Correlative Microscopy Approaches to Understand Interactions between Microstructure and Creep Cavitation in Type 316H Austenitic Stainless Steels

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Abstract

Creep cavitation can significantly limit creep ductility and lifetime of energy materials at elevated temperatures. Although cavity growth mechanisms are well established, creep cavity initiation and early-stage growth need to be better understood. This study utilized a correlative microscopy approach together with image registration to study links between local microstructure and creep cavitation in a Type 316H austenitic stainless steel. This provides new insights into cavity initiation mechanisms.

1. Introduction

Creep cavitation is one of the dominant damage mechanisms for high-temperature components, e.g. austenitic stainless steel boiler header in Advanced Gas-cooled Nuclear Reactors (AGRs). Such components experience high stresses and temperatures during service, and detailed microscopy shows the presence of creep cavitiation in the heat-affected zone of weldments. The cavitation is linked closely to the changes in precipitation at grain boundaries caused by thermal ageing [1]. It has been recognized that creep cavity initiation and growth can be linked with stress state and local microctructural environment, for example, grain size, grain boundary misorientation, boundary orientation relative to loading direction, and grain Schmid Factor, etc. There is a lack of statistical analyses in terms of correlations between local microstructural environment and creep cavitation in the current literature. Traditional scanning electron microscopy can give insights into cavitation processes at local microstructural features, but single images only provide interrogation of a very limited region of the material. Applying a correlative approach using a combination of microscopy techniques, stitched images across larger length scales and image recognition allows these nanoscale insights to be understood at engineering component length - scales [2]. In this study, stitched higher-resolution scanning electron microscopy (SEM) images and stitched electron backscatter diffraction (EBSD) data were collected over the same area of a crept 316H austenitic stainless steel notch specimen. The SEM and EBSD data were correlated using an advanced image registration algorithm to investigate the effect of local microstructural parameters on creep cavity initiation in a statistical manner.

2. Results

A total of 162 continuous SEM frames with 30% overlap were collected over the notch region of the specimen and were stitched using ImageJ software (the stitched SEM image is shown in Fig. 1a, where extensive creep cavitation is present). The stitched SEM images have a pixel resolution of approximately 0.24 µm. Deep learning image processing software Dragonfly [3] was then used to segment all creep cavities from the stitched higher resoluion SEM image and exported as a binary image. EBSD data of the same area was then collected at a step size of 3 µm. The Inverse Pole Figure (IPF) of the EBSD data is shown in Fig. 1b. Grain boundaries were calculated from the EBSD data set through MTEX Matlab toolbox as shown in Fig. 1c. To correlate the SEM and EBSD data set, a spatial coordinate relation needs to be identified between the two. Therefore, a number of control point pairs, for example, 2D boundary triple junctions, inclusions, boundary edges, were identified on both the SEM and EBSD images. A transformation function can then be determined through these control points. After building the correlation, the creep cavities segmented from the stitched SEM image were projected onto the grain boundary map calculated from the EBSD data. Fig. 1d shows the grain boundary creep cavity distribution, where yellow color indicates the cavitated grain boundary segments.

In this study, kernel average misorientation (a qualitative indicator of local strain gradient), grain boundary crystallographic misorientation, global Schmid Factor, grain boundary trace orientation relative to loading direction, and grain size were obtained from the EBSD data. By correlating the SEM and EBSD map, and by projecting the creep cavities onto the EBSD data set, the effects of the local microstructural parameters on creep cavitation were analysed statistically. It was found that creep cavity initiation exhibits a strong correlation with local strain gradient, some correlation with grain boundary misorientation and grain size, and a weak correlation with global Schmid Factor and grain boundary trace orientation. Critically, the proportion of precipitation on boundaries is also strongly correlated with cavitation, showing that grain morphology alone is insufficient to fully describe the cavity initiation process in these 316H steel specimens.

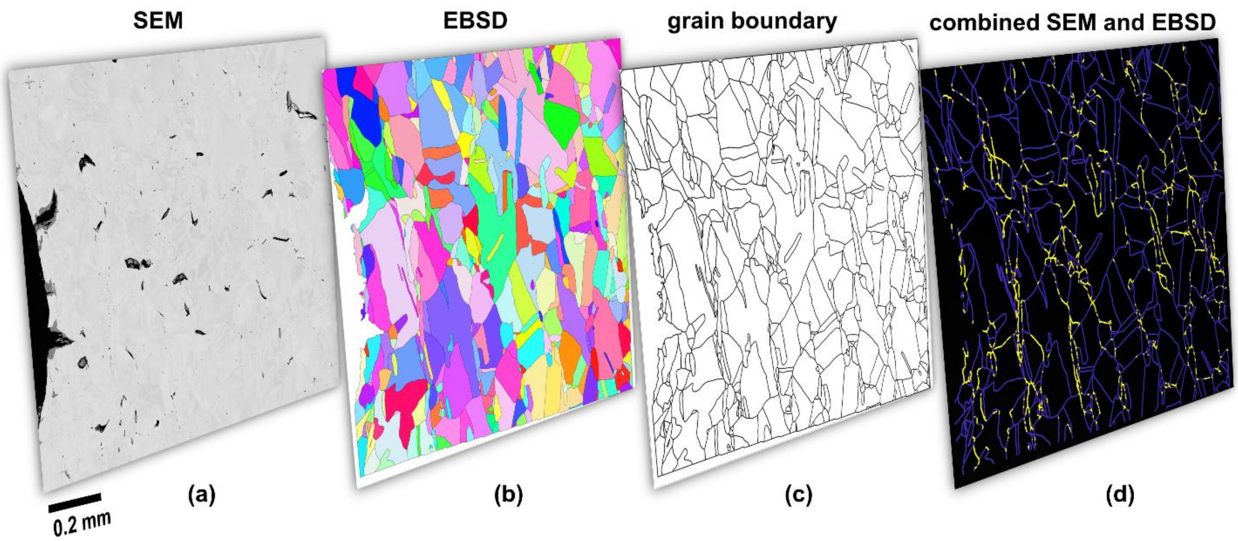

Fig.1 – Correlative SEM-EBSD microscopy approach for studying interactions between local microstructure and creep cavitation. (a) stitched SEM image; (b) stitched EBSD Inverse Pole Figure; (c) EBSD grain boundary map; (d) creep cavity distribution map.

3. Conclusions

The new correlative SEM-EBSD microscopy approach presented here brings new insights into the mechanisms of creep cavity initiation and early-stage growth. Correlations between creep cavitation and typical microstructural parameters were studied statistically in a crept 316H austenitic stainless steel specimen. Creep cavity initiation was closely linked with local strain gradient, grain boundary misorientation and grain size, as well as the nature of precipitation on boundaries.

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