EFFECT OF LOCAL HETEROGENEITY ON FRACTURE DRIVING FORCES

G. M. Castelluccio[1*]

[1] *School of Aerospace, Transport and Manufacturing, Cranfield University, Bedfordshire, UK*

* *Presenting Author email:* castellg@cranfield.ac.uk

Abstract
Traditional fracture theories infer the local crack growth driving forces by surveying the mechanical response far from the crack. Although this approach has successfully predicted fracture by assuming isotropic and homogeneous materials, local heterogeneity such microstructural heterogeneity can affect fracture response. This presentation will evaluate the differences between the local and far field driving forces using different microstructure-sensitive modelling approaches. We will discuss the effects of grain size, texture and crack morphology on crack tip fracture driving forces in metallic materials. We will also explore the role of microstructures as a buffer between the local and far fields considering the propagation of uncertainty from constitutive models into fracture prognosis. To conclude, we will discuss the implications for traditional experimental methods based on far field measurements smearing out important crack tip variability.

1. Introduction

Much experimental research has demonstrated the critical role of microstructure attributes on fracture resistance. For example, single-phase metallic materials typically increase their fracture toughness upon grain size refinement. However, traditional fracture driving forces—crack tip opening displacement (CTOD), stress intensity factor (K), and J-integral—were derived for isotropic domains and may become ill-defined for heterogeneous materials. Indeed, the J-integral can become path-dependent and shielding or anti-shielding effects arise next to an interface with different mechanical properties.

As a result, microstructure-toughness relationships have usually relied on empirical experimental correlations rather than on quantifuing micro- and meso-scales strengthening mechanisms. Recent research efforts have aimed at understanding the role of microstructure on fracture by means of multiscale physics-based modeling approaches. This work considers crystal plasticity and phase field models for single-phase metallic materials to compare the local and far field fracture driving forces. Microstructure-sensitive simulations explain the dominant role of mesoscale attributes and demonstrate a strategy to design fracture resistant materials.

2. Implementation and Results

To evaluate the role of grain size and crystal orientation on fracture toughness, we implemented a crystal plasticity approach in Abaqus [1] along with synthetic microstructural representations. The approach conveys the physics of dislocation interactions at multiple length scales and mesoscale “material-invariant” parameters that can be shared across FCC materials [2,3]. In addition, we recreated graded microstructures [1] surrounding ductile “long cracks” with a length to width ratio of a/w=0.5 and a semi-circular crack tip (Figure 1 a and)). Following ten microstructural realizations, we computed the role of the microstructure gradients on the crack tip opening and sliding displacements, as shown in Figure 1c). The results demonstrate that a microstructural gradient can bias the crack tip displacements, which can affect the crack growth direction. On the contrary, the crack mouth displacements are not biased by the microstructure and present much lower variability. Hence, the results demonstrate that traditional plastic hinge model used in standards to infer CTOD from CMOD measurements smear out the local crack tip variability.

A second example considers the role of the crack shape on fracture driving forces in Ni-base superalloy single crystal. By reconstructing cracks with X-ray microscopy, we digitalized the crack morphology into finite element phase field models and computed the J-integral from multiple contours along the crack path. The results in Figure 2 demonstrate the role on cracking of the local heterogeneity in single crystals. The local J-integral varies along the crack perimeter, locally arresting damaging mechanisms.

3. Conclusions

Our analysis of fracture processes considering microstructure-sensitive models demonstrated different mechanisms in which mesoscale attributes affect fracture. These strategies can be used to engineer fracture toughness and advance novel materials and manufacturing routes.

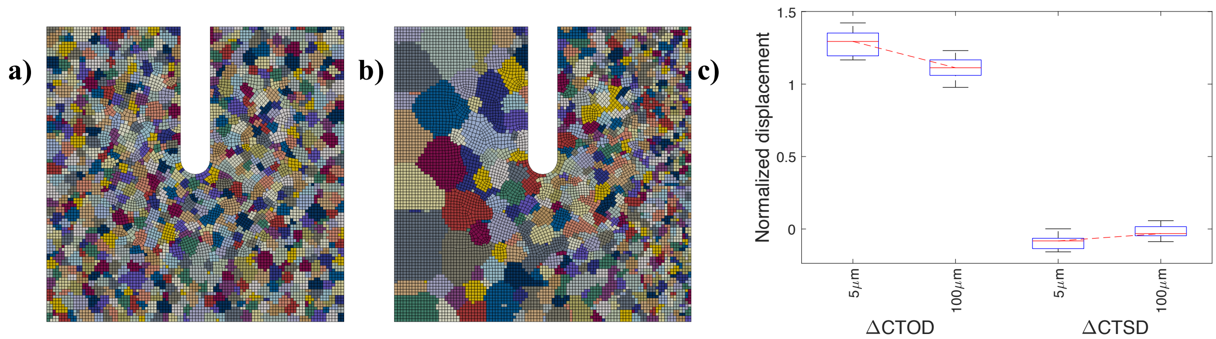

Figure 1. Finite element meshes of polycrystalline microstructures a) Isotropic and b) Y-Axis gradient. c) Boxplots for the change in crack tip displacements for multiple microstructural Y-axis gradients realizations under force control.

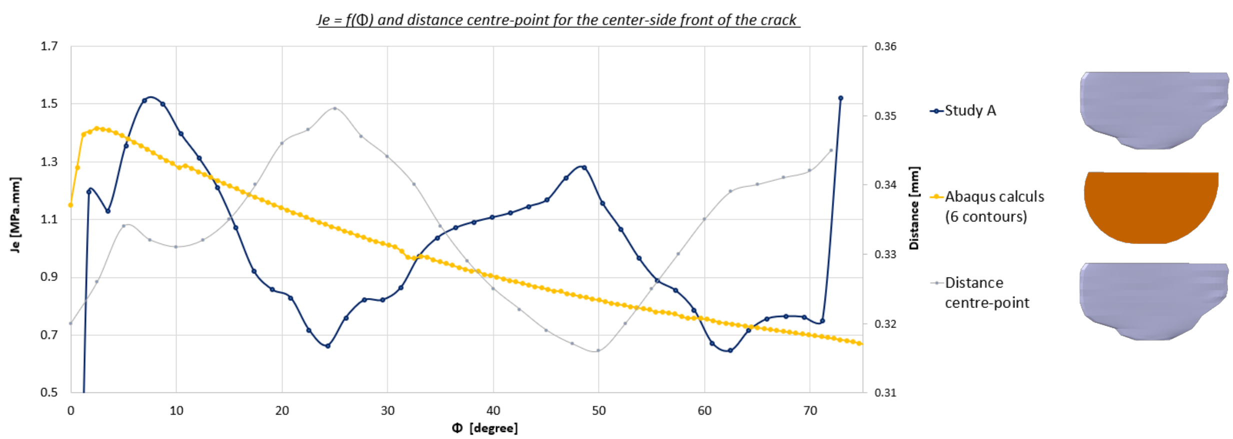

Figure 2. J-Integral calculation along the crack path for a Ni-base superalloy single crystal. Compared to the smooth semielliptical crack shape, the J-integral oscillates for the realistic crack morphology [4].

References

[1] G.M. Castelluccio, H. Lim, J.M. Emery, C.C. Battaile, Fatigue & Fracture of Engineering Materials & Structures 44 (2021) 2337–2355.
[2] S. Dindarlou, G.M. Castelluccio, International Journal of Plasticity (2022) 103306.
[3] F. Ashraf, G.M. Castelluccio, International Journal of Plasticity 161 (2023) 103494.
[4] T. Huyghe, X-Ray Microscopy Data Integration: Premise of a Digital Twin, Masters thesis, Cranfield University, 2022.