 is created. The data employed for establishing the aforementioned graphs do not depend on the coating adhesion, since the film is only vertically loaded during the perpendicular impact test. Furthermore, in the second procedures stage, employing a FEM model of the inclined impact test at an inclination angle θ, the coating maximum stress S_F induced by a force F is calculated. In these calculations, an ideal adhesion (CSR = 1) is assumed. If the film-substrate adhesion is not ideal (CSR < 1), the coating strains are higher compared to the developed ones at the same load in the case of an ideal adhesion. Hence, the actual coating stress S^*_{eqv} is larger than S_F, thus leading to film fatigue failure at a smaller number of impacts NI* than the expected NI_F according to the established Woehler diagram (see Fig. 4). The parameter NI* is experimentally determined by conducting inclined impact