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Effect of structure and residual stresses of diamond coated cemented carbide tools on the film adhesion and developed wear mechanisms in milling

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ABSTRACT

This article deals with the wear mechanisms of variously adherent nano-composite or multi-layer diamond coated tools in milling. The adhesion and residual stresses of these films on cemented-carbide inserts were characterized via inclined impact tests at diverse temperatures. The obtained results were evaluated through FEM-supported mathematical methods for estimating the maximum film residual stress and the shear failure stress (SFLS) of the coating–substrate interface. The coated inserts were used in milling AA7075 T6. The developed wear mechanisms were elucidated considering the film structure, the defined temperature-dependent SFLS and the FEM-determined stress and temperature distribution in the tool wedge region during cutting.

1. Introduction

The film adhesion, structure and residual stresses affect significantly the diamond coated tool life, especially in interrupted cutting processes. Recent investigations revealed that low film adhesion is associated with insufficient fatigue strength of the diamond coating–substrate interface which leads to a rapid film delamination and substrate revelation in milling [1,2]. Coating detachment in a restricted region of the tool rake also develops even in cases of well-adherent diamond coated tools, when the shear strength of the coating interface is exceeded, among others, due to film thickness decrease on the cutting edge roundness because of wear. This phenomenon has not yet been clarified as well as the effect of the film structure and residual stresses on the wear mechanisms of diamond-coated tools. Residual stresses develop in a diamond film mainly due to epitaxial crystal differences and thermal expansion coefficients mismatch of the diamond coating and its cemented-carbide substrate [3–5]. Furthermore, multi-layered diamond coating systems, with successive nano- and micro-structured layers, could absorb a part of the residual stresses because of the more deformable micro-structured layers compared to nano-composite ones. This article aims at elucidating the developed wear mechanisms of insufficiently, or well-adherent diamond coated tools in milling, considering their structures and residual stresses.

2. Experimental details

Cemented-carbide inserts of HW-K05/K20 SPGN120308 ISO specifications were coated with nano-composite (NCD), or multi-layered (MLD) films via the hot filament method using a CC800/9Dia CEMECON coating machine [6]. Cobalt-etching procedures were carried out prior to diamond coating deposition for attaining sufficient adhesion [1]. In this way, an adhesive thin interface layer was created. During the deposition process the filament and substrate temperatures were 2000 and 900 °C, respectively. The total pressure amounted to 30 mbar. The carbon to hydrogen ratio was equal to 1%, the coating rate 0.5 μm/h and the gas flow 2 l/min. Four groups of coated inserts were produced by varying the deposition parameters. The cooling time was held constant and equal to 9 h. Applying a deposition time of 10 h, two insert's groups, the NCD and NCD/ba ones were manufactured. At this deposition duration, the structural residual stresses were negligible and mainly thermal ones were developed in the nano-composite film structure [7]. The NCD/ba group possesses an intentionally worse adhesion compared to the NCD one achieved by appropriate variation of the cobalt-etching parameters. Moreover, two further groups were created possessing nano-composite (NCD/hsrs), or multi-layer film structure (MLD) with overall ten successive and alternate nano- and micro-structured layers. These nano- and micro-structured layers had

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approximately 0.34 and 0.66 μm thickness, respectively. In the latter two coating cases, the deposition time was intentionally shortened. As a consequence, structural compressive residual stresses developed in the diamond coating structure, which were overlaid with the also compressive thermal ones. Hereupon, the MLD coating is expected to withstand more effectively the repetitive impacts during milling, since the layer's interfaces obstruct the crack propagation [8]. Conversely, in the case of NCD films, the cracks usually propagate straight down to the substrate, worsening their wear behaviour in cutting [9].

The fatigue strength of the manufactured diamond coated cemented-carbide inserts at various temperatures up to 400 °C was assessed via inclined impact tests at diverse loads and cycles [1]. Via an evaluation of the related results, the temperature-dependent shear failure stress (SFLS) was determined. This metric represents the maximum shear stress which can load a coating interface region without film detachment after one million repetitive impacts. The evaluation was performed by the FEM-supported methodology described in [10], using the LS-DYNA software. The milling investigations were carried out by means of a three-axis numerically controlled milling centre using AA7075 T6 as workpiece material. The FEM calculations of the cutting loads and temperatures, as well as the determination of the developed stress fields at various coating wear stages in the cutting edge roundness region, were carried out using the DEFORM and the ANSYS software packages, respectively.

3. Characterization of the investigated diamond coatings

3.1. Determination of the residual stresses

Residual stresses in diamond films usually enhance the coating adhesion since they contribute to roughness locking in the coating–substrate interface. However, they may overstress the substrate material in its interface region, thus deteriorating the coating adhesion. For determining the maximum residual stress in the investigated diamond coatings, the experimental-analytical procedure described in [7] was employed. The experimental procedure comprises the conduct of inclined impact tests on the coated specimens. During this test, depending on the applied repetitive impact load, a fatigue failure in the NCD coating–substrate interface develops after a certain number of impacts causing the film detachment. After this damage, the highly compressive stresses in the NCD coating structure are released elevating the coating in the detached circular region up to a certain maximum height (bulge formation) [1].

In Fig. 1, characteristic diamond film bulges developed at certain impact loads, after approximately the shown number of impacts. The bars at the right figure part demonstrate the determined thermal and structural equivalent stresses in the investigated coating cases. These stresses were determined by means of the mentioned analytical methods [7], taking into account the mechanical properties and the dimensions (diameter and height) of the formed bulges. The thermal compressive residual stresses in the diamond film occur due to its lower thermal expansion coefficient compared to that of the cemented-carbide substrate. In the case of NCD and NCD/ba insert's groups, the structural residual stresses are negligible at ambient temperature compared to the thermal ones. On the contrary, the film residual stresses of NCD/hsrs and MLD coated inserts are attributed to both thermal and structural ones resulting during the CVD process and the subsequent cooling. The structural stresses in the MLD films are lower compared to the corresponding ones of the NCD/hsrs ones. Hereupon, it can be assumed that the micro-structured layers of the MLD coating absorb a part of the developed residual stresses, since they are more deformable compared to the nano-structured ones. The thermal residual stresses are reduced as the operational temperature grows, whereas the structural ones remain practically stable up to a temperature of roughly 400 °C.

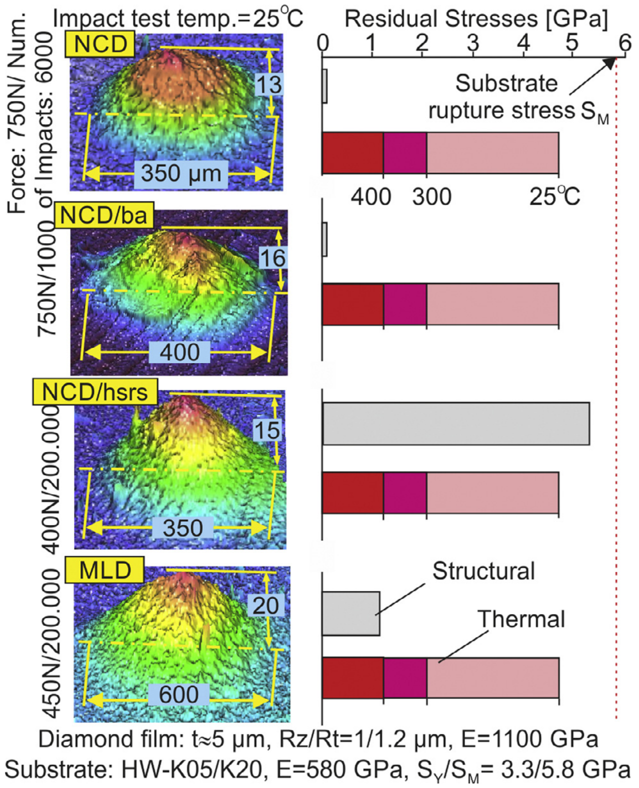

Fig. 1. FEM-calculated thermal and structural stresses in the investigated coatings based on the dimensions of the developed bulges at various loads and number of impacts.

3.2. Quantification of the films' adhesion

Factors improving the adhesion of diamond coatings are the fatigue strength and thermal stability of their adhesive interlayer as well as the locking of roughnesses in the interface region between diamond film and substrate. A potential overstressing of the substrate material in the interface region deteriorates the coating adhesion. The experimentally detected maximum forces in the inclined impact test for avoiding the fatigue failure of the diamond coating–substrate interface after 10^6 impacts at diverse temperatures are illustrated in Fig. 2a. These critical impact forces and the temperature-dependent film residual stresses shown in Fig. 1 were the input data for calculating the shear failure stress (SFLS) according to the mentioned method described in [10]. The displayed SFLSs in Fig. 2b represent temperature-dependent thresholds triggering an interfacial coating–substrate adhesive failure in every coating case after 10^6 repetitive impacts. The higher the operational temperature, the lower the maximum applied force and the SFLS are for avoiding an adhesive film fatigue failure. The restricted thermal stability of the NCD/ba coating–substrate interface leads to a strong reduction of its interfacial fatigue strength versus the temperature associated with an intensive SFLS decrease. At temperatures less than approximately 200 °C, the lowest critical impact forces and SFLSs possess the NCD/hsrs coatings compared to the NCD and MLD ones. In this case, on the one hand, the sum of the structural and thermal residual stresses in the region of the film interface at temperatures less than approximately 400 °C is larger than the substrate rupture stress S_M (Fig. 1). Here, the temperature reduction to an ambient one leads to the formation of micro-cracks in the substrate interface region. In this way, the SFLS of NCD/hsrs films is lower compared to MLD and NCD coatings at temperatures less than about 100 °C. On the other hand, when the temperature grows, roughnesses between film and substrate in the interface region remain locked in the case of the NCD/hsrs films since the structural stresses are practically not affected. Hence, the related SFLS remains almost stable and over about 150 to 300 °C it is greater compared to the related ones of the MLD and NCD films, respectively. In the latter two cases, the