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Predicting fretting fatigue in engineering design

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ABSTRACT

The progress in fretting fatigue understanding and predictability is reviewed, with engineering applications in mind. While industrial assessments often relies on simple empirical parameters, research in fretting fatigue should allow the design engineer to improve confidence in the fretting fatigue analysis.

Fretting fatigue cracks often form in multiaxial stress fields with severe gradients under the contact area, and are inherently difficult to predict.

By describing the fretting stress gradients using comparisons with the mechanical fields surrounding cracks and notches, crack nucleation threshold conditions and finite life can efficiently be determined. Also, non-local stress intensity multipliers provide promising tools for the industrial finite element analysis, often involving complex geometries and loading conditions.

The use of multiaxial fatigue criteria to determine fretting fatigue nucleation life is also reviewed. Researchers have shown that critical plane calculations with some stress-averaging method can predict fretting fatigue crack initiation. However, the frictional interface causes non-proportional loading paths, and the application of critical plane methods is not straight forward.

1. Introduction

Fretting is the phenomenon in which contacting surfaces subjected to oscillatory relative movement experience surface damage. Over time, cracks form at the surface and result in *fretting fatigue* related failures. Fretting can greatly reduce the fatigue life of the contacting parts.

Although the mechanisms of fretting have been studied for over a century, its exact nature and behaviour is still not well understood [1–3]. As early as in 1911, “fretting” was mentioned in relation with the formations of debris in plain fatigue tests [4], interpreting it as *surface wear*. Later, the term fretting fatigue arose, as researches started acknowledging its negative effect on fatigue life [5,6]. It became apparent during the following decades that fretting fatigue was indeed a complicated phenomenon; Collins [7] proposed dependence on more than 50 parameters. However, due to the difficulties involved in accurately controlling and monitoring different parameters during fretting fatigue tests, early experiments and discussions were questionable [8]. The phenomena involved are also known to be interconnected, and Collins suggested that the parameters could be narrowed down into eight broader categories: Amplitude of relative slip, magnitude and distribution of the contact pressure, the local state of stress, number of cycles, material and surface conditions, cyclic frequency, temperature, and environments surrounding the surfaces [7]. Further complications are realised as the length scales involved in fretting fatigue are often on the same order of magnitude as material microstructural features [9] and surface features [10].

Fretting fatigue have mainly been studied for metallic alloys and ceramics used in engineering. In bearings, loss of clearance may be caused by fretting wear, but also jamming due to debris [11]. In biomaterials, debris formations induces inflammations in the host tissue [12,13]. Highly loaded components like turbine blades [14,1] and axle press-fits [15–17] may catastrophically fail due to fretting initiated cracks being driven to propagate into the substrate. Other examples are spline couplings, keyed joints, flexible marine risers and pipe fittings [18–21].

2. Mechanisms of fretting fatigue

The fretting fatigue process is usually separated into different stages. The initial phase is often concerned with wearing off the oxide layer on the surfaces. After the oxide layer is worn off, cold-welds form at the surface asperities, increasing the coefficient of friction. Subsequent loading of the surfaces then cause these micro-welds to break, forming wear debris [22]. This wear debris can work as an abrasive medium, but can also form a protective third body layer reducing wear [11]. Additional loading cycles may introduce plastic

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Nomenclature

$2N_f$	number of cycles for fatigue failure
ΔK_{th}	threshold stress intensity factor range
δ	relative slip
$\Delta \epsilon$	strain range
$\Delta\gamma$	shear strain range
$\Delta\sigma_1$	plain fatigue limit
ϵ'_f	fatigue ductility coefficient
γ'	shear fatigue ductility coefficient
ν	Poisson's ratio
σ'_f	fatigue strength coefficient
σ_T	stress in tangential direction of contact
σ_y	yield stress
τ	contact shear stress
τ_a	shear stress amplitude
τ'_f	shear fatigue strength coefficient
a	contact semi-width
a_0	El Haddad intrinsic length parameter
b	fatigue strength exponent
b_0	shear fatigue strength exponent
c	fatigue ductility exponent
c_0	shear fatigue ductility exponent
E	Young's modulus
f	coefficient of friction
G	shear modulus
g_{max}	maximum gap of contacting profile (unloaded)
k	Findley's influence factor
P	contact normal force
Q	contact sliding force
Y	LEFM Geometrical factor

deformation and microcracks to the surfaces, which cause additional wear debris and the potential of further propagating cracks into the material. These cracks eventually grow out of the contact stress fields and becomes dominated by the far-field stresses, if present.

In *partial slip* conditions, the friction is high enough to restrict the surfaces from global sliding and there is only a very small amount of local sliding between the generally adhered surfaces. These conditions are the most prone to fretting fatigue [23,24]. The competing effects of *tribologically transformed structure* [25], particle detachment and nucleation of fatigue cracks [26] makes a quantitative prediction for a given material and given operating conditions very difficult. The crack initiation process is highly dependent on the material microstructure [27,28].

Wear is often neglected in fretting fatigue analysis, but is reported to sometimes affect the fretting fatigue life [27,29,30]. The exact reasons for the underlying phenomena are still debated, but it is likely depending on material combination and loading conditions. Material removal due to surface wear may eliminate nucleating cracks at the surface. Wear also redistributes the contacting pressure [31], even in the partial slip regime as studied by Shen et al. [23]. They concludes that the wear could not be neglected. However, as other researchers have reported, wear in partial slip conditions is minor [27] and can in many cases be neglected for small values of slip. Frictional contacts are also known to sometimes *shake down*, i.e. residual shearing tractions building up and restricting further sliding, eventually leading to a steady state response being notionally adhered [2,32].

The fretting problem is quite different, depending on whether the contact is *complete* or incomplete. For incomplete contact, at least one of the mating surfaces is of convex shape and the contact area is related to the load. For complete (conforming or flat) however, notionally sharp corners introduce stress singularities. For tangentially loaded incomplete contact, there is no frictional shakedown effect, and some local sliding will always occur. Thus, incomplete contacts are more prone to partial slip fretting fatigue.

3. Fretting maps

Various visual descriptions of fretting have been researched using fretting loops or fretting maps to characterise the fretting problem and to separate the regimes involved. Fretting loops plot the relation between friction force and displacement amplitude, sometimes along a third, temporal axis. Fretting loops form the basis for many fretting maps [33].

The slip amplitude was early identified as one of the most defining parameters for fretting. Vingsbo and Söderberg [24] introduced the concept of fretting maps with three different regimes of sliding conditions.

1. *Stick regime* with low sliding action and low surface damage (oxidation and wear). Low fretting damage.
2. *Mixed stick-slip regime* had fretting fatigue with small amounts of wear. Accelerated crack growth rate reduced fatigue life.
3. *Gross slip regime* showed severe damage due to wear but crack formations were limited. In the gross slip regime, the wear coefficient increased by several orders of magnitude.

Hence, this fretting map could be used to determine the fretting regimes for a set of conditions. Fig. 1 illustrates the different regimes. Fretting maps was an important development in the work of fretting assessment. Today they are used to describe the overall fretting behaviour, including contact conditions, fretting regime, wear mechanism, crack nucleation and propagation [33].

Some years after Vingsbo and Söderberg, Zhou and Vincent [26,34] proposed to separate the problem using two different types of fretting maps, *running condition fretting map* (RCFM) and *material response fretting map* (MRFM). RCFM distinguished between partial slip regime, mixed fretting regime and slip regime, and is in some ways quite similar to Vingsbo and Söderberg. It is however, maybe more correct in unifying the stick and partial-slip regimes, since in reality there will always be some local sliding. The material response fretting map was related to the *post hoc* degradation analysis of the specimen.

Different maps related to the number of cycles have also been proposed [35]. In 2006 Zhoul et al. [36] reviewed the progress in fretting maps and covered additional proposals, but arrives to the

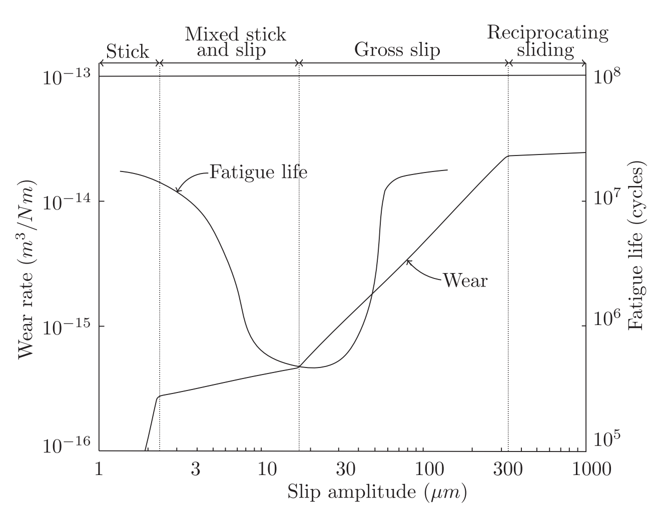

Fig. 1. Relating the slip amplitude to fretting regime, as proposed by Vingsbo and Söderberg [24].