Using in-situ HRDIC bend testing to examine local-stress state driven plasticity in pure copper

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Abstract. Components rarely undergo pure, monotonic, tensile loading in service. We therefore ask why do we often only examine materials under quasistatic tension? In this study, we implement in-situ bend testing within the scanning electron microscope to address this question, exploiting the natural spatially heterogeneous stress state inherent in a bending geometry. By coupling this with high-resolution strain mapping and electron backscatter diffraction-based orientation mapping, we have a quantitative tool that can be used to understand relationship between long range stress states and local plasticity at the microscale. We demonstrate this experiment in oxygen-free copper, with a view to expanding this to cyclic loading.

Introduction

In-service components are rarely loaded in a simple manner. Complex component geometries naturally drive stress states with significant deviations from simple, uniaxial loading, often including elements of tension, compression and shear simultaneously. Temperature gradients increase the complexity further. Finally, components are typically loaded in a dynamic fashion in-service, often in a cyclic way during steady state operation or in a more complex time-dependent manner during start-up, shut-down or off-normal events. As such, simple tensile testing is a significant deviation from reality. If we are to use a microstructural-based understanding to design and quality components for challenging industrial environments, for example the UK's Spherical Tokamak for Energy Production (STEP), we need to probe this complex space.

In-situ bend testing with copper

Previous work on copper-base alloys [1,2] using high-resolution digital image correlation (HRDIC) has revealed highly heterogeneous deformation at the microstructural length scale. The advent of highly automated in-situ testing with HRDIC in the scanning electron microscope (SEM) has allowed for an increase in experimental complexity and temporal resolution [3], permitting us to examine strain-path dependent mechanisms.

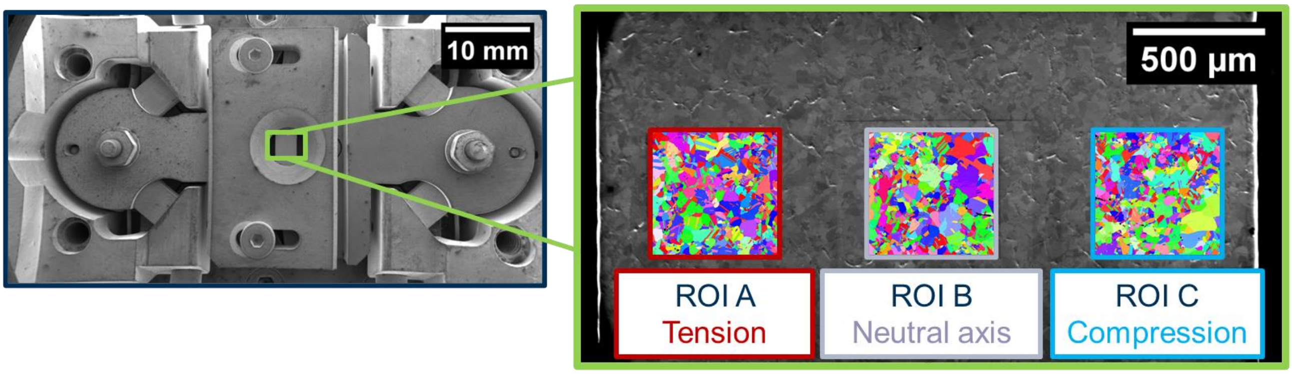

Figure 1: Overview image the of the bending test fixture in the SEM, with detail of the three regions of interest across the specimen, highlighting the variety of stress-states that can be observed.

In-situ mechanical testing is technologically limited by what can be accommodated within the SEM chamber, however, bend testing represents an intermediate case between simple, uniaxial testing, and the complex multi-axial operating environments found in-service. Four-point bending offers a large region of constant bending moment in the longitudinal direction whilst producing a spatially varying stress state from tension to compression across the axis of bending. In this study, we examine oxygen free copper, investigating three regions of interest (ROIs) across the sample, placed in the tensile, neutral and compressive regions of the specimen (Figure 1).

Strain maps following deformation (Figure 2) show the typical heterogeneous strain patterning expected with a combination of both slip and grain boundary sliding. The effect of the macroscopic stress state is clear, with minimal plasticity in the region at the neutral axis but with similar strain patterns visible in the tensile and compressive areas. Due to the large sizes of the ROIs (~350 x 350 µm), there are also appreciable variations in stress state across individual regions of interest. As such, individual strain maps are a superposition of the local crystal driven stress state and the macroscopic stress state. This single experiment offers a wealth of data, allowing us to unpick the primary driving factors of local plasticity.

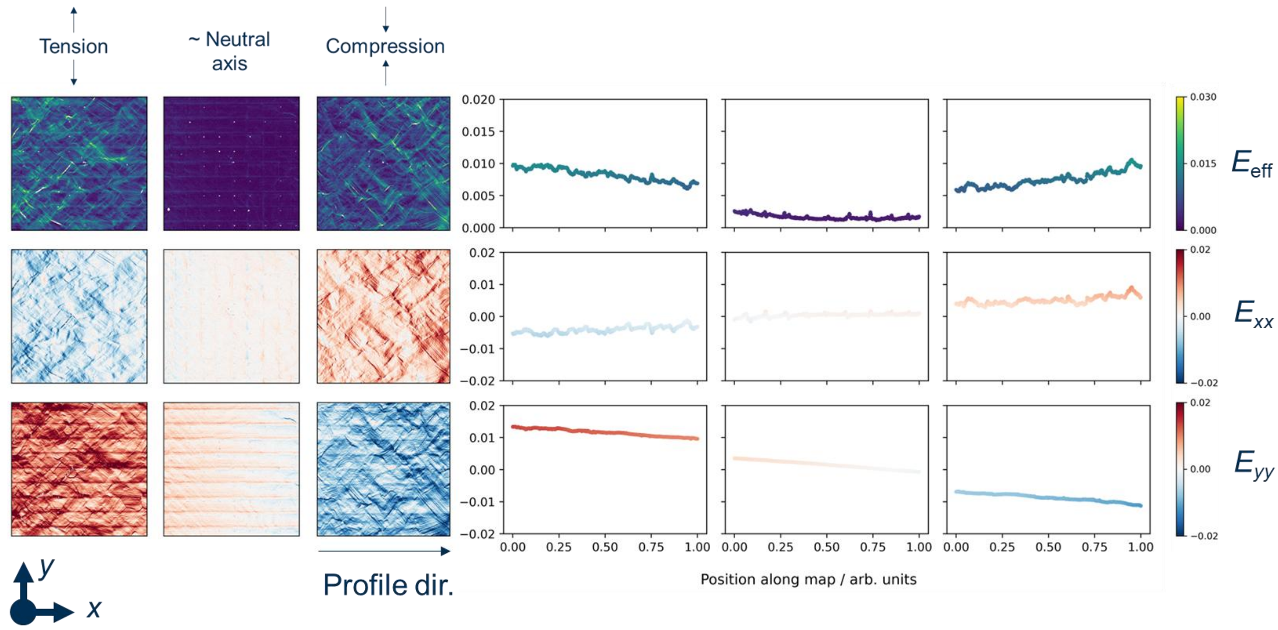

Figure 2: Strain component maps (E_{eff}, E_{xx}, E_{yy}) for the three regions of interest with profiles of mean strain taken across each map.

Conclusions

The effect of macroscopic stress state induced by bending has been examined at the microstructural length scale, with a clear impact on plasticity through slip and grain boundary sliding observed. These effects are observed both between regions with different nominal stress states and within regions with spatially varying strain fields. This technique offers both the ability to examine the interaction between local and global stress fields and a streamlined methodology to examine a wider parameter state within a single test, in the spirit of Materials Testing 2.0 [4].

References

[1] B. Poole, A. Marsh, D. Lunt, C. Hardie, M. Gorley, C. Hamelin, A. Harte, Nanoscale speckle patterning for combined high-resolution strain and orientation mapping of environmentally sensitive materials, Strain n/a (2024) e12477. https://doi.org/10.1111/str.12477.

[2] B. Poole, A. Marsh, D. Lunt, C. Hardie, M. Gorley, C. Hamelin, A. Harte, High-resolution strain mapping in a thermionic LaB6 scanning electron microscope, Strain n/a (2024). https://doi.org/10.1111/str.12472.

[3] A.D. Smith, D. Lunt, M. Taylor, A. Davis, R. Thomas, F. Martinez, A. Candeias, A. Gholinia, M. Preuss, J.M. Donoghue, A new approach to SEM *in-situ* thermomechanical experiments through automation, Ultramicroscopy 280 (2026) 114244. https://doi.org/10.1016/j.ultramic.2025.114244.

[4] F. Pierron, Material Testing 2.0: A brief review, Strain 59 (2023) e12434. https://doi.org/10.1111/str.12434.