Slip and slide - capturing early deformation behaviour in copper-base alloys

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Abstract
A true fusion reactor environment cannot be replicated prior to the operation of power-station scale fusion devices, and as such predictive models are required to facilitate component design. Deleterious deformation effects are often underpinned by microstructurally controlled phenomena and, as such, full-field strain mapping is necessary at the microstructural length scale to inform physically based models. However, strain mapping following significant levels of deformation can be challenging to interpret, especially in materials where multiple deformation mechanisms are present. Here, we employ in-situ mechanical loading with many snapshots of strain to unpick the temporal evolution of plastic deformation in fusion relevant copper-base alloys, focussing on the relative contributions of two primary deformation modes: grain boundary sliding and dislocation slip.

Keywords: HRDIC, SEM, EBSD, microstructure

Possible sessions: Special session - Automated high spatial and temporal resolution in-situ testing in the SEM

Introduction

Knowledge of materials performance under the untestable fusion environment remains a significant engineering challenge in delivering a power-station scale fusion device capable of producing net electricity output [1]. The unique service environment cannot be replicated and, therefore, we are reliant upon high-fidelity, physically based modelling to inform component performance and design. An extremely thorough and rigorous understanding of the underlying deformation kinematics of fusion relevant materials is required to provide the input data for these modelling efforts. A focus on the microstructural length scale is required as it is at this length scale where many governing degradation mechanisms occur.

Quantifying deformation with full-field SEM-based high resolution digital image corelation (HRDIC) strain mapping is the ideal tool to understand behaviour at this length scale. When coupled with electron backscatter diffraction (EBSD)-based orientation mapping, we have direct linkage of deformation kinematics with the microstructure. However, this is not without caveats. Traditionally, this testing has been performed ex-situ, taking the sample between the SEM and the load frame for each step of applied deformation. This time-consuming process limits the number of strain steps to perhaps two or three. The end results are highly spatially resolved strain data, but with very little knowledge of the evolution of plasticity with applied global strain. When multiple deformation modes are present, the primary questions become which of these phenomena occurred first, and how do their relative contributions compare. The advent of integrated, automated in-situ testing allows us a more informed view to tackle these questions.

Deformation behaviour of copper-base alloys

Copper-base alloys, primarily precipitation hardened CuCrZr, and Oxygen-free high-conductivity copper (OFHC-Cu) are of prime interest for heat sink components, owing to their high thermal conductivity. However, there mechanical performance is less well understood.

Previous studies in these materials have highlighted grain boundary sliding as an important deformation mechanism as well as the expected dislocation mediated slip [2,3]. However, interrupted studies to 1.5% could not determine which mechanism initiates first and whether these mechanisms are complementary or competing as deformation patterning appeared to be fully established at small strains. Therefore, it is necessary to study these materials at the onset of plasticity, before the macroscopic yield point and at high temporal resolution.

These types of experiment are not practical to perform manually due to the time-consuming image collection phases, necessitating automated testing. In this work, we use an integrated in-situ testing solution comprising a TESCAN CLARA field emission SEM with a NewTec Scientific MT1000 mechanical tester. This system allows for fully automated image capture as a function of applied deformation. By mapping strain at high temporal and spatial resolutions, we find that grain boundary sliding initiates at very low strains and prior to the onset of significant slip activity (Figure 1). This finding challenges the assumption that dislocation slip is the primary mediator of plasticity and has profound impacts on representative crystal plasticity models of these materials.

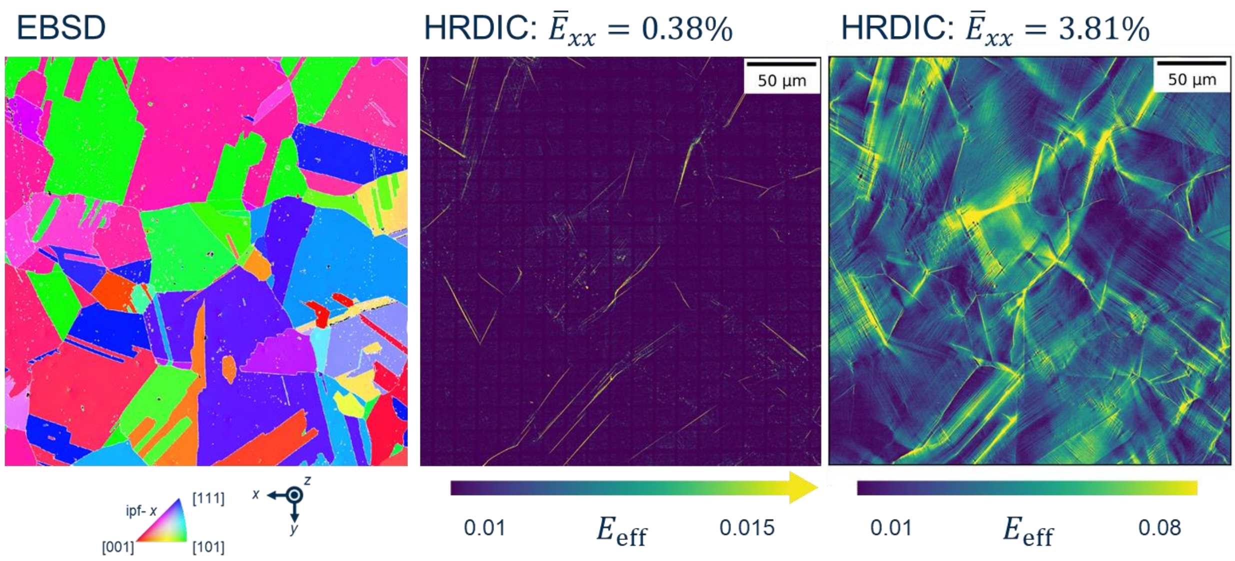

Figure 1: Progression of strain patterning (maps of effective shear strain) in peak aged CuCrZr with the EBSD-derived grain orientations for the region of interest. The two snapshots of strain highlight the early onset of grain boundary sliding, followed by complex distributions of slip at larger global strains.

Complementary techniques

To further explore the deformation kinematics, we employ additional characterisation post-test around features of interest, for example at the interaction of slip bands with chromium particles or in the vicinity of sliding grain boundaries. Cross correlation-based high-angular resolution EBSD (HREBSD) is used to quantify lattice rotation and elastic strains, and to estimate geometrically necessary dislocation densities, relating these measures to total strain measures from HRDIC. This leverages the EBSD compatible nature of the DIC speckle pattern used in this work [3]. Electron channelling contrast imaging can also be used to directly image crystallographic defects at the nanometre length scale, allowing detail insights into the dislocation structures governing the behaviours observed with HRDIC and to validate quantitative analysis provided by the DefDAP python toolbox [4].

Conclusion

We demonstrate the successful application of fully automated in-situ mechanical testing with HRDIC strain mapping on fusion relevant copper-base alloys. This technique allows us, for the first time, to understand the progression of microstructural strain localisation as a function of applied global deformation. Grain boundary sliding is observed to occur before dislocation mediated slip. Through quantifying the local effects of these phenomena, we can better understand their impact on component scale performance and build physically-based materials models better representative of true mechanical behaviour.

References

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