Correlating Microstructural Deformation and Slip System Activation using HRDIC, EBSD, and Crystal Plasticity

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Abstract. We explore the microstructural deformation of JRQ steel using high-resolution digital image correlation (HRDIC) during in-situ tensile testing, paired with electron backscatter diffraction (EBSD) to link local strain fields to underlying grain orientations. This correlation enables the identification of activated slip systems, which are then used to validate subsequent crystal plasticity simulations that incorporate the sample microstructure and displacement conditions. Together, these methods provide a detailed view of grain scale plasticity, advancing our understanding of deformation processes in nuclear steels with applications in advanced structural integrity assessments.

Introduction

As materials are subjected to tensile stress, the deformation at the grain scale plays a pivotal role in governing overall material response, influencing both strength and ductility [1]. Traditional methods of evaluating deformation often lack the resolution to capture grain-level behaviour and slip system activation, which are key to accurately predicting material performance. Recent advances in experimental techniques, such as HRDIC and electron backscatter diffraction (EBSD), offer powerful tools to investigate these localized deformations [2]. By coupling HRDIC with EBSD, it is possible to observe the relationship between strain fields and grain orientations, providing critical insights into the activation of specific slip systems during plastic deformation [3]. However, experimental observations alone are insufficient to fully capture the complexities of these processes [4]. Crystal plasticity modelling, which integrates the microstructure with boundary conditions, offers a way to simulate the activation of slip systems and further the understanding yielded from experiment alone [5]. This work combines these approaches, providing a comprehensive understanding of microstructural deformation and slip system activation in JRQ steel under tensile loading.

Methods

Experimental. Flat dog-bone specimens of JRQ steel were mechanically polished to achieve a surface finish suitable for electron backscatter diffraction (EBSD) analysis, enabling the characterization of the initial grain microstructure. Following EBSD, a high-contrast, Tin based speckle pattern was applied to the specimen surface to facilitate high-resolution HRDIC. The speckled specimens were subjected to in-situ tensile testing at room temperature using TESCAN device at the Henry Royce Institute. The specimens were strained incrementally up to 15%, with 78 high-resolution frames captured. Each frame encompassed a 450 µm by 450 µm region of interest. The captured images were analysed to compute full-field displacement and strain maps. Displacement data along the X and Y directions were extracted along the edges of the region of interest as functions of position, providing boundary conditions for subsequent modelling.

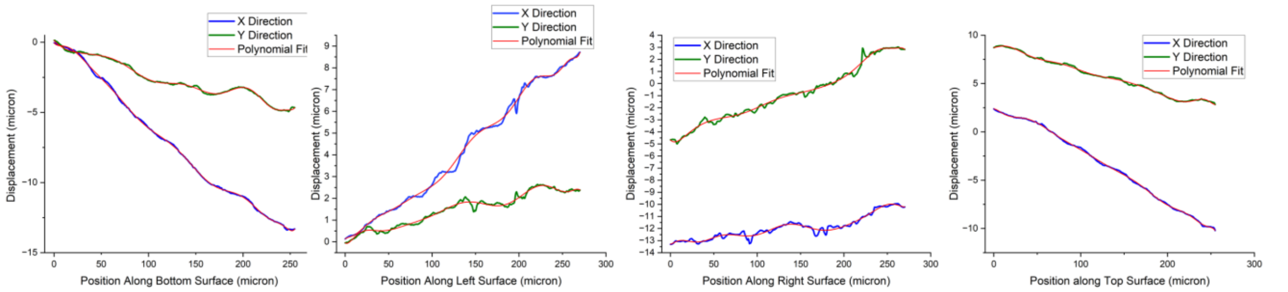

Figure 1-4: Extracted displacements along edges of the region interest fitted with a high order polynomial fit.

Modelling. To enable direct application of experimental boundary conditions in the finite element model, the displacements measured along the edges of the HRDIC region of interest were fitted using high-order polynomial functions. These fitted functions allowed the displacement data to be parsed and applied within a crystal plasticity finite element framework. The model employed was tailored for body-centred cubic materials and incorporated a dislocation-based slip hardening law alongside a power-law slip rate formulation. The parsed displacement functions were imposed via displacement-controlled boundary conditions, applied linearly over time to replicate the evolution of loading in the experiment. This approach ensured that the reconstructed microstructure in the simulation experienced boundary conditions equivalent to those in the physical test. The simulated microstructure was directly derived from the grain orientations obtained through EBSD analysis of the specimen's top surface. To link experimental observations with crystallographic features, an open-source Python package was used to correlate the local strain fields measured via HRDIC with the underlying grain orientations. By examining the orientation of slip banding in relation to the crystallographic axes, the activated slip systems within individual grains were identified. Comparison of experimentally observed slip systems, as well as the strain and displacement fields, with the crystal plasticity simulation results, enables validation of the model and contributes to the understanding and prediction of deformation behaviour at the grain scale.

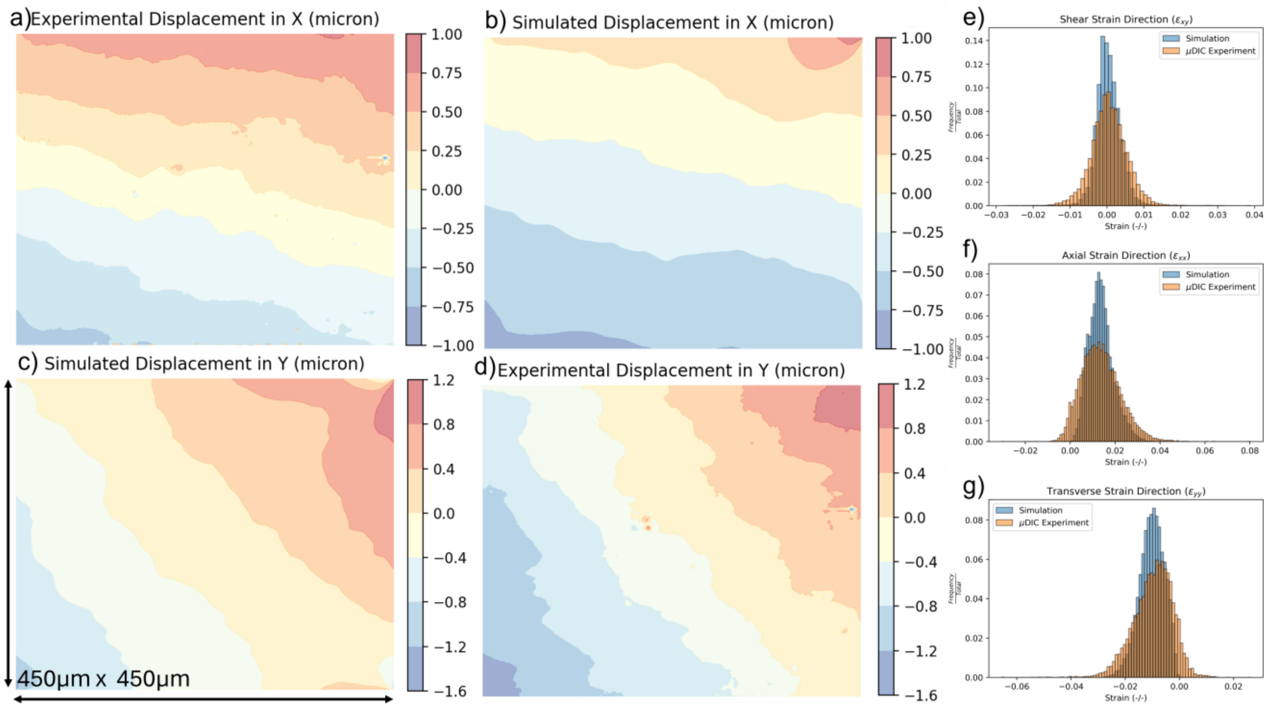

Figure 2: The experimental displacement field and the simulated displacements using the fitted boundary conditions (a-d). Histograms showing a comparison in strain field between experiment and simulation for axial, transverse, and shear strain components (e-g).

Results

Figures 2a-2d show that the methodology used can be successfully used to recreate experimentally observed displacements within a simulation of a grain microstructure, with close matching between displacement fields in the axial (XX) and transverse (YY) direction. Figures 2e-2g show histograms showing the distribution of strain values across the region of interest. When each histogram is fitted with a normal distribution, the difference in the calculated mean was small. The standard deviation between the distributions for simulated and experimental data were larger. This suggests that the implementation of boundary conditions induces the correct levels of strain and plasticity. However, the crystal plasticity model predicts a more homogenous strain field than is observed, indicating that the model requires further development to capture local variability resulting from the crystallographic orientation of grains adjacent to one another.

Conclusion

An HRDIC experiment for in-situ loading and testing of specimens of JRQ steel was performed at the Henry Royce institute. The resulting strain field was correlated to the underlying grain microstructure using electron backscatter diffraction analysis to identify individual slip system activation. The displacement field and microstructure were reproduced using a crystal plasticity finite element model to enable model validation by comparing the ability of the model to reproduce experimental results of grain length scale deformation.

References

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