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# Fretting: a Failure Mechanism in Fatigue of Strands

## Fretting: un mécanisme d´endommagement en fatigue des câbles

## Fretting: ein Schadensmechanismus des Ermüdungsverhaltens von Litzen

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### SUMMARY

Several aspects of fatigue properties of strands can be explained through the fretting behaviour of constitutive steels. This paper gives indications about the fretting behaviour of steels through the effects of slip amplitude and normal loadings. Fretting maps are discussed from which cracking domains are identified.

### RÉSUMÉ

Le comportement en fatigue des câbles est souvent associé à la resistance au fretting des fils métalliques. Ce papier présente quelques données relatives à la résistance au fretting d'aciers en insistant sur les effets spécifiques de l'amplitude de glissement et du chargement normal. Les cartes de fretting permettent de bien identifier les domaines à risques dans lesquels s'amorcent préférentiellement les fissures de fatigue.

### ZUSAMMEMFASSUNG

Die Lebensdauer von Litzen steht häufig im engen Zusammenhang mit dem Reibungsverhalten der einzelnen Drähte. Diese Arbeit befaßt sich mit den Auswirkungen der Parameter Normalkraft und Reibungsamplitude auf das Reibungsverhalten von Stählen. Sogenannte Reibungskarten erlauben die Identifizierung von Risikobereichen in denen bevorzugt Ermüdungsrisse auftreten.

## 1. INTRODUCTION

The mounting of metallic wires or strands is widely used in many industries because of the good compromise achieved when taking into consideration ductility, stress to failure, fatigue strength or cost. These industrial applications which include the cables used in mines, aerial tramways, ship moorings, ski tows, fibres in tyres and break cables, require good resistance to fatigue loadings.

Many efforts have been made to try to increase this fatigue strength by means of thermomechanical treatments of the wires, by superficial coatings or by modifying the assembly architecture so as to diminish the local mechanical loading.

When considering the data in the available literature, fatigue results appear to be very scattered and any explanation remains very hazardous due to the great number of test parameters [1]. Furthermore, it is difficult to run fatigue tests with the actual cables and extrapolation of short time duration testing to industrial lifetimes of more than fifty years is still under discussion.

Both theoretical and experimental aspects have been considered as presented in this workshop. It is clear that any attempt to describe the fatigue strength from the ultimate stress or to set predictive models requires further knowledge of the fatigue mechanisms [2]. However results are now available on the effects of the loading (tensile, bending, torsion) and on the first failures especially of the wires in the internal layers [1,3]. More and more friction between the wires appears to be a major mechanism which can initiate notches and thus fatigue cracking.

With the hypothesis of a friction effect in the fatigue failure mechanism, fretting is increasingly seen to be the main cause of the fatigue life reduction [1, 4, 5]. Waterhouse has analysed the influence of heat treatments and decarburising on the fatigue behaviour of .7 carbon steel wires. The initiation of fatigue cracks was seen at the limit between the central sticking zone and the peripheral ring in which sliding occured [7, 8]. Several coatings (copper or silver) were then considered as good anti-fretting palliatives [9].

Because of the increasing interest in the fretting effect to describe the fatigue drops, this paper deals with an analysis of the degradations which can be observed in all the contacts submitted to small displacements. The risks of fatigue crack initiation will be particularly discussed using the new interface tribology concepts.

## 2. INTERFACE TRIBOLOGY CONCEPTS

Many industrial parts can suffer large drops in their fatigue lifetime whenever local contacts exist. Indeed secondary loadings can induce small displacements between quasi-static assemblies and thus give rise to wear (matter loss) or fatigue (cracking) processes.

Very harmful for industry, this specific degradation is known as fretting-wear, fretting-corrosion or fretting-fatigue. The word fretting is in fact related to small displacement amplitude movement occuring between contacting surfaces and the second word is used to describe the mechanism which induces the damage. However these terms can lead to misconceptions and we would first like to provide a basis for wear aproaches. Indeed, contacts can induce the stopping of machine elements by function loss, fracture or the appearance of nuisances (noise,...).

Materials submitted to contact loadings suffer local stress and strain fields. These fields are related to many parameters which depend on mechanical, material or surface properties and which can vary in time due to the velocity accommodation mechanisms. The knowledge of these fields throughout the contact life is required to determine the material behaviour but it is often difficult to calculate or at least estimate the local stress and strain. Due to local overstressing or overstraining, the material can fail by crack initiation or plastic deformation and brittleness. This first damage is defined as the first wear step. For well-controlled stress and strain fields, this material response is not to be considered totally as dispersive and, moreover, its prediction is possible.

The classical dispersion of wear results found in the literature is a consequence of the so-called second step related to the "use" of the first material response by the contact so as to accommodate the imposed velocity. This behaviour can be illustrated by two examples :

- if the material first fails by debris detachment, the wear regime can explain matter loss. A source and sink approach of the third body justifies the scattering of the results from their possible protective role. For instance, the protection depends on whether the debris are recycled or not during continuous friction (scraping or snow plow effect), whether they are trapped or not due to the displacement amplitude for alternative friction, whether the contact is opened or closed,...

- if cracks are formed, the propagation path depends on the failure mode at the crack tip. Thus the nature of the friction regime can cause the same initial crack to form spalls, to propagate up to the fracture of the part or to arrest.

Without going into the details of recent developments, it can be said that friction and wear have moved :

- from the tribology of volume [10], where body A was rubbed againt body B and wear rates and friction were monitored ;

- through the tribology of surfaces [11], where surface science brought to this domain a solid scientific base ;

- to the tribology of interfaces which focuses on the role of the interfaces or third bodies, whether natural (debris) or artificial (solid lubricants).

The tribology of interfaces is concerned with two basic problems : (i) third-body formation, composition and role, and, (ii) third-body kinematics.

Modelling for wear or durability considers each element of the triplet "mechanisms, first and third bodies" englobing dimensions which go from to the nanometer up to the meter scales [12].

- Mechanisms are gear boxes, bearings, brakes, cables, etc. Mechanisms transmit loads from one machine component or "first body" to another and first bodies only function properly when they are at least separated by an efficient "third body". Running conditions (configuration, loads, speeds, temperature, environment, etc...) imposed by a given mechanism on the rubbing first bodies have to be either calculated or estimated (either theoretically or experimentally) as they govern wear and life.

- The first bodies are the rubbing surfaces and the subsurfaces in which the displacement is to be accommodated. They are homogeneous, coated or have a functional property gradient.

- The third bodies separate the two first bodies partly or fully under the conditions imposed. Oil films, solid lubricants, debris beds are third bodies. Bulk and screen properties govern the type of load carrying mechanisms.

Recently, the velocity accommodation mechanisms have been analyzed [13, 14]. All mechanisms combine a site and a mode. The five sites are the two first bodies and the third body which itself includes the two screens and its bulk. Four modes have been identified : elastic, rupture, shear and rolling.

The main guides due to interface tribology concepts are summarized below:

- Wear is not an intrinsic property of materials and extrapolation from laboratory benches to industrial applications is hazardous.

- Adhesion, abrasion, corrosion and fatigue are not wear mechanisms. They govern particle detachment and cracking which is only one of the steps of the wear process.

- A detached particle is a wear particle only when it is lost for the contact and the presence of debris in a contact does not accelerate wear. In most instances, in dry friction, the protection afforded by the debris is greater than the damage caused by its presence.

- A given material cannot be a priori considered as a "good" or a "bad" anti-wear material. Pairings of materials can give good solutions to well-identified wear problems. For instance a hard coating can quickly form debris which then protect the bulk material if the debris can be trapped in the contact.

- The running of accelerated fretting tests can lead to erroneous conclusions.

- A wear law can only be established for a given mechanism if all elements of the triplet are identified.

- Interface tribology promotes simulation rather than the use of wear laws.

These few results are general. In the case of fretting, it is clear that the first bodies can play a more major role than under continuous sliding. The triplet approach appears very basic for fretting problems also.

## 3. CRACKING INDUCED BY FRETTING

Fretting wear terms suggest that the small displacements mainly result in particle detachment and matter loss. Debris have been shown to often nucleate in a specific superficial area called a Tribologically Transformed Structure (T. T. S.). Once formed, the debris is trapped, crashed and then oxidised. In the case of steels, red powder is classical. The two synthesis books written by Waterhouse are generic documents for all aspects of fretting [15, 16].

Generally, cracking is related to fretting-fatigue and few results describe cracking as a degradation in the case of fretting-wear, i.e. without external loading. Vingsbo et al. [17, 18] have shown that such cracking appears at the limit between the sticking and the sliding zones. Pellerin [19] studied the conditions for crack initiation of aluminium alloys. These approaches refered to wear maps developed below.

Cracking under fretting fatigue was studied by several authors. Chivers and GORDELIER [20] described fretting fatigue as the super imposing of skin stresses due to the contact loading and stresses due to the cyclic external loading. NISHIOKA and HIRAKAWA have taken into account the modification of the friction coefficient values which appear in the very first cycles [21].

Fracture mechanics were used to define the critical crack length which induces failure [22, 23, 24, 25]. At the beginning of the fretting fatigue test, cracking is governed by the two loadings while the fretting loading can be negligible from a given crack length. Propagation laws have been used, including, for instance, crack closure to justify specific behaviours [26].

Many researchers has tried to pinpoint in an accurate way the effect of parameters such as the material strength, the bulk stress, the R ($\sigma_{min}/\sigma_{max}$) ratio, the normal load, the displacement amplitude as well as frequency, hardness, residual stresses, temperature, environment, ... [27, 28, 29]. The results will not be discussed here but a fatigue limit drop up to 70 % can be noted.

All these results refer to delicate experiments. Very often the slip amplitude is not well-controlled despite the fact that it is one of the main parameters which control crack initiation. To rationalize experimental approaches, a good knowledge of contact mechanics is required.

## 4. CONTACT MECHANICS BASES

It is not possible to explain in only a few paragraphs how and to what extent contact mechanics govern fretting fatigue. The subject is well documented and an excellent review is given in Ref. 20.

Efficient models for stress, deformation, temperature and stress intensity factor maps for homogeneous, cracked, smooth or rough solids now exist.

Based on restrictive hypotheses, Hertz theory permits a good estimation of the pressure distribution p in a contact submitted to a normal loading Fn. In the case of ball/plane contacts, stress calculations from Boussinesq and Cerutti indicate that the radiant $\sigma_r$ stress (i. e. $\sigma_{xx}$ in the plane y = o) useful to estimate the crack nucleation risks reaches a maximal value at the limit of the contact :

$$\sigma_{r\,max} = (1 - 2\,\nu)\,Po/3$$

with Po as the maximum pressure at the contact center and $\nu$ Poisson's coefficient.

In the case of a tangential loading, gross slip as described by Coulom's law or partial slip (Cattaneo [30] and Mindlin [31]) must be considered.

For gross slip regime, calculations were made by Hamilton and Goodman [32] and then by Sackfield and Hills [33].

$\sigma_r$ was a compressive stress at the front of the contact and the maximum at the rear is increased by a "tangential term".

$$\sigma_{r\,max} = (1 - 2\nu)\,Po/3 + (4 + \nu)\,\pi\,\mu\,Po/8$$

in which $\mu$ is the friction coefficient. Of course, in the case of a cycling of the tangential loading, this overstress can nucleate a fatigue crack if it reaches the fatigue limit of the material.

The tangential loading strongly modifies the development of the plastic zone beneath the contact. For a normal loading, the plastic zone is obtained when $Po \geq 1.6\ \sigma_y$ ($\sigma_y$= yield stress) while it is formed for $Po \geq 0.60\ \sigma_y$ with a friction coefficient equal to 0.5. The cumulative overstraining can induce a material transformation leading to the T.T.S..

Depending on their location in the contact, these overstraining or overstressing phenomena can act in a competitive way to justify the material response.

In the case of a cylinder-plane contact, stress calculations were given by Poritsky [34], Smith and Lin [35] and more recently by SACKFIELD and HILLS [33]. The maximum stress value at the contact rear is now given by the tangential expression :

$$\sigma_{xx\,max} = 2\mu\ Po$$

Partial slips are characterised by two contact zones :

- a peripheric slip zone
- a central sticking zone with a c radius. These calculations are based on elastic hypotheses while plastic deformation is generally proved for fretting experiments. For fretting-fatigue experiments, Bramhall [23] and O'Connor [22], Nowell and Hills [36] have considered a flat specimen with a cylinder pad. The tangential load dissymetry tends to increase the maximum $\sigma_{xx\,max}$ at the rear of the contact.

Crack initiation in the case of fretting without external cycling has not yet been intensively considered. Research undertaken by Bramhall [23], O'Connor, Nowell and Hills [24, 25, 36] has established the effect of the displacement amplitude at the contact edge on the life time.

## 5. FRETTING MAPS

Our fretting methodology is based on the following experiments which have been described elsewhere [37].

a) Fretting tests are conducted under a normal load Fn fixed in the range 200 to 1000 N and for a displacement range of ± 10 to ± 100 µm. The tangential force is continuously recorded during the N cycles.

b) Friction logs i.e. tangential load versus displacement as a function of the number of fretting cycles, are plotted.

c) After testing, all the samples are cut and polished for optical and electron microscopy examinations so as to detect surface and bulk damages.

Many metallic, polymeric or composite materials have been tested. Tangential force-displacement cycles have been used to define three fretting regimes (a, b, c) which are associated with the three material responses (i, ii, iii) defined from optical examinations.

a) Stick regime : the tangential loads increase with the displacement and then decrease linearly with the same value, during the reverse movement. The cycle is closed (actually a small opening of the cycle may exist, which is below the accuracy of the measurement : Mindlin's description of partial slip may apply sometimes for this kind of cycle) ; no sliding is achieved at the interface ; only elastic deformation of the device and of the sample occurs for the imposed displacement.

b) Mixed regime : in this cycle, after the elastic part, the relation between the tangential load and the displacement is no longer linear. This cycle is called an elliptic cycle. The non-linear part of the curve represents a decrease in the rigidity while the non-reversibility of the curve indicates that sliding occurs in the contact, at least partially. Such elliptic cycles can also be recorded for large cracks which accommodate the displacement by an "opening-closing" process but the Ft-D slope then strongly diminishes.

c) Gross slip regimes : in a parallelepipedic cycle, the tangential load remains quasi-constant beyond a small value of the displacement. This occurs when complete sliding takes place in the contact. The elastic part of the cycle is the same as that observed in the closed cycle and the real displacement is smaller than the imposed displacement.

Concerning the material response, three cases were identified :

i) low damage surfaces only suffered small plastic deformation of some asperities. Very few particles were seen, resulting probably from the initial stages and the microdisplacement on the edge of the contact area. This was considered as a "non degradation" response and mainly related to the stick fretting regime.

ii) two main kinds of cracks have been observed. Deep cracks of some millimeters in length were located at (or very close to) the contact boundary for the stick or mixed regime. For partial slips with sticking and sliding zones the longer cracks were always noted at the boundary while plastic deformation was revealed in the center of the contact. In the case of gross slip, cracks were detected everywhere in the contact [38].

iii) Debris were always seen during the slip regime. For several metallic alloys, we showed that debris are formed from the specific area called a Tribologically Transformed Structure (T.T.S.). This zone reacted differently from the non transformed initial structure (white layer for steels). It is very hard and is formed by a nanometric grains and composed of the stablest phase as described by the equilibrium diagrams. The quick formation of the T.T.S. justifies that a same alloy treated under several thermomechanical treatments exhibits the same fretting behaviour because the debris rheology depends only on the T.T.S. [19, 39].

For wear induced by fretting, the following process is now admitted :

a) the gross slip induces a destruction of surface screens and sets a two-body problem.

b) wear particles are formed following adhesion and plastic deformation. The strain hardened material (e.g. the T.T.S) embrittles, it fractures and metallic debris is detached.

c) once formed the particles crash and oxidize to form the third body layer.

d) the displacement is accommodated by shearing in oxide platelets.

If debris are trapped, the maintenance of a powdered bed governs the subsurface protection and wear. Debris indeed fight wear and are not at all wear particles.

When analysing the friction logs, the Ft-D cycles and the material responses, the concept of fretting map allows for a good control of the wear process. A running condition fretting maps (RCFM) is similar to the maps introduced by Vingsbo and Söderberg.[17] RCFMs describe the various fretting regimes for a given number of cycles when the normal load and displacement are modified. They are related to the contact conditions : stick, gross slip and partial slip. To take into account the friction log shape, a mixed regime is preferred to partial slip since it is generally obtained through several cycle shapes. (parallelepipedic followed by closed then elliptic cycles).

The material response fretting maps (MRFM) give the three domains defined on the basis of the microscopic observations (Non Degradation, Cracking, Particle Detachment) in the same kind of normal load versus displacement representation. Generally MRFMs cannot be superimposed on the RCFMs : the Particle detachment domain is associated with gross slip regime but the cracking domain first depends on the number of cycles as in any fatigue problem. The cracking domain first appears in the mixed regime domain and then spreads over the stick domain.

The prediction of the MRFMs requires :

- the comparison of the tensile skin stress to the fatigue limit of the material,
- the modelling of the T.T.S. related to the cumulative plastic strain in the upper layers.

The RCFMs identify the fretting regime and thus permit the calculation or the estimation of the stress and strain fields. If we consider that similar running conditions induce the same fretting regime, two cases can be analysed :

- the RCFM domain is a gross slip regime. Thus the main degradation is particle detachment resulting from overstraining, cyclic hardening and T.T.S. formation. For a same material group, the formation mechanism and the nature of the T.T.S. are very similar. Thus two same based alloys will have very similar tribological behaviours all the more so since the debris will have the same tendency towards oxidation and trapping.

- In the case of the stick or mixed regime, cracking is the main risk which depends on the $\sigma_{xx}$ value at the contact frontier. Classical fatigue properties govern the nucleation of the fatigue cracks and their propagation. The two previous alloys will have far different behaviours according to their fatigue properties and, for instance, their residual stress levels. These differences increase with the number of cycles.

The definition of the MRFM gives development engineers a tool for the qualitative prediction of material behavior. Indeed, the knowledge of the displacement in the structure and of the local loading allows for the prediction of the major risk in terms of durability (fissuration) and of loss of function (debris formation). Even if the character of the step is too qualitative, it is a new and useful method. To give an example, the MRFM allows for the situation of the maximum risk of fissuration which is not necessairly associated with exterior maximum loading.

The two maps that we propose here have, in our opinion, the principal interest of displaying the critical area called cracking which corresponds to the criteria of crack propagation. Different measures can be adopted for industrial purposes taking these two maps into consideration.
The mixed and sticking areas of the RCFM can be diminished in order to limit the maximum value of the constraint $\sigma_{xx}$. Thus the use of sliding varnish can bring about the diminishing of the risk of $\sigma_{xx}$ going beyond the fatigue stress . As a second possibility, the use of the MRFM map shows the interest of increasing the fatigue strength of materials : this increase is of little usefulness if the contact is in total sliding. It is significant in the mixed regime. Here a shot peening is an excellent way to fight against cracking in small displacement. The user disposes of a third method, not developed here, which consists in the use of a third body or a film in which the difference in velocity can adapt between the two first bodies.

The use of maps and velocity accommodation mechanisms seems to us to be the means to rationalize the seeking of solutions. This same approach has been used to justify the corrosion action in fretting.

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