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# Behaviour of shot peening combined with WC-Co HVOF coating under complex fretting wear and fretting fatigue loading conditions

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**Abstract:**

This study investigated the fretting and fretting fatigue performance of tungsten carbide–cobalt (WC–Co) HVOF spray coating systems. Fretting wear and fretting fatigue tests of specimens with shot peening and WC–Co coatings on 30NiCrMo substrates were conducted. The WC-Co coating presents very good wear resistance and decreases by more than 9 times the energy wear coefficient (α) under fretting conditions. The tested coating reduces crack nucleation under both fretting and fretting fatigue studied situations. Finally the crack arrest conditions are evaluated by the combined fretting and fretting fatigue investigation. It is shown and explained how and why this combined surface treatment (shot peening and WC–Co) presents a very good compromise against wear and cracking fretting damage.

**Keywords:** Fretting Fatigue, Fretting Wear, Cracking Modelling, Shot Peening.

## 1. Introduction

The fretting phenomenon is defined as small oscillating movements in the contact between two surfaces, where at least one of them is subjected to vibration or cyclic stress. Depending on the displacement amplitude between contacting surfaces, partial slip or gross slip regimes can be observed [1]. Under partial slip conditions damage is controlled mainly by cracking, but under the gross slip regime, the wear phenomenon dominates. Sometimes one of the contacting parts is also subjected to constant or cyclic bulk stress. This type of fretting configuration is called fretting fatigue. Short cracks originally initiated by fretting loading can propagate due to the fatigue stress up to rupture. It is therefore extremely important to analyse such complex behaviour in order to predict damage and provide relevant palliatives. A tungsten carbide–cobalt (WC–Co) coating applied by the high velocity oxy-fuel (HVOF) process is being used in some applications to replace chrome plating or anodizing [2]. WC-Co coatings manifest excellent wear properties and they are widely used as protective coatings on surfaces where abrasion, erosion and other forms of wear exist [3].

## 2. Experimental procedure

### *Fretting wear test apparatus*

The fretting wear test setup used in this study is based on a cylinder/plane configuration device mounted on a 25 kN servo-hydraulic machine (Figure 1). Further details of this setup and the experimental methods used can be found in [4].

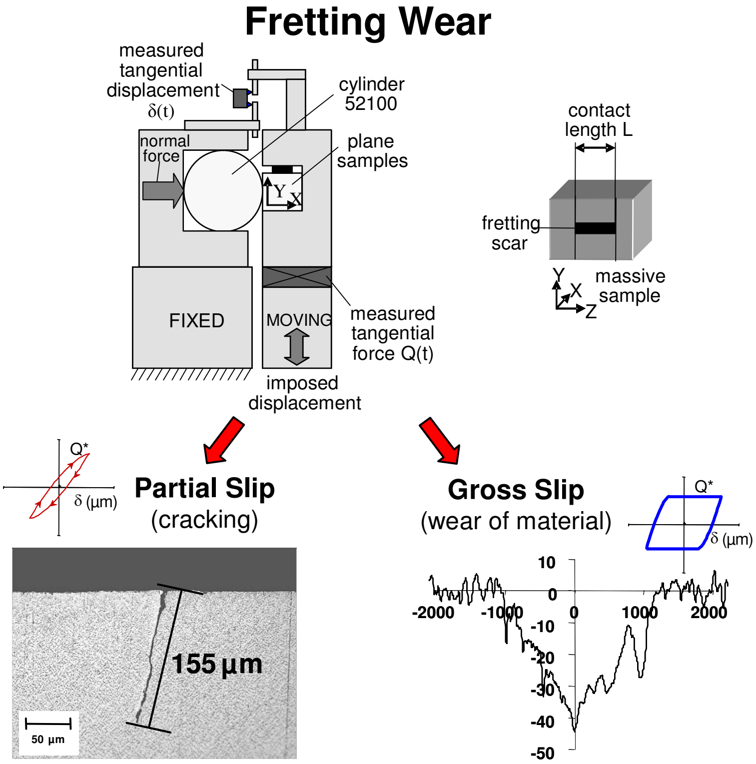

Figure 1: Fretting wear test configuration (cylinder/plane) and the main damages in partial slip and gross slip regimes.

During the fretting test the normal force (P), tangential force (Q) and relative displacement (δ) were measured and recorded. The radius of the cylinder was R=40 mm and the length of the pad L=5 mm cause plain strain conditions near to the central axis of the fretting scar (Figure 1). The normal load was kept constant for all fretting wear tests at P=400 N/mm, inducing a

$p_o$=600 MPa maximum Hertzian pressure and contact half-length a=420 µm. Fretting tests were performed under constant-amplitude displacement at a frequency of 40 Hz and 250 000 cycles for partial slip and 5 Hz and 25 000 cycles for gross slip conditions.

### *Fretting fatigue test apparatus*

An overview of the fretting fatigue test setup is provided in Figure 2. The conventional fretting fatigue setup [5] is installed on a 100 kN servo-hydraulic fatigue machine. The fretting fatigue specimen mounted in hydraulic grips is subjected to a cyclic fatigue load ($\sigma_{FF}$). A simple sphere/plane configuration was used. Pads were fixed onto the rigid plate, a static normal load (P) was symmetrically applied.

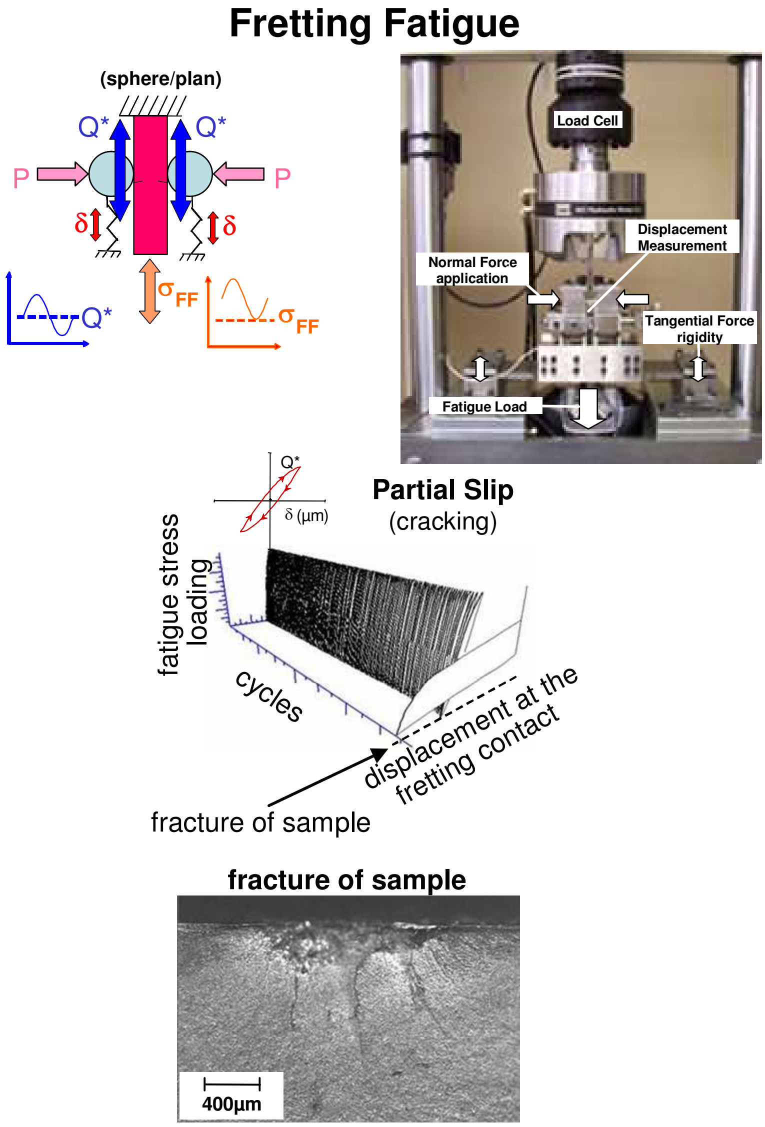

Figure 2: Fretting fatigue test configuration (sphere/plane) and fretting log for fretting fatigue conditions.

The contact loading is associated with the relative displacement at the contact point between the fatigue specimen and the fretting pad [6]. One original feature of the LTDS fretting fatigue setup is the possibility of adjusting the fretting apparatus compliance in order to achieve and maintain a given tangential fretting load (Q*). Relative displacement in the contact was measured by a laser sensor installed on the fretting pad clamp and a reflecting mirror was fixed on the flank of fatigue specimen at the contact position level. The fretting cycles (Q-$\delta$), were plotted along a time log, thus providing the so-called “fretting log” for fretting fatigue conditions. During the test, fatigue loading ($\sigma_{FF}$), normal force (P), tangential force in the contact (Q) and relative displacement ($\delta$) were measured and recorded.

### *Material and surface treatments*

The plain specimen and the associated substrates for surface treatments were made of 30NiCrMo steel. The plain specimens were machined to 10x10x15 mm rectangular prisms with one face polished to an $R_a < 0.05$ µm average roughness. Similar roughness values were measured on the 52100 AISI steel cylinder and sphere counter-body surface. The chemical composition and mechanical properties of the studied material are the following: Chemical composition, weight % (0.31% C; 1.06% Mn; 1.1% Cr; 0.79% Ni); Elastic modulus, E=200 GPa; Poisson ratio, $\nu$=0.3; Yield stress, $\sigma_{Y02}$=740 MPa; Maximum stress, $\sigma_R$=890 MPa; Fatigue bending limit, $\sigma_{d(R=0)}$=400 MPa.

Shot peening treatments on the plain surfaces was conducted following the conventional 0.0063A procedure (200% covering and balls of 0.6 mm diameter). Carried out with the use of an air blast machine, it satisfies the MIL-S-13165 standard, equivalent to an ALMEN intensity of 0.2-0.3 mm (from the AFNOR NFL 06832 standard). The average measured roughness of the specimens was $R_a$=2 µm. The residual stress distribution was measured by mean of XRD layer removal technique. The evolution of the compressive residual stress field obtained on the treated surface is presented in Figure 3.

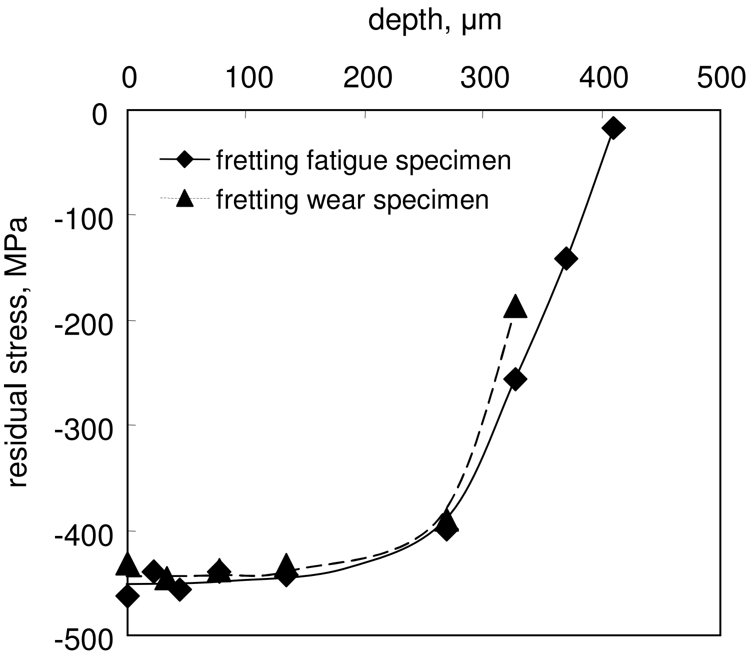

Figure 3: Illustration of the measured residual stress fields after applying MIL-S-13165 shot peening surface treatment.

A tungsten carbide thermal spray coating (HVOF WC-Co coating) was applied to some part of the shot peened specimens. A WC-17%Co powder, with a mean particle size of 35 µm, was used for spraying from 228 mm distance. The DJ 2700 HVOF gun with flow of $O_2$-214 l/min, $H_2$-684 l/min, $N_2$-396 l/min and air 343 l/min was used to reach a 140 µm coating thickness. Then the surface were polished to achieve an $R_a$=0.1 µm average surface roughness.

### *Fretting test procedure and damage assessment*

Before the tests the specimens were ultrasonically cleaned, first in acetone, and secondly in ethanol. All the tests were carried out in ambient laboratory conditions, at room temperature (~23°C) and with a relative humidity between 40 and 50%. In order to quantify the wear volume, the specimens were ultrasonically cleaned to eliminate as much debris as possible. Several regularly-spaced surface profiles, perpendicular to the fretting scar, were then made. An average fretting wear surface was then computed and, multiplied by the contact length (L), which allowed the plane wear volume ( $V_P$ ) to be estimated. A similar procedure to measure the wear of the cylinder part ($V_C$) was followed. The total wear volume of the tribo-system was then calculated ($V_T$=$V_P$+$V_C$). Hence, the total wear volume evolution versus the accumulated dissipated energy during the fretting test could be plotted. More information concerning the fretting wear energy methodology can be found in a previous work [4].

Under fretting fatigue test conditions, in addition to contact fretting loading, the tested material is subjected to homogenous bulk stress. The applied fretting fatigue investigation methodology consists in identifying the threshold crack arrest conditions for the given fatigue loading when the test overruns $10^7$ cycles.

## 3. Results and discussion

### *Identification of sliding fretting regimes*

The transition between partial slip and gross slip conditions [7] is quantified by analysing the fretting cycle by the computing a non-dimensional energy sliding criterion $A=E_d/E_t$; where $E_d$ is the dissipated energy of the corresponding cycle and $E_t=4\cdot\delta^*\cdot Q^*$ is the total energy [8].

As illustrated in Figure 4, there is no significant difference in the coefficient of friction at the transition ($\mu_t \approx 0.81$) between shot peening treatment and plain steel.

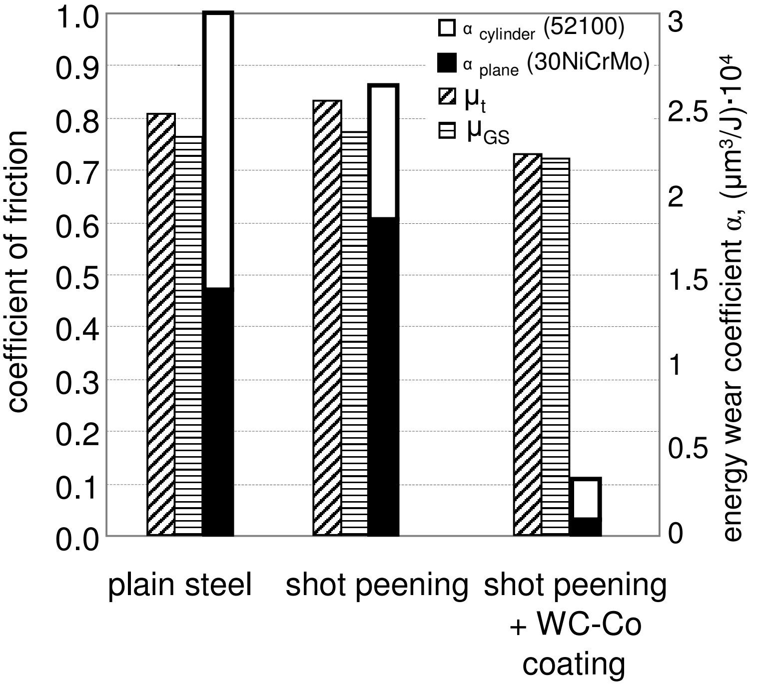

Figure 4: Evolution of the coefficient of friction: ▨ - at the transition between partial slip and gross slip $\mu_t$, ⊟ - in full sliding gross slip conditions $\mu_{GS}$ and quantification of the wear volume based on a dissipated energy approach (cylinder/plane configuration).

After transition (PS/GS) the friction coefficient under gross slip conditions ($\mu_{GS}$) decreases by about 0.05. The thermal sprayed WC-Co coating displays slightly smaller transition, and gross slip friction coefficients, than the metal/metal configuration (0.72-0.73). The representative fretting friction values ($\mu_t$, $\mu_{GS}$) defined for the studied contact couples are compiled in Table I.

Table I: Fretting friction coefficient obtained for plain steel and studied surface treatments (cylinder/plane configuration).

| Surface treatment | plain steel /52100 | shot peening /52100 | shot peening + WC-Co coating /52100 |
|---|---|---|---|
| $\mu_t$ | 0.81 | 0.83 | 0.73 |
| $\mu_{GS}$ | 0.76 | 0.77 | 0.72 |

***Quantification of wear under fretting gross slip conditions***

The wear of materials observed under gross slip conditions was studied using four displacement amplitudes (±25, 50, 75 and 100 µm). Many authors quantify the wear rate using Archard's law [9]. The present study uses an energy approach [8], which displays higher stability. This energy wear approach compares the wear volume to the accumulated dissipated friction energy ($\sum E_d$), or to the work of the tangential force. The observed, linear evolutions allow the determination of energy wear coefficients:

$$\alpha = \frac{\Delta V}{\Delta \Sigma E_d}, \ (\mu m^3/J)$$

Figure 5 confirms the linear dependence; however this evolution does not cross the origin of coordinates but presents a slight shift along the energy axis.

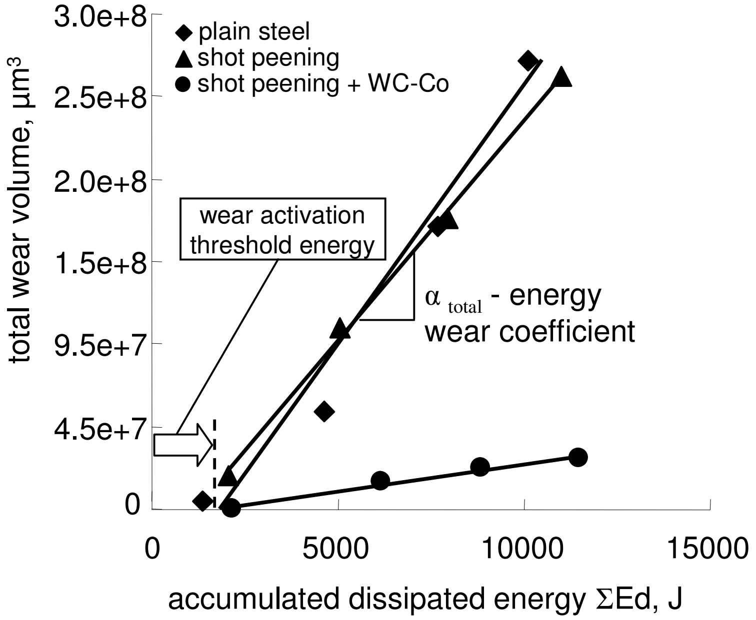

Figure 5: Energy wear coefficients obtained for the studied tribo-systems (cylinder/plane configuration).

Previously associated with an incipient wear incubation threshold energy ($E_{dth}$) [10], it has been shown [10] that this energy can be related to the activation of a so-called Tribologically Transformed Structure TTS [11]. All the studied tribo-systems display similar threshold energies and can be directly analyzed by comparing the associated energy wear coefficients α (Table II).

Table II: Results of fretting wear study under gross slip conditions and fretting fatigue limits (sphere/plane configuration, $10^7$ cycles, $p_0$=600 MPa, a=840 µm, Q*=530 N).

| | Energy wear coefficients α, $\mu m^3/J$ | | | Fretting fatigue limit | Assessment crack length |
|---|---|---|---|---|---|
| Surface treatments | $\alpha_{plane}$ | $\alpha_{cylinder}$ | $\alpha_{total}$ | $\sigma_{FFmax}$ | $l_{max}$ |
| | $\mu m^3/J$ | $\mu m^3/J$ | $\mu m^3/J$ | MPa | µm |
| plain steel | 14534 | 16372 | 30906 | 60 | 158 |
| shot peening | 18738 | 7936 | 26674 | 250 | 165 |
| shot peening + WC-Co | 920 | 2356 | 3276 | 260 | 0 |

It is observed that the shot peening treatment has a very little impact on wear resistance. This confirms a previous study performed on TI-6Al-4V [12]. The plastic deformation induced by shot peening is expected to increase the material's hardness and potentially its wear resistance. However, this tendency is not observed, and even the reverse can be shown (Figure 5). The contact strain loadings are so severe that they erase the previous plastic strain history, and overshadow the shot peening impact. Deeper investigations are required to explain this behaviour. Very good results are observed for the tungsten-carbide cobalt (WC-Co) coating which increases the wear resistance by a factor of 9 (Figure 5).

***Quantification of fretting cracking under partial slip regime***

The cracking under stabilized partial slip conditions is analyzed by considering the two following parameters which are: the crack nucleation threshold of the tangential force amplitude ($Q_{th}^{*}$) and the maximum crack length defined at 90% of the maximum tangential force amplitude associated to the sliding transition: $l_{max}(90\%Q_t^{*})$. The methodology described in a previous work [4] has been applied to identify these parameters (Figure 6).

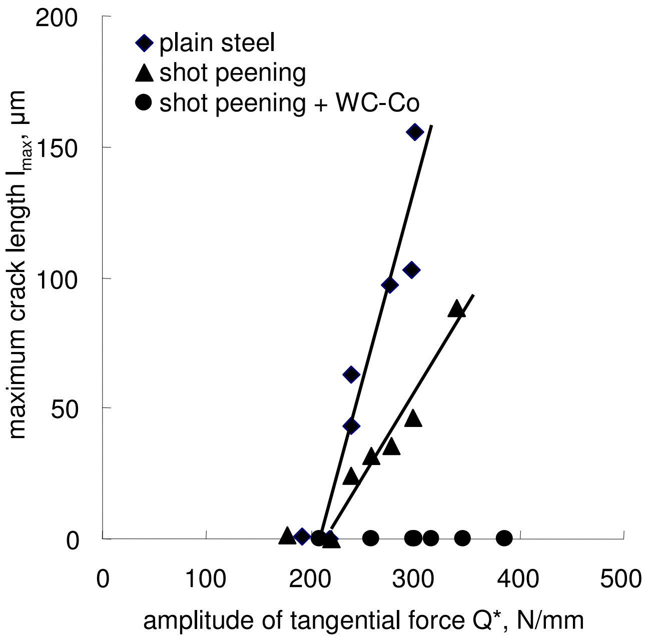

Figure 6: Fretting wear cracking nucleation and propagation evolution of studied tribo-systems under partial slip conditions (cylinder/plane configuration).

For the plain 30NiCrMo materials the crack nucleation threshold amplitude is $Q_{th}^{*}$=218 N/mm, and the maximum observed crack length is $l_{max}$=155 µm. The cracking evolution for shot peening treatment demonstrates no influence on the crack nucleation threshold, but presents a good benefit in terms of crack propagation reduction. Indeed, the intensive surface strain deformation tends to rapidly relax the initial compressive stresses induced by the shot peening treatment. Hence the potential benefit of shot peening regarding crack nucleation is very limited. When the cracks propagate below the surface, higher compressive stress states are maintained. The potential influence of shot peening on the crack propagation rate reduction is then greater. However, this will require complex and specific analyses which could not be performed in the framework of this research. Nevertheless a basic qualitative comparison between the initial 300 µm depth compressive domain with the maximum 155 µm crack length assessment tends to confirm the above conjecture.

Analysis of the WC-Co coating shows that no crack nucleation take place within the studied loading conditions. The results suggest that such treatment appears to be a very efficient fretting cracking palliative. However, the plain fretting cracking investigation which is pertinent to record the contact's impact on crack nucleation and initial crack propagation is not sufficient to describe fully the global cracking behaviour. Combined fretting and bulk fatigue loading has to be investigated to evaluate how an initial surface crack can propagate until the specimen fails.

### *Quantification of fretting fatigue cracking under partial slip regime*

One specific feature of the LTDS fretting fatigue apparatus is that it allows the tangential force amplitude to be monitored, so an iso-fretting fretting fatigue endurance curve can be obtained. However this setup system was not able, at that time, to adjust a cylinder/plane configuration. A simple sphere/plane contact, giving an equal maximum Hertzian pressure ($p_0$=600 MPa) was used, with a 100 mm radius spherical surface shape, to which a P=886 N normal force was applied. It provided a=840 µm contact radius. A pre-load methodology was applied to adjust an alternating fretting loading (i.e. fretting loading ratio $R_{Fretting}=Q^*_{min}/Q^*_{max}=-1$) and repeated fatigue stressing (i.e. fatigue stress ratio $R_{Fatigue}=\sigma_{FFmin}/\sigma_{FFmax}=0$). A constant Q*=530 N tangential fretting force amplitude loading was applied for all the fretting fatigue tests. The corresponding fretting fatigue endurance curves are displayed in Figure 7 and the associated fretting fatigue limits are summarized in Table II.

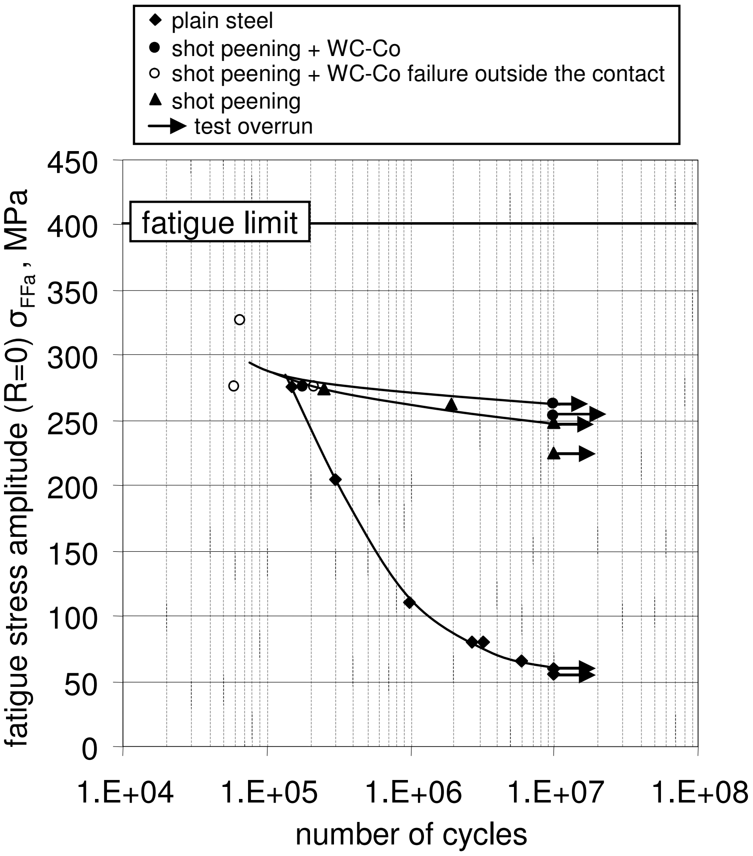

Figure 7: Iso-fretting fretting fatigue endurance curve ($p_0$=600 MPa, P=886 N, Q*=530 N, $R_{Fretting}$=-1, $R_{Fatigue}$=0, $\sigma_{FFa}=(\sigma_{FFmax}-\sigma_{FFmin})/2=\sigma_{FFmax}/2$).

A first comparison with plain fatigue limit clearly shows that the endurance reduction is dramatic for the untreated steel, with a reduction factor of more than 85%. This tendency has been observed in numerous previous investigations [5]. However, one interesting aspect of this work is that the iso-fretting condition permits direct quantitative comparison of the whole fatigue loading range and the surface treatments. Both the shot peening and combined WC-Co coating treatments display a significantly better performance. The endurance reduction at the fatigue limit is less than 35%. Note that for the highest fatigue loading ranges, the failures on the shot peening+WC-Co specimen were observed outside the contact zone. It infers that this treatment fully protects against fretting loading, but can reduce the plain fatigue performance of the material. More precise investigation is, nevertheless, required to confirm this.

Another question concerns the damage mechanism associated with the given fatigue limits. The unbroken fretting fatigue specimens were examined at the fretting fatigue limit. The corresponding crack lengths are reported in Table II. From this comparison it can be concluded that the fretting fatigue limit corresponds to a crack nucleation threshold for the

WC-Co coating, and to crack propagation arrest conditions for the referenced material and shot peening treatment. Such results are fundamental. They clearly outline the difference between the shot peening+WC-Co and the plain shot peening treatment. They also outline that, depending on the material and surface treatments, predicting and modelling the fretting fatigue endurance must take into account either a crack nucleation approach or a crack arrest description. Hence, if they confirm that for plain steel and shot peening the crack arrest approach is appropriate [13] they also demonstrate that for the WC-Co coating then a crack nucleation formulation must be adopted. Hence the crack arrest is identified at about 160 µm, which corresponds to a half compressive zone which plays an effective role in the crack arrest condition and can explain the significant difference with the untreated steel.

## 4. Conclusions

This paper investigates a shot peening treatment and a WC-Co coating applied to 30NiCrMo steel against 52100 steel under plain fretting and complex fretting fatigue loading. This analysis leads to the following conclusions: the studied tribo-systems present mainly stable friction behaviour. Only WC-Co decreases the value of the coefficient of friction; shot peening treatment has very little influence on fretting wear resistance under gross slip conditions and has no influence on the crack nucleation threshold ($Q_{th}$), but performs well against crack propagation under plain fretting and the studied fretting fatigue conditions. The fretting wear resistance of the WC-Co coating is very good under gross slip conditions and decreases by more than 9 times the energy wear coefficient ($\alpha$) as well as reducing the crack nucleation under both fretting and fretting fatigue studied situations. Prediction of fretting fatigue endurance is dependent on the surface treatment. A crack nucleation approach must be considered for the WC-Co coating whereas a crack arrest formulation is required for the uncoated systems.

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