Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

Comparison of Shot Peening and Nitriding Surface Treatments Under Complex Fretting Loadings

K.J. Kubiak [1-2, b], S. Fouvry [1,a], B.G. Wendler [2,c]

[1] Laboratoire de Tribologie et Dynamique des Systèmes, CNRS UMR 5513, Ecole Centrale de Lyon, 36 Avenue Guy de Collongue, 69131 Ecully, France

[2] Technical University of Lodz, Institute of Materials Engineering, Stefanowskiego 1, 90924 Lodz, Poland

krzysztof@kubiak.co.uk

Keywords: fretting, shot peening, nitriding, friction, cracking, wear.

Abstract. Considered as a plague for numerous industrial assemblies, fretting associated with small oscillatory displacements is encountered in all quasi-static contacts submitted to vibrations. According to the sliding conditions, fretting cracks and/or fretting wear can be observed in the contact area. On the other hand an important development has been achieved in the domain of surface engineering during the past three decades and numerous new surface treatments and coatings are now available. Therefore there is a critical challenge to evaluate the usefulness of these new treatments and/or coatings against fretting damage. To achieve this objective, a fast fretting methodology has been developed. It consists in quantifying the palliative friction, cracking and wear responses through a very small number of fretting tests. With use of defined quantitative variables, a normalized polar fretting damage chart approach is introduced. Finally, to evaluate the performance of the assemblies after these protective surface treatments under complex fretting loadings, an original sequence of partial slip and gross slip sliding procedure has been applied. It has been demonstrated that performing of a very short sequence of gross slip fretting cycles can critically decrease the resistance of the treated surfaces against cracking failures activated under subsequent partial slip loadings.

Introduction

Fretting is a small oscillatory movement, which may occur between contacting surfaces subjected to vibrations or cyclic stresses. Considered to be very detrimental for modern industry,

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

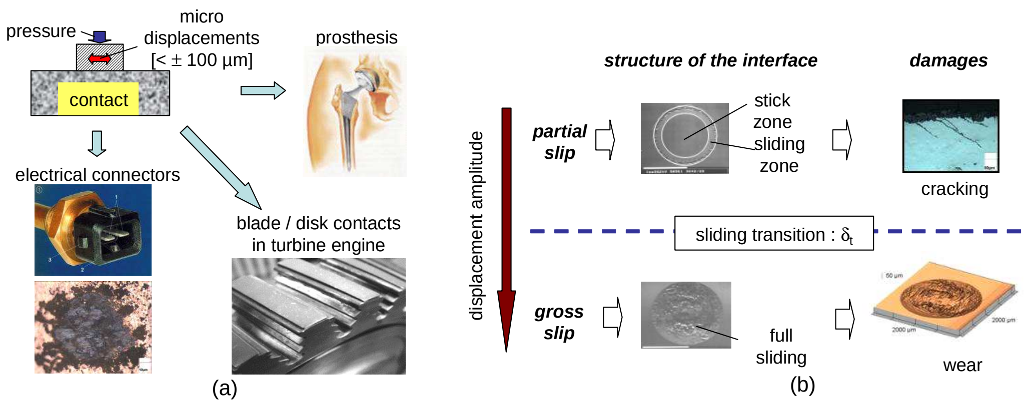


Figure 1: (a) Illustration of the fretting damages in different assemblies; (b) Different forms of fretting damage as a function of the imposed displacement amplitude.

fretting is encountered in all quasi-static assemblies submitted to vibrations. Therefore numerous advanced technological products of modern industry, like helicopters, aircrafts, trains, ships, trucks, suspension cables of bridges, electrical connections etc. are potentially endanger by fretting damage (see Fig. 1a) [1].

Partial slip observed at small displacement amplitudes corresponds to a combined contact area between fretting bodies displaying sliding and sticking zones. Gross slip displacements are greater and related to full sliding conditions. Whaterhouse et al. [2] first indicated a correlation between the sliding regime and the damage evolution (Fig. 1b). It has been shown that for a given normal load and at stabilized sliding conditions fretting cracking is being encountered mainly in the partial slip regime, whereas fretting wear is being observed most of all for larger gross slip amplitudes. The transition from one damage mechanism to the other one, linked to the transition displacement amplitude (δ_t), is not clearly marked. However, competitive wear and cracking phenomena are usually observed near this transition. It is worth to note that first idea of this transition has been supplemented to the fretting map concept first introduced by Vingsbo [3] and completed subsequently by Vincent and co-authors [4].Quantitative approaches have been developed since then to formalize either the cracking phenomena from multiaxial fatigue approaches [5-7] or wear kinetics based on a dissipated energy concept [8, 9].

However it is extremely rare that a researcher assumes a task of a global analysis covering both cracking and wear aspects and very little has been done to provide such a global description of fretting damage. Even less has been made for a comparison of palliatives like surface treatments. It is the purpose of this research to appease such a fundamental need by focusing it on the following aspects:

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at
http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

- development of a fretting wear test in order to analyse both wear and cracking damage induced by fretting with use of a single contact geometry.

- development of a simplified test methodology to identify the constitutive fretting damage (i.e. friction, wear and/or cracking) in a series of less than 10 fretting tests.

- the impact of a combined gross and partial slip slidings on cracking behaviour in the contact area.

Applied to the fretting couple with a reference steel, this methodology has been used to compare two different treatments of the steel surface: the shot peening and plasma nitriding.

Experimental procedure

Fretting test

As previously mentioned the applied normal loadings must satisfy the stress conditions allowing cracking to take place. The displacement control needs also a sufficient resolution to cover both partial and gross slip conditions. These two requirements have been achieved by adapting an original fretting wear test apparatus on a classical tension-compression (25 kN) hydraulic machine described elsewhere [10]. The contact configuration is presented in Fig. 2a. The normal force (P) is maintained at a constant value, while the tangential force (Q) and displacement (δ) are recorded continuously. It allows for the plotting of Q–δ fretting loops (Fig. 2b). Closed (narrow) Q–δ fretting loops correspond to a partial slip condition, whereas opened (quadratic) ones are associated to a gross slip condition. Quantitative variables including the displacement (δ^*) and tangential force (Q^*) amplitudes, the dissipated energy (E_d) and the sliding amplitudes (δ_g) can be extracted from these loops. In order to obtain a dynamic overview of the whole fretting test, the consecutive fretting cycles are being assembled in a three-dimensional form of a fretting log (Fig. 2c). The global loading parameters like:

the average tangential force amplitude

$$\overline{Q^*} = \frac{1}{N}\sum_{i=1}^{N} Q^*{}_i$$

and Archard's product of the normal force by the sliding distance:

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

$$PS = \sum_{i=1}^{N} P_i \cdot 4 \cdot \delta_{gi}$$

can then be calculated.

Prior to testing, all the specimens have been submitted to cleaning in ultrasonic bath first in acetone and next the sliding surfaces have been cleaned with ethyl alcohol just before bringing them into contact. All the tests have been carried out in an ambient laboratory environment (in air, at room temperature), in unlubricated conditions and at the relative humidity of the air 40-50%.

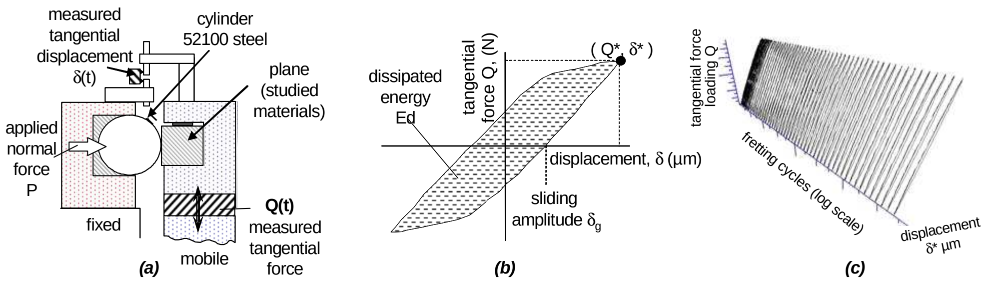


Figure 2 : Test procedure : (a) Fretting setup; (b) Extraction of the contact loading parameters from the fretting loop (gross slip condition); (c) Illustration of the fretting log chart under partial slip conditions.

2.2 Studied materials and surface treatments

Substrate and counterbody

Inspired by an industrial application, the studied tribo-couple consists of a low alloyed 30NiCrMo8 steel (used as the substrate for different surface treatments) and a counterbody made of 52100 AISI steel. The 30NiCrMo8 steel was machined in the form of 10x10x15 mm rectangular prisms with one polished face of the roughness value Ra < 0.05 µm. A similar value of the roughness parameter Ra has been measured on the counterbody surface of the 80 mm diameter cylinder made of the hardened 52100 AISI steel (Fig. 3a). In order to establish properly plane strain conditions, the contact length (L) was fixed at 5 mm inducing a/L ratio below 0.1 (a - half width of the Hertzian contact area).

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

The steel substrate 30NiCrMo8 under investigation was heat treated at 820°C, oil quenched at 20°C and tempered at 520±5ºC for 2 hours. The mechanical properties of the steel as well as of the counterbody are given in Table 1.

Table 1 : Mechanical properties of the steels forming the fretting couple.

	52100 (counterbody)	30NiCrMo8 (substrate)
Elastic modulus, E (GPa)	210	200
Poisson ratio, ν	0.29	0.3
Yield stress, σ_{Y02} (MPa)	1700	740
Maximum stress, σ_R (MPa)	2000	890

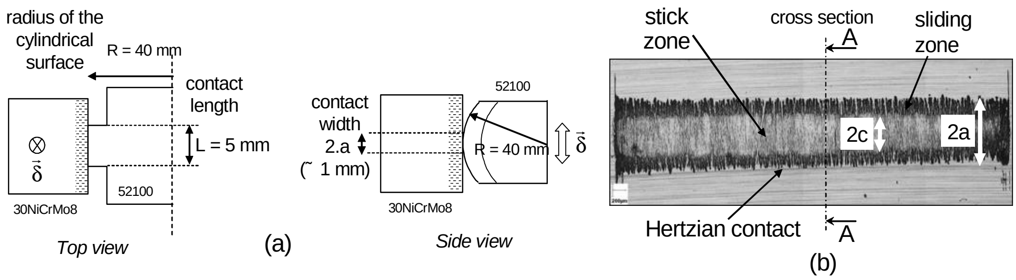


Figure 3 : Contact configuration during the fretting test: (a) Cylinder/plane configuration; (b) Image of a fretting scar on the substrate surface tested in the partial slip regime.

Treatments of the substrate surface

Shot peening

Shot peening of a part of the rectangular prisms has been conducted following the conventional procedure 0.0063A (200% recovering and balls of 0.6 mm diameter). Carried out with 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 AFNOR NFL 06832 standard). The value of the average roughness parameter Ra of the substrate surface after shot peening was equal to 2 µm.

Nitriding

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

Another part of the rectangular prisms has been plasma-nitrided in the conventional commercial process NIVOX 130. After the process the average microhardness of the treated surface was equal to 720 $HV_{0.1}$, an average value Ra of the surface roughness was equal to 0.2 µm and the average thickness of the nitrided layer was about 424 µm. The structure of the nitrided layer is shown in Fig. 4.

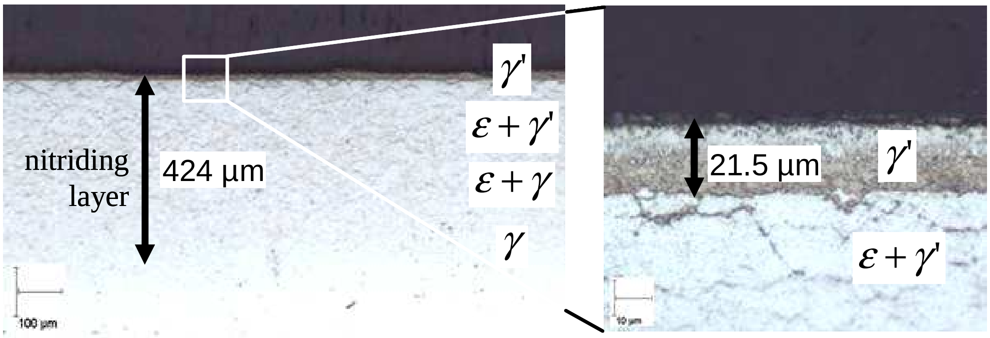


Figure 4 : Optical micrographs of the cross section with the nitrided layer.

2.3 Procedure of damage quantification

Crack length quantification

Due to a particular stress field distribution in the contact area the cracks nucleating during fretting wear are growing rather slowly and do not provoke a rupture of the flat specimen. Therefore, the given cracking analysis consists in measuring and comparing the crack length below the surface as a function of the loading conditions. The following expert procedure has been applied: the plane specimen on which the fretting test has been performed is being cut in two parts along a plane perpendicular to the specimen surface submitted to wear at the middle of the fretting scar. After careful polishing the surface of the cross-section is submitted to optical microscopy observations in order to measure the position and the length of the deepest crack (l_{max}) (Fig. 5)

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

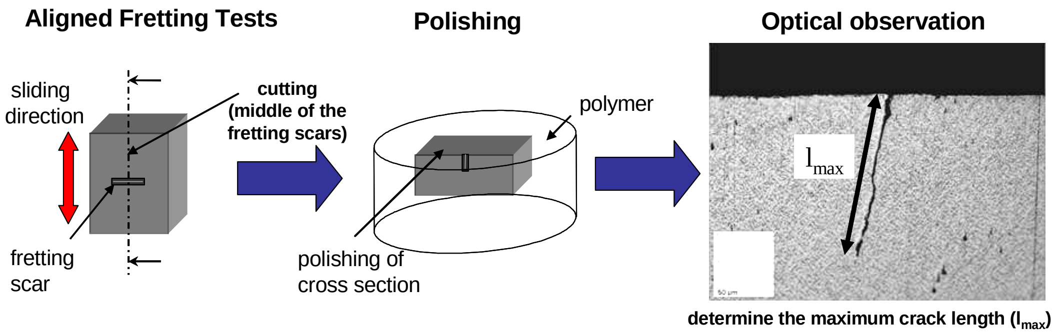


Figure 5 : Fretting crack expertise.

Wear volume measurement

One advantage of the 2D cylinder/plane configuration is that the wear volume can be directly and precisely estimated from a limited number of low cost 2D surface profiles, as the fretting scars are linear. The following procedure was applied. First, the specimens were ultrasonically cleaned to eliminate as much debris as possible. In the next step a number of equidistant surface profiles was made in the direction perpendicular to the length of the fretting scar (i.e. along the sliding direction). An average fretting wear surface is then computed which, multiplied by the contact length (L), allows the plane wear volume (V_P) to be estimated. It is worth to note that in a previous comparison with complete 3D surface profiles the difference between the both estimations was less than 7 %.

The wear volume of the counter-body (V_C) was defined in the same way by extracting the cylinder shape from the surface profiles. Finally, the total wear volume in the contact area was estimated:

$$V_T=V_P+V_C$$

3. Development of experimental methodology

3.1 Definition of the contact conditions

It is well known from different assessments in the field of Tribology and Fatigue that the closer is the test configuration to the pertinent geometry of an industrial implementation, the finer is the

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

prediction of the endurance of the palliative solution. Precise FEM modelling must first be undertaken to reckon the real distribution of the pressure field in the vicinity of the contact area. Due to the extreme loading range and the complexity of the contact configuration, usually the contact geometry in the industrial assemblies can not be reproduced in the available laboratory test. Nevertheless, in order to examine the severity of the contact stress, the cylinder/plane configuration used in the experiments was adjusted to reproduce as closely as possible the external peak pressure. It has been achieved by applying a constant normal force 2000 N which provided a representative p_o=600 MPa maximum peak pressure and an equivalent a = 430 µm half width of the contact area (Fig. 6a). Even though the current FEM computations can provide a reasonable estimation of the pressure distribution in this area, the prediction of the pertinent displacements is more difficult. A simple solution is to cover a sufficient range of displacements in order to identify first the transition from partial slip to gross one, next quantify the cracking phenomena under partial slip conditions and finally to reckon the part of the wear due to fretting under gross slip conditions (Fig. 6b) [9].

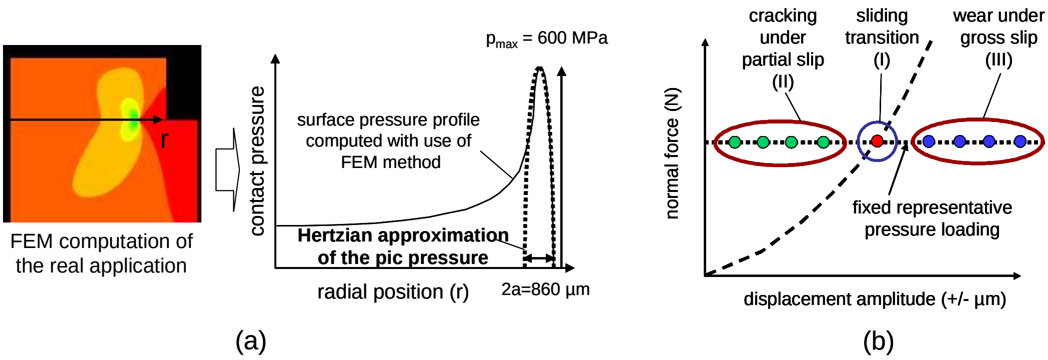


Figure 6 : Definition of the loading parameters: (a) Illustration of the methodology to identify a representative Hertzian loading conditions, (b) Illustration of the three steps fretting damage methodology applied for the Hertzian contact configuration defined in (a).

3.2 Fretting sliding analysis and identification of pertinent friction parameters

To identify the displacement amplitude marking the transition from partial to gross slip regime, an incremental displacement methodology has been adapted [11]. It consists in imposing a very small displacement amplitude at the beginning and increasing it by regular steps. Hence, through a

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

single fretting test, a complete overview of the sliding response is provided. It should be noted that the coherence of this methodology is fully dependent on the value of the increment $\Delta\delta$ of the displacement amplitude and on the number ΔN of fretting cycles imposed to stabilize the sliding contact after consecutive increments of the amplitude (Fig. 7a).

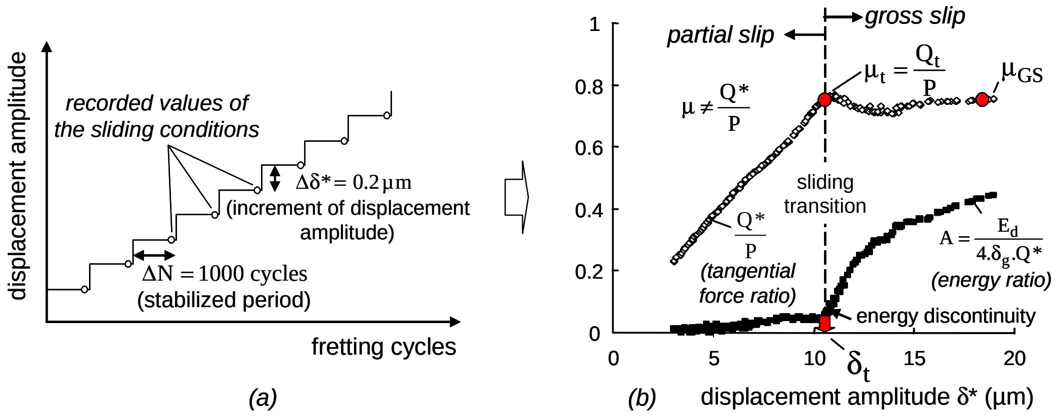


Figure 7 : Illustration of the incremental sliding method applied to a single fretting test, where the fretting sliding response can be quantified. (a) definition of the procedure; (b) results of the procedure applied to the 30NiCrMo8/52100 fretting couple: identification of the sliding transition (δ_t), of the friction coefficient at the sliding transition (μ_t) (representative of the friction law under partial slip) as well as of the friction coefficient under stabilized gross slip conditions (μ_{GS}).

It has been shown in previous investigations that a perfect coherence with classical constant sliding test conditions has been achieved for the case in which the increment $\Delta\delta$ of the sliding amplitude remained smaller than $\Delta\delta$=0.2 µm and the number of stabilizing cycles was greater than 1000 cycles. The response of the reference fretting couple 30NiCrMo8/52100 is illustrated in Figure 7b. The normalized tangential force ratio (Q/P) as well as the dissipated energy criterion $A=E_d/(4\cdot Q^*\cdot\delta^*)$ are plotted versus the applied displacement amplitude.

In agreement with the Mindlin's formalism, the sliding transition (δ_t) from partial to gross slip is related to an energy discontinuity. This discontinuity is associated also to a maximum value of the tangential force amplitude and related to the friction coefficient at the sliding transition (μ_t). It has been confirmed in previous studies that this value is quite representative of the local friction coefficient operating through the sliding domain under partial slip conditions [12]. For the

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at
http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

displacement amplitudes greater than the transition one, the full sliding takes place , which favours the wear processes. In result, a compliant interfacial third body is being produced which decreases the friction coefficient. A stabilized friction value, representative of the friction law under gross slip conditions is then identified (μ_{GS}).

The quantitative variables (δ_t, μ_t, μ_{GS} Q_t) defining the tribological behaviour of the tribosystem under investigation are compiled in Table 2 and the mean values of different friction coefficients for the different fretting couples are given in Figure 8. It can be note that these values calculated from the fretting tests are rather greater than those encountered in numerous conventional tests (see e.g. a value 0.8 of the friction coefficient for the plain steel fretting contact in Figure 8). Smaller friction coefficients have been observed under gross slip condition due to the third body accommodation mechanisms. However, this decrease of friction is rather moderate (between 0.05 and 0.1). It follows also from this comparison that the shot peening has a very little impact on the friction coefficient. A more significant decrease of the coefficient has been observed after the nitriding of the steel surface. Indeed, it is well known that the γ' phase has a significantly lower friction coefficient against the plain steel counterbody. This fact corresponds well with our results from Figure 8. Nevertheless, even in that case the decrease of friction coefficient is not greater than 0.2 and suggests that fretting sliding promotes rather greater friction coefficients in comparison with those in numerous conventional tribotests.

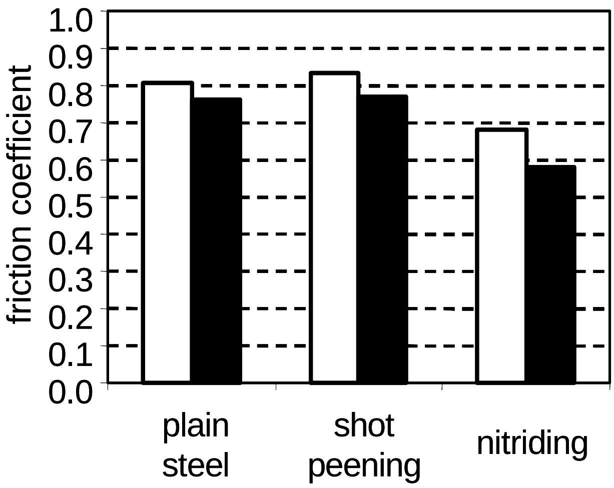


Figure 8 : Mean friction coefficients reckoned with use of incremental sliding analysis : □ friction coefficient μ_t defined at the displacement amplitude δ_t ; ■ friction coefficient under stabilized gross slip conditions (μ_{GS}).

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

Hence the studied treatments do not decrease effectively the friction coefficients and can not be compared with those which provoke a drastic decrease due to application of low friction lubricant coatings [13, 14]. However the present application, imposing a fixed assembly, can not tolerate any relative sliding, and a low friction coefficient is not specifically required. This tendency can be generalized in numerous mechanical components where a similar friction coefficient rather than the reference system are often preferred to limit heavy and tiresome re-designing of the assembly.

3.3 Analysis of the fretting cracking under partial slip conditions

Figure 9a illustrates the methodology of quantifying the cracking response under partial slip. The maximum crack length is achieved at the maximum tangential loading next to the sliding transition. Above this transition the lower value of the friction coefficient and a competitive effect of wear tend to decrease the crack extent [2, 9]. To investigate crack development, constant tangential force amplitudes have been applied by properly adjusting the partial slip displacement amplitude. It has been shown in the previous analysis that for a test duration of around 250 000 cycles the cracks are no longer developing. To maintain stable partial slip conditions, the first fretting test is adjusted to a tangential force amplitude slightly below the transition value (0.9 Q_t). A second test is conducted around 75% of the transition amplitude. By comparing the corresponding maximum crack lengths, the successive test conditions are adjusted to fully describe the crack length evolution versus the tangential force amplitude and to assess the threshold crack nucleation (Q_{th}) as precisely as possible.

Therefore in 4 to 6 fretting tests, two quantitative variables defining crack nucleation in the contact area as well as its length can be quantify:

- The tangential force amplitude (Q_{th}) correspond to the threshold crack nucleation.

- The maximum crack length defined at 90% of the maximum tangential force amplitude and related to the maximum crack length of the fretting contact for the studied pressure condition: $l_{MAX}=l_{max}(90\%\ Q_t)$. The different tribo-systems have been investigated and the corresponding parameters are compiled in Table 2.

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

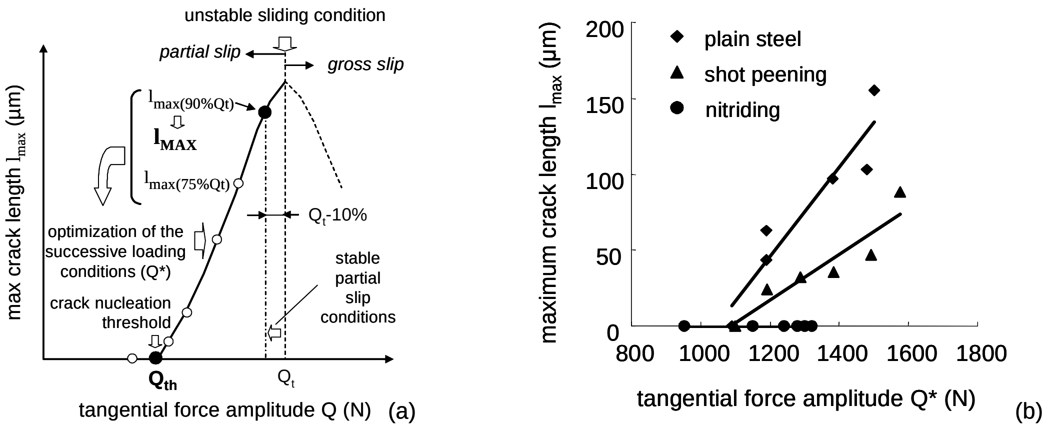


Figure 9 : Illustration of the simplified fretting cracking methodology: (a) identification of the basic cracking parameters (crack nucleation threshold Q_{th}; fretting crack propagation parameter $l_{MAX}=l_{max}(90\%\ Qt)$); (b) application of the methodology to the three tribosystems investigated in the work.

The evolution of crack length versus the applied tangential force amplitudes for the three tribosystems investigated in the work is given in Figure 9b. Taking into account a limited number of the fretting tests, linear approximations have been used to describe the evolution of the crack length. In case of the reference plain 30NiCrMo8 steel the crack nucleation threshold Q_{th} is near to 1100 N and cracks propagate up to their maximum length l_{MAX} of approximately 110 µm. It looks also like the shot peening treatment does not improve significantly the resistance to crack nucleation but displays a significant benefit regarding the propagation. To explain such a behaviour it is essential to consider the very sharp stress gradient in the vicinity of the fretting contact. The cumulated cyclic plastic strain with a maximum on the top surface, tends to relax rapidly the primary compressive stresses provoked by the treatment. Hence the potential beneficial impact of the shot peening on the surface crack nucleation is rapidly declined. It should be noted that this phenomenon depends to a great extent on the elastoplastic behaviour of the material. During the ensuing propagation stage, the crack extends below the surface, crossing domains less affected by the contact loading. Free of cyclic plastic strain, the initial peening compressive stresses are maintained. A higher compressive stress state is imposed at the crack tip which consequently decreases its propagation rate.

The analysis of the effect of nitriding on the cracking response of the reference steel shows that no crack nucleation has been activated within the loading conditions used in the experiments.

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Therefore such a treatment appears to be the best fretting cracking palliative among those investigated in the work. However, wider analyses, including the successively developed variable fretting test conditions as well as fretting fatigue loadings, are required for complete evaluation of the impact of any surface treatment on crack propagation.

3.4 Quantification of wear under gross slip

To compare the wear behaviour under gross slip, four displacement amplitudes from ±25 to ±100 µm were applied. Unlike the cracking phenomena, the wear steady state in this regime is reached after a few thousand cycles, so the test duration can be reduced to 25000 cycles. For the first approximation the Archard model [15] can be applied, (i.e wear volume versus the P·S product). A linear plot has been used for approximation of the wear kinetics and its slope defined as Archard's wear coefficient has been reckoned:

$$K = \frac{\Delta V}{\Delta PS}$$

In order to infer the various wear mechanisms and in particular the mass transfer phenomena from one to the other counterface, the wear of the plain specimen, that of the cylinder as well as the total volume wear of the system will be analysed. One can see from Figure 10a that the plot of the wear volume versus the Archard's product is well approximated by a linear function. However, the plot does not cross the origin of the coordinate system, there is a small shift along the P·S axis associated to wear incubation threshold energy. It has been shown in the previous work [16] that this energy can be related to the cumulated plastic transformation first required to modify the initial microstructure to a rather hard phase called Tribologically Transformed Structure TTS [17].

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

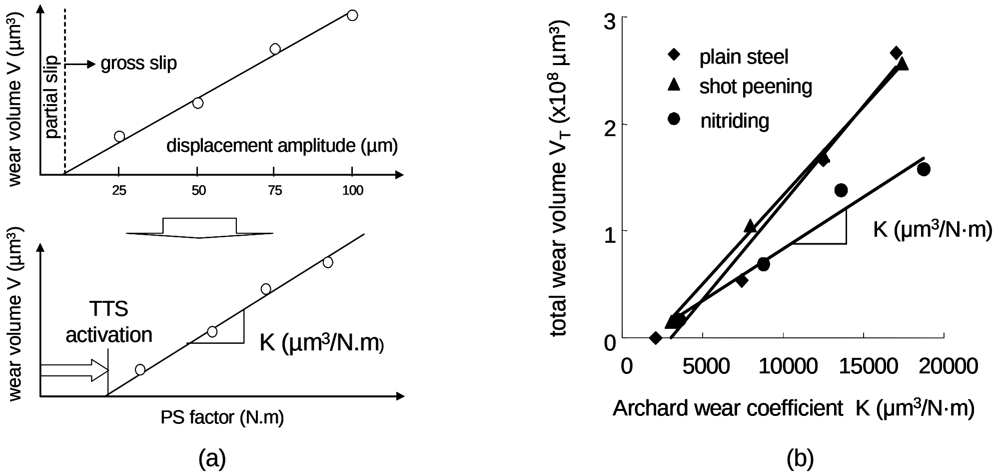


Figure 10 : (a) Illustration of the methodology applied to quantify wear under gross slip conditions; (b) application to the total wear quantification of the tribosystems under investigation.

This very brittle structure is being successively fractured and generates the incipient wear debris. All the tribosystems investigated in the work involve metallic materials which promotes similar threshold energies. Therefore, the pertinent wear palliatives can be analysed directly with use of the Archard’s wear coefficients (Fig. 10b, Table 2).

This comparison in terms of total wear resistance indicates that the shot peening treatment has no impact on wear resistance. Unlike the shot peening the nitriding treatment increases effectively the resistance of fretting wear - the relevant Archard’s coefficient is approximately twice less than that for the reference plain steel.

Compiling the different Archard’s coefficients allows the comparison of flat and cylinder counterbodies (Fig. 11). In case of the reference fretting couple 30NiCrMo8/52100 contact, there is a homogeneous wear in the contact area between the two first bodies. More interesting is the wear response of the same fretting couple with the 30NiCrMo8 steel after shot peening. The plastic deformation induced by peening treatment must have increased the surface hardness and one could expect that its resistance to wear would be greater. In fact the opposite effect is being observed. To explain this behaviour one must take into account the brittleness of the plastically transformed surface and numerous microcracks generated during the peening treatment. Nevertheless more complete investigations are necessary to confirm and better quantify this result.

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at
http://www.scientific.net/MSF.513.105

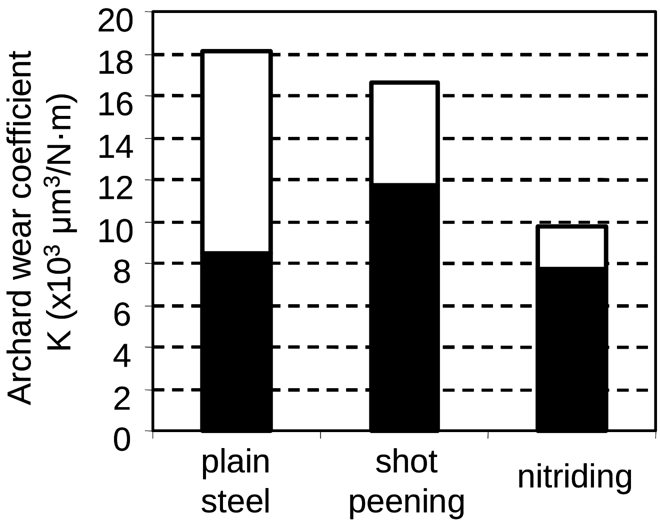


Figure 11 : Wear kinetics of the tribosystems under investigation: □ : K_{52100}cylinder counterbody; ■ $K_{TREAT.}$ rectangular prism made of the reference steel after different surface treatments; □ + ■ : K_{TOTAL} total volume wear of the fretting couple.

On the other hand the wear rate of the reference steel after nitriding treatment is nearly the same as that of the plain steel. This result can be related to the brittleness of the γ' phase. In fact the major gain in terms of the resistance to fretting wear is observed for the 52100 counterbody. This result can be explained if one takes into account that the debris of the brittle γ' phase form a compliant third body between the first bodies of the fretting couple which renders difficult the direct metal-metal interaction and, in consequence, decreases the adhesive wear identified for the previous tribosystem.

To sum up this fast fretting analysis one can say that nitriding treatment is potentially a promising treatment against wear induced by debris formation. However, in the present study, the durability of its benefit action could not be evaluated. More complete investigations are required to quantify the endurance of treated surfaces [18]. One should consider this fast procedure a first and limited approach which can be completed by more exhaustive but also more expensive investigations.

3.5 Cracking response under combined gross and partial slip conditions

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

It has been shown in the previous investigation that nitriding treatment displays a rather good performance against fretting wear in gross slip regime and excellent resistance against cracking activated by stabilized partial slip loadings. However in numerous industrial applications, due to unstable or irregular dynamic behaviour, both partial and gross slip sliding are being encountered. It is therefore fundamental to find out the performance of the surface treatment under combined partial and gross slip sliding conditions. In a first attempt to achieve this objective, an original methodology has been developed which consists in applying consecutively gross and partial slip sliding in the same fretting scars. The purpose of the research was to check if the primary gross slip slidings can suppress or prevent crack nucleation in the contact zone of the reference material after different treatments under stabilized partial slip loadings. The following procedure has been defined. First a fixed number 25000 cycles at a fixed amplitude from the gross slip regime (±100 µm) has been applied. During this initial sequence a significant wear of the contact surface is being observed, which critically modifies the stress distribution. In order to set out the Hertzian partial slip conditions, the new intact cylinder surface has been placed exactly at the same position of the gross slip fretting scar. Then 250 000 partial slip fretting cycles have been applied. Finally, after completion of each the fretting test, the worn surfaces have been submitted to microscope inspection in order to quantify the crack extension.

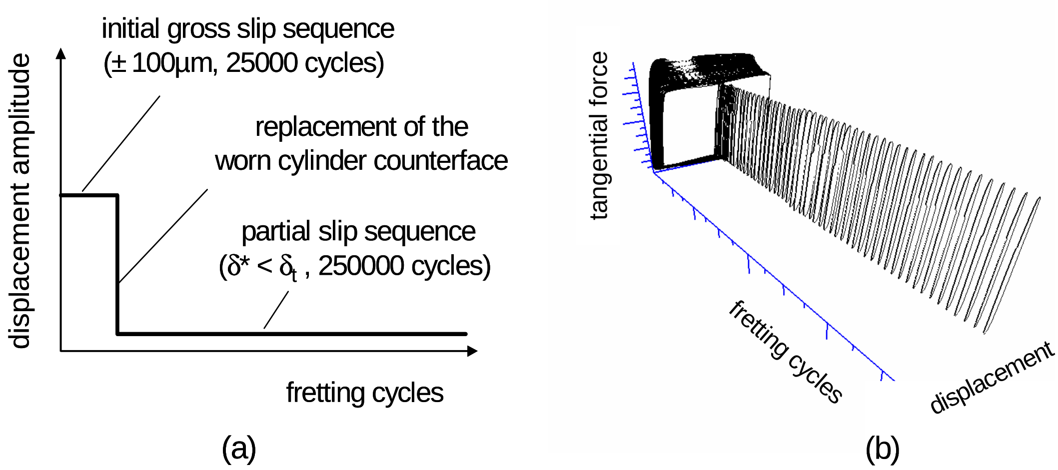


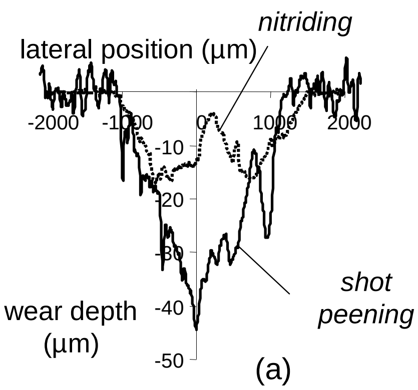
Figure 12 : Illustration of the combined gross/partial slip loading sequence: (a) a scheme and basic parameters of the combined fretting test; (b) a scheme of the pertinent fretting log.

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

A scheme of the whole fretting test and of the relevant fretting log of the sequence of the applied loadings are given in Figure 12. Surface profiles of fretting scars have been conduced at the end of gross slip sequence (Fig. 13a). The greater resistance to wear of the nitrided surface is clearly visible. One can see also that the wear depth extension is significantly lower than thickness of the treated surface (the latter is approximately equal to 200 µm and 400 µm for the shot peening or nitriding treatment, respectively).

Figure 13b clearly present that the application of a rather small number of the gross slip sequence critically decreases the resistance to cracking immanent for both the treatments under investigation. Indeed, the results after the treatments overlap these obtained for the untreated reference steel. A likely explanation of this result is that the primary gross slip slidings, due to a lower friction at the interface, decrease the transition sliding amplitude and, in consequence, the interval of the tangential force amplitude of the partial slip. Another important finding from Figure 13b is that both the shot peening and nitriding treatments have similar crack nucleation threshold and crack propagation rate as the reference steel. Considering the previous remark concerning the limited wear depth extension, the loss of the resistance to cracking can only be explained by an overall relaxation of the initial compressive residual stress generated by the treatments under investigation.



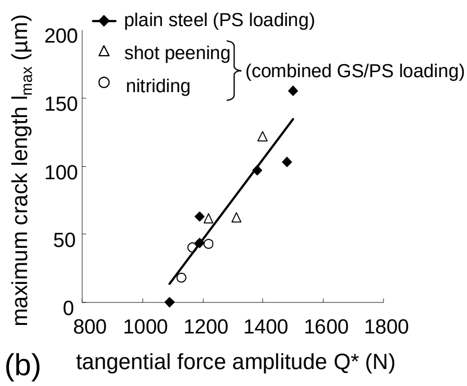


Figure 13 : (a) comparison of the wear scar profiles after fretting test under gross slip regime; (b) evolution of the maximum crack length of the different surface treatments submitted to the combined GS/PS fretting loading.

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

Contrary to the partial slip conditions, severe gross slip ones promote extended plastic strain upon and below the contact interface. Such plastic deformation seems to fully remove the compressive residual stresses produced by the surface treatment. This is the reason, that during subsequent fretting in the partial slip regime, the cracking response is the same as that for the untreated plain steel. This combined partial/gross slip analysis proves that an incipient short period of gross slip sliding critically declines the resistance of the reference steel against fretting cracking achieved due to palliative surface treatments. It also demonstrates the fundamental interest of combined gross/partial slip sequence approaches to validate a fretting cracking palliative strategy.

4. Synthesis and conclusions

Different parameters defined from this simplified fretting damage methodology set forth in the foregoing sections have been compiled in Table 2. It permits a quantitative comparison of different aspects associated with fretting damage such as friction behaviour under partial and gross slip conditions, the wear under gross slip regime, crack nucleation and propagation at stabilized partial slip conditions and finally the cracking response for combined gross and partial slip conditions.

To provide a synthetic illustration of the performance of different palliative treatments, an optimized fretting damage chart is introduced. The pertinent performances are normalized versus the reference system in such a way that the calculated ratio is below one if the treatment is beneficial or above 1 if it is detrimental.

The following variables are considered:

Fretting tribological properties:

$$\underline{\mu_t} = \frac{\mu_t}{\mu_t(\text{ref})}, \quad \underline{\mu_{GS}} = \frac{\mu_{GS}}{\mu_{GS}(\text{ref})}, \quad \underline{Q_t} = \frac{Q_t}{Q_t(\text{ref})}, \quad \underline{\delta_t} = \frac{\delta_t}{\delta_t(\text{ref})}$$

Fretting wear properties (25000 gross slip fretting cycles):

$$\underline{K_{TOTAL}} = \frac{K_{TOTAL}}{K_{TOTAL}(\text{ref})}, \quad \underline{K_{52100}} = \frac{K_{52100}}{K_{52100}(\text{ref})}, \quad \underline{K_{TREAT.}} = \frac{K_{TREAT.}}{K_{TREAT.}(\text{ref})}$$

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at
http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

Fretting cracking properties under stabilized partial slip conditions (250000 cycles):

$$\text{Nucleation : } \underline{Q_{th}} = \frac{Q_{th}}{Q_{th}(ref)}, \text{ Propagation : } \underline{l_{MAX}} = \frac{l_{MAX}}{l_{MAX}(ref)}$$

Fretting cracking properties under combined gross slip sequence (±100µm during 25000 cycles) followed by partial slip conditions (250000 fretting cycles):

$$\text{Nucleation : } \underline{Q^*_{th}} = \frac{Q^*_{th}}{Q^*_{th}(ref)}, \text{ Propagation : } \underline{l^*_{MAX}} = \frac{l^*_{MAX}}{l^*_{MAX}(ref)}$$

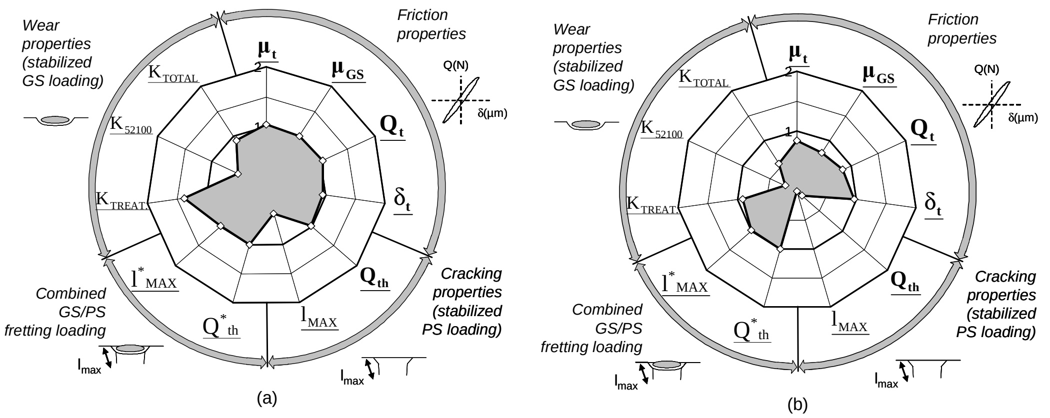


Figure 14 : Normalized polar charts for two different fretting palliative treatments (reference fretting system : 30NiCrMo8/52100 contact) (a) shot peening treatment, (b) nitriding.

Different plots are at the disposal, however the polar charts, first adapted for fretting analysis by Carton and co-authors [19] appear the user-friendly. It is here extended and normalised to compare the responses of the surface treatments under investigation (Fig.14). A rapid overview shows that the peening treatment does not modify the friction behaviour, does not change the crack nucleation response but increases the resistance to crack propagation under stabilized partial slip conditions. It does not change the resistance to wear but infers relative differences between treated (plane) and untreated (cylinder) surfaces. Finally the nitriding treatment characterized by lower friction behaviour, displays a very good resistance to crack nucleation and their propagation under stabilized partial slip conditions and brings about presents lower wear kinetics (in fact, the decrease of wear of the pertinent fretting couple is in the most part attributed to the 52100 counterbody).

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at
http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

Concerning the resistance to crack nucleation under combined Gross Slip/Partial Slip (i.e. GS/PS) conditions the analysis clearly shows the decline of the benefit effect of the treatments under investigation. The compressive residual stresses appear to be fully erased and the cracking behaviour after the both surface treatments becomes to that of the untreated reference steel.

It has been shown in the work that having an optimized palliative strategy most of the fretting damage responses can be quantified through a limited number of tests. It has been indicated also that synergic damage phenomena can operate during combined partial and gross slip slidings. This research has been conducted for plain contact loading without introducing external stressing. In fact, numerous industrial assemblies are subjected to combined fretting fatigue loading. Therefore the present results can not be directly extrapolated to such situations. It should be pointed out that these results must be carefully interpreted and specific precautions must be taken before extending them to any different loading mode.

Table 2 : Compilation of fretting wear coefficients reckoned from the fast fretting methodology under partial, gross and combined gross/partial slip conditions.

Surface treatments		plain steel	shot peening	nitriding
Friction behaviour				
$\mu_{t(GS/PS)}$	-	0.81	0.83	0.68
$\mu_{(GS)}$	-	0.76	0.77	0.58
Q_t	N	1615	1669	1362
δ_t	µm	16.4	15.6	15.9
Archard wear coefficient K under gross slip conditions				
K_{plan}	µm³/Nm	8482	11689	7722
$K_{cylinder}$	µm³/Nm	9650	4943	2042
K_{total}	µm³/Nm	18132	16632	9764
Fretting cracking under partial slip loading sequence				
Q^*_{th}	N	1090	1100	no crack
$\sim 0.9^*Q_t$	N	1480	1490	1220
l_{MAX}	µm	102.83	46.49	no crack
Fretting cracking under combined gross/partial slip loading sequence				
Q^*_{th}	N	-	1090	1090

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

~0.9*Q_t	N	-	1490	1220
l_{MAX}	µm	-	121.59	42.64

To sum up this fretting palliative selection method appears to be a convenient way to compare various surface treatments. It offers a well based selection strategy when a wide range of surface treatments is potentially interesting. However it cannot replace a complete investigation required for a definite validation of an industrial implementation. These two different approaches are not competitive but fully complementary: the fast methodology can be conducted as a first means for choice among a wide range of possible palliative surface treatments, whereas classical fretting map analysis must be performed to validate a choice through a restricted number of solutions.

References

[1] Hoeppner D. "Mechanisms of fretting fatigue and their impact on test methods development", ASTM STP 1159, 1992, 23-32.

[2] Waterhouse R.B., "Fretting Fatigue", R.B. Waterhouse (Ed.), Applied Science, London, 1981.

[3] Vingsbo O., Soderberg. S. "On Fretting Maps" Wear 126, 1988, 131-147.

[4] Vincent L. "Materials and Fretting", Fretting Fatigue, ESIS 18, 1994, 323-337.

[5] Araujo J. A., Nowell D., "The effect of rapidly varying contact stress fields on fretting fatigue", International Journal of Fatigue, 24, 2002, 763-775.

[6] Vallellano C., Dominguez J., Navarro A., "On the estimation of fatigue failure under fretting conditions using notch methodologies", Fatigue Fract. Eng., M26 (5), 2003, 469-478.

[7] S. Fouvry, K. Elleuch, G. Simeon, " Prediction of crack initiation under partial slip fretting conditions ", Journal of strain analysis (ImechE) 37, No.6, 2002, 549-564.

[8] Mohrbacher H., Blanpain B., Celis J.P., Roos J.R., " Oxidational wear of TiN coating on tool steel and nitrided tool steel in unlubricated fretting", Wear, 180, 1995, 43-52.

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105

Published in Materials Science Forum, Vol. 513, p.105-118, (2006) – Scientific Net
http://dx.doi.org/10.4028/www.scientific.net/MSF.513.105

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

[10] Fouvry S., Duo P., Perruchaut Ph. “A quantitative approach of Ti-6Al-4V fretting damage: Friction, Wear and crack nucleation “, Wear, 2004, in press.

[11] Voisin J. M., Vannes A. B., Vincent L., Daviot J., Giraud B., "Analysis of a tube-grid oscillatory contact: methodology for the selection of superficial treatments", Wear, 181-183, 1995, 826-832.

[12] Proudhon H., Fouvry S., Buffière J.Y., “A fretting crack initiation analysis taking into account the surface roughness and the crack nucleation process volume”, International Journal of Fatigue, in press.

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

[14] Zhou Z R, Vincent L. "Lubrification in Fretting a review", Wear 225-229, 1999, 962-967.

[15] Archard J., "Contact and rubbing of flat surfaces", Appl. Phys., 24, 1953, 981-988.

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

[17] Sauger E., Fouvry S., Ponsonnet L., Martin J.M., Kapsa Ph., Vincent L., “Tribologically Transformed Structure in Fretting”, Wear 245, 2000, 39-52.

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

[19] Carton J.F., Vannes A. B., Vincent L., "Basis of a coating choice methodology in fretting", Wear, 185, 1995, 47-57.

This is the pre-peer reviewed version of the following article: K. Kubiak, S. Fouvry, B.G. Wendler, Comparison of shot peening and nitriding surface treatments under complex fretting loadings, Materials Science Forum, Vol.513, (May 2006), p. 105-118, doi: 10.4028/www.scientific.net/MSF.513.105, which has been published in final form at http://www.scientific.net/MSF.513.105