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RESEARCH

Explanation of the Wear Behaviour of NCD Coated Carbide Tools Facilitated by Appropriate Methods for Assessing the Coating Adhesion Deterioration at Elevated Temperatures

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A B S T R A C T

The determination of the temperature dependent interface fatigue strength of Nano-Crystalline Diamond (NCD) coatings facilitates a thorough understanding of the NCD coated cutting tools wear mechanisms. In the present paper, the fatigue strength of the interface region between a NCD film and its hardmetal substrate was investigated by inclined impact tests at various temperatures. Depending upon the impact load and the applied temperature, after a certain number of impacts, damages in the film-substrate interface develop, resulting in coating detachment and lifting. These effects were attributed among others to the release of highly compressive residual stresses in the NCD coating structure. The attained inclined impact test's results contributed to the explanation of the wear-evolution of NCD-coated tools with diverse film-substrate adhesion qualities. The related milling experiments using as work material AA 7075 T6 verified the dominant effect of the film adhesion on the NCD coated tool life.

1. INTRODUCTION

Polycrystalline diamond tools (PCD) as well as hardmetal inserts coated with Nano-Crystalline Diamond films (NCD) can be effectively applied in machining of non-ferrous materials such as of Al-Si alloys [1-3]. Especially in interrupted cutting processes, where the cutting edges are subjected to cyclic loads, the fatigue strength of the film-substrate interface may impair significantly the NCD-coated tool life [3,4]. To overcome this problem, various procedures have been developed for reinforcing the bonding between the NCD coating and its cemented carbide substrate. Usually, selective chemical Co-etching is conducted on hardmetal tools for depleting superficially the non-adhesive cobalt which moreover, catalytically facilitates the diamond graphitizing [3]. Besides, three dimensional thermally and compositionally graded interfaces are created for increasing the adhesion of diamond films on cemented carbide inserts with different grain sizes [5,6].

Depending upon the impact load and the applied temperature, after a certain number of impacts, damages in the film-substrate interface develop, resulting in coating detachment and lifting. These disastrous effects were attributed among others to the release of highly compressive residual stresses in the NCD coating structure [4,7-9]. The residual stresses are developed in the NCD film during cooling from the deposition temperature due to the large thermal expansion mismatch of diamond coatings and hardmetal substrates [7-9].

The present paper describes the application of inclined impact test for assessing the temperature dependent fatigue strength of NCD coatings' interface. Moreover, it elucidates the effect of the NCD film's adhesion on the wear evolution of NCD-coated tools in milling aluminium alloy AA 7075 T6, which is a characteristic material for aerospace applications. Hereupon, two kinds of NCD-coated inserts were manufactured with intentionally different interface fatigue strength and thus adhesion level; these were employed in the conducted milling experiments.

2. EXPERIMENTAL DETAILS

For investigating the fatigue strength of the NCD coating-substrate interface, CVD diamond coatings were deposited by a CC800/9Dia CEMECON coating machine on cemented carbide specimens of HW-K05 ISO specifications [10].

The NCD film's adhesion fatigue strength was assessed via inclined impact tests at various loads and cycles (Fig. 1a). The load inclination angle was 15° (Fig. 1b). At these experimental conditions, remarkable shear stresses develop in the coating substrate interface leading, already at low impact loads, to high equivalent stresses [11]. At the start of a new test, an unused region of the carbide ball surface was employed. 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. 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 applied force increases progressively up to a set maximum value. The coating and substrate stresses, calculated by the methods described in [12], are demonstrated in Fig. 1c at the loads of 250 and 750 N. The colours correspond to certain ranges of the von Mises stresses according to the monitored scales at the figure bottom. When the maximum force is reached, the ball velocity is nullified, its direction changes and the indenter motion becomes upwards. According to the calculated stresses, the coating and the substrate are elastically deformed [12]. The confocal microscopy 3D measurement system μSURF of NANOFOCUS AG and EDX analyses were conducted for evaluating the impact test imprints. The FEM calculations for describing the formation of film elevations after the coating-substrate interface failure (film bulges) were carried out by the ANSYS software package [13].

3. INCLINED IMPACT TESTS ON NCD COATED SPECIMENS

3.1 Inclined impact tests on NCD coated specimens at ambient temperature

Initially, the inclined impact tests on the NCD coated specimens were performed at ambient temperature. The impact load magnitudes, the corresponding cycle numbers and the coating condition after the accomplishment of the individual tests are exhibited in Fig. 2. At a load of 850 N cracks developed in the bonding region between film and substrate propagate rapidly. In this way, the coating in the specimen-ball indenter contact area delaminates at a high rate. At the load of 850 N, film bulges are formed already after less than 40.000 impacts. These are totally damaged and removed after a restricted number of further repetitive impacts (≈ 10.000 impacts).

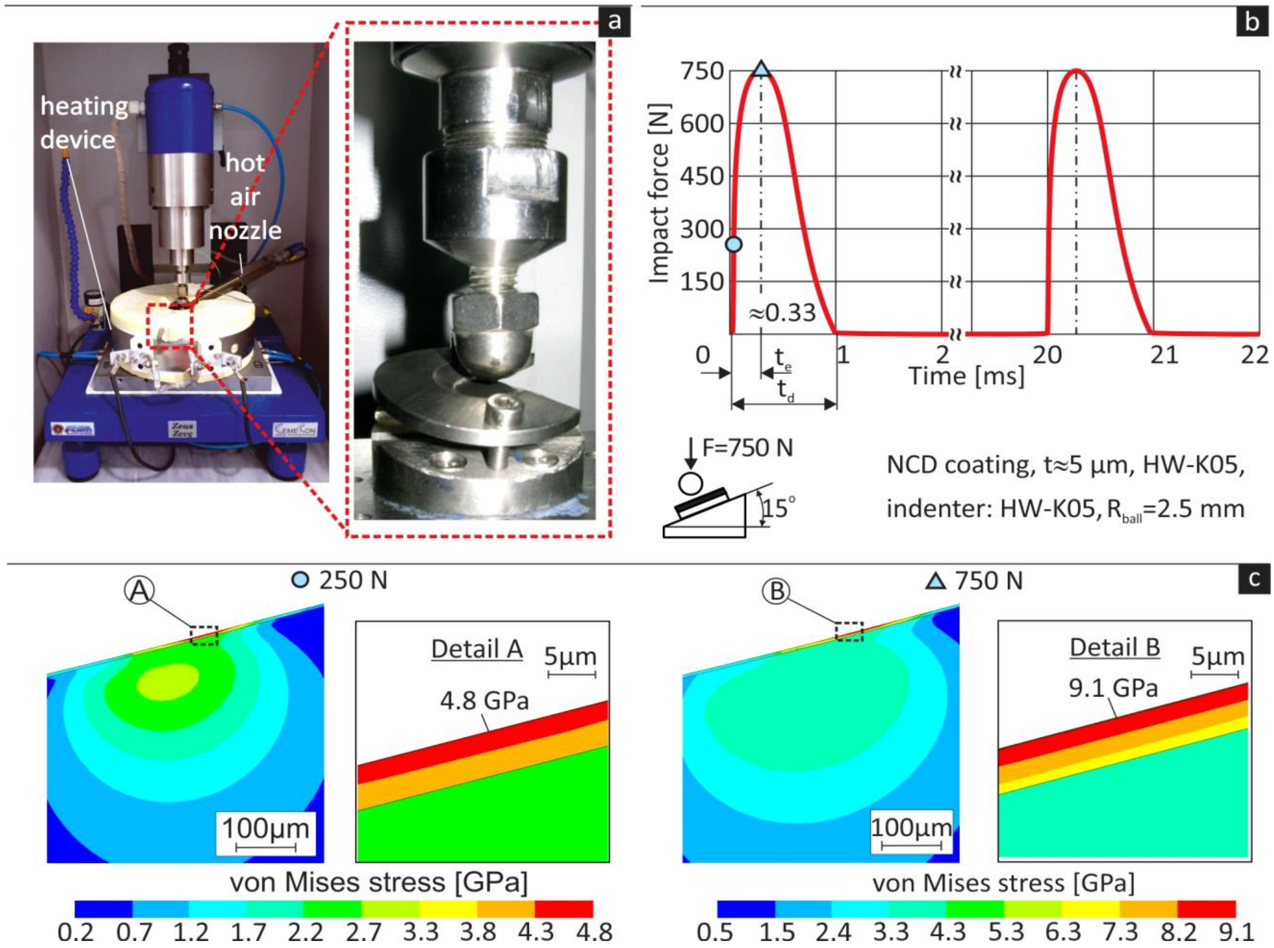


Fig. 1. (a) the mechanical unit of the employed impact tester, (b) characteristic data of the applied force signals and (c) the developed von Mises stress fields in the coating and its substrate during the inclined impact test.

On the contrary, at the lower force of 750 N, the bulge formation starts after more than approximately 700.000 impacts, the evolution of the film detachment is slow and the coating is destroyed and entirely removed after about 700.000 further impacts. Finally, at the intermediate load of 800 N, the first film bulge develops after approximately 70.000 impacts and the film is totally removed after less than overall ca. 150.000 repetitive loads. At forces less than roughly 730 N, the film bonding withstands at least 1.500.000 impacts without damage. Hence, the force of 730 N can be considered as a threshold load, which is associated with the fatigue strength of the film interface region.

In this context, the Woehler-like diagram of Fig. 2 can be employed for assessing the fatigue strength of NCD coatings' interface. The developed film bulges were scanned by white light via confocal microscopy. Relevant measurement results, obtained at the impact load of 750 N after various numbers of impacts are illustrated in Fig. 3.

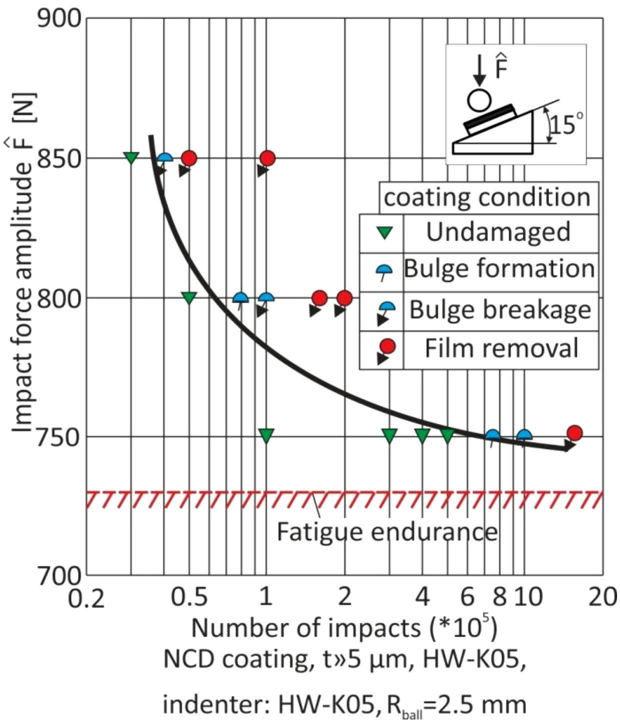


Fig. 2. NCD coating condition after the inclined impact test at various loads and numbers of impacts (Woehler-like diagram).

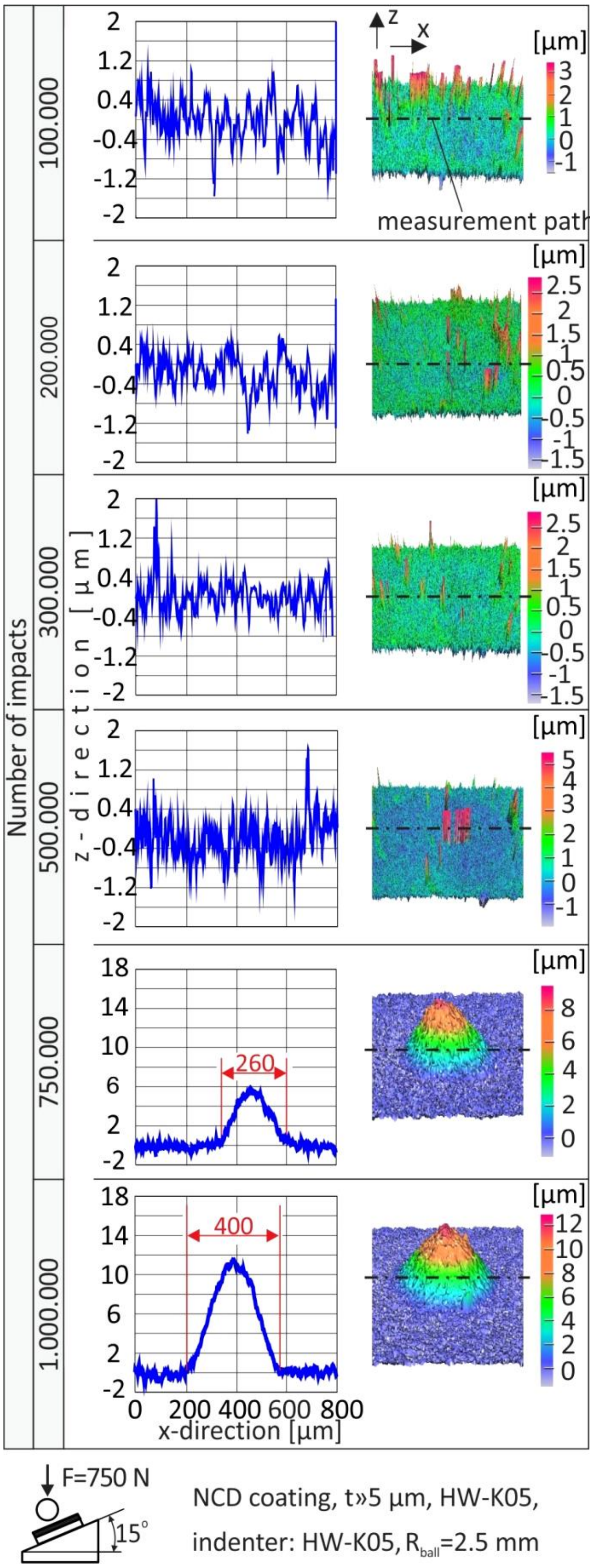


Fig. 3. Impact test results at an impact load of 750 N after various numbers of impacts.

The graphs capture the surface topomorphies after the indicated number of repetitive impacts. Up to approximately 700.000 impacts, as already described, the coated surface remains unaffected, whereas no film lifting can be observed. Over 700.000 impacts, the film interface fails progressively in the contact area between the ball indenter and the specimen, and a coating elevation results. This leads to the film bulge formation induced by the release of the NCD coating residual stresses. After 750.000 and 1.000.000 impacts, film bulges with maximum heights of about 6 µm and 11 µm respectively are formed.

According to the presented results, the successive impacts lead to a progressive weakening of the film-substrate interface, the NCD film residual stresses are released and film bulges are formed.

3.2 Inclined impact tests on NCD coated specimens at elevated temperature

Further inclined impact tests were carried out in the case of NCD coated cemented carbide substrates at a temperature of 300 °C. An overview concerning the occurring topomorphy of the NCD coated inserts after the conduct of inclined impact tests at various loads and number of impacts at ambient and elevated temperature is illustrated in Fig. 4.

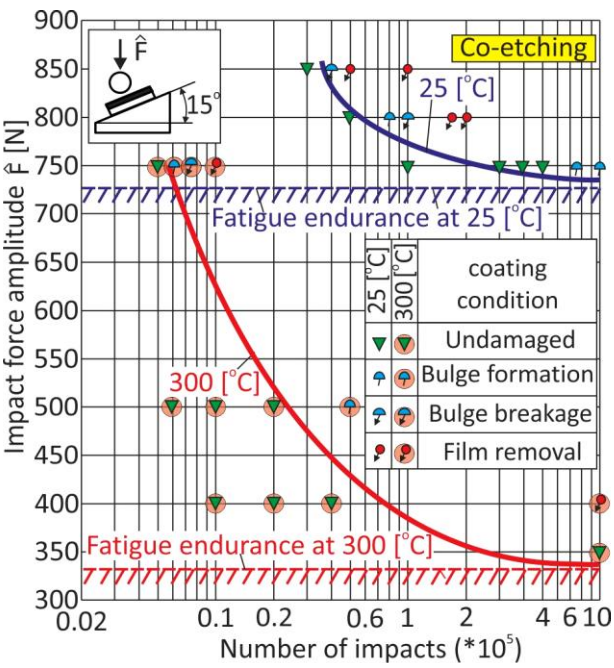


Fig. 4. NCD coating conditions after inclined impact tests with Co-etching substrate treatment.

At the temperature of 300 °C, depending upon the applied load, damages in the film-substrate interface region result. These lead to coating detachment after a smaller number of impacts compared to ambient temperature. The bulges are destroyed by further repetitive impacts and the coating is totally removed. Concluding these results, it can be stated that when the NCD coated specimen are heated at a temperature of 300 °C, the film interface damage is initiated at a comparably to 25 °C lower threshold load.

4. THEORETICAL EXPLANATION OF THE FILM BULGE'S FORMATION DURING THE INCLINED IMPACT TESTS

For explaining the development of the film bulges depending on the coating data and on the film residual stresses, two FEM models were employed. The first one describes the development of thermal stresses in the NCD structure during cooling from the deposition temperature to ambient one. The second one simulates the film lifting after the fatigue failure of its interface and the residual stresses release.

4.1 FEM calculation of thermal residual stresses in the NCD film structure

An axisymmetric FEM model of the semi-infinite layered half space was developed for calculating the film thermal residual stresses. The plasticity model of the kinematic hardening rule was used, because this model leads to a rapid convergence in the relevant FEM calculations. The kinematic hardening assumes that the yield surface remains constant in size and the surface translates in stress space with progressive yielding [13,14]. The multi-linear kinematic hardening options applied in the conducted investigations use the Besseling model, also called sub-layer or overlay model, so that the Bauschinger effect is included [12,15]. The materials used are considered as isotropic and strain rate independent. Based on these assumptions, the mechanical behaviour of a multilayer nanocomposite diamond coating is sufficiently simulated. The simulation software was the ANSYS package and the corresponding mathematical relations are documented in [13]. The initial temperature of 900 °C is associated with the NCD film deposition. The cooling rate of the coated specimens from the deposition temperature to ambient one was slow (overall cooling time approximately 9 h). Based on this fact, the shrinkage of the coated specimens during cooling was uniform. In this way, the film compressive residual stresses are created mainly by the significantly lower thermal expansion coefficient of the NCD film compared to the relevant one of its cemented carbide substrate.

By the described FEM model, the resulting stress fields after cooling from CVD process temperature to ambient one were calculated (see Fig. 5a). The maximum equivalent stress amounts to ca. 4.8 GPa.

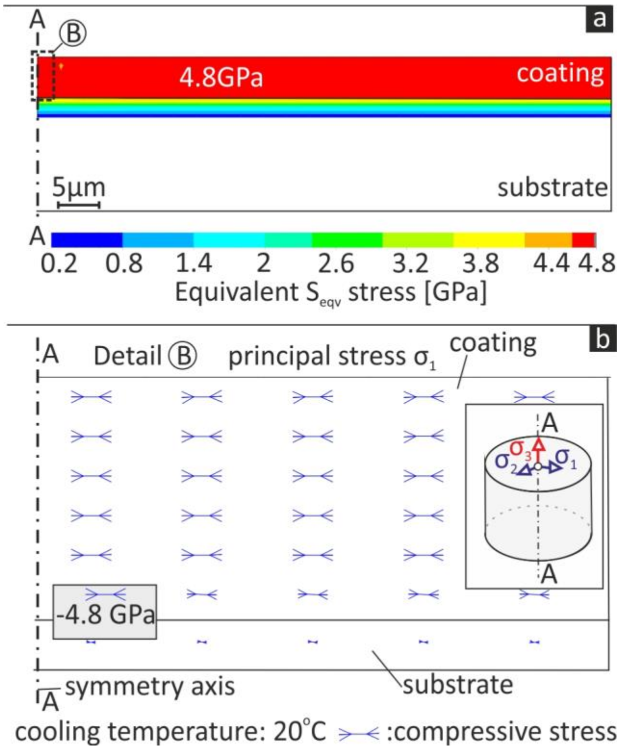


Fig. 5. (a) the developed equivalent stress field after cooling from the deposition temperature to the ambient one and (b) the relevant principal stress σ_1 field.

The distribution of the compressive residual principal stress σ_1 in the relevant direction is schematically shown in Fig. 5b. The displayed symbols indicate the kind (compressive or tensile) and the size of the residual principal stress σ_1 at various positions inside the NCD film thickness. All stresses are compressive. Moreover, due to the axisymmetric FEM model, the principal stresses at every point are equal in both σ_1 and σ_2 directions. In the perpendicular σ_3 direction, the stresses are almost negligible. The calculated stress field is homogeneous almost in the entire thickness of the film after cooling.

By conducting similar FEM calculations developed thermal principal stresses σ_1 and σ_2 and the relevant equivalent ones in the NCD film were determined in the temperature range between 25 °C and 700 °C. In Fig. 6, the developed residual stresses in the NCD film structure versus the operational temperatures are shown. The higher the applied temperature, the lower the residual stress developed in the NCD film structures is.

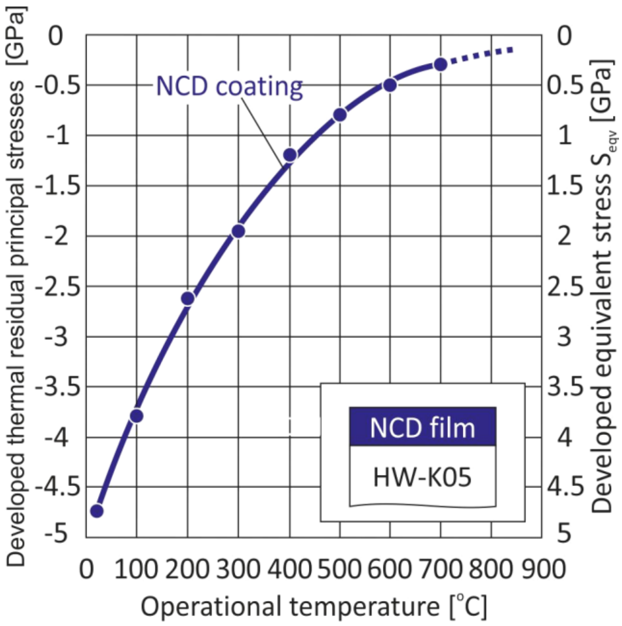


Fig. 6. Effect of the operational temperature on the developed residual principal and equivalent stresses in the NCD coating.

4.2 Effect of thermal residual stresses on the geometry of the formed film bulges on NCD coated specimens at ambient temperature

The goal of the developed FEM model is to describe the geometry of the formed film bulges considering their measured dimensions. The bulge geometry was simulated by approximately 2500 elastic shell elements with bending capabilities as exhibited in Fig. 7 [13]. The employed element is defined by four nodes, four thicknesses and an elastic stiffness. Each node has six degrees of freedom, nodal translations in x, y, z directions and rotations about the nodal x, y and z-axes. Large deflections capabilities are included [13]. The NCD film Poisson's ratio was set equal to 0.07 considering published results in the literature [16]. A film material free of residual stresses was assumed. The FEM model elements are stressed by a uniformly distributed hydraulic pressure as displayed in the figure bottom. The pressure increases until the deformation height in z direction at the most elevated central bulge region is equalized to the relevant measured film bulge maximum height. By the developed FEM model, a reverse mechanism is simulated compared to the real one, leading to the film elevation. In the reality the coating is deformed by the residual stresses, when these are released after the coating detachment. In this way, the film is loaded by mechanical stresses resulting by the superposition of the residual stresses with the developed ones during the film bulge material lifting. After the film bulge formation equilibrium between residual and mechanical stresses is established.

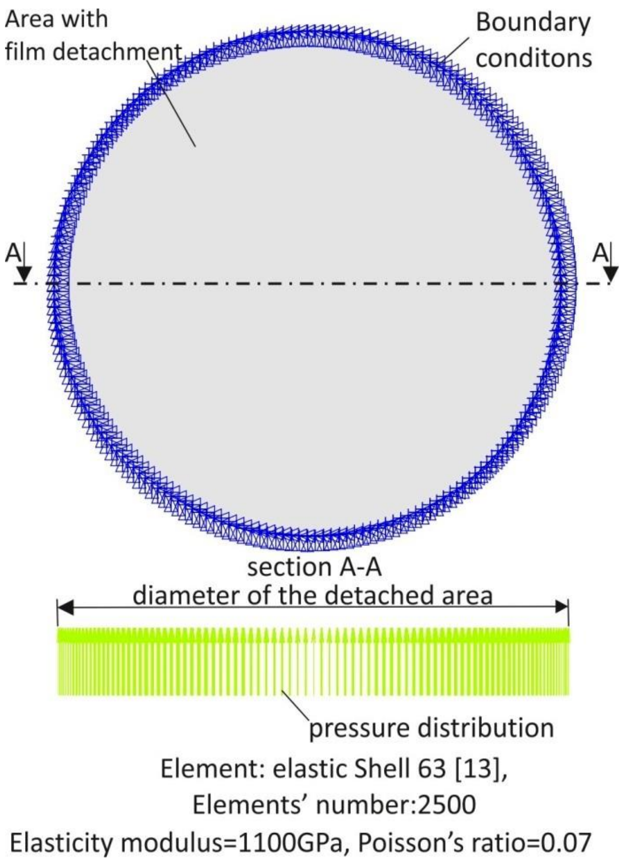


Fig. 7. Simulation of a coating bulge geometry by elastic shell elements.

Characteristic results attained by the developed FEM model are illustrated in Figure 8. In the upper figure part, the measured imprint at an impact load of 750 N after 1.000.000 impacts is exhibited. The film bulge diameter and height amount approximately to 400 µm and 11 µm respectively. The calculated imprint with the same dimensions is shown at the bottom figure part, as well as the calculated maximum von Mises stress which amounts to ca. 4.8 GPa. The principal stress in σ_1 and σ_2 directions of the elements located on the top of the formed bulge is tensile and both equal to 4.8 GPa (see Fig. 8).

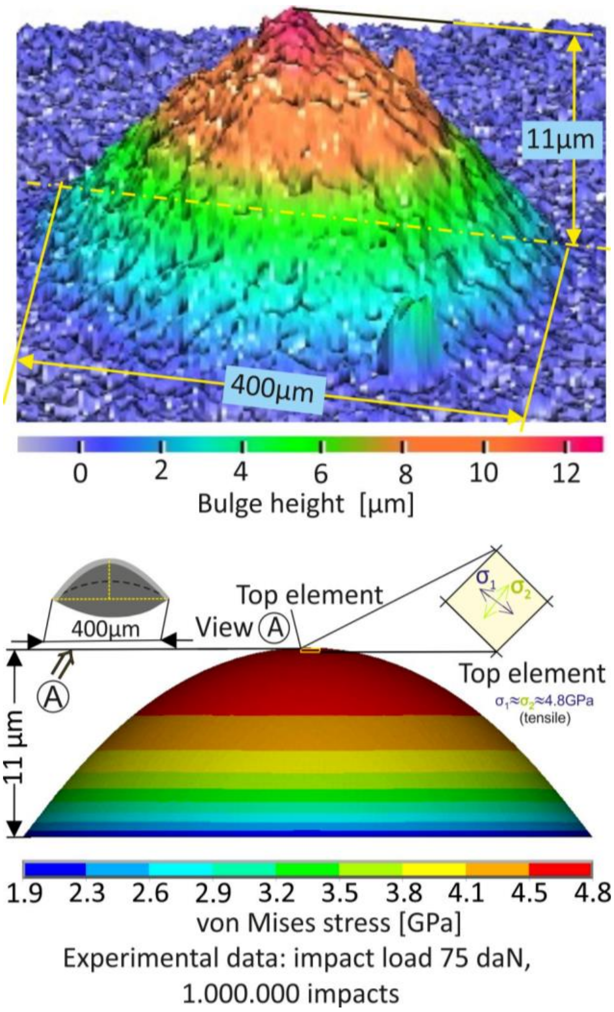


Fig. 8. Distribution of the measured displacement *z* and von Mises film stresses in the detached film region.

The FEM calculated thermal residual principal stresses in the film structure associated with these experimental data, are compressive and amount to 4.8 GPa (see Fig. 5). Hence, the thermal residual stresses of the elements on the top of the film bulge are roughly compensated by the developed mechanical stresses during the film lifting.

4.3 Effect of thermal residual stresses on the geometry of the formed film bulges on NCD coated specimens at elevated temperature

In Fig. 9a, the measured imprint at an impact load of 750 N after 6.000 impacts at a temperature of 300 °C is monitored. The detached film diameter and the bulge height amount to approximately 335 µm and 12 µm respectively. By employing the described FE model, the required principal stress in σ_1 and σ_2 directions at the bulge top for obtaining the film elevation height of roughly 12 µm were calculated. The stress σ1 and σ2 amounts to approximately −7.9 GPa (see Fig. 9b), being significantly larger than the developed thermal residual stress in the NCD film (see Fig. 6). In this way, the developed bulge height cannot be explained only by the release of the NCD film residual stresses after its detachment from the substrate. Hereupon, it can be assumed that chemical reactions are initiated at 300 °C resulting in gases, which act an additional pressure on the film bulge internal surface. More specifically, according to conducted EDX micro-analyses, sulphur remaining with a maximum value of 9.5 % wt. and standard deviation of about 5.5 % appear in the revealed substrate after the NCD film fracture.

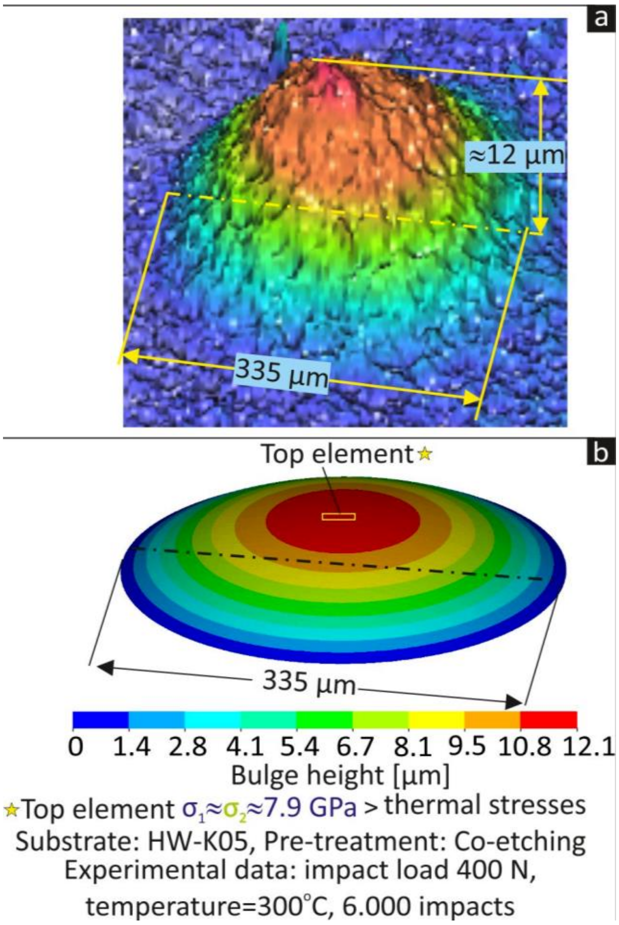


Fig. 9. (a) film bulge geometry after inclined impact test on NCD film on a substrate treated by Co-etching and (b) FEM calculated residual stresses for achieving the same bulge geometry.

Thus, due to the developed stress fields during the inclined impact test (see Fig. 10, stage 1), the interface zone is damaged and nano S-containing derbies develop (Fig. 10, stage 2).

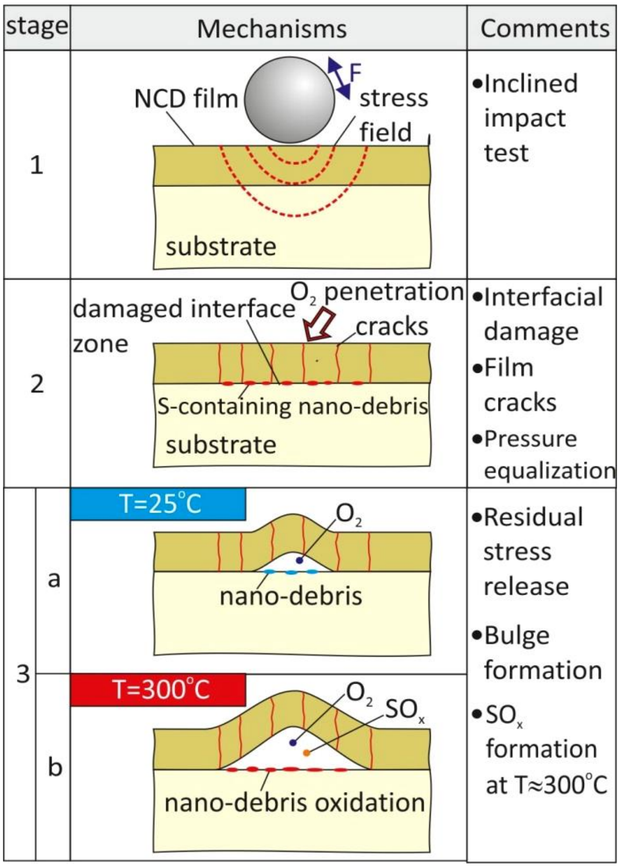


Fig. 10. Schematically presented mechanisms leading to diverse dimensions of NCD film bulges at various temperatures.

These react with the air oxygen penetrated in the film interface region, as already described, resulting in the formation of sulphur oxides SO_x [17,18]. The reaction speed is negligible at room temperature, but it is accelerated at higher ones. In this way, no additional internal pressure on the bulge subsurface is exerted at ambient temperature (Fig. 10, stage 3a), opposite to 300 °C (Fig 10, stage 3b), where the developed gases push the film subside leading to the enlarged bulge heights at the temperature of 300 °C in the case of Co-etched hardmetal substrate (see Fig. 9a).

5. EXPLANATION OF THE WEAR BEHAVIOUR OF NCD COATED HARDMETAL TOOLS

For explaining the cutting performance of NCD coated tools and associating it with their film-substrate adhesion quality, cemented carbide tools with different adhesion qualities were produced: NCD coated hardmetal inserts with improved adhesion (T1) and further ones with insufficient adhesion (T2). For coating the hardmetal tools with different NCD adhesion qualities, the parameters of the substrate chemical pre-treatment were appropriately varied.

5.1 Fatigue strength of the NCD film interface of the employed hardmetal inserts of diverse adhesion qualities at various temperatures

The results of the conducted inclined impact tests that were performed at 25 °C and 300 °C on the examined NCD coated tools, T1 and T2, are demonstrated in Fig. 11. In this figure, the impact load amplitude, the corresponding cycle number and the coating condition after the accomplishment of the individual tests can be seen. The critical impact force for avoiding an interface fatigue failure at ambient temperature amounts to 740 N and 640 N for the improved T1 and the insufficient T2 adhesion respectively. In both examined adhesion cases, the increased operational temperature of 300 °C leads to a deterioration of the interface fatigue strength, as analytically presented and explained in Sections 3.2 and 4.3. It is worth mentioning that the percentile decrease of the interface fatigue strength grows versus the temperature in the case of the treatment T2 compared to T1.

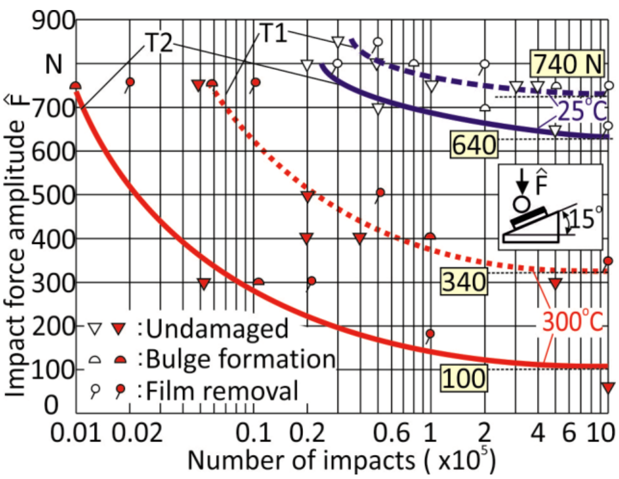


Fig. 11. Impact test results at various loads and temperatures for different film adhesion qualities.

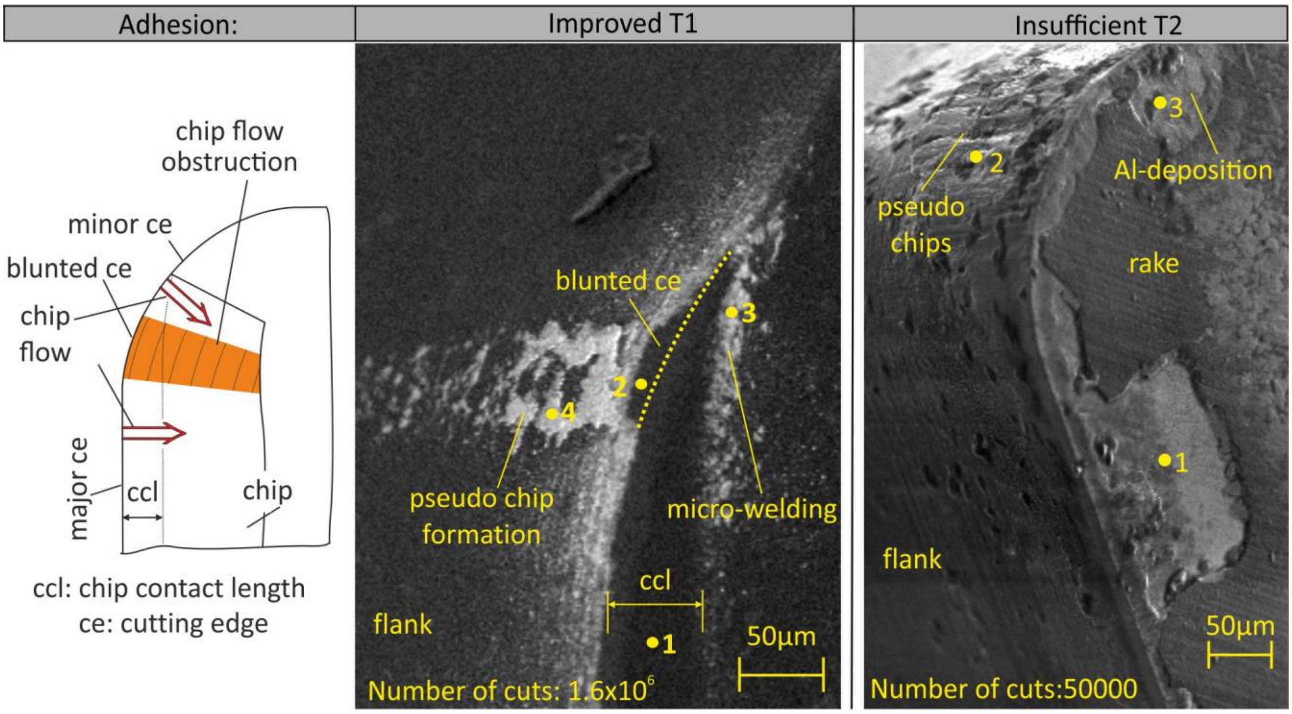
More specifically, the related percentile decrease of the critical impact force at 25 °C amounts to about 13.5 %. This reduction increases up to round 70.5 % at the test temperature of 300 °C.

In this way, it is reasonable to assume that NCD-coated tools with insufficient fatigue strength cannot be successfully applied in cutting applications at such temperatures. This assumption is verified as documented in the next section.

5.2 Wear evolution in milling using NCD-coated hardmetal inserts with improved or insufficient adhesion

Milling investigations were conducted using the manufactured NCD-coated tools with improved (T1) and insufficient adhesion (T2) respectively. The experiments were carried out with the aid of a three-axis numerically-controlled milling centre and performed only with compressed air for the chip removal. As expected, in the case of NCD-coated tools with improved adhesion, no film detachment appeared. Taking into account the relatively low cutting temperatures, the prevailing film wear mechanism in the carried out investigations was mainly associated with the coating abrasion.

The wear behaviour of the NCD coated tool with the improved adhesion (T1) can be observed at the left SEM photo of Fig. 12. A limited substrate revelation was detected after approximately 1.6 million cuts at the transient area between the major and the minor cutting edge. In this region, due to the progressive blunting of the cutting edge and the chip flow obstruction depicted in the sketch at the left part of Fig. 12, a local cutting load and temperature peak develops. At this friction area, the work material behaves plastically and it is pressed out of the contact zone [1]. In this way, aluminium material firmly adheres to the flank resulting in a pseudo (deceptive) chip formation. Moreover, aluminium micro-particles drawn away from the chip underside are deposited on the tool rake. Evidences concerning these mechanisms can be observed in the left SEM micrograph displayed in Fig. 12. The supplied EDX micro-analyses at the bottom of Fig. 12 also verify the aforementioned statements.



area	C	Al	W
1	100.0	0.00	0.00
2	96.13	3.52	0.35
3	62.26	37.74	0.00
4	94.34	5.66	0.00

area	C	Al	W
1	74.96	14.98	10.06
2	85.16	14.73	0.11
3	35.72	61.36	2.92

EDX micro-analysis (atomic %)

Fig. 12. SEM micro-graphs of NCD coated tools with improved adhesion (T1) after 1.6 million cuts and with insufficient adhesion (T2) after 50 thousand cuts.

The cutting edge condition of a NCD-coated insert with insufficient interface fatigue strength (T2) is demonstrated in the right SEM photo of Fig. 12. Cutting edge chippings and extended film failures on the rake already occur after only roughly 50.000 cuts. This happens since the fatigue failure of the NCD film-substrate interface takes place earlier compared to milling applying the NCD coated hardmetal with the improved adhesion quality (T1), as it was expected considering the results introduced in Fig. 11. Furthermore, due to the increased friction and thus high thermal loads after the NCD coating failure, large pseudo chips develop on the flank, as it can be observed in the right SEM photo of Fig. 12.

6. CONCLUSIONS

The NCD coating-substrate interface fatigue strength is a key factor for assessing the coated tool life in milling. The NCD coating-interface fatigue was investigated using inclined impact tests at ambient and elevated temperatures. The investigations of milling AA 7075 T6 showed that the NCD film-substrate interface strength at elevated temperatures is a key factor for explaining the wear behaviour. An insufficient adhesion leads rapidly to a delamination of the NCD-coating and to a substrate revelation. Hereupon, the inclined impact test is an efficient test method facilitating the assessment of the NCD film substrate interface at ambient and elevated temperatures.

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