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WEAR OF PVD HARD COATINGS IN SLIDING CONTACTS

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Abstract: *Tribological behaviour of PVD thin hard coatings has been analysed in this paper. Only few studies on PVD coatings' tribology in sliding contacts have been published up to now. The mechanisms that influence sliding friction and wear phenomena of PVD hard coatings are, therefore, yet poorly understood. The works available generally rely on experimental approach with no deeper explanation of physical phenomena or respective mathematical models. The aim of this work is to compare the capability of the wear models, to present the complex of parameters that influence sliding wear rate and to introduce an analysis of practical procedure for determining the wear of (Ti,Al)N based hard coatings' in sliding contacts.*

Key words: Sliding wear models; PVD hard coatings; Wear analysis

1. INTRODUCTION

PVD thin hard coatings are primarily used to minimize friction and increase wear resistance of metal-cutting and -forming tools, as well as in some bearings, gearings and other applications [1]. In most of the available works [2], [3], [4], [5] mainly dry sliding conditions and abrasive wear mechanisms have been considered along with pin-on-disc tests. The use of PVD hard coatings in engineering applications to greater extent, would assume that their wear and friction behaviours in respective conditions, where abrasion is often not acceptable, are better known. The empirical methods used in works above support the development of materials' tribological properties but do not suggest which coating type is the most suitable for particular application and do not allow the practicing engineer to predict the wear in particular contact. Mathematical wear models have to be identified and verified with appropriate experiments for prognosis of wear performance. Many of known wear models are hardly applicable in engineering design, due to complexity and use of specific and rare parameters. The linear wear model, also referred to as Archard's wear model, and some of its modifications, have therefore been used most extensively in practical engineering applications.

2. WEAR ANALYSIS METHODS AND WEAR MODELS IN SLIDING CONTACTS

One of the most important engineering tasks is the prediction of wear rate and its minimization in particular contact. The wear rate in sliding contacts can be described by a general differential equation:

$$\frac{dh}{ds} = f(x), \quad (1)$$

where h is the wear depth (m) and s is the sliding distance (m), x is either load, velocity, temperature, material parameters, lubrication etc). Generally, the dominating parameters in sliding wear models are sliding velocity and the normal load. First parameter can be determined by the mechanism kinematics. The load influence determination is often more complicated. Hertz formulae can be used for contact stress distribution in the cases of non-conforming contacts of elastic bodies. The main disadvantage of the Hertz theory is that it is based on some assumptions that idealize the properties of contacting bodies and the contact conditions. In fact, properties of the coating and surface layer at contact zones change during wearing process under the influence of high contact pressure and sliding velocities. The chemical reactions, resulting in the formation of secondary compounds and structures, also occur in the contact area. Hertz theory neglects the fact that, in contact interaction, stresses increase in a thin surface layer, the thickness of which is comparable with the size of contact region. Thus, the properties of a thin surface layer play an important role in the subsurface stress and wear analysis [6]. In those cases numerical method such as finite element analysis (FEA), must be used for contact stress distribution determination and wear simulation [7].

Application of FEA is limited in some cases, as it is not fast enough to cover the whole lifetime of the contacting body using complex material model and sufficient elements in contact [8]. According to last statement in FEA the number of elements and extra features to consider (friction, plasticity, etc) must be minimized. If major simplifications are allowed, the Winkler's surface model can be used for saving computing time. In Winkler's model the interacting contact surfaces are modelled as a set of "springs", resisting on the rigid base.

Applications of wear simulation methods with FEA and linear wear model have been successfully adapted to PVD hard coatings abrasive wear investigation [9]. According to linear wear model, the volume rate is proportional to the normal load. The model is based on experimental observations and was initially written in form

$$\frac{V}{s} = K\frac{F_N}{H}, \quad (2) \qquad [10],$$

where V is the volume wear (m^3), s is the sliding distance (m), F_N is the normal load, H is the hardness (Pa) and K is the wear coefficient.

The wear depth is more important than wear volume in engineering calculations. Dividing both sides of equation (2) by the apparent contact area, the wear depth is

$$h = kps, \qquad (3)$$

where h is the wear depth, p is the normal contact pressure (Pa) over that particular discrete region, s is sliding distance, $k=K/H$ is the dimensional wear coefficient (Pa^{-1}).

It can be concluded that in case of coated materials the specimen structure is not homogenous. In addition, the contact pressure varies during the wear process. Thus, it is perspective to use linear wear model combined with numerical structural analysis methods such as FEA for hard coatings' wear study.

3. THE PARAMETERS THAT INFLUENCE WEAR OF PVD HARD COATINGS

The wear rates of PVD hard coatings are influenced by many parameters [2], [3], [4], [5]. The list of the main parameters is presented in table 1. More detailed overview of effect of the parameters on hard coatings wear has been offered below.

Wear mechanism is one of the parameters that have an effect on the evolution of the PVD hard coatings' wear process. Adhesion, two-body and three-body abrasive, tribo-oxidation and surface fatigue wear mechanisms can occur. Studies of wear resistant coatings reveal that coatings are most effective when resisting abrasive wear [1]. However, it has been mentioned that thin hard coatings are effective only if fine particles are present in the contact. If the size of the abrasive is larger and comes near to coating thickness then coatings' abrasive wear resistance decrease. Different types of hard coatings can be applied as solid lubricants to suppress the adhesive wear in poorly lubricated and high stress contacts. For example, TiN coatings prevent the adhesion and seizure between the cutting tool and metal chip [1]. The same coating has been successfully used for increasing the wear resistance in gearing.

Coating hardness is the main parameter, which affects the wear rate of hard coatings. If investigated wear mechanism is adhesive or two-body abrasive mechanism the wear coefficient proved to have a linear dependence on the coating hardness. In three-body abrasive wear mechanism, the wear coefficient dependence on the coating hardness is absent [9] (Fig. 1).

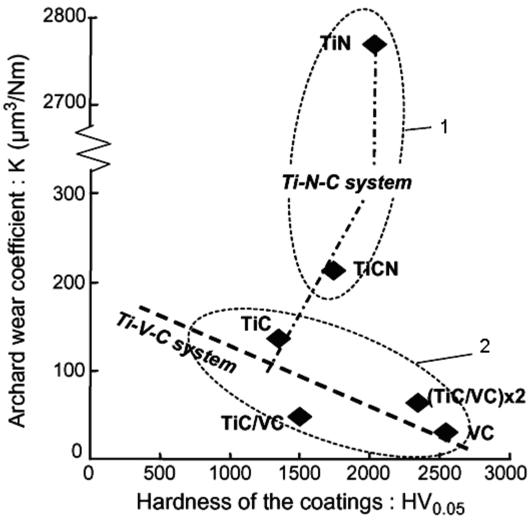

Fig. 1. The wear coefficient K versus coating hardness $HV_{0,05}$ for alumina ball as counterbody. 1– three-body abrasion; 2– two-body abrasion process [9].

Substrate material hardness influences on wear rate must be determined. It has been verified that wear rates increase with the substrate material hardness growth [5].

Surface roughness is an important factor in wear process. Generally, the smoother surface proves the lower wear rates. However, extra smooth surfaces in small scales require the optimal roughness verification due to the increase of contact bodies' atoms attraction. The appropriate surface roughness of coating and substrate is offered in table 1.

Table 1. The parameters that influence the wear of PVD hard coatings.

Friction and wear test parameters	
Wear mechanism -adhesive -abrasive two-body three-body -erosive wear -tribo-oxidation -surface fatigue	**Sliding velocity and distance** -constant velocity -variable velocity (0,5-10) m/s -rotation motion -reciprocating motion -displacement amplitude ±5 mm
Normal and tangential load -constant -variable ((5-500) N)	**Temperature** -room (~20 ºC) -high (up to 300°C)
Wear tests duration -50-5000 cycles	**Relative humidity** -50-60%
Specimen shape, geometrical deviations and size -plate is preferable	**Counterbody material, physical and chemical properties, surface roughness, shape geometrical deviations and size**
Coating characteristics	
Coating surface properties -surface roughness Ra =(0,01-0,2) μm	**Coating crystal structure and structural defects** - crystal structure type (cubic;hexagonal; mixed)
Coating chemical compound and properties -Al concentration -(Ti:Al) atomic ratio -oxidation resistance in air (400-1200) ºC	**Coating and substrate physical properties** -microhardness (1000-3000) HV - nanohardness (18-52)GPa -Young's module (200-600) GPa -Poisson's ratio (0,2 -0,3) -thermal conductivity (1,7-0,055) Kcm^2/s
Coating thickness -varies 1-5 μm for monolayered	**Number of coating layers** -monolayered -multilayered
Substrate characteristics	
Substrate material crystal structure and structural defects -crystal structure type (depends on material)	**Substrate physical properties** -microhardness - nanohardness -Young's modulus -Poisson's ratio -(depends on material)
Substrate interface strength -depends on material	**Substrate surface properties** -surface roughness Ra =(0,01-0,05) μm

Chemical compound of the coating also influences the wear process. Previous research [2] has shown that wear rate of TiAlN films decreases with increasing Al content because of protective layers of amorphous aluminium oxides, which are formed on the top of TiAlN film at high temperatures [2]. Last fact explains a much improved oxidation resistance at elevated temperatures of TiAlN coatings compared to TiN. It is known that CrN coatings as well as AlCrN have much slower oxidation in air in contact with copper [1]. The reason of TiN oxidation is the catalytic effect of copper. TiN oxidation leads to the formation of titanium oxide that is rapidly worn away. The better corrosion resistance of AlCrN explains the lower friction coefficient and wear rates revealed in AlCrN and TiAlN studies [4].

Crystal structures of hard coatings vary from cubic to hexagonal structure. The PVD hard coating compositions deposited from cathode materials have different atomic ratios (Ti:Al) what influence the coating crystal structure. The cubic crystal structure is the most preferable for TiAlN coatings as wear rate is the lowest [2] .

Crystal structure defects affect the wear characteristics. The presence of pores in the coatings' structure decreases the wear resistance. It has been shown [5] that even if the two coatings' has the same hardness, the wear coefficient can vary due to structural defects.

Coatings thickness is a critical factor that affects the hard coatings wear rates. It has been shown [11] that mechanical properties and the hardness of thin TiAlN coatings with thickness in range of (3–8) μm for cemented carbides significantly affect the wear rates. On the contrary, thick (8–10) μm coatings' wear depends mainly on the thickness of coating itself. Coating thickness is effected by deposition time. According to coating growth mechanism the thicker is coating the greater is superficial **grain size** that leads to hardness and wear resistance reduction [11]. This explains why thin coatings have superior mechanical strength.

Substrate material properties must be taken into account in coatings wear studies. Hard coatings are generally applicable to protect wear of softer material. The substrate material choice depends on the fact that deposition temperature must be lower than material critical temperature. (Ti,Al)N based coatings are deposited at T=500 ºC and therefore is not suitable for alloys which are not thermostable.

The substrate interface strength proved to have an effect on coating wear rate and thus, on lifetime [3]. The stronger are interface the longer is coating lifetime. Lately multilayered coatings are developed to guarantee a strong adhesion between coating and the substrate and to obtain wear-protective coatings with low chemical reactivity and low friction, as well as to increase the hardness and toughness of the coating [11], [12].

Sliding velocities and **displacement amplitudes** have to be defined. It is suggested [3] that the sliding distance reduction leads to the wear rate decrease due to the decrease of nominal contact pressure at the specimen surface.

Temperature effect on wear is questionable. No correlation between friction coefficient and test temperature has been found in some studies [5]. However, the wear rate of TiAlN decreased above temperature of 673 K, because of the formation of Al_2O_3 [2].

To conclude, the linear correlation between coating hardness and wear coefficient of adhesive wear mechanism in dry sliding condition is present. However, sliding velocity and temperature effect as well as other parameters influence on wear resistance needs further investigation.

4. PVD HARD COATINGS IN SLIDING CONTACTS

Since there are many parameters that affect the wear of PVD hard coatings a method integrating experimental research and simulations must be applied. None of available works considers the influence of several (3-5) parameters at once. The experimental research provides data concerning wear rate and sliding friction coefficient versus wear process parameters. The statistical analysis of experimental data allows finding the correlation between the wear model and the experimental results. The obtained equations can be used for wear prediction in engineering design.

4.1. TRIBOMETERS

The pin-on-disc, Calo-wear (KaloMax), and tribometers with reciprocating motion are mostly used for sliding wear investigation. Coated plate specimens versus pin or ball specimen are preferable to use in wear tests (Fig. 2, 3). The wear process of point contact is in the centre of attention as it can be a starting point for more complicated types of contact wear studies.

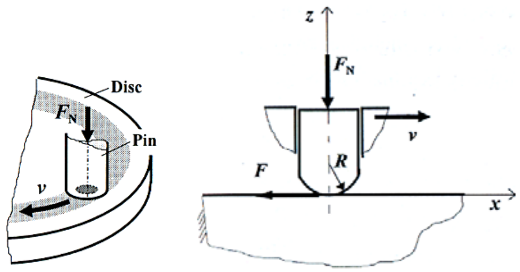

Fig. 2. The schematic of pin-on-disk (a) and reciprocating (b) tribometer.

Each wear testing method has its advantages and shortcomings. The disadvantage of pin-on-disc tribometer (Fig. 2 (a)) is possible accumulation of counterbody material in the inner areas of wear tracks. For example, Si_3N_4 counterboby leads to silicon presence in the wear track in pin-in disk tests [4]. The exhaust of the debris out of the contact zone in reciprocating test (Fig. 2 (b)) has been observed at once [4].
Another method calo-wear test with KaloMax (Fig. 3) has a high wear volume uncertainty [13], mainly due to variation in normal force on the sample and the wear of the sphere (ball). The normal force control between the sphere and the specimen is enabled as it is derived only from the weight of the sphere.

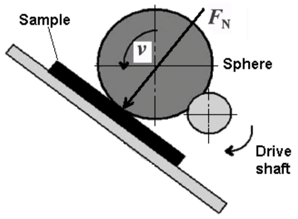

Fig. 3. The schematic of calo-wear (KaloMax) tribometer.

As fine distinctions between different sliding tests modes have been found the comparative tests should be done. The main friction and wear test parameters are offered in table 1.

4.2. THE WEAR PHENOMENA ANALYSIS

The wear process characteristics vary. Dimensional linear wear (µm) [3] and wear rate ($\mu m^3/Nm$) [9] versus sliding distance (m) or coating hardness (HV) are usually measured (Fig. 1). The width of wear track is also considered. Coefficient of sliding friction is measured against either sliding distance (m) or number of cycles. All characteristics must be calculated along with respective uncertainties for these materials according to test results with sliding wear testing machines.
SEM analysis should be done to control the coating quality after sliding tests. Optical microscopy is also needed for the wear scar's morphology definition. X-ray difractometer is used to define chemical components and the phase structures of the micro-zones inside the wear scars.

5. CONCLUSION

Summarizing, many of previous studies give the superficial knowledge of hard coatings wear based on empirical studies. The wear phenomena should be investigated.
The wear rate of PVD hard coatings in

sliding contacts depends primarily on sliding distance, coating hardness and normal load. Adhesive mechanism is acceptable. In this case, the linear correlation between wear coefficient and coating hardness is present.

The linear wear model (2) combined with FEA simulations is the most preferable in coating studies of sliding contacts for considering the nonhomogeneity of material and variations of contact pressure.

The maximum possible number of parameters that influence the wear characteristics must be taken into account.

The applications of specific hard coatings with particular wear characteristics should be offered.

Comparative wear tests should be done to obtain reliable results.

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