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Development of a Wöhler-like approach to quantify the Ti(C_xN_y) coatings durability under oscillating sliding conditions

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ABSTRACT

The selection of a proper material for the particular engineering application is a complex problem, as different materials offer unique properties and it is not possible to gather all useful characteristics in a single one. Hence, employment of different surface treatment processes is a widely used alternative solution. In many industrial applications, coating failure may be conducive to catastrophic consequences. Thus, to prevent the component damage it is essential to establish the coating endurance and indicate the safe running time of coated system. To this study PVD TiC, TiN and TiCN hard coatings have been selected and tested against polycrystalline alumina smooth ball. The series of fretting tests with reciprocating sliding at the frequency 5Hz have been carried out under 50-150N normal loads and under wide rage of constant as well as variable displacement amplitudes from 50μm to 200μm at a constant value of relative humidity of 50% at 296K temperature. To quantify the loss of material a dissipated energy approach has been applied where the wear depth evolution is referred to the cumulative density of friction work dissipated during the test. Different dominant damage mechanisms have been indicated for the investigated hard coatings, which is debris formation and ejection in case of TiC coating and progressive wear accelerated by cracking phenomena in case of TiN and TiCN coatings. Energy-Wöhler wear chart has been introduced, in which the critical dissipated energy density corresponds to the moment when the substrate is reached after a given number of fretting cycles. Two different methods to determine the critical dissipated energy density are introduced and compared. The Energy-Wöhler approach has been employed not only to compare the global endurance of the investigated systems but also to compare the intrinsic wear properties of the coatings. It has been shown that the fretting wear process is accelerated by the stress-controlled spalling phenomenon below a critical residual thickness and a severe decohesion mechanism is activated. Finally the applicability of the investigated method to other coated systems subjected to wear under sliding conditions is discussed and analyzed. The perspectives of this new approach are elucidated.

Keywords: wear, carbide and nitride coatings, coating endurance, reciprocating sliding.

1. INTRODUCTION

Degradation of surface layers in kinematic or static pairs due to wear is one of the principal industrial problems resulting in necessity of repairing or replacing mechanical components. Wear is a complex process and is considered as an interdisciplinary one in which different mechanical, physical, and chemical phenomena are involved. Fretting as a specific type of wear is defined as a small displacement amplitude oscillatory motion between two nominally motionless solid bodies in contact under normal load [1]. Depending on the fretting conditions (displacement amplitude, normal load) surface fatigue and/or surface wear induced by debris formation are progressing [2]. In a great part of mechanical applications the vibrations are being induced and the systems work under variable loading conditions. This in turn provokes degradation under oscillating sliding which leads to the failure of the elements. The devastation by fretting has been identified in rolling bearings, keys, riveted or screw joints, steel ropes, electric connectors, medical implants and is potentially dangerous for all kinds of transport vehicles.

Protection against fretting has to be taken into account at design stage of the nominally motionless junction. By designing an appropriate contact geometry of the junction, the concentration of stresses and consequently fatigue cracking can be avoided. Proper designing can also contribute to decrease of reciprocal displacement amplitude [3]. Nevertheless, destruction under oscillating sliding can not be completely excluded as this kind of damage was reported even for displacement amplitudes less than

1μm [4]. One of the effective methods of protecting against fretting wear is application of the appropriate surface engineering techniques. These can increase the tribological properties of the components by: inducing a residual compressive stress, decreasing the coefficient of friction, increasing the surface hardness and finally by controlling the surface chemistry [5-8].

Among different surface engineering techniques, the physical vapour deposition (PVD) and chemical vapour deposition (CVD) ones are the most widely used to mitigate the fretting wear rather than to improve the fretting fatigue strength. To enhance the resistance to fretting fatigue the treatments which are conducive to compressive residual stresses in the outer layer of the component are recommended [8], e.g. shot-peening, ion implantation, carburizing, nitriding or ion beam enhanced deposition. Nevertheless some preliminary results [9] show that hard PVD and CVD coatings can also improve the fretting fatigue strength of steels.

In numerous industrial applications, coating failure may be conducive to catastrophic consequences. Thus, to prevent the component damage, it is essential to establish the coating endurance and indicate the safe running time of the component. In fatigue investigations the lifetime of the specimen under uniaxial tension stress is often described in terms of useful and widely applied Wöhler's fatigue charts, which relate the number of cycles (N) to failure with maximal amplitude of cyclic stresses. The relevant Wöhler's graphs allow to establish the endurance limit of a material, i.e. the maximal tension value at which the specimen failure will not occur even after great number of cycles (i.e. from the range of $10^8 \div 10^9$ cycles or greater). The approach has been applied with success to study the fretting fatigue by adding the lateral loading pads to the classical fatigue rig [9-12]. This action takes immediate effect on the position of the Wöhler's curve and the influence of fretting fatigue can be expressed by the decrease of the endurance limit (Fig. 1).

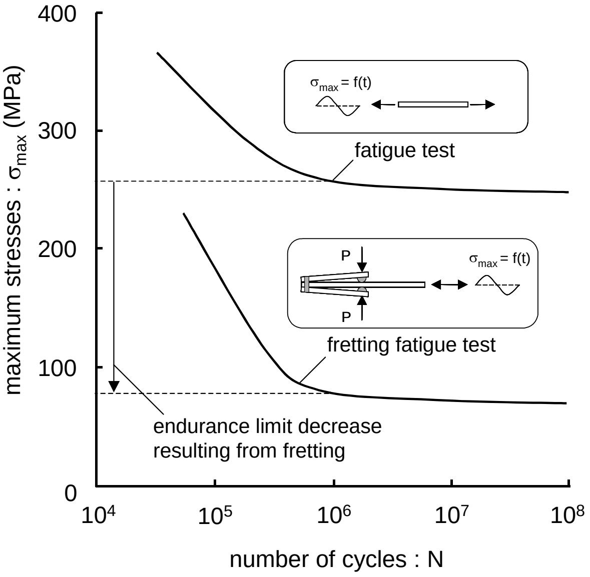

Figure 1. Wöhler's curves for fatigue and fretting fatigue tests [12].

Application of Wöhler's curves to compare different surface treatments under fretting wear regime was proposed by Langlade et al. [13]. However the authors consider the endurance of a coating as a function of maximum pressure. The energy Wöhler-like concept introduced in this work appears more "universal" as the energy dissipated due to friction is a unique parameter that takes into account the crucial loading variables, which are: the pressure, sliding distance and friction coefficient.

2. EXPERIMENTAL DETAILS

Fretting tests were carried out using an electrodynamic shaker activating a specific fretting rig (Fig. 2) manufactured by DeltaLab. Tests were carried out in a closed chamber where both the temperature and the relative humidity (RH) were controlled and kept constant: 50% RH at 296K.

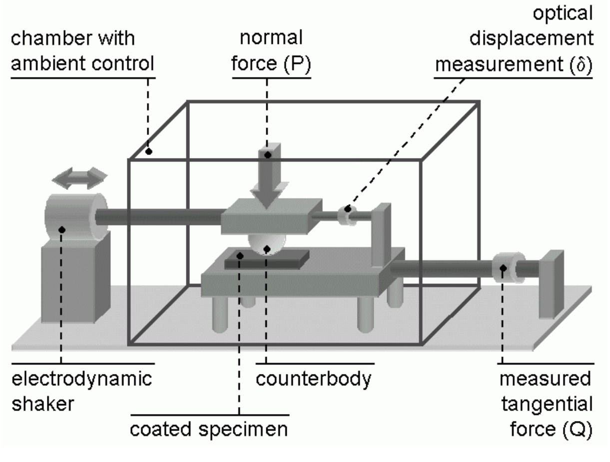

Figure 2. Schematic of the fretting rig.

All the fretting wear experiments have been carried out under reciprocating sliding at the frequency (f) 5Hz. Tests have been realised for the number of cycles starting from 1000 and usually less than 20000 ones. A wide range of displacement amplitudes (50μm - 200μm) and normal loads (50N - 150N) has been applied in order to verify the validity of the approach under different loading conditions. For the investigated contact geometry and materials of the friction node the maximum Hertzian pressure in the node was equal to 1075MPa, 1350MPa and 1550MPa for the normal load 50N, 100N and 150N, respectively.

During the fretting tests the normal force (P) has been kept constant, while the tangential force (Q) and displacement (δ) have been recorded. Thus the fretting loop Q – δ could be drawn for each cycle (Fig. 3) and its basic characteristics, as the total dissipated energy (Ed) (i.e., the area of the hysteresis) [14], the sliding amplitude (δ_g), the displacement amplitude (δ_*) and the tangential force amplitude (Q_*) could be determined.

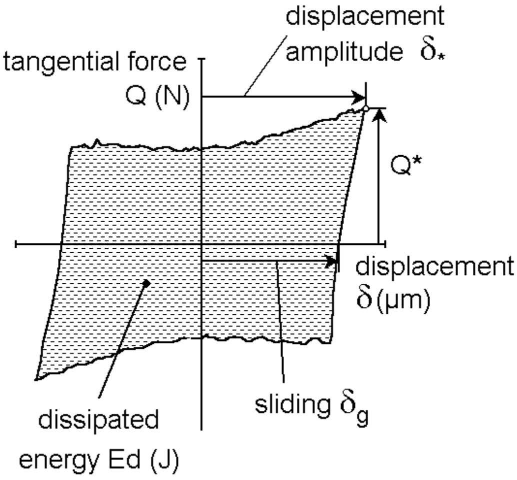

Figure 3. Characterization of the fretting cycle.

High speed steel Vanadis23 (1,28 wt.% C; 4,2 wt.% Cr; 5,0 wt.% Mo; 6,4 wt.% W and 3,1 wt.% V) has been used as the substrate material for hard coatings deposition. Three different kinds of hard coatings have been selected to this study: titanium carbide (TiC), titanium nitride (TiN) and titanium carbonitride (TiCN). Titanium carbide coating has been manufactured with use of the indirect method [15], which consist first in deposition of thin titanium layer by magnetron sputtering, next in heating the samples in a vacuum furnace at the temperature 1423K in order to induce the outward diffusion of carbon atoms from the HSS steel substrate into the titanium layer and activate the solid state reaction $Ti+C \Rightarrow TiC$ in the layer and, subsequently, in oil quenching of the samples directly from the heating temperature followed by double tempering at 823K. Titanium nitride and titanium carbonitride hard coatings have been deposited by means of arc PVD method with use of a single source device. In that case the HSS substrates before deposition underwent a typical preparation: heat treatment (oil quenching and double tempering), mechanical grinding and polishing with diamond paste, immersing in acetone and cleaning in ultrasonic bath, glow discharge cleaning in working chamber (first cleaning stage) and high energy cleaning and heating by titanium ions (second cleaning stage). Finally, the TiN or TiCN coatings have been arc deposited onto the substrates.

As the counter-body during the fretting tests a polycrystalline alumina ball with a R=12,7mm radius has been used. This ceramic material, as distinct from, e.g., a steel ball, was selected in order to reduce the material transfer from the tested coating surface onto the ball surface. The mechanical properties as well as the surface roughness (Ra) of all the materials employed in this work are summarized in Table 1.

Table 1. Mechanical and surface properties of the materials used in the work.

	Manufacturing method	Thickness t (μm)	Hardness H	Young's modulus E (GPa)	Poisson ratio ν	Surface roughness Ra (μm)
Vanadis23	-	-	64 HRC	230	0.3	0.2
Alumina	-	-	2300 $Hv_{0.1}$	370	0.27	0.01
TiC	Indirect method	1.6	1250 $Hv_{0.05}$	510	0.2	0.2
TiN	Arc PVD	4.0	2000 $Hv_{0.05}$	600	0.25	0.2
TiCN	Arc PVD	2.5	1700 $Hv_{0.05}$	550	0.25	0.2

3. RESULTS

The coating endurance is conventionally related to its perforation. Hence, in comparison with the wear volume analysis, wear depth quantification appears more suitable to predict the coating lifetime. By considering the dissipated energy as the controlling parameter of wear, we assume that the wear depth is related to the cumulative dissipated energy density [16-19]. The general expression for the density of the energy dissipated at the centre of the contact area (E_{dh}) during the i^{th} fretting cycle is expressed as:

$$E_{dh}(i) = 4 \cdot \delta_g(i) \cdot \mu_e(i) \cdot p_m(i) \qquad (J/\mu m^2) \tag{1}$$

under condition that $r(i) > \delta_g(i)$ (where $r(i)$ is defined as an actual wear scar radius) and the mean pressure $p_m(i)$ is equal to:

$$p_m(i) = \frac{P(i)}{A_r(i)} \quad (MPa), \tag{2}$$

where $A_r(i)$ and $P(i)$ are the contact area and the normal load (respectively) for the i^{th} fretting cycle. It has been outlined [20] that the contact area increase must and can be formalized to describe properly the wear depth extension.

For each test the local energy density is summed up in order to obtain the cumulative dissipated energy density at the centre of the contact area:

$$\sum E_{dh} = \sum_{i=1}^{N} E_{dh}(i) \quad (J/\mu m^2) \tag{3}$$

Nevertheless within a single test duration the energy density evolution is never constant. An increase of the contact area and/or a variation of the sliding amplitude influence the energy density which suggests that an average value of the energy density should be taken into account:

$$\overline{E}_{dh} = \frac{\Sigma E_{dh}}{N} \quad (J/\mu m^2) \tag{4}$$

Drawing comparison of this mean value with the number of fretting cycles an energy density–coating endurance chart (i.e. $\overline{\mathrm{E}}_{\mathrm{dh}}$ – Nc curve), equivalent to the Wöhler's fatigue one, can be developed. Durability of a coating is then related to the critical number of cycles (Nc) after which the coating is worn through up to the substrate. Numerous interrupted tests have been completed for a TiC coating, where the perforation of the coating has been confirmed by means of the surface profilometry and optical observations (Fig.4).

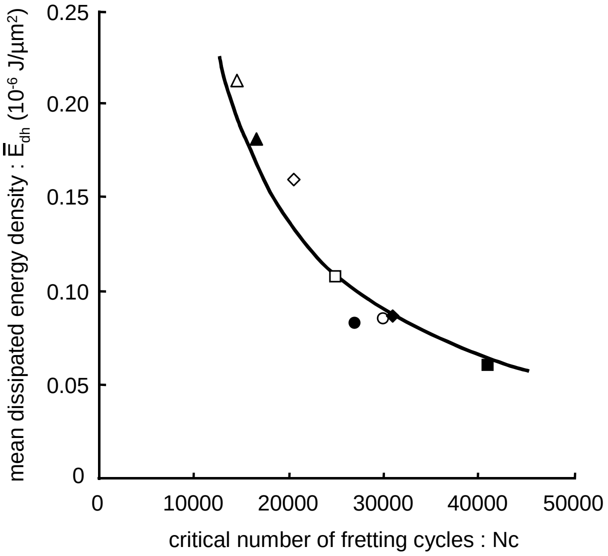

Figure 4. TiC coating endurance for different sliding amplitudes: constant ones (■ 50µm, □ 100µm, ◊ 150µm, Δ 200µm) and variable (♦ (50/100)µm$_{x1}$, ○ (50/100)µm$_{x2}$, ● (50/100)µm$_{x4}$, ▲(150/200)µm$_{x1}$). Fretting test conditions: RH=50%, f=5Hz, P=100N [20].

In order to achieve the coating perforation numerous long-lasting fretting tests have been carried out in which the coating has been worn through several times and a mean critical value has been calculated. Therefore, it is a highly expensive and time-consuming procedure, especially when relatively thick hard coatings with a good wear resistance are being examined. Hence, for the TiN and TiCN coatings decreased number of fretting tests have been realized and a tentative curve, which separates the tests in which the coating has been worn through from those in which the coatings were still not damaged, has been drawn in Fig. 5.

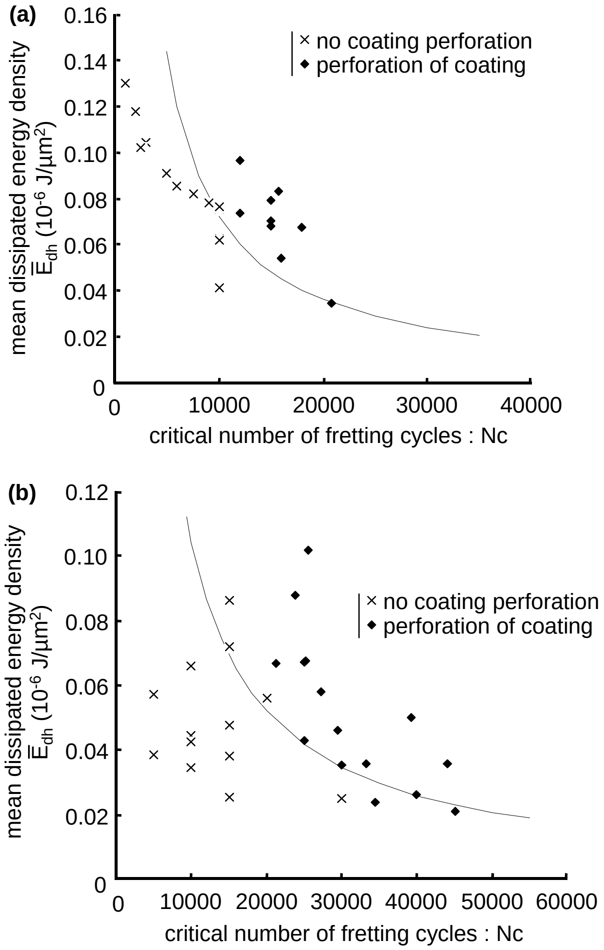

Figure 5. Durability estimation of (a) TiN and (b) TiCN coatings. Solid line corresponds to the mean coating endurance. Fretting test conditions: P=50-150N, δ=50-200µm, RH=50%, f=5Hz.

4. DISCUSSION

The course of an energy Wöhler's curve is determined by a critical energy density (E_{dhc}) which is a specific quantity of energy that has to be delivered to the coating in order to worn through its total thickness. This critical value is a characteristic and invariable parameter for each material and defines its tribological behaviour. A representative single value of E_{dhc} corresponds well with a Wöhler's curve in case of TiC coating (Fig. 4). Considering the durability of TiN and TiCN coatings (Fig. 5) it can be noticed that a slight shift of a Wöhler's curve in a vertical direction would describe more suitable a borderline between tests with and without perforation of a coating. It suggests different inherent damage mechanism involved in degradation of investigated hard coatings. It has been found also, that in case of the TiC coating the wear scars have a typical U-shape, whereas in case of TiN and

TiCN coatings the wear scars have a modified W-shape. This difference is due to the dominant damage mechanism by debris formation and their subsequent ejection in case of TiC coating and to progressive wear accelerated by cracking phenomena in case of TiN and TiCN coatings. Debris are formed due to micro-fracture of the coatings provoked by important tensile stresses in the coatings generated by the spherical alumina counter-body under high normal loads. It has been proved in the previous work [21] that the characteristic W-shape of a scar is related to a modification of the surface geometry by the generation of a third-body and to its occurrence within the contact area. When the fretting is progressing an annular spatial distribution of this third-body on the surface of the counter-body (alumna ball) is being generated. This evolution of the contact geometry changes the shear and pressure fields in the contact area to a great extent. As a result, the maximum stress value observed in the centre of the contact at the beginning of the test is displaced toward its border with increasing test duration. Wear of TiN and TiCN coatings becomes a process related rather to the number of applied oscillating sliding cycles than to the energy quantity delivered to the system and tends to the pure fatigue behaviour (Fig. 6).

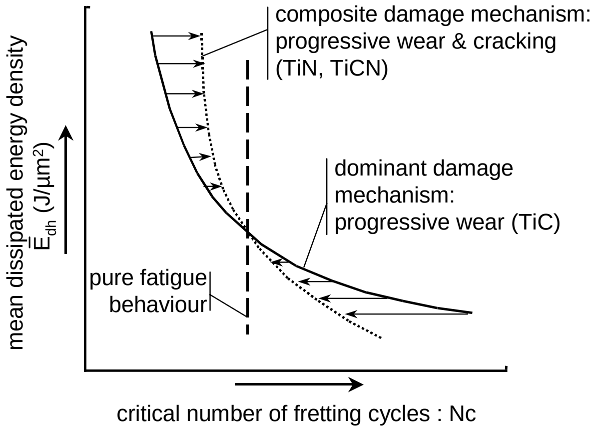

Figure 6. Interpretation of the endurance of investigated hard coatings.

The coatings durability determined by means of perforation condition can be estimated also in a shorter way, taking into account a linear evolution of the wear depth as a function of the cumulative energy density, which is given in Fig. 7. Hence, the energy wear coefficient (β) can be obtained by relating wear depth with the cumulative dissipated energy density:

$$\beta = \frac{h}{\sum E_{dh}} \quad (\mu m^3/J) \tag{5}$$

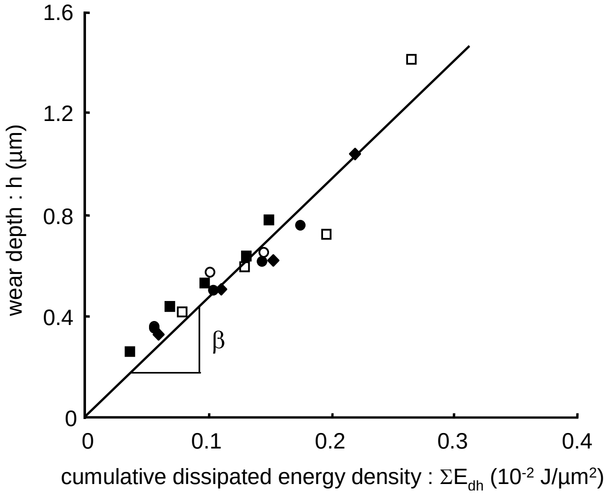

Figure 7. Local wear analysis: determination of the energy density wear coefficient β (474µm^3/J) as the slope of the wear depth as a function of the cumulative dissipated energy density for different displacement amplitudes: constant ones (■ 50µm, □ 100µm) and variable (♦ (50/100)µm$_{x1}$, ○ (50/100)µm$_{x2}$, ● (50/100)µm$_{x4}$). Fretting test conditions: TiC/alumina, RH=50%, f=5Hz, P=100N [20].

For a given coating thickness (t), the critical dissipated energy density is identified as:

$$E_{dhc} = \frac{t}{\beta} \quad (J/\mu m^2) \tag{6}$$

Nevertheless, in practice a slightly shorter coating lifetime than the one predicted by the energy wear coefficient has been obtained. The experimental data indicate that the coating lifetime is shorter due to stress controlled decohesion at the coating/substrate interface. Therefore, the coating durability should be estimated by an effective dissipated energy density E_{dhe}:

$$E_{dhe} = \frac{t_e}{\beta} \qquad \text{with} \qquad t_e = t - t_r \tag{7}$$

where t_e is the effective coating thickness removed before decohesion and t_r is the critical residual thickness destroyed due to stress controlled spalling phenomenon. The difference between the critical dissipated energy density determined from Eq. (6) and the effective dissipated energy density is equal to 21% for TiC, 11% for TiN and 6% for TiCN. The damage mechanisms at the substrate/coating interface are rather complex and not fully understood. These differences can be related to a number of mechanical and physico-chemical factors, however the most important ones seem to be: nominal coating thickness, coating morphology, loading conditions, adhesion forces and changes of the stress distribution within the contact area. To explain the damage mechanism the coating/substrate interface needs further study including the effect of the above factors.

The assessment of fretting wear of hard coatings in one global Wöhler-like chart (Fig. 8) gives a distinct visualisation of surface treatments durability under oscillating sliding. According to Eq. (1) it is evident that increasing the pressure in the contact or the displacement amplitude, more energy is dissipated within the contact area and the coating failure can take place after a smaller number of fretting cycles. This aspect is clearly displayed in the chart and the critical number of fretting cycles can be predicted easily. A comparison of the effect of different surface treatments on fretting behaviour of the same element can also be realised quickly and easily.

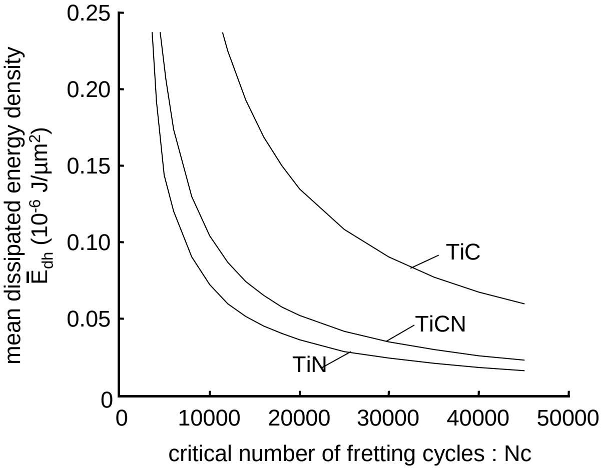

Figure 8. Durability of hard coatings as a function of the critical number of fretting cycles for different coatings with a given thickness: TiC-1.6μm, TiCN-2.5μm, TiN-4μm.

Fig. 8 shows the practical durability prediction of the coatings under investigation for a particular tribosystem and for a given coating thickness. The approach allows also to assess the intrinsic wear properties of the coating. As the result, a unitary mean dissipated energy density can be introduced as a ratio of the mean dissipated energy density to the coating thickness: $\sum \bar{E}_{dh} / t$ (Fig. 9). One can see that with use of this intrinsic parameter the difference in durability between the thicker coating (TiN) and the thinner one (TiC) is clearly greater.

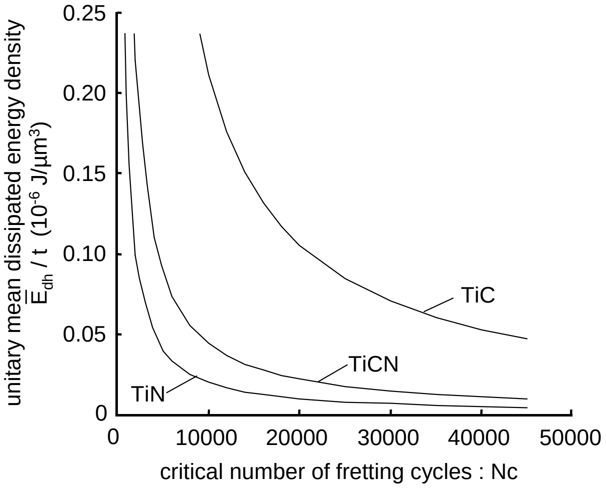

Figure 9. Durability of hard coatings as a function of unitary mean dissipated energy density versus critical number of fretting cycles.

The proposed methodology allows to establish the durability of the investigated PVD coatings and can be used for characterization of other surface engineering techniques. Lifetime of different surface techniques including diffusion treatments (e.g. carburizing, nitriding, oxidation) can be determined as well by defining the nominal thickness of the coating where the particular properties are considered. It can be employed also to the components manufactured of bulk materials to define the safe running time of the element until the loss of material provoking a critical change of the contact geometry.

5. CONCLUSIONS

The following conclusions can be made from this study of hard coatings durability under oscillating sliding.

- The critical value of the dissipated energy density has been proposed as a factor indicating the specific quantity of energy that has to be delivered to the coating in order to wear through its total thickness.
- Energy-Wöhler wear chart has been introduced, in which the critical dissipated energy density corresponds to the moment when the substrate is reached after a given number of fretting cycles.
- The chart can be employed not only to compare the global endurance of the investigated systems but also to compare the intrinsic wear properties of the coatings.

- Different dominant damage mechanisms have been indicated for the investigated hard coatings, which is debris formation and ejection in case of TiC coating and progressive wear accelerated by cracking phenomena in case of TiN and TiCN coatings. These differences are related to the evolution of the interface due to the debris adhesion to the counter-body surface, which leads to the shear and pressure fields modification in the contact area.
- Lifetime of the component after a particular surface treatment can be identified both by means of the tests with the coating perforation or with use of the energy wear coefficient β.
- Coating endurance is not only related to its resistance to wear: is also controlled by the stress distribution at the substrate/coating interface.

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REFERENCES

[1] R.B. Waterhouse, Fretting Fatigue, Elsevier Applied Science, London, 1981.

[2] O. Vingsbo, S. Soderberg, On fretting maps, Wear 126 (1988) 131-147.

[3] S. Guzowski, Effect of contact interaction in clamped joints on fretting wear development, Tribologia 5 (1998) 698-707.

[4] P.J. Kennedy, L. Stallings, M.B. Petersen, A study of surface damage at low amplitude slip, Proc. Conf. "ASLE-ASME Lubrication Conf.", Hartford, 1983.

[5] S.J. Harris, M.P. Overs, A.J. Gould, The use of coatings to control fretting wear at ambient and elevated temperatures, Wear 106 (1985) 35-52.

[6] J. Labedz, Effect of residual stresses on wear of the surface layer of components operating under fretting conditions, in: R.B.Waterhouse and A. Niku-Lari (Eds.), Metal Treatments against Wear, Corrosion, Fretting Fatigue, Pergamon Press, pp, 87-98, 1988.

[7] R.B. Waterhouse, The effect of surface treatment on the fatigue and fretting-fatigue of metallic materials, in: R.B.Waterhouse and A. Niku-Lari (Eds.), Metal Treatments against Wear, Corrosion, Fretting Fatigue, Pergamon Press, pp, 31-40, 1988.

[8] Y. Fu, J. Wei, A.W. Batchelor, Some considerations on the mitigation of fretting damage by the application of surface-modification technologies, Journal of Materials Processing Technology 99 (2000) 231-245.

[9] K. Sato, S. Kodoma, Effect of TiN coating by the CVD and PVD processes on fretting fatigue characteristics in steel, in: R.B. Waterhouse and T.C. Lindley (Eds.), Mechanical Engineering Publication, pp, 513-526, 1994.

[10] O.J. McDowell, Fretting corrosion tendencies of several combinations of materials, Symposium on fretting corrosion, ASTM, Philadelphia, pp, 40-53, 1953.

[11] T.C. Lindley, K.J. Nix, The role of fretting in the initiation and early growth of fatigue cracks in turbo-generator materials, Conf. Multiaxial Fatigue, ASTM, Philadelphia, pp, 340-360, 1985.

[12] C. Bleuzen, Evaluation de la susceptibilite au fretting d'alliages aeronautiques, le fretting corrosion, Senlis (1998) 39-57.

[13] C. Langlade, B. Vannes, M. Taillandier, M. Pierantoni, Fretting behavior of low-friction coatings: contribution to industrial selection, Tribology International (2001) 49-56.

[14] S. Fouvry, Ph. Kapsa, L. Vincent, Quantification of fretting damage, Wear 200 (1996) 186-205.

[15] B. Wendler, Simultaneous surface and bulk hardening of HSS steels, Surface and Coating Technology 100-101 (1998) 276-279.

[16] T. Liskiewicz, S. Fouvry, B. Wendler, Impact of variable loading conditions on fretting wear, Surface and Coatings Technology 163-164 (2003) 465-471.

[17] S. Fouvry, T. Liskiewicz, Ph. Kapsa, S. Hannel, E. Sauger, An energy description of wear mechanisms and its applications to oscillating sliding contacts, Wear 255 (2003) 287-298.

[18] E. Sauger, S. Fouvry, L. Ponsonnet, Ph. Kapsa, J.M. Martin, L. Vincent, Tribologically transformed structure in fretting, Wear 245 (2000) 39-52.

[19] V. Fridrici, S. Fouvry, Ph. Kapsa, P. Perruchaut, Impact of contact size and geometry on the lifetime of a solid lubricant, Wear 255 (2003) 875-882.

[20] T. Liskiewicz, S. Fouvry, Development of a friction energy capacity approach to predict the surface coating endurance under complex oscillating sliding conditions, Tribology International 38 (2005) 69-79.

[21] S. Fouvry, Ph. Kapsa, H. Zahouani, L. Vincent, Wear analysis in fretting of hard coatings through a dissipated energy concept, Wear 203-204 (1997) 393-403.