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EXAMINING SUB-GRAIN DRIVING FORCES FOR SMALL CRACK GROWTH

William Musinski[1]*, David Menasche[2], and Paul Shade[3]

[1]University of Wisconsin-Milwaukee, Milwaukee, WI, USA, [2]Hamiltonian Group, LLC, Washington DC, USA
[3]US Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH, USA
** Presenting Author email: musinski@uwm.edu*

Abstract

High energy X-ray diffraction microscopy (HEDM) techniques and micro-computed tomography were combined with in-situ cyclic loading to examine the evolution of sub-grain-level fatigue crack growth within a Ni-base superalloy at room temperature. A focused-ion beam notch was introduced within the specimen to concentrate damage within the characterized microstructure region of interest. The test specimen was subjected to fatigue cycling with pauses for periodic micro-computed tomography and HEDM measurements to characterize the sporadic growth of the crack front and grain-level strains ahead of the crack front. The HEDM data was used to instantiate a crystal plasticity finite element model and compared to experimentally determined grain-level strains, sub-grain reorientation, and crack path.

1. Introduction

The high energy X-rays supplied by synchrotrons have enabled the non-destructive 4D analysis of microstructure-level information that can be used to validate microscale deformation and fatigue crack growth processes. From these validated models the effect of variants in microstructure on their representative failure distributions can be simulated for potential new material exploration and certification. Ultimately, these high-fidelity models can help supplant some of the traditional experimental qualification efforts with less-expensive, faster-running microstructure-sensitive models. Towards the development of more robust microstructure-sensitive fatigue models, this paper describes the combination of HEDM and crystal plasticity finite element (CPFE) techniques to examine the evolution of sub-grain-level driving forces for small crack growth in a Ni-based superalloy.

2. Results

Three-dimensional crack growth at the microstructure scale was non-destructively probed for a millimeter-sized low-solvus, high-refractory (LSHR) Ni-based superalloy specimen with a 1mm x 1mm cross-sectional area that was subjected to stress-controlled R=0.05 fatigue cycling with a maximum stress level of 1000 MPa. After approximately 3,000 fatigue cycles a crack initiated from an 80um long by 40um deep notch that was milled out (prior to fatigue cycling) using a focused-ion beam. Micro-computed tomography images at various cycle counts (up to 9500 cycles) were segmented via a U-Net convolution neural network architecture [Menasche et al., 2021] to obtain sub-grain-level crack path evolution. In addition, 3D grain structure and grain level strains were obtained via near-field and far-field HEDM techniques. These three data streams were then co-registered onto a common 3D coordinate system for all loading states.

From the 4D microstructurally small crack (MSC) growth dataset several experimental insights have been found. We will limit our results and discussion to the polycrystalline microstructure within the region of interest near the initial FIB notch. Figure 1a illustrates the local crack growth rate as a function of location in the polycrystalline microstructure. The local crystallographic orientation of the crack plane normal at each point of the 3D crack front is colored by its location within the inverse pole figure (IPF) triangle and is shown in Fig. 1b. Considering Figures 1a and 1b, there was an initial correlation with faster growth along the {111} family of slip planes. However, this trend was not generalizable for the remainder of the small crack growth experiment.

The near-field-HEDM-measured, spatially-resolved orientation of the polycrystalline microstructure was compared between load states to calculate the misorientation rotation matrix (referred to here as the grain reorientation) that rotates each grain from an initial load state to the load state of interest. This grain reorientation, represented as an angle-axis pair, is used here as a signature for plastic behavior (as shown in [Musinski et al., 2021]). The reorientation angle magnitude and reorientation axis direction measured from the initial loading state to fatigue cycle 4,000 are shown in Figures 1c and 1d, respectively. In Fig. 1d, the reorientation axis direction is colored by the IPF triangle direction within the local crystal reference frame.

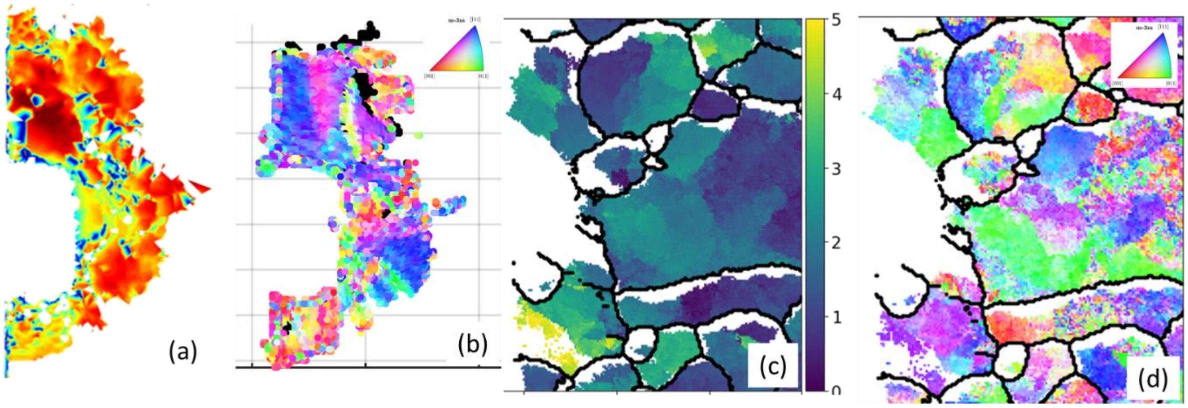

Fig. 1 – Metadata associated with MSC growth from FIB notch within region of interest. (a) Magnitude of local crack growth rate, (b) crack plane normal colored by location in IPF triangle, (c) local reorientation angle and (d) reorientation axis direction between initial loading and fatigue cycle 4,000.

Figs. 1c and 1d indicate the prevalence of sub-grain deformation domains where, within the sub-grain deformation domain, there are clusters of similarly oriented reorientation axes. These similarly oriented reorientation axes can indicate the activation of different slip system(s) in each of the sub-grain deformation domains. Following the recent slip activation analysis via grain reorientation analysis by [Musinski et al., 2021], the prevalence of magenta <112> and green <110> reorientation axes would indicate that single slip (of 1 slip system) and coplanar slip (of 2 coplanar slip systems) within the {111}-<110> family of slip systems are both heavily active in the region near the FIB notch.

A crystal plasticity finite element model was instantiated via a custom Python workflow that included calls to Dream.3D and Abaqus CAE for microstructural and mesh construction. The finite element models contained cracks representing the physical material condition at the various loading states. The stress/strain evolution as a function of crack state was simulated via CPFE and compared to the HEDM-measured strains in the crack growth experiment. Correlations between microstructurally small crack driving force, growth along a given crystallographic plane, grain re-orientation, and crack growth rate are further expounded upon in an upcoming paper currently in preparation.

3. Conclusions

The crack growth data from an HEDM experiment was used to validate a CPFE model for plasticity development, grain reorientation, and crack growth at the microstructure scale.

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References

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