TESTING OF THE IMPACT LOAD AND TRIBOLOGICAL BEHAVIOUR OF W-C:H HARD COMPOSITE COATINGS

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1. Introduction

Hard carbon based composite coatings are more and more frequently used in practical applications, such as automotive industry, where not only good adhesion and wear resistance, but also reasonable thermal stability, low wear at elevated temperatures and impact resistance are required. Diamond-like carbon coatings have a range of tribological properties that are controlled with the incorporation of additional elements such as silicon, nitrogen or metal. Considerable scientific and industrial interest is focused in nanocomposite coatings containing tungsten in the diamond-like amorphous hydrogenated carbon matrix (W-C:H). These coatings generally possess high hardness, low friction coefficients against a range of counterfaces, good wear resistance and good adhesion to a range of substrates by controlling the interlayers responsible for promoting good adhesion and control of residual stress in the coatings[1]. Numerous papers deal with the tribological behaviour and properties of DLC coatings[2,3]. Density, hardness and compressive stress of W-C:H coatings were studied as a function of composition and structure and deposition conditions[4]. The effect of slightly different hydrogen content in W-C:H coatings on microstructure, adhesion and tribological properties was studied in ref.[5]. A detailed structural characterization of W-C:H showed the existence of a submicrometer scale columnar structure and intercolumnar defects within the coating[6]. This structure could be related to failure mechanisms during tribological and wear tests. In the case of W-C:H coatings the outweighing degradation mechanism was a combination of polishing wear with micro- or nano-delamination and micro-pitting[7]. Nevertheless, no results of detailed studies of tribological parameters temperature dependency have been published yet.

The dynamic impact wear tester developed in our laboratory has been used to evaluate the impact resistance of thin hard composite coating in dynamic loading wear applications. Impact testing of the coatings was proposed by Knotek et al in the 1990's (ref.[8]). During testing the specimen was cyclically loaded by tungsten carbide ball that impacts against the coating/substrate surface. After each the test, wear scars were evaluated by means of optical microscope and profilometer. Results of these tests show usability of coatings in dynamic load and enable to optimize the design of the coating/substrate system for the particular use. The test simulates a wide range of tribological systems. The impact test offers an important new method for determination of the fracture toughness of hard thin coatings.

2. Experimental Details

The substrates made from high speed steel were used with tempering temperature of 550 °C. They were polished with brush papers and finally with diamond pastes. The substrate hardness was 62 HRC. W-C:H coatings were deposited with combined PVD and PACVD processes. Thickness determined by calotest method was about 2 μm. The dynamic impact wear tester developed in the Institute of Scientific Instruments ASCR in collaboration with Brno University of Technology has been used to evaluate modified DLC coatings. Setting of the impact tester: impact force from 200 N to 600 N, number of impacts could be varied from 1 to 100 000. The tungsten carbide ball 5.00 mm in diameter with guaranteed geometry and surface roughness was used. After each test, wear scars were evaluated by means of profilometer Talystep (Taylor-Hobson) and confocal microscope LEXT OLS 3100 (Olympus). Impact tester has been used in our laboratory for more than two years to evaluate hard coatings produced in coating centres and both its hardware and software were improved to achieve minimum scattering of measured values caused by the device. Nowadays the range of values scattering on homogenous coating/sample system does not exceed several percent.

The coatings hardness and Young modulus were measured with nanoindenter Fisherscope H100. The results were: indentation force $F = 50$ mN, universal hardness $H_u = 6380 \pm 120$ MPa, $W_e/W_{tot} = 58$ %, $E = 151 \pm 4$ GPa. Parameters measured with higher indentation forces (up to 1 N) did not differ substantially. In order to verify the adequate mechanical properties of W-doped a-C:H coatings, the tribological performance was studied using standardized pin-on-disc CSM Instruments measuring device. The tests were carried out in the temperature range from 20 °C (room temperature, RT) to 200 °C, thus the thermal stability could be determined. The testing conditions were set as follows 5000 cycles, normal load 5 N, linear speed 0.05 m s^{-1}. The testing ball-coating contact was unlubricated and the relative air humidity at room temperature was about 40±5 %. As counterparts the ceramic Al_2O_3 balls with diameter of 8 mm were used.

The tribological performance was determined not only with respect to the friction coefficients, but from the point of view of wear rates and free wear debris characterization as well. The coating wear rates were evaluated on the basis of cross-section wear track profile measurements, the wear rates of balls were calculated from spherical wear cap images taken from optical microscopy. The wear rates were determined as the worn volume per sliding distance and load[9]. Each tribological test was carried out three times with expected measured parameters standard deviation of about 10 %. In this paper the average values of friction coefficient and wear rates are presented. To determine the dominant wear mechanism, the wear tracks were studied using optical microscopy, scanning electron microscope JEOL JSM-6460 LA and confocal microscope. Additionally, the measurements of coating hardness were taken into account.

3. Results

3.1. Impact tests

Fig. 1 shows crater volumes against the number of impacts plotted at three different impact forces. Volumes were calculated provided that the shape of the crater was approximated by a rotational paraboloid, by using the radius and the average depth of the crater measured by profilometer. Average values were calculated from at least five repetitive measurements carried under identical conditions. The wear rate was calculated using central part of the dependence (from 5 to 50 000 impacts) as a quotient of the variation of crater volume ΔV and the number of impacts. In the Tab. I the wear rates for three values of impact forces are summarized.

In the Fig. 2 the crater volume corresponding to wear rate of coating/substrate system and bare substrate is presented. In spite of this high load the coating has beneficial effect on the system wear resistance in the whole range, namely for higher number of impacts.

Table I
Wear rate of the coating/substrate system in dynamical mode for the load forces 200 N, 400 N and 600 N

F [N]	200	400	600
ΔV [mm^3]	3.4 E-8	14 E-8	23 E-8

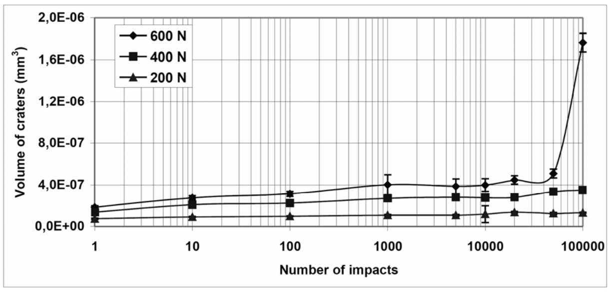

Fig. 1. **Mean values of crater volume, impact force varies from 200 N to 600 N**

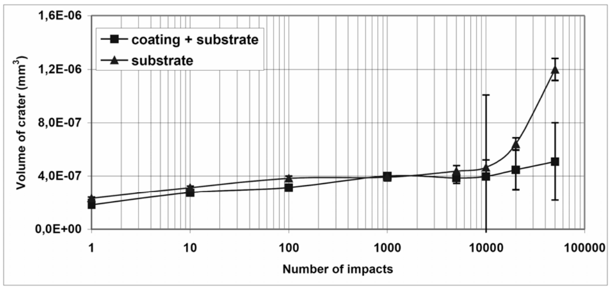

Fig. 2. **Comparison of wear rate of coating/substrate system and bare substrate at 600 N**

3.2. Tribological tests

The tribological measurements clearly showed high-temperature coating applicability limit. The friction coefficient at 200 °C became unstable and higher values of about 0.45 were obtained. The coating wear scars were very coarse with deep abrasive scratches that in many cases reached the substrate surface.

The typical evolution of friction coefficient with number of cycles is showed in Fig. 3. At RT the friction process is stable, short run-in could be observed and at about 500 cycles the steady-state phase was reached with average friction coefficient of about 0.1. The testing ball exhibited almost no notable surface damage, only high coverage with compact carbon-containing wear debris interlayer was observed. Thus, third body friction occurred predominantly. The calculated coating wear rate value of about $0.43 \cdot 10^{-6}$ mm^3 N^{-1} m^{-1} corresponded to the low measurability limit. The wear track appeared very smooth with very low surface damage, thus, only polishing wear mechanism occurred.

At 100 °C the sliding process partially lost its stable behaviour. Up to 1500 cycles the friction coefficient exhibited unsteady evolution with higher value of about 0.5. The sliding interlayer was not compact enough and, thus, ceramic ball hard surface affected the tested coating directly. Higher amount of free wear debris were produced and this process

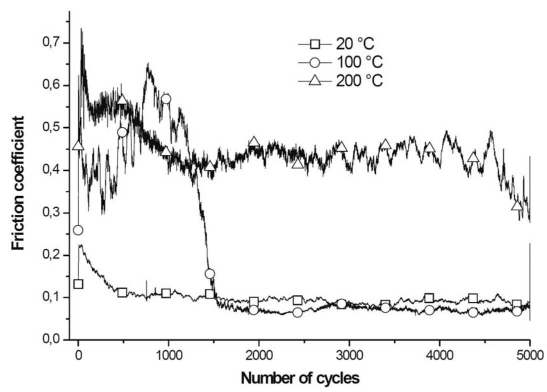

Fig. 3. **Typical friction curves of Al_2O_3 ball against W-C:H coating at RT, 100 °C and 200 °C**

resulted in consequent friction coefficient reduction above 1500 cycles. The ball wear scar was negligible, the contact surface exhibited partial coverage with free wear debris. The value of coating wear rate increased to $12 \cdot 10^{-6}$ mm^3 N^{-1} m^{-1}, maximum penetration depth was about 0.5 μm that corresponded to 50 % of total coating thickness. The wear tracks were rather coarser with many scratches parallel to the contact movement and significant effect of abrasive wear mechanism was observed. At 200 °C the evolution of friction coefficient was unstable reaching high value of about 0.45. The free wear debris did not affect the ball-coating interface; no compact sliding interlayer was observed. Thus, the ceramic ball surface slid directly on the tested surface and induced very high abrasive wear of coating. The coating wear rate reached the value of about $31 \cdot 10^{-6}$ mm^3 N^{-1} m^{-1} and the penetration depth exceeded in some cases the coating thickness. The failure of ball surface was negligible.

4. Conclusions

The impact tests demonstrated low wear rate of the coating/substrate system in a wide range of dynamical load. Coating erosion occurred and the substrate was gradually uncovered only for the highest impact force of 600 N and the number of impacts exceeding 50 000. At 100 000 impacts approximately one half of the coating was removed.

The comparison of the wear rate coating/substrate system and the bare substrate clearly demonstrated that the coating significantly extended the lifetime of the tribological system even for high loads and high number of loading cycles.

The results of tribological testing showed the temperature limit of about 200 °C. The increase in wear rate was probably due to lower humidity, graphitization and coating hardness reduction at elevated temperature. This phenomenon is under further investigation.

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W-C:H hard composite coatings were studied. The comparison of the wear rate of the coating/substrate system and the bare substrate obtained from dynamic impact test clearly demonstrated that the coating significantly extended the lifetime of the samples even for high loads and high number of loading cycles. The obtained results will support the research and development of new metal-doped a-C:H coatings, which exhibit promising properties for future engineering applications, especially in dynamically loaded contacts.