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Multiaxial fatigue criteria versus experiments for small crack under rolling contact fatigue

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ABSTRACT

Rolling contact fatigue (RCF) is traditionally a very critical loading condition for fatigue and, moreover, material defects (as inclusions and inhomogeneities) play a significant role in determination of the service life of materials exposed to out-of-phase stresses, which typically occur at the interface and below the surface of contacting bodies.

In this paper we summarize the results previously obtained for two different hard steels (that is, a bearing and a gear steel), together with a new set of experimental data for a mild railway wheel steel, that have been subjected to out-of-phase multiaxial fatigue loading, simulating RCF conditions in presence of small shallow pre-cracks.

Then, the experimental results obtained have been discussed by employing the Dang Van and Liu–Mahadevan criteria, which are criteria extensively applied in the case of RCF problems.

The results show that the Liu–Mahadevan criterion is close enough to experimental RCF tests, while the Dang Van criterion needs a substantial modification for the load cases when a negative hydrostatic stress component is present.

1. Introduction

Multiaxial fatigue has been the subject for the proposal of many criteria intended to predict fatigue strength (or fatigue life) under multiaxial conditions from a limited number of tests under uniaxial or torsional conditions. Among the different multiaxial loads, the out-of-phase (OOP) conditions that are typical of rolling contact fatigue (RCF), both for subsurface and surface failures, are in general the most detrimental for mechanical applications, with a severe reduction of the allowable fatigue shear strength respect to simple torsion.

RCF is traditionally treated in terms of an allowable Hertzian pressure [1], while the Dang Van criterion [2] has been the theory widely adopted for several applications including RCF [3–5], due to the treatment of out-of-phase stress components histories and the simple definition of allowable shear stress, as a linear function of the hydrostatic stress σ_h. Nevertheless, fatigue failure assessments under RCF cannot be made regardless of the influence of small defects. Service life of high strength steel bearings is found to be affected by the presence of small inclusions whereas catastrophic failures of railway wheels are triggered by sub-surface defects [6]. Therefore, it is important to consider the presence of defects for a significant strength prediction under RCF conditions.

In the literature two typical treatments of RCF in presence of defects are adopted: (a) calculation of the stress intensity factor (SIF) at the tip of defects and by comparing it with the threshold stress intensity factor range, ΔK_{th}, obtained under Mode II/III [7,8] and (b) use of a fatigue criterion in which the fatigue limit depends on defect size by assuming, according to Murakami's concept, that defects can be treated as small cracks [9].

The approach (a) is more rigorous since it employs a threshold condition for crack propagation based on the threshold values $\Delta K_{II,th}$ (or $\Delta K_{III,th}$), which are obtained in shear/torsion tests and account for shear mode failure mechanisms. However, this approach is found to overestimate the real threshold under RCF conditions. As a matter of fact, the authors have presented a novel series of experiments on microcracked specimens subjected to out-of-phase loads, which have clearly shown that the threshold $\Delta K_{III,th}$ in RCF conditions (both for a gear and a bearing steel) is much lower than that under simple torsion [10,11], due to the crack opening caused by the severe plastic deformation and rubbing of crack lips. However, up to now there are no experimental results for applications like the railway wheels, where mild steels are adopted.

The approach (b), for which the fatigue limit depends on defect size, does not appear to be fully correct when applied to RCF problems. As a matter of fact, for materials containing defects, even when a multiaxial fatigue criterion is able to correctly predict the

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Nomenclature

LP	loading path
OOP	out of phase
p_0	maximum contact pressure
R	stress ratio
RCF	rolling contact fatigue
s	ratio between the fully reversed torsional fatigue limit and the fully reversed uniaxial fatigue limit
SIF	stress intensity factor
α	angle between the fracture plane and the critical plane
α_{DV}	Dang van material parameter
β, η, k	Liu–Mahadevan material parameters
kv	cyclic yield shear stress
Δa	coplanar crack depth
ΔK	stress intensity factor range
ΔN	number of cycle
$\sigma^H_{a,c}$	hydrostatic stress amplitude acting on the critical plane
$\sigma_{m,c}$	normal mean stress acting on the critical plane
$\sigma_{a,c}$	normal stress amplitude acting on the critical plane
σ_h	hydrostatic stress
σ_W	fully reversed uniaxial fatigue limit
$\tau_{a,c}$	shear stress amplitude acting on the critical plane
τ_W	fully reversed torsional fatigue limit
$\sqrt{\text{area}}$	crack size expressed in terms of square root of the projected crack area
$\sqrt{\text{area}_0}$	fictitious crack length parameter

Subscripts

I	Mode I
II	Mode II
III	Mode III
th	threshold
I,th,LC	Mode I threshold for long crack
III,th,OOP	Mode III threshold for out-of-phase loading

behavior of smooth specimens, it fails in describing the condition of non-propagating small cracks in presence of a high negative hydrostatic stress [12].

In the present paper we would like to address these two open points. Firstly, we present a summary of experimental results on very small defects under RCF conditions for two hard steels (respectively, a bearing and a gear steel), together with new results for a mild steel adopted for manufacturing railway wheels.

Then, the above experimental data are analyzed in terms of the criteria usually adopted in RCF applications (namely, Dang Van criterion [13,14] and Liu–Mahadevan criterion [15,16]). Finally, the conditions for the applicability of such criteria are discussed.

2. Experiments for Mode III thresholds in RCF

The materials tested for investigating Mode III crack thresholds under pure torsion and RCF conditions are two hard steel, a bearing steel and a Q&T steel for gears (SAE 5135 steel), and a ductile steel widely used for manufacturing railway wheels (R7T steel). Ultimate tensile stress (UTS) as well as monotonic and cyclic yield stress (0.2% plastic strain offset) are listed in Table 1.

As it can be observed, the three materials are very different in terms of monotonic and cyclic properties.

2.1. Specimen shape and dimension

All the fatigue tests were carried out onto micronotched hourglass specimens (Fig. 1). After machining, the specimens were hand polished and then electro-polished (surface removal 30–40 μm) in order to reduce the residual stresses.

After surface finish, artificial micronotches were then introduced onto the surface of the specimens by EDM machining: three different defects were introduced, characterized by a size (expressed in terms of Murakami's $\sqrt{\text{area}}$ parameter) of 220, 315 and 630 μm. Defect sizes are shown in Fig. 1.

2.2. Precracking and fatigue test details

All specimens were preliminary pre-cracking in Mode I in order to induce the formation of small non-propagating cracks at the bottom of the notches. The pre-cracking procedure was carried out under tension–compression, with a stress ratio $R = -2$ for 10^7 cycles, at stress levels slightly lower than the fully reversed uniaxial fatigue limit. After pre-cracking procedure all the specimens were observed under a scanning electron microscope (SEM) to verify the success of pre-cracking procedure, and if not successful, the Mode I loading was repeated. More details can be found in [10,11,17].

After the pre-cracking procedure, the specimens were subjected to torsional and out-of-phase tests at different Mode III stress intensity factor range, ΔK_{III}, values. The out-of-phase (OOP) tests were carried out according to three different load paths: in the case of the bearing steel, two load paths provided by SKF (the industrial partner) were adopted (namely load paths LP1 and LP2, which represent the stress state experienced by a sub-surface defect parallel and inclined in respect to the free contact surface respectively), while the gear and the railway steel were subject to a load path LP3, very similar to LP1. The three load patterns are shown in Fig. 2.

The tests were conducted in force/torque control using an MTS 809 Axial Torsional System. The surface-mixed mode crack advance was constantly monitored during the test by employing the method of plastic-replicas.

Following the fatigue test, all the specimens were examined under SEM, after having removed the debris clopping the defect, by intense ultrasonic cleaning in acetone. Both the specimen surface appearance and the co-planar (XZ plane in Fig. 1) fracture surface morphology were investigated (the latter inspected after static cryogenic rupture in liquid nitrogen). The coplanar crack growth rate was estimated at the end of each test as $\Delta a/\Delta N$, where Δa is the coplanar crack depth and ΔN is the number of cycles at the end of the test.

Table 1
Tensile properties of the three steels.

Material	UTS (MPa)	Monotonic yield stress (MPa)	Cyclic yield stress (MPa)
Bearing steel	2360	1980	2070
Gear steel	2150	1395	1735
Railway wheel steel	875	545	480