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A failure assessment diagram for components subjected to rolling contact loading

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A R T I C L E I N F O

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A B S T R A C T

A failure assessment diagram for the evaluation of the safe working area of components subjected to rolling contact loading is proposed. Rolling contact fatigue limitation is treated in terms of non-propagation condition of inherent defects, following the El-Haddad model for the short-cracks growth threshold. Static fracture and ratchetting limitations are also added to the diagram. In this way, the approach gives an overview of the possible damage mechanisms, automatically indicating which is expected for a specific case. In particular way, the diagram presents different areas: a safe zone (infinite life), a rolling contact fatigue zone almost independent on defects content, a rolling contact fatigue zone dependent on defects, a ratchetting zone and a static fracture zone. Depending on material properties, operating conditions and inclusion content, a reference point can be drawn on this diagram, indicating in which area the component is working and, consequently, if it is safe or which damage mechanism is expected.

Some experimental evidences referring to rolling contact tests carried out in the past where re-interpreted and verified by this approach, highlighting the role of working conditions, material properties and inclusion content in determining the damage mechanism.

1. Introduction

Many different damage typologies can be present in a component subjected to rolling contact loading, depending on several factors, deriving from working conditions (contact stress distribution, lubricant effect, etc.), material (yield and fatigue strength, inclusions content, crack growth threshold, etc.) and manufacturing (surface finishing, residual stresses, etc.), see for instance Johnson [1] and Olver [2]. Damage typologies are currently named in different ways, depending on morphology, origin, dimensions and applicative industrial sectors: scuffing, wear, spalling, micro and macro pitting, shelling, case crushing, surface distress and galling, are only a few examples of this wide terminology. However, all these damage typologies take origin from three main damage mechanisms: wear, rolling contact fatigue (RCF) and ratchetting.

Wear is a very complex phenomenon which can have different forms, mainly adhesive and oxidative as shown by Kapoor [3] and Johnson [4]. Really, it is not clear if it can be considered an independent damage mechanism rather than a RCF or a ratchetting process on the roughness scale; extensive researches have been carried out on this topic, but the question is still open.

RCF can be surface or subsurface originated, mainly depending on the stress distribution caused inside the component by the contact actions, as reported by Sraml et al. [5] and on an eventual variation of the material properties along the depth, like for surface hardened components, as shown by Bormetti et al. [6]. The fatigue process typically follows a mechanism of accumulation of dislocation along slip bands, subsequent crack nucleation and propagation; it can be favoured by the presence of notches (like surface asperities or scratches) or inclusions, depending on their size and typology and on the material notch sensitivity: in particular, in components made of hard materials, micro-structural or geometrical in-homogeneities, acting as local stress raisers, promote the activation of the fatigue phenomenon in the surroundings of the in-homogeneity itself, as highlighted by Auclair et al. [7] and Melander [8]. A typical example is the formation of “butterflies” and subsequent micro-cracks around non-metallic inclusions in high strength steels for bearings, shown by Vincent et al. [9] and Nelias et al. [10]. According to the fatigue limit definition in fracture mechanics, structural integrity against this phenomenon can be guaranteed if inherent or early nucleated micro-cracks are not able to growth.

Ratchetting is typical of soft materials and dry contact with presence of significant sliding; it implies an incremental monotonic plastic strain which can lead to crack initiation due to material ductility exhaustion, when a critical strain is reached, see for instance Tyfour et al. [11] and Su and Clayton [12]. Ratchetting can happen both on surface roughness micro-scale (typically a few microns) due to contact pressure peaks induced by the asperities, or in the whole bulk surface layer interested by macro Hertzian stress field, as shown by Kapoor et al. [13]. Anyway, this damage phenomenon is very fast (for example, in rail/wheel contact, crack nucleation due to ratchetting generally happens after

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Nomenclature

a	crack length
a_o	intrinsic crack length
a_D	critical crack length
a_{DV}	Dang Van parameter
b	contact area half width
ΔK_{eq}	equivalent stress intensity factor range
ΔK_{th}	short-crack growth threshold
$\Delta K_{th\ l.c.}$	long-crack growth threshold
$\Delta\tau_o$	reversed torsion fatigue limit for a defect-free material (single amplitude)
$\Delta\sigma_o$	reversed uni-axial fatigue limit for a defect-free material (double amplitude)
K	stress intensity factor
K_{IC}	fracture toughness
K_{Icr}	critical mode I stress intensity factor
K_{eff}	effective mode I stress intensity factor
f	friction on the rolling surface
f_c	friction between the crack faces
p	Hertzian pressure
p_o	rolling contact fatigue pressure limit for a defect-free material
p_{cr}	critical Hertzian pressure
p_{sh}	shakedown pressure
R	load ratio
r_y	crack tip plastic zone correction
σ	nominal stress
σ_{cr}	critical nominal stress
σ_{UTS}	ultimate tensile stress
σ_Y	yield stress
$\tau_{\max}(t)$	instantaneous Tresca stress
τ_Y	yield shear stress
τ_{yz}	orthogonal shear stress
y	stress intensity factor correction
z	depth from contact surface

a few thousand of contact cycles). Once a crack has formed, its propagation can lead to failure typologies similar to some of those due to RCF, although the crack nucleation mechanisms and the correspondent thresholds are different. Indeed, Kapoor [14] showed that fatigue and ratchetting are independent failure processes. Structural integrity against this phenomenon can be guaranteed if the contact pressure remains below the shakedown limit, which depends on contact geometry, material cyclic properties and friction on the contact surface, as indicated by the well known shakedown maps.

Different damage mechanisms can occur simultaneously in the same component, or some of them can be absent, because its activation threshold has not reached; see for example the interesting experiments carried out by Cheng and Cheng on roller bearings [15], where early pitting was progressively removed by wear, and subsequent subsurface originated spalling occurred. Furthermore, the active damage mechanisms can be in competition, being the failure caused in this case by the faster one, as highlighted by Kapoor [14] and Donzella et al. [16]. As a result, some damage typologies are typical or more common in certain applications, while other can be almost absent. For example, steel bearings suffer subsurface fatigue starting at inclusions, especially non-metallic ones like alumina; gears mainly experience surface fatigue favoured by sliding and lubricant; railway wheels and rails are mainly subjected to surface crack initiation due to ratchetting. Much effort has been spent to understand these damage mechanisms in several important industrial sectors like those cited above, which has lead to the development of design procedures, recommendations or standards. These researches are however quite sectorial and often valid only for a specific component typology, as witnessed by the adoption of different nomenclature for similar forms of damage and the proposal of different failure prediction criteria. As a consequence, it is still difficult to have a clear and comprehensive understanding of the damage evolution in a general case, and in particular way to predict the favoured failure mechanisms and their thresholds.

In this work, an approach for the structural integrity assessment of components subjected to rolling contact loading is proposed with respect to both RCF and ratchetting occurrence, also highlighting the influence of defects and inclusions. The aim of this approach is to determine the safe working conditions of the component in order to avoid damage caused by these phenomena. Therefore, the work is addressed to the definition of the damage onset threshold, with no matter to its subsequent evolution. In particular, regarding fatigue, the short-cracks approach has been used, considering the transition from a fatigue limit of nominally defect-free material to a linear elastic fracture mechanics (LEFM) described crack propagation threshold. The El Haddad model [17] has been used to describe this transition field in terms of crack propagation threshold, following the assumption that micro-cracks form very quickly at defects and inclusions, and fatigue in avoided if their propagation is impeded. The well known Kitagawa–Takahashi diagram has been translated in a failure assessment diagram expressed as a function of the Hertzian contact pressure, useful to assess the safe working area and the effect of defects and inclusions in determining the fatigue threshold. The ratchetting threshold has been then added to this diagram, allowing a fast evaluation of the competition between the two damage mechanisms.

2. Development of a failure assessment diagram for rolling contact loading

As is known, failure assessment diagrams (FAD) were introduced about thirty years ago by Dowling and Townley [18] and Harrison et al. [19], in order to assess the failure limit of a flawed structure, considering the interaction between fracture and plastic collapse. The FAD concept takes origin from the crack tip plasticity phenomenon and correspondent models like the early ones of Irwin [20] and Dugdale [21], able to correct the stress intensity factor (SIF) increasing its value above the linear elastic one. Several FAD formulations have been subsequently developed, in order to better describe the material behaviour in the plastic field. This was achieved by taking in to account strain hardening, as reported by Bloom [22], calculating the crack driving force in terms of J-integral by means of a power law as proposed by Shih and Hutchinson [23], or by a reference stress approach like that shown by Ainsworth [24]. The more recent FAD formulations allow also considering Lüders plateau and inhomogeneous configurations like weldments, see for example the SINTAP report edited by British Steel [25]. An excellent overview on FAD evolution can be found in Zerbst et al. [26]. For the purpose of this paper, it is however sufficient to recall the basic concepts for a FAD development, by considering the simplest model of Irwin in the case of a through crack