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P.J. Ashton, A.M. Harte, S.B. Leen

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A strain-gradient, crystal plasticity model for microstructure-sensitive fretting crack initiation in ferritic-pearlitic steel for flexible marine risers

P. J. Ashton [a], A.M. Harte [b,c], S. B. Leen [a,c]

[a] Mechanical Engineering, College of Engineering and Informatics, NUI Galway, Ireland

[b] Civil Engineering, College of Engineering and Informatics, NUI Galway, Ireland

[c] Ryan Institute for Environmental, Marine and Energy Research, NUI Galway, Ireland

Abstract
A three-dimensional, strain-gradient, crystal plasticity methodology is presented for prediction of microstructure-sensitive length-scale effects in crack initiation, under fatigue and fretting fatigue conditions, for a ferritic-pearlitic steel used in flexible marine risers. The methodology, comprising length-scale dependent constitutive model and scale-consistent fatigue indicator parameters, is calibrated and validated for representative (measured) dual-phase microstructures under strain-controlled low cycle fatigue conditions. Prediction of the effects of length-scale on fretting crack initiation is based on a three-dimensional, crystal plasticity, frictional contact model to predict fretting crack location and initial growth path, accounting for the effects of crystallographic orientation. The length-scale dependent fatigue and fretting simulations predict (i) significant beneficial effect of reducing length-scale for low cycle fatigue life, (ii) complex cyclically- and spatially-varying effects and differences due to changing contact and grain length-scales, and (ii) that fretting damage generally decreases with decreasing (contact-grain) length-scale.

1.0 Introduction
Fretting damage occurs when a small-scale (typically micro-scale) cyclic relative displacement exists between two surfaces in contact. Fretting is a concern for engineering designers as localised regions of high stresses and strains in the contact act as ideal locations for fatigue cracks to nucleate, and potentially grow under a bulk load, depending on the fretting regime. The combination of relative displacement, coefficient of friction (COF) and normal load determines the fretting regime, which can be classified as gross slip, partial slip, and mixed slip regimes. Gross slip causes significant wear and material removal, and is generally considered the least detrimental fretting regime, since nucleated cracks are either 'ground away' during the wear process or propagation rates diminish due to wear-induced contact evolution and stress redistribution [1],[2].The partial slip regime causes a stick zone with slip zones near the edges of contact, where the shear traction is large enough to overcome the resisting frictional force, as shown in Figure 1. This fretting regime is of most concern in the context of fatigue due to the absence of significant wear. Fretting fatigue failure can typically be divided into three stages; crack nucleation, short crack growth within the fretting contact region and long crack growth through the component in the presence of a bulk load. The mechanisms which drive the fretting-dominated crack initiation and short crack propagation are not fully understood and are therefore the focus of this work. In particular, the role of microstructure in fretting crack initiation has not yet been fully quantified. The key aim of this paper is to develop a micromechanical finite element modelling framework to study the mechanisms which drive fretting fatigue failure.

Finite element modelling is commonly used to predict crack initiation in fretting fatigue, where stress and strain based parameters such as Fatemi-Socie (FS) [3], Smith-Watson-Topper (SWT) [4] and Ruiz [5] parameters are employed to indicate crack location. For example, Araujo and Nowell [6] compared theoretical results with experimentally observed fretting fatigue cracks. The FS and SWT