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# Analysis of the stress gradient effect in fretting-fatigue through nonlocal intensity factors

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ABSTRACT

This paper proposes a new method to describe the stress gradient effect in fretting-fatigue. Through the analysis of the mechanical fields in the proximity of the contact edges, it has been possible to extract nonlocal intensity factors that take into account the stress gradient evolution. For this purpose, the kinetic field around the contact ends is partitioned into a summation of multiple terms, each one expressed as the product between nonlocal intensity factors, $I^s$, $I^a$, $I^c$, depending on the macroscopic loads applied to the mechanical assembly, and spatial reference fields, $\underline{d}^s$, $\underline{d}^a$, $\underline{d}^c$, depending on the local geometry of the part. This description is obtained through nonintrusive post-processing of FE computation and is conceived in order to be easily implementable in the industrial context. As a matter of fact, for any given macroscopic load and geometry, a set of nonlocal intensity factors is computed that permits to characterize the mechanical fields close to the contact edges. Such *nonlocal* description has the advantage of being (i) geometry independent so that the nonlocal intensity factors can be used to compare laboratory test with real-scale industrial assembly, (ii) applicable to industrial FE models usually characterized by rougher meshes compared to the ones used to describe fretting-fatigue in the academic context. An extensive validation is carried out through the comparison with experimental data for plain fretting and fretting-fatigue tests on different materials.



## 1. Introduction

Fretting occurs every time two contacting bodies experience a relative tangential displacement usually caused by oscillating forces or vibrations. Combined with cyclic bulk fatigue loading, the so-called fretting-fatigue is a frequent source of failure constituting a major concern in safety–critical industries such as aerospace [1] or nuclear power generation [2]. Experimental test campaigns have shown that this phenomenon has an important negative effect on the material fatigue limit [3].

It is broadly accepted that the causes of the breakdown effect lie in the peculiarities that differentiate fretting-fatigue from plain fatigue, *i.e.* (i) the surface damage resulting from friction due to the relative displacement between the parts and (ii) the strong stress gradient introduced by the contact.

Concerning the surface damage, several authors have analyzed the critical role played by fretting wear in the determination of the fatigue life of the part [4–8]. What is usually observed is that three regimes can be determined in function of the slip amplitude: stick regime, mixed stick–slip regime and gross slip regime. If the contacting surfaces are in stick condition the wear rate is null and there is no important effect in term of fatigue life reduction. On the contrary, in the second regime, a huge increase in the shear stress at the stick–slip boundaries is observed and then the nucleation risk of shear type cracks augments. Minimum life is experienced in this condition while, in presence of gross slip, the increase of wear rate has a positive effect, removing the embryo cracks formed in the previous stage [9].

Despite the big concentration factor induced by the contact at the stick–slip boundaries, a rapidly decreasing stress field may lead short cracks to arrest even before they break the strongest microstructural barriers. As a consequence, both the highest stress point (*hot spot*) and the stress gradient evolution are needed in order to characterize the material fatigue limit [10]. In particular, Amargier et al. [11] proposed a $(q_{max}-p_0)$ representation of the crack initiation threshold to highlight the effects of the stress gradient, Fig. 1. Using these local quantities to analyze the test campaign conducted on a cylinder-plain fretting apparatus, Amargier's results show that the increase of the pad radius provokes the decrease of the initiation threshold. In other words, for

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**Nomenclature**

| | |
|---|---|
| $\underline{d}^s$ | symmetric spatial reference field |
| $\underline{d}^a$ | antisymmetric spatial reference field |
| $\underline{d}^c$ | complementary spatial reference field |
| $I^s$ | intensity factor (symmetric part) |
| $I^a$ | intensity factor (antisymmetric part) |
| $I^c$ | intensity factor (complementary part) |
| $\underline{v}(\underline{x}, t)$ | velocity field expressed in the reference frame attached to the contact edge |
| $q_{max}$ | maximum tangential shear stress at the contact surface |
| $p_0$ | maximum normal pressure at the contact surface |
| $P$ | linear normal force applied to the cylinder pad |
| $Q$ | fretting linear tangential force applied to the cylinder pad |
| $Q^*$ | fretting linear tangential amplitude |
| $\delta$ | fretting displacement |
| $\sigma_{fa}$ | maximum fatigue stress amplitude |
| $\Delta K$ | stress intensity factor range |
| $f(r)$ | radial evolution of the spatial reference field |
| $\underline{g}$ | tangential evolution of the spatial reference field |
| $\xi_e(t)$ | error of the elastic approximation |
| $\xi_{tot}(t)$ | error of the total approximation |
| $\mu$ | Coulomb friction coefficient |
| $\tilde{\mu}$ | nonlocal Coulomb friction coefficient |
| LEFM | Linear Elastic Fracture Mechanics |
| Ys | Yield Strength |
| UTS | Ultimate Tensile Strength |

the same stress value at the contact surface, different geometries generate different stress gradient evolutions with a direct effect on the fatigue life of the part.

In the last years, several fatigue criteria have been developed in order to take into account the gradient effect. Almost all of them can be divided into two major families. On the one hand, the nonlocal stress fatigue models [12–16] are usually based on averaging methods over a *critical distance*. More precisely, the theory of critical distances [17] is used together with a multiaxial criterion to predict the experimental results in fretting-fatigue. On the other hand, the approaches based on stress intensity factor computation [13,18–21], analyze whether the crack will stop or not by predicting the evolution of the linear elastic stress intensity factor, $\Delta K$, within the whole short crack domain.

Both approaches have shown to be able to predict the gradient effect with a certain degree of accuracy. For instance, Araújo et al. [12] used the theory of critical distances in conjunction with the modified Wöhler curve method showing that the results obtained match the experimental fretting-fatigue limit with an accuracy rate of $\pm 20\%$. Applying a different model (short crack approach), Dini et al. [19], analyzed the evolution of $\Delta K$ as a function of the crack length and compared it to the threshold defined by the K–T diagram. A good prediction of the fretting-fatigue threshold is obtained as well.

Even if the methods presented above show satisfactory results in predicting the gradient effect, some important limitations make them difficult to implement in an industrial context. For instance, the analysis of the $\Delta K$ evolution as a function of the crack length implies to set up a computational strategy to determine the crack path resulting from the macroscopic load application. This operation is heavily time-consuming. On the other hand, the methods based on the theory of critical distances require an accurate computation of the stress gradient evolution through the use of a really fine mesh (micron size range), condition difficult to reproduce in industrial FE models.

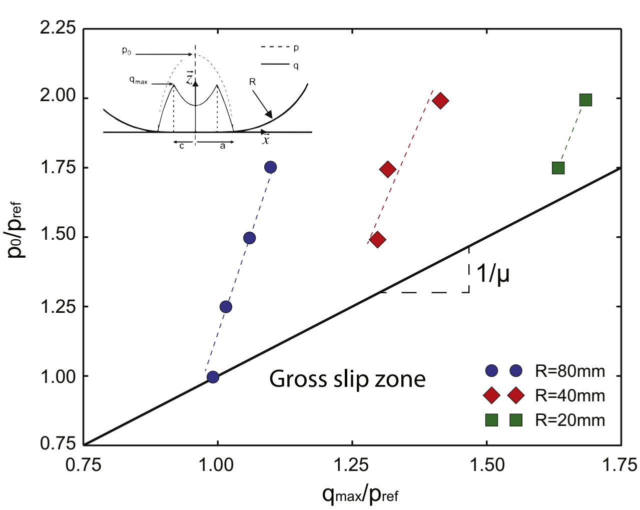


**Fig. 1.** Experimental crack initiation boundaries for Inconel 718 in plain fretting [11].

The goal of this paper is to propose a practical solution to overcome the aforementioned limitations and it will be divided into three major parts.

In the first section, a new method to describe the stress gradient effect through nonlocal intensity factors is developed. The interest of the approach comes from the geometry independent nature of the nonlocal intensity factors. Therefore, they can be used to characterize the stress field around the contact edges for any given geometry and represent an objective way to compare experimental results coming from different test campaigns. This description is obtained through nonintrusive post-processing of FE computations and is conceived in order to be easily implementable in an industrial context. To some extent, the method proposed can be seen as a generalization of what has been proposed by Giannakopoulos [22,23] and Hills [24]. It can be applied to any given geometry and for contact configurations where the size of the partial slip zone cannot be neglected.

In the second part, the experimental data used to validate the approach are presented. These results are the outcome of the experimental works conducted by Fouvry et al. [14], Ferré et al. [15] and Amargier et al. [11].

In the last part, the method is applied to describe the crack initiation frontiers that, as previously highlighted (Fig. 1), are strongly influenced by the gradient effect. Experimental data are employed to verify whether the nonlocal stress intensity factors can be used as objective quantities to describe crack initiation. For this purpose, the initiation map expressed as a function of $q_{max}$ and $p_0$, is compared to a nonlocal representation where $q_{max}$ and $p_0$ are replaced by $I^a$ and $I^s$. The results underline how the nonlocal intensity factors may constitute a useful tool to describe crack initiation, eliminating size effects caused by the stress gradient.

## 2. Model

### 2.1. Background

One of the main characteristics of fretting-fatigue is the contact between the surfaces that generates a severe stress gradient,