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Fretting fatigue tests on shrink-fit specimens and investigations into the strength enhancement induced by deep rolling

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ABSTRACT

The shrink-fit connection undergoes fretting fatigue at the edge of the contact, where both stress concentration and micro-slip take place. A fretting test set-up with a round-shaped specimen is proposed that eliminates lateral edge contact and misalignment, and is also appropriate for deep rolling. Comparative experiments showed a notable strength improvement, induced by deep rolling, along with the beneficial effect of friction reduction due to lubrication. Multiple cracks with clear shallow paths were evident after SEM observation, thus the maximum shear stress amplitude was assumed as a correlating parameter, while the crack arrest was inappropriate especially for deep rolled specimens.

1. Introduction

Mechanical components with a highly loaded contact and local micro-slippage can undergo fretting fatigue. Examples of fretting fatigue include the dovetail interface of turbomachinery [1–4] and the shrink-fit (tubular or cylindrical) connection [5–11]. Fretting testing is essential in designing admissible loads and also to validate different modelling approaches. Experimental fretting tests can be classified into: (1) full or small scale replication of the actual fretting configuration, as experienced by the in-service component, and (2) idealised test layout where the contact is accurately controlled [12,13]. Examples of component testing have been presented by Golden et al. [4,14] regarding the dovetail interface, by Bertini et al. [9] and Alfredsson [10] regarding shrink-fit connection, and Azevedo et al. [15] regarding cable clamping, as well as others for different applications. Controlled contact fretting tests are well summarised in Hills and Nowell [12], and the usual layout is the “bridge” type with a two sided contact pad. Many examples of this kind of testing have been reported in the literature, such as the books by Attia and Waterhouse [16], Hoeppner et al. [17] and Mutoh et al. [18]. The main limitation of bridge type testing is that the displacement can never be the same on the two sides of the contact pad, thus leading to dissimilar fretting configurations, though nominally equal [12]. This problem can be solved after fixing one side of the contact bridge to the rigid part of the testing frame. This solution has been reported by McVeigh et al. [1], Rossino et al. [19], Araújo et al. [20], Lykins et al. [21,22], Szolwinski and Farris [23], and others. The contact configuration of bridge type testing may be Hertzian, cylindrical to flat [24,25,23], or even sphere to flat [26], while sharp complete contacts without rounded corners have recently been proposed by Hojjati-Talemi et al. [27], Giner et al. [28] and Noraphaiphipaksa et al. [29]. Although the “flat and rounded” contact is common for dovetail joints, only a few examples are available in the literature, such as McVeigh et al. [1] and Namjoshi et al. [30]. Despite the simplicity of bridge testing, two further problems need to be considered: the lateral edge contact and the tilt. The lateral edge contact effect was investigated by Kim and Mall [31], who correctly analysed plane strain at the centre and plane stress at the sides. Of these two cases, the plane stress should be the less critical provided that a precise lateral alignment is ensured, which otherwise would load to an edge stress singularity. A potential solution was proposed by Liu and Hill [32] who introduced rounded lateral edges which led to a non-singular boundary stress distribution. Preventing any angle misalignment between the specimen and the pad also needs to be considered. This issue can induce a non uniform pressure along the transversal direction, as shown by Kim and Mall [31] and also discussed by Wittkowsky et al. [26]. In addition, the flat either rounded or not rounded contact, may tilt during the load cycle, thus producing a non-optimal contact fluctuation [33]. The fretting test layout proposed in this paper is based on a round geometry with a small conical angle, for shrink-fitting, and loaded by cyclic bending. This contact configuration does not involve an

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Nomenclature

SIF	Stress Intensity Factor
FE	Finite Element (model)
SEM	Scanning Electron Microscope
KT	Kitagawa–Takahashi (diagram)
CoF	Coefficient of Friction
f	CoF value
R_a	surface average roughness
σ_a	bending stress amplitude
N_f	number of cycles to failure
E	Young's modulus
ν	Poisson's ratio
σ_{ij}	stress components for the singularity problem
r	radial coordinate for stress singularities
m	order of singularity
p	pressure distribution at the fretting interface
s	shear traction at the fretting interface
R	fatigue load cycle ratio
$K_\mathrm{I}, K_\mathrm{II}$	mode I and mode II SIFs
$\Delta K_\mathrm{I,p}$	positive (or tensile) part of the mode I SIF range
ΔK_II	mode II SIF range
α	crack direction angle, also used for critical plane orientation
$\Delta K_{\mathrm{th},-1}$	threshold SIF range, $R = -1$
$\Delta\sigma_{-1}$	fatigue limit (or fatigue endurance) stress range, $R = -1$
L	El Haddad length evaluated for $R = -1$
$\Delta K_\mathrm{th,0}$	threshold SIF range, $R = 0$
$\Delta K_\mathrm{th,0,Asy}$	short crack threshold SIF range, asymptotic model, $R = 0$
$\Delta K_\mathrm{th,0,EH}$	short crack threshold SIF range, El Haddad model, $R = 0$
τ_a	shear stress amplitude
$\sigma_\mathrm{n,max}$	maximum normal stress
$\sigma_\mathrm{n,min}$	minimum normal stress.
$\sigma_\mathrm{n,a}$	normal stress amplitude
κ, λ	multiaxial fatigue material parameters
κ_i, λ_i	multiaxial parameters obtained by combining different load ratios
$\tau_\mathrm{a,eq}$	equivalent multiaxial fatigue shear stress amplitude
η	multiaxial criterion assessment stress ratio

edge effect nor misalignment, however, the bending causes a contact pressure oscillation during the load cycle (resembling the tilting issue) but thoroughly taken into account by means of a finite element model. This testing layout is both aimed at an accurate contact load configuration, and also reproduces a shrink-fit connection, thus the obtained results can even be rescaled to actual components.

The modelling approaches to fretting fatigue are summarised by Nowell et al. [34], Hills et al. [35] and are: analogies either with crack or notch, Ciavarella [36–38] and Naboulsi [39]; asymptotic approaches both for complete and incomplete contacts, Dini, Nowell, Hills et al. [34,35,40–43]; short crack arrest on the Kitagawa–Takahashi (KT) diagram, Araújo et al. [19,20,44] and Vallelano et al. [45]; and finally a multiaxial fatigue critical plane approach, usually associated with a material size in order to incorporate the gradient effect, Araújo et al. [19,20,46]. Of these approaches, crack arrest implicitly assumes that fretting is a *tensile* driven fatigue mechanism, indeed the reference threshold Stress Intensity Factor (SIF) is according to the mode I, which is the opening mode. The aim of the present paper is to show comparative results and assess the effect of the deep rolling surface treatment, which induces highly compressive residual stresses. As shown later, the crack opening is completely prevented, after deep rolling, thus the crack arrest criterion is questionable for these fretting tests since the first stage of fatigue propagation is no longer driven by mode I loading. A multiaxial fatigue critical plane approach, based on the shear stress amplitude, is expected to be more suitable. The consistency of the predictive model can also be tested on the basis of the crack propagation direction, especially by taking into account the early stages of the crack. The initial crack orientation in fretting fatigue is broadly discussed in the literature. The papers by Lamacq and Dubourg [17,47] distinguished type I and type II cracks as initially shallow, rather than almost perpendicular to the surface, and they were clearly attributed to shear and normal tensile stresses, respectively. The vertical orientation of the initial crack, without a shallow preliminary stage (type II) was observed by Giner et al. [28], Muñoz et al. [24] and also Mutoh et al. [17,18,48] who supported the maximum tangential stress criterion, for identifying the direction, even at the very early stage of the crack. In contrast, the present paper shows very shallow cracks with the shear playing a predominant role with respect to the tensile stress.

The present paper includes both experimental and modelling topics. Initially, a new design test geometry is outlined, which is dedicated to the shrink-fit application, either featuring flat and rounded contact or possibly with sharp complete contact. Next, the effects of lubrication and the deep rolling on improving the fretting fatigue strength are investigated. Finally, the modelling of the nucleation process is reported, comparing and discussing various approaches where SEM investigation has been essential for identifying the initial orientation of the crack.

2. Experimental activity

2.1. Fretting fatigue test setup

The proposed experimental setup is shown in Fig. 1. The two fretting parts are the shaft, which is the specimen, and the hub, which plays the role of the fretting pad. As in the configuration proposed by Juoksukangas et al. [49], the cyclic bulk stress was generated by bending instead of axial loading. The bending load was generated by a hydraulic actuator and was fully reversed for all the tests performed. The rear flat surface of the hub was bolted to the mounting parts of the testing frame, and a cantilever scheme was thus obtained. The working frequency of the test was 10 Hz and it was basically limited by the relatively large stroke due to the cantilever compliance. By checking the two extreme values of the actuator displacement, approaching the end of the test, it was possible to identify which side the crack had been propagated to (Fig. 1). The remaining ligament was finally broken after having stopped the test. The recorded number of cycles to failure includes both nucleation and propagation up to a crack size of approximately half the specimen cross section.

As mentioned in the Introduction, the usual configuration with a flat specimen and a lateral contact pad can undergo an edge effect and misalignments. The round shape however, has no edge and mount tilting is prevented by the cylindrical mating of the contacting surfaces. Another advantage of the axisymmetric shape was the easy application of the deep rolling treatment on the shaft specimen. The small conical angle of the two mating parts means that the contact pressure preload can be fine tuned with an adjusting nut which was wrenched during the shrink-fit operation. In principle, the hub acts as a bridge pad, constrained on one side,