DOI: 10.2478/v10077-010-0010-4

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CAVITATION DEGRADATION MODEL OF HARD THIN PVD COATINGS

ABSTRACT

A cavitation degradation process and fatigue phenomenon were described. Similarly to fatigue phenomenon, cavitation pulses division into three fractions was suggested. The action of each fraction was respectively compared to low-cycle fatigue, high-cycle fatigue and low-amplitude fatigue. The action of each fraction was described separately. Detailed analysis of the influence of each fraction on the degradation process shows that besides mechanical loading also thermal loading occurs. The cavitation erosion is assumed to be the sum of degradation of each fraction. Thus, the model of PVD coatings degradation under action of cavitation pulses include variable-amplitude and variable-temperature fatigue.

Key words: *hard PVD coatings, cavitation, fatigue fracture, impact*

INTRODUCTION

Cavitation phenomena occurs in fast flowing liquid, e.g. in water, through a barricade which disturbs the flow and causes the rapid pressure decrease below the critic pressure. Moreover, all liquids contain some dissolved gas, which is the source of cavitation nuclei. The number and magnitude of cavitation bubbles depend on the level of the water pressure decrease and nucleation sides in water. Brennen in Ref. [1] have showed that in the cavitation cloud are typically 10^9-10^{14} cavitation nuclei and the number of cavitation nuclei increases along with its radius decreases. The increase of the liquid pressure results in the cavitation bubble collapse. Cavitation bubbles collapse violently emitting either the micro-jets or shock waves with high velocities, pressures and temperatures. Because impacts of shock waves and/or micro-jets act in a very short time in the range from nanoseconds to tens of microseconds, they are called the cavitation impulses. Bourne [2] has show that the impulse pressure might reach the pressure of GPa and velocity impact of 600 m/s, while Momber [3] has evaluated the duration of stress pulse generated by microjet impact to be the range of $2 \cdot 10^{-9}$ s. Krella and Czyżniewski [4] have showed that material respond to the action of a cavitation pulse lasts approximately $2 \cdot 10^{-5}$s. Impacts of cavitation impulses are the source of noise and material damage. Knapp [5] has assessed that only one of 30,000 cavitation bubbles is able to cause plastic deformation (pit) in soft pure aluminium. This shows that only few cavitation impulses have the amplitude in the range of hundreds MPa, whiles the majority of cavitation pulses have the amplitude in the range from kPa to tens MPa.

Philipp and Lauterbour [6] investigating the implosions of cavitation bubbles introduced non-dimensional distance parameter $\gamma = s/R$, where s is the distance from the centre of cavitation bubble to a solid surface and R is the maximum radius of cavitation bubble. They noticed that bubbles generated in the ranges $\gamma \leq 0.3$ and $\gamma = 1.2$ to 1.4 were the most aggressive and caused the greatest damage, because the jet hit the solid boundary directly with maximum speed without being decelerated by a water layer. This group of impacts act with maximum dynamic force in a few nanoseconds to microseconds and can cause plastic response of a given material.

When the distance of bubbles implosion was in the range between $\gamma = 1$ - 2, then the velocity of the jet was still very high, but the water layer between bubble and solid surface decelerates it and the final impact velocity was smaller than the maximum velocity of the jet. The jet velocity at the moment of impact onto the solid surface can be less than 120 m/s [6]. The jet still impacts with high dynamic force and initiates stress in the impact zone. The loading rate is still high but the loading time is much longer than in previous case. These impacts cause the elastic-plastic response in the degraded material.

When the distance of bubbles implosion was further than two cavitation bubbles ratios (γ>2.2), the influence of water layer increases and the impact velocity of the jet will fall down below 20 m/s. Low dynamic force connected with long time of impact causes mainly elastic response of the material.

Cyclic impact of cavitation pulses onto a material surface causes its gradual degradation called “cavitation erosion”. The material degradation is the global result of action of all cavitation pulses. Due to wide range of amplitude of cavitation pulses, cavitation erosion can be compared to fatigue fracture. The aim of this paper is to analyse the degradation mechanism of the hard coatings deposited by means of the cathodic arc evaporation PVD under the action of cavitation and propose the cavitation degradation model for the hard coating – steel substrate system.

FATIGUE PHENOMENON

A fatigue phenomenon is a fracture phenomenon that occurs after a large number of load cycles where a single load of the same magnitude would not do any harm. Wöhler curve (Fig. 1) showed that with the decrease of the amplitude of the load the number of cycles needed to cause fracture increases. When the amplitude of the load is below the threshold level, then fracture do not occur despite the huge number of cycles. This threshold level is called the fatigue limit. The fatigue limit is assumed to be the maximum amplitude of stress that do not cause failure after 10^7 cycles (solid line) [7, 8]. In the case of variable-amplitude loading, the fatigue strength decreases with the increase the number of cycles [7, 8]. Thus, the descent line is still observed even after 10^7 cycles (broken line).Taking into consideration the stress amplitude and the number of cycle needed to cause the fracture, fatigue phenomenon is divided into three regions: quasi-static fatigue, low-cycle fatigue and high-cycle fatigue. Quasi-static fatigue concerns degradation under high amplitude stress close to tensile strength and quite low number of cycles. Macro plastic deformation and micro crack initiation and growth will occur in every cycle. Thus, the initiation period is very short and takes approximately one or few cycles. In low-cycle fatigue also macro plastic deformation occurs in every cycle, but micro crack initiation lasts from several cycles up to tens of cycles. High-cycle fatigue occurs at lower stress amplitudes and macro plastic deformation arises after hundreds of cycles.

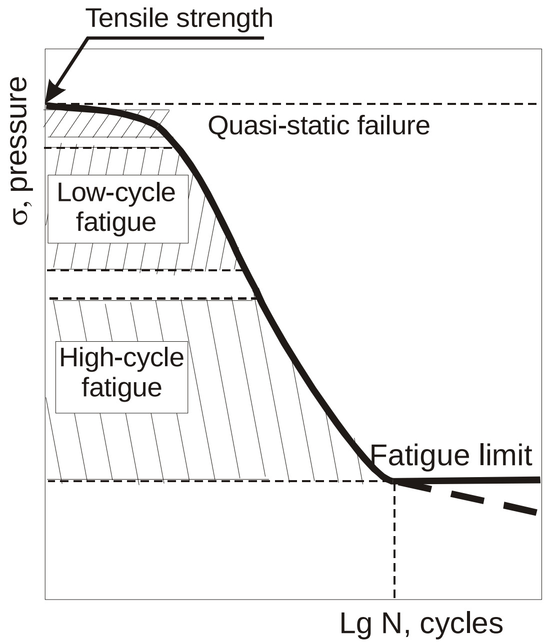

Fig. 1. The Wohler - lg N fatigue curve [7,8]

The cycle loading causes the increase of dislocation density, stress level and local strain hardening or softening depends on material. The fatigue fracture can be divided into three main steps: initiation period, crack grow period and final failure [7]. During incubation period cyclic slip bands are generated by cyclic dislocation movement. Cyclic slip has characteristic geometry (Fig. 2) indicating the crack initiation in slip intrusions or in crevices of the material.

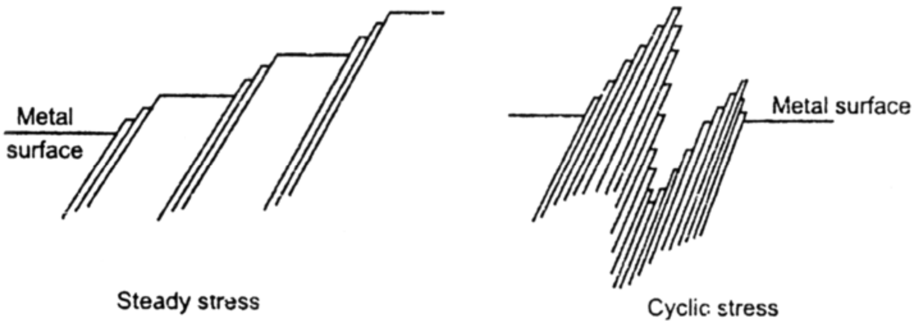

Fig. 2. Geometry of slip at the material surface [7]

Taking into consideration fatigue fracture phenomena and Philipp and Lauterbour's investigation [6], cavitation pulses can be divided into several fractions depending on their power or amplitude. The easiest division is into three groups or fractions, like is was done by Philipp and Lauterbour, but instead of the parameter γ, the amplitude of cavitation pulse should be considered. The first fraction will be the group of cavitation pulses whose amplitude is high enough to cause plastic deformation. This mean that this group of cavitation pulses is the group of cavitation bubbles whose distance before collapse was lower than cavitation bubbles radius ($\gamma < 1$). The second fraction will be the group of cavitation pulses which can cause the elastic or elastic-plastic deformation. They belong to the group of cavitation bubbles of $1 < \gamma < 2$ and can be compared to the high-cycle fatigue. The third fraction can be the group of cavitation pulses whose $\gamma > 2$ and their amplitude is below the fatigue limit. Although this division is very rough, it can illustrate the influence of each fraction in the degradation process.

FRACTION DEGRADATION

Fraction 1. Action of these impacts can be compared with action of shock loading or high-amplitude quasi-static or low-cycle fatigue. When a dynamic force impacts on the surface of a given material, it initiates complex stress in the impact zone. The material is compressed down in a single direction of the hitting micro-jet. The highest compressive stresses arise just under the impact spot. Due to high strain rate, delivered and generated heat has not enough time to transfer, so the process has an adiabatic character in the spot of impact. Thus, the deformation process is accompanied by a step increase in entropy. Violent accumulation energy on the surface in the spot of impact can cause the local change of material properties, e.g. local thermal softening facilitating the deformation process. Moreover, in case of cavitation erosion this phenomena is intensified by heat delivered from the collapse of cavitation bubbles. After implosion the material surface is rapidly cooled by water. Thus, additional to mechanical stress cycles thermal cycles occur.

Under the impact, stress is spreading as a elastic wave followed by plastic front travelled with slower speed. High loading rate causes high strain rate and, as a consequence, an increase of elastic-limit stress. This is connected with the speed of dislocation generation and motion. Just after few nanoseconds of shock loading the phase transformation and dislocation activity may occur [6]. All discontinuity spots are the sites of stresses and dislocation pile-ups. Thus, they are also the sites of nucleation and development voids within the material. As a consequence, this leads to micro-cracks initiation. Due to all mention actions the stress wave decays and finally vanishes. Thus, the response of the material is spatially limited and temporary. It is assumed that plastic deformation or a microcrack is caused by every impact or few impacts of high amplitude pulses.

Presented description concerns bulk materials. In the case of coated materials, the degradation is complicated by coating-substrate interference. The draft of coated materials degradation under action of fraction 1 pulses is shown in Fig. 3. High-amplitude cavitation pulse hitting with high loading rate a smooth surface of a hard coating – soft substrate system causes rapid increase of residual stress and entropy at the spot of impact (Fig. 3a). The increase of entropy causes thermal coating softening and facilitates the coating deformation. The degradation process of hard coatings is strongly depended on the temperature. At low temperatures hard coatings deform via shearing along grain boundaries [9, 10]. At higher temperatures, when the temperature exceeds 0.5 T/Tm, where T-temperature of deformation, Tm-melting temperature, creep process influences the deformation of hard coatings [10]. Thus, in different zones of the spot of impact different deformation mechanisms occur. They change from creep process to shearing along grain boundaries. The size of creep zone is depended on the thermal conductivity of the coating. Because hard coatings deposited by PVD method are ceramic coatings which have low thermal conductivity, the creep zone is quite narrow. Thus, hard thin PVD coating, which have columnar structure, deforms mainly via shearing along grain boundaries (Fig. 3b). If the impulse amplitude is close to endurance limit, the coating fractures immediately after the hit. Otherwise, the coating is deformed. The deformed coating presses the soft substrate. This causes the elastic-plastic response of the substrate. During unloading the deformed coating and substrate relax and tend to return to the initial position. Because the hard coating has higher elastic modulus than that of the steel substrate, it tends to return faster than the substrate. The adhesion force engenders the collective return of the coating and the substrate, but high amplitude and repetition of loading and unloading cycle declines the adhesion very quickly leading to the delamination and fracture (Fig. 3c).

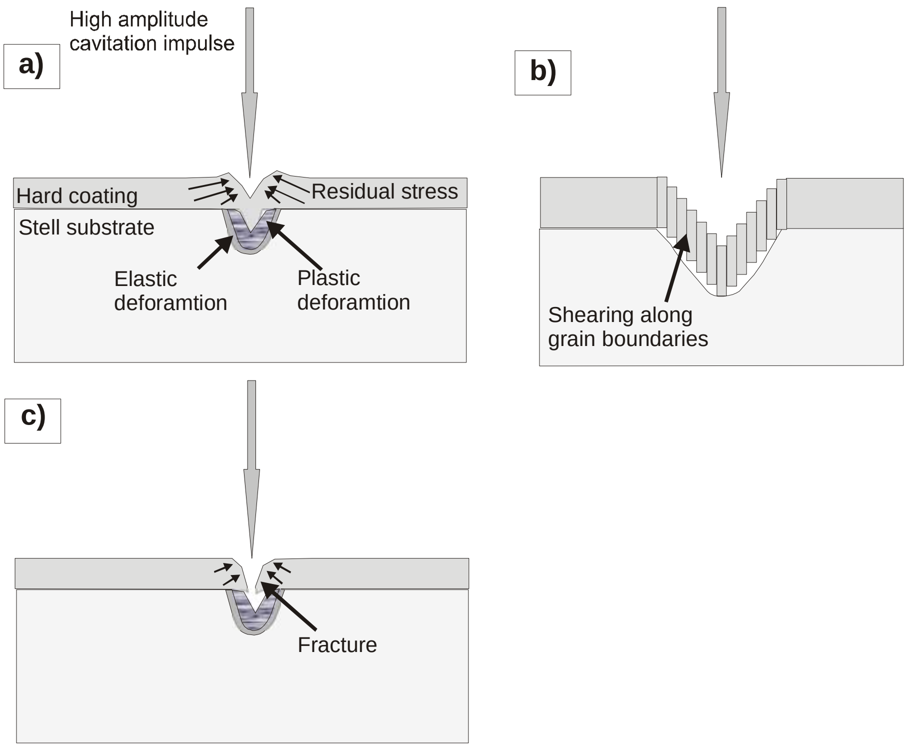

Fig. 3. Degradation of coated materials by high amplitude cavitation pulses of fraction 1

Fraction 2. The action of this group of impacts act with wide range of dynamic force causing gradual degradation of the coating - substrate system leading to removal of coating particles. For that reason degradation made by this group of impacts was compared to high-cycle fatigue fracture. Degradation needs time to occur. A dynamic force initiates complex stress in the impact zone, which propagates as a wave in the material. Heat generated by millions of pulses with wide range of impact pressure may be locally transferred depending on thermal conduction coefficient of a given material. An increase of material temperature influences the local material expansion. Every impact increases stress level and the dislocation density in the spot of impact. The gradual increase of dislocation density causes the gradual increase of work hardening. Plastic deformation and crack initiation need the time to occur.

The draft of degradation of a PVD coating under action of fraction 2 pulses is shown in Fig. 4. Cavitation pulses hit a smooth surface of a hard coating – soft substrate system causing elastic deformation of the coating and an increase of residual stress in the coating at the spot of impact. The elastic deformed coating presses the soft substrate causing the elastic response of the substrate (Fig. 4a). After repeated action of impacted pulses in the spots of impact the plastic deformation of the substrate occurs (Fig. 4b). Ma et al. [9] and Carney et al. [11] have noticed the undulation of the surface of the hard coating - steel substrate systems under cyclic impact loading as a result of coating adjustment to plastically deformed substrate. They have obtained that the substrate deformation occurs faster than that of the TiN hard coating. Thus, the undulation of hard coating is strictly related to the substrate deformation. During unloading the deformed coating and substrate relax and tend to return to the initial position. Due to high elastic modulus, the hard coating tends to return faster than the substrate, but the adhesion force engenders the collective return of the coating and the substrate (Fig. 4b). The repetition of loading and unloading cycle increases residual stress in the coating leading to its deformation. The PVD coating is deformed mainly via shearing along grain boundaries. Moreover, repeated cycles of pressure pulses decline the adhesion. In addition, heat delivered from the cavitation implosion and generated during deformation is partially transferred to the surrounding area. This causes thermal expansion of the coating and the substrate and facilitates dislocation movement and deformation. Cooling, that occurs during unloading, causes thermal mismatch between the PVD coating and the steel substrate. As a result, it leads to the adhesion declination and finally to the delamination. When cumulated residual stress in the coating exceeds the strength of the coating, coating fracture occurs (Fig. 4c).

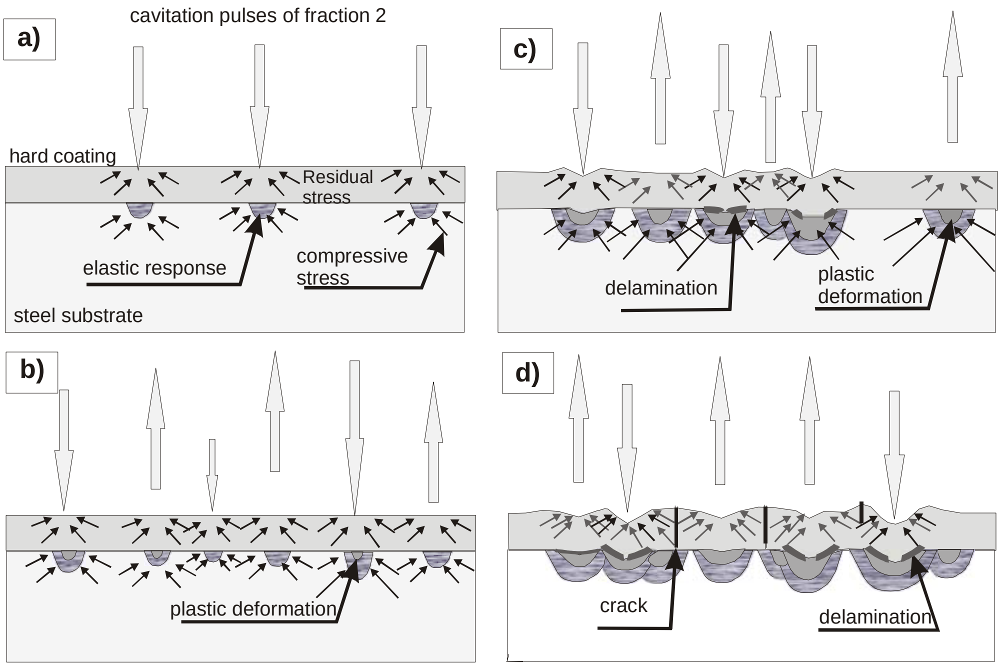

Fig. 4. Degradation of coated materials by cavitation pulses of fraction 2

Fraction 3. This fraction is the most numerous group of impacts. Impacts of this group act with low dynamic pressure causing only elastic response of the coating – substrate system in the spot of impact. Due to low amplitude of this group pulses, the deformation process has isothermal character. Huge number of low-amplitude pulse impacts cause the gradual increase of the dislocation density due to lattice friction [12- 14].

The draft of the action of this fraction pulses is shown in Fig. 5. Huge number of low-amplitude pulses causes the elastic response of the hard coating. The deformed coating presses the substrate and causes its elastic response: an increase of dislocation density and increase of residual compressive stress in the spots of pressure (Fig. 5a). With the time (Fig. 5b), the sites of the substrate with increased dislocation density increases as well as increases the residual stress in the spots of impact. Nevertheless, cumulative energy delivered to the substrate is too small to cause essential change in the dislocation structure or work hardening.

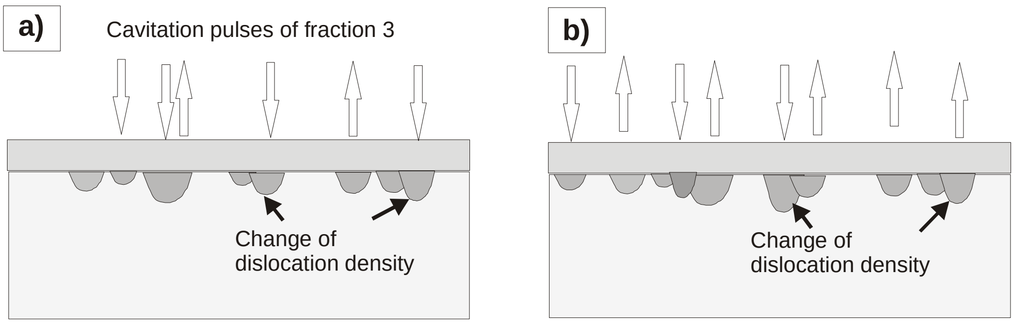

Fig. 5. Degradation of coated materials by cavitation pulses of fraction 3

CAVITATION EROSION MODEL OF THE PVD COATINGS

Cavitation pulses of all fractions hit the PVD coating independently and simultaneously. The total degradation is the sum of degradation of each fraction (Fig. 6).

At the beginning of degradation cavitation pulses or stress pulses hit a smooth surface of a hard PVD coating (Fig. 6a). The response is spatially and temporary limited. The compressive residual stress, which always occurs in the PVD coatings, counteracts the penetration of a cavitation pulse into the coating. Because of high hardness and high elastic modulus of the coating, the impact energy is mainly absorbed by the coating on the elastic response. The elastically deformed coating presses the soft substrate. This causes the elastic or elastic- plastic response of the substrate depending on the impact force / pressure. Impact loading introduces additional complex stress distribution: compressive stress in the spot of impact: in the coating and in the substrate and tensile stress at micro-undulated crests. The initiated stress is proportional to the impact stress and impact duration. Fraction 1 pulses cause an increase of entropy in the spot of impact, but fraction 2 pulses generate heat which can be transferred to the surrounding area depending on the thermal conductivity. The local increase of the temperature of the coating causes its local thermal softening. Local thermal softening facilitates coating deformation due to lessen locally Young’s modulus and locally lessens the level of dislocation density due to facilitation of the dislocation motion and locally lessens the level of residual stress. Other aspect of the thermal action is the local thermal expansion of the coating. The volume that undergoes the thermal expansion is dependent on the thermal conductivity of the coating. The thermal conductivity of the coating also affects the increase of substrate temperature. The increase of the temperature of the substrate causes its local expansion. Different thermal properties of the coating and the substrate result in different local expansion and the thermal mismatch between the coating and the substrate, which leads to additional introduction of thermal stress and the delamination.

During stress unloading the deformed coating and substrate tend to return to the initial position and also the rapid cooling occurs, which causes rapid contraction of the coating and the substrate. Because the coating has higher elastic modulus, it tends to return faster than the substrate. The adhesion force engenders the collective return of the coating and the substrate. Rapid cooling process contributes to the thermal mismatch between the coating and the substrate, which leads to the adhesion declination, and also to the dislocation density increase of rapidly cooled sites of hard coating- steel substrate systems and increases additional thermal stress. Thus, the thermal effect of the implosions of cavitation bubbles causes thermal fatigue besides mechanical fatigue.

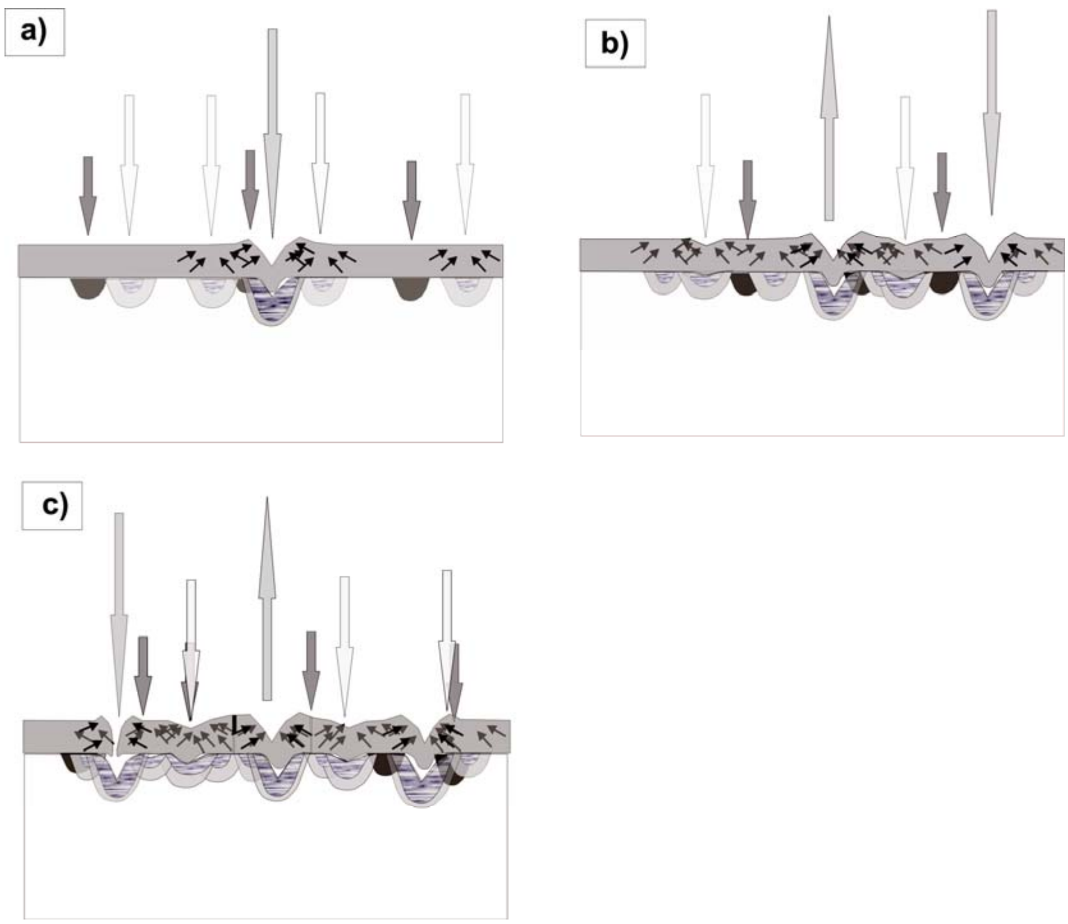

Fig. 6. Cavitation erosion model of the PVD coatings

Cyclic impacts of the cavitation pulses (Fig. 6b) repeat the process of local loading and unloading. The cycling loading causes the cycling elastic deformation of the hard coating, which progresses mainly via the grain boundary sliding. The grain boundary sliding is also the source of voids initiation along the grain boundary and progression of the existing ones. The cyclic elastic responses of the coating forces repeated elastic-plastic reaction of the substrate. The repeated local loading causes an increase of the residual compressive stress in the spots of deformation, but also increases residual tensile stress at micro-undulation crests. High compressive stress in the surface layer is, in general, very positive and protects the surface before degradation. Nevertheless, very high compressive stress in the coating may lead to the stress mismatch between the coating and the substrate, and as a result to the coating delamination. If the stress level in the substrate reaches a threshold value, which is close to the yield stress, every new input of energy causes local plastic deformation.

As the number of loading-unloading cycles increases (Fig. 6c) the system of hard coating and soft substrate undergoes undulation due to the adjustment of the coating to the plastically deformed substrate and the level of the stress in the coating and in the substrate becomes very high. In the spots of impacts high compressive stress have arisen, but on the top of deformed coating – high tensile stress. When the tensile stress reaches the value of strength limit, any additional energy delivered from the new impact causes coating rupture. The cohesive fracture releases some compressive stress. Other aspect of the increase of loading cycle is gradual decline of adhesion due to mismatch mechanical properties of the coating and the substrate. Mentioned thermal effect of cavitation pulses, beside the softening of the coating and the substrate, also causes thermal expansion of the thermally activated region of the system. The thermal mismatch between the coating and the substrate accelerates the coating delamination and introduces thermal stress. Thus, thermal effect of cavitation pulses accelerates the delamination process. When delamination is so large that the substrate cannot support the coating, any impact can cause the coating rapture.

CONCLUSIONS

The obtained analysis allow the following conclusion:

- The cavitation degradation models of coated materials should consider the thermal properties of a coating and a substrate.
- The cavitation degradation models have to include the fatigue damage accumulation under variable - amplitude loading.
- The cavitation degradation models have to include the thermal fatigue damage under variable - temperature loading.

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