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Effect of PVD film's residual stresses on their mechanical properties, brittleness, adhesion and cutting performance of coated tools

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ABSTRACT

Coated cemented carbide inserts with diverse compressive residual stresses in the film structure were manufactured applying different substrate bias voltages. Moreover, a portion of the coated specimens was annealed for eliminating compressive residual stresses. Residual stress measurements, nanoindentations, nano- and inclined-impact tests, as well as FEM-supported calculations were performed for assessing the coating's mechanical properties, cohesion, brittleness and adhesion. Furthermore, the cutting performance of the coated inserts was investigated in turning AISI 1045. According to the attained results, coating residual stresses affect significantly the film properties and wear behavior. Hereupon, a certain residual stress level can be considered as optimum.

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Introduction

Residual stresses developed in the film structure affect significantly the coated tool performance [1–3]. Hereupon, compressive stresses are considered as advantageous for loaded components and tools, as they counteract the crack initiation and propagation in the film. Higher compressive stresses are associated with longer coated tool life, unless a certain stress maximum is exceeded worsening the coating brittleness and herewith the cutting performance as well [4].

The application of PVD coatings on cutting tools has met wide approval and has emerged as significant method of improving tool cutting performance. PVD coatings are usually characterized by high residual stresses in their structure due to the thermoelastic effects and grown-in defects, generated by particles of high kinetic energy during deposition [5,6]. The magnitude of the developed compressive residual stresses during the film deposition depends on the process parameters such as of bias voltage [7]. The conducted investigations aimed at elucidating the effect of the level of the residual stresses in the PVD film structure on the wear behavior of coated tools. It is expected that properties such as fatigue, toughness, residual stresses and adhesion, which are pivotal for cutting with coated tools, are significantly affected by

the coating residual stresses. To determine these properties, innovative experimental procedures combined with FEM supported computations were performed [8].

In this context, PVD TiAlN coatings with a thickness of approximately 2 μm were deposited at diverse bias voltages for attaining various magnitudes of compressive residual stresses in their structures. A portion of the coated cemented carbide inserts with the lowest compressive residual stresses was annealed at 700 °C in an inert gas atmosphere for creating tensile stresses in the coating. The developed structural residual stresses were registered using adequate measurement methods, whereas thermal residual stresses developed during cooling from the deposition temperature to the ambient one were analytically estimated by means of appropriate FEM supported calculations. The coating strength properties were determined via a FEM supported evaluation of the obtained nanoindentation's results. Nano-impact and inclined -impact tests were performed to assess the films' cohesion, brittleness and adhesion. The coated tools were used in turning hardened steel. By correlating the investigated film properties with the attained wear behavior of the coated inserts, a maximum film residual stress level can be considered as optimum.

Experimental details

Ti₄₅Al₅₅N coatings were deposited on cemented carbide inserts HW-K05 (SNMA120408, 94 wt.% WC + 6 wt.% Co) by DC arc

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evaporation method using 3 fold substrate fixture rotation at a total N_2 pressure of 4.5 Pa and 150 A arc current/cathode (six cathodes) [2]. Prior to the coating deposition, the cemented carbide inserts were etched by Ar-ions. Three individual deposition processes were conducted applying different substrate bias voltages (–40, –65 and –85 V). In this way, three tool batches were manufactured named as A01 (–40 V), B01 (–65 V), and C01 (–85 V) respectively. One portion of inserts from batch A01 (named as A01-HT) was heat treated at 700 °C after the coating deposition, in order to attain slight tensile residual stresses in the film structure.

For evaluating the coating's mechanical properties, nanoindentations were conducted at a maximum load of 15 mN using a "FISCHERSCOPE H100" device. 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]. After approximately 20 measurements, the moving average of the maximum penetration depth is stabilized. The PVD film's mechanical properties were determined by nanoindentation results analytical evaluation, employing methods introduced in the literature [9].

The films' cohesion and brittleness was assessed by nano-impact tests. The nano-impact tests were performed via a diamond cube indenter employing a Micro Materials Ltd equipment [10–12]. 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 penetration depth during the repetitive impacts is continuously monitored. In this way, the actual film deformation, as well as its damage evolution is captured. The applied impact loads amounted to 30 mN and 40 mN and the maximum number of impacts was equal to 1800.

The films' cohesion and adhesion were determined by inclined impact tests. The inclined impact tests were conducted by means of an adequate electromagnetic impact device, manufactured by the Laboratory for Machine Tools and Manufacturing Engineering of the Aristotle University of Thessaloniki in conjunction with CemeCon AG [13]. During the inclined impact test, an oscillating oblique load induces repetitive shear stresses into the region between film and its substrate. The repetitive shear stresses can cause a fracture in the coating-substrate interface [13]. Moreover, a film cohesive failure during the conduct of the inclined impact test can take place, as a result of an increased coating brittleness or low mechanical properties. The coated inserts in the conducted inclined impact tests were loaded at an impact force of 250 N for various numbers of impacts (see Fig. 1a). The inclination angle of the load relatively to the coated surface was 15°. At the start of a new test, an unused region of the carbide ball surface was employed. The load signal duration t_d and impact time t_e are displayed in Fig. 1b. These were practically constant in all carried out experiments.

The cutting experiments were carried out on a CNC Gildemeister MD10S lathe using AISI 1045 as workpiece material of approximately 170 HV hardness. The experiments were performed in orthogonal (radial) cutting without coolant or lubricant. The applied cutting speed v_c was 500 m/min. The inserts were clamped in a tool holder at a rake and clearance angle of 6°. The cutting width was kept constant equal to 2 mm. Feed was chosen with respect to the cutting edge radius in order to minimize its influence on the wear behavior and amounted to 0.1 mm/rev.

Finally, residual stress measurements based on depth resolved scattering vector method were executed using a General Electric X-ray diffractometer, type Seifert XRD 3003 eta, equipped with Co K α radiation [1,2]. PVD coatings of few micrometers thickness

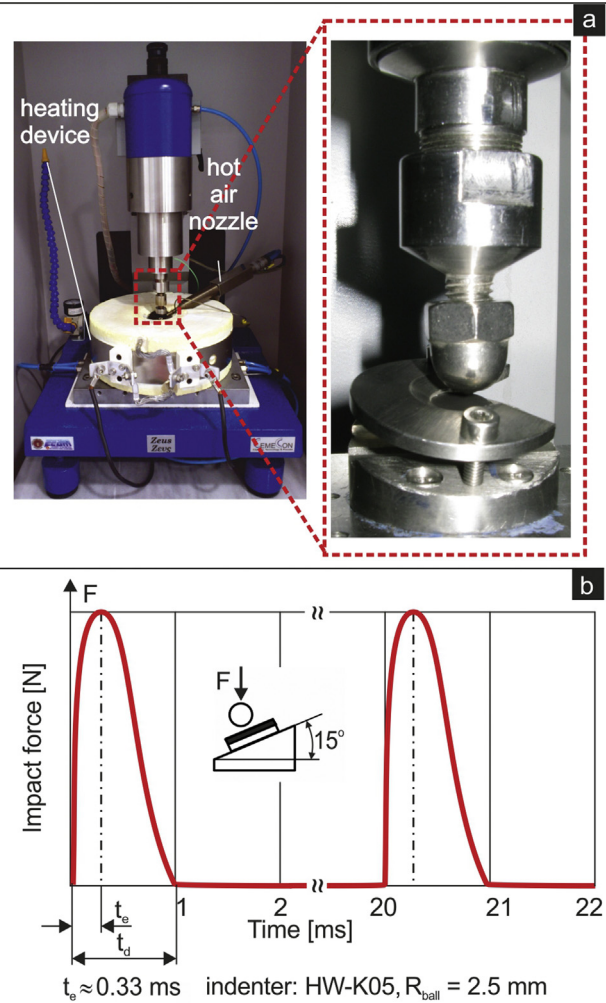


Fig. 1. (a) The mechanical unit of the employed impact tester. (b) Characteristic data of the applied force signals.

exhibit strong residual stress depth gradients [14]. Classical XRD stress measurement procedures like the common $\sin^2\psi$ method cannot deliver depth resolved information [15]. During the last years advanced XRD methods have been developed, which allow a non-destructive determination of residual stress depth distributions in thin coatings such as grazing incidence (GID), scattering vector or energy dispersive methods [1,16–19].

Experimental and analytical results

Determination of the coating's mechanical properties by a FEM-supported nanoindentation's results evaluation

Compressive stresses increase the film hardness, thus diminishing the penetration depth during the nanoindentation. To determine the effect of the residual stresses on the film mechanical properties, nanoindentations were conducted. The achieved load-displacement diagrams for all investigated coating cases are illustrated in Fig. 2. The determined film's mechanical properties are exhibited in the table at the lower part of Fig. 2. The higher the compressive residual stress, the better the film withstands the indenter penetration, yielding to decreased maximum indentation depth and improved mechanical properties. In the case of the heat treated (A01-HT) tools from the A01 batch, the film mechanical properties deteriorate due to the elimination of the compressive residual stresses. In the table of Fig. 2, the calculated yield to

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