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Fatigue strength of diamond coating-substrate interface assessed by inclined impact tests at ambient and elevated temperatures

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ABSTRACT

The effect of two different treatments of cemented carbide substrates, prior to the deposition of a nanocrystalline diamond (NCD) coating, on the film interface fatigue strength was investigated at ambient and elevated temperatures. The first substrate treatment of the cemented carbide substrate was a selective chemical Co-etching and the second one the deposition of a Cr-adhesive layer. Inclined impact tests at 25 °C and 300 °C were performed on the NCD coated specimens. The related imprints were evaluated by confocal microscopy measurements and EDX micro-analyses. The thermal residual stresses developed in the film structure at various temperatures were estimated by Finite Element Method (FEM) calculations. A fatigue damage in the NCD coating interface region was induced by the repetitive impacts. After this damage, the compressive residual stresses in the NCD film are released leading to its lifting from the substrate (bulge formation) and subsequent coating failure. The NCD film-substrate interface fatigue behavior is significantly affected by the test temperature. Based on the attained results at diverse substrate treatments, Woehler-like diagrams were developed for monitoring the fatigue failure of NCD coating interface area at 25 °C and 300 °C. The interfacial fatigue strength worsens as the impact test temperature grows in both examined substrate treatment cases. Moreover, Co-etched substrates compared to coated ones by an adhesive Cr-interlayer possess higher interfacial strength at ambient and elevated temperatures. These phenomena were investigated and related explanations are described in the paper.

1. Introduction

The interface fatigue strength of NCD coatings is a prevailing factor for attaining a sufficient tool life [1–3]. The determination of the temperature dependent interface fatigue strength of NCD coatings facilitates a thorough understanding of the NCD coated cutting tool wear mechanisms. Thus, the experimental cost for optimizing machining conditions can be restricted. An efficient method for investigating the substrate-coating interface fatigue strength is the inclined impact test. During this test, an oscillating oblique load induces repetitive shear stresses into the region between film and its substrate [4,5]. If the developed interface stresses at the maximum impact force or during the substrate-film relaxation, between successive impacts, exceed the interfacial fatigue toughness, a failure occurs. This failure is caused by micro-cracks developed in the film interfacial area during the repetitive impacts. The micro-cracks' propagation and consequently the appearance of macro-damages facilitate the prevalence of the atmospheric pressure in the damaged film-substrate region. Moreover, induced by the release of NCD coating residual stresses after the film detachment, bulges are formed [3]. The film bulge formation has been analytically described in [3,6]. The residual stresses develop during the coated specimens' cooling from the deposition temperature to ambient one, due to the significantly smaller thermal expansion coefficient of the diamond coating compared to its cemented carbide substrate [3,7–9].

An alternative way for obtaining sufficient NCD coating adhesion is the reduction and in general the isolation of cobalt on the cemented carbide surfaces. Moreover, increased rough carbide surfaces can lead to higher nucleation rate of diamond films [1,9]. In the conducted investigations, prior to the NCD coating deposition on cemented carbide substrates, two different methods were applied for improving the NCD bonding region. The first one was a selective chemical Co-etching, aiming at depleting the superficial Co-content and producing adhesive cobalt compounds stable at the diamond deposition temperature [1]. In the second method through the deposition of an adhesive Cr-interlayer with a thickness of few micrometers, it was attempted to isolate the superficial cobalt. The Co-etching method is characterized by a potentially remaining porosity in the etched zone, which deteriorates the interface strength of NCD films [1]. This negative effect is avoided by the deposition of an adhesive Cr-interlayer, which in turn may influence the fatigue strength of the NCD film interface due to its restricted mechanical strength properties.

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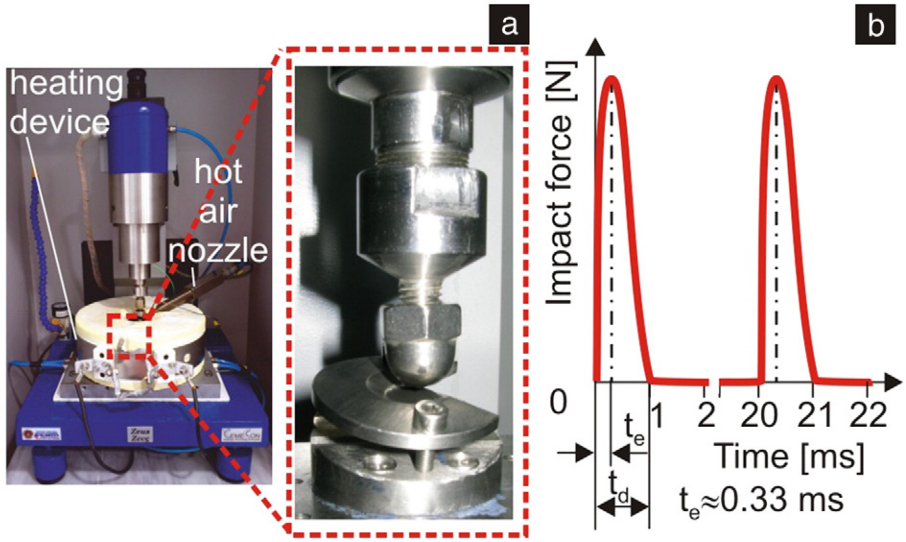

Fig. 1. (a) The mechanical unit of the employed impact tester; (b) characteristic data of the applied force signals.

In the present paper, inclined impact tests for investigating the interface fatigue strength of NCD films at ambient and elevated temperatures were employed. Based on the attained impact test results, Woehler like diagrams were developed for monitoring the fatigue behavior of the investigated NCD coated specimens at 25 °C and 300 °C. In this way, threshold loads for the film delamination due to fatigue were determined for both substrate treatment cases. The temperature and pretreatments effects on the interface fatigue strength of NCD films were explained considering also the results of appropriate FEM calculations.

2. Experimental details

Cemented carbide specimens of HW-K05 ISO specifications were coated by nanocrystalline diamond coatings via the hot filament method employing a CC800/9Dia CEMECON coating machine [10]. During the deposition process the filament and substrate temperatures were 2000 °C 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 for a total process time of around 19 h. The deposition time and the overall cooling time were approximately 10 h and 9 h, respectively. In this way, a uniform shrinkage of the coated specimens during cooling from the deposition temperature was attained. The obtained NCD film thickness was approximately 5 μm with nanocrystalline structure. The Cr-interlayer of ca. 4 μm thickness was manufactured by a High Power Pulsed Magnetron Sputtering (HPPMS) PVD process, prior to the NCD film deposition [11].

The NCD films' fatigue strength at 25 °C and 300 °C was assessed via inclined impact tests at various loads and cycles. The developed experimental set-up is shown in Fig. 1a. The impact tester device was designed and manufactured by the Laboratory for Machine Tools and Manufacturing Engineering of the Aristoteles University of Thessaloniki in conjunction with CemeCon AG. A specimen heating device was integrated in the impact tester. Pressed hot air of the test temperature was supplied for removing fragments of the ball indenter or of the coating [12]. The load signal duration t_d and the impact time t_e are displayed in Fig. 1b. These were practically constant in all carried out experiments. The applied force increases up to a set maximum value. Confocal microscopy 3D measurements, using the device μSURF of NANOFOCUS AG and EDX analyses were conducted for evaluating the impact test imprints. The FEM calculations for determining the thermal residual stresses and for describing the formation of film bulges were performed by the ANSYS software package [13].

3. Inclined impact tests on NCD coated specimens

3.1. Application of an adhesive Cr-interlayer on cemented carbide substrates

The NCD coated specimens with a Cr-interlayer of ca. 4 μm thickness were subjected to repetitive impacts at 25 °C and 300 °C using the inclined impact tester. Characteristic imprints developed on the heated at 300 °C NCD coated specimens at an impact load of 400 N, after various numbers of impacts, are illustrated in Fig. 2. The imprints scanned by white light via confocal measurements show the surface topomorphy after the indicated number of impacts. Already at a low number of 10,000 impacts, a film bulge of ca. 3.5 μm height is formed due to the interface fatigue failure and subsequent thermal residual stress release and film detachment. After 15,000 impacts at the same load, the bugle was partially broken, whereas after 20,000 impacts the entire film bulge was removed.

In Fig. 3a, characteristic topomorphies of developed imprints on NCD coated inserts at an impact load of 750 N after 5000 and 10,000 impacts at ambient temperature are displayed. After 5000 impacts no sign of film failure is visible. A sudden interface failure takes place after the conduct of further 5000 impacts. It is worth pointing out that in this case, no film bulges could be detected prior to the NCD coating removal. A similar behavior concerning the NCD coating failure, without a bulge formation, was revealed also at a lower load of 400 N (see Fig. 3b).

An overview of the obtained impact results at 25 °C and 300 °C on the NCD coated specimens with a Cr-interlayer, is illustrated in Fig. 4. The impact load magnitudes, the corresponding cycle numbers and the coating condition after the accomplishment of the individual tests are also displayed in this figure. In the inclined impact tests at ambient temperature, no film bulges were detected as already mentioned. These phenomenon will be explained in Section 4.2. At a load of 400 N, film bulges are formed after only 10,000 impacts. These are totally damaged and removed after a limited number of further repetitive impacts (≈10,000 impacts). At forces less than roughly 225 N, the film bonding withstands at least 1,000,000 impacts without damage. Hence, the force of 225 N can be considered as a threshold load, which is associated with the fatigue strength of the film interface region at the temperature of