In-situ Neutron Diffraction Analysis of OFHC Copper Under Low-Cycle Fatigue for Fusion Applications

Wan W. Mohammad[1], Nicolò Grilli[1], Burcu Tasdemir[1], Mehdi Mokhtarishirazabad[1], Simon McKendrey[1], B. Poole[2], Cory Hamelin[2], Mahmoud Mostafavi[3], Joe Kelleher[4], David Knowles[1,5]

[1]Solid Mechanics Research Group, School of Electrical, Electronic, and Mechanical Engineering, University of Bristol, UK, [2] UK Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire, UK, [3]Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Victoria, Australia, [4]ISIS Neutron and Muon Source, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, Oxfordshire, UK [5]Henry Royce Institute, Manchester, UK

[1]wan.wanmohammad@bristol.ac.uk

Abstract. Oxygen Free High Conductivity (OFHC) copper has been proposed as a heat sink interlayer for fusion reactor divertor components. This study investigated the low-cycle fatigue (LCF) behaviour of OFHC copper using in situ neutron diffraction at room temperature. Fatigue tests were conducted on different heat treatment samples at a total strain range of $\Delta\varepsilon$ = 0.6% and a strain ratio of R = -1 to examine the evolution of internal lattice strains under cyclic loading. Neutron diffraction analysis provided information on strain accumulation and redistribution of stress evolution throughout the fatigue cycles. The results revealed that cyclic softening and hardening were found to vary with the as-drawn condition, exhibiting fluctuations in the activation of soft and hard grain families throughout cyclic loading. This behaviour was captured through the evolution of peak lattice strain shifts and peak broadening, highlighting the role of microstructural recovery and recrystallisation in fatigue behaviour. These findings contribute to a deeper understanding of mechanisms under LCF and validate predictive mesoscale models for fusion reactor component design.

Possible Sessions

8. Fatigue & Fracture, 13. Metals and Microstructure, 18. Nuclear Applications: Fusion

Introduction

The European DEMOnstration Fusion Power Plant DEMO is a crucial step in advancing sustainable fusion energy, bridging the gap between ITER and commercial fusion reactors. OFHC copper is used as an interlayer material to join Tungsten (W), used as the first wall material, and Copper-Chromium-Zirconium (CuCrZr) alloy is used as a cooling pipe. These components endure significant thermomechanical stresses, and severe damage due to high thermal load cycles, combined with high electromagnetic loading, irradiation damage and complex cyclic loading due to the plasma pulsed mode operation in service [1]. Therefore, it is crucial to know the impact of cyclic loading to assess its effects on the component's fatigue lifetime.

Neutron diffraction is a powerful in-situ technique that enables the measurement of internal strain and stress evolution at the polycrystalline scale under mechanical loading [2], [3]. Its high penetration depth enables bulk crystallographic strain measurements, providing insights into grain-scale partitioning and intergranular stress evolution during cyclic loading. This study focuses on in-situ diffraction to characterise the fatigue response of OFHC copper under fusion-relevant loading and serves as a benchmark for the validation of crystal plasticity finite element (CPFE) modelling to predict local grain-scale deformation. CPFE enables first-principles prediction of mechanical behaviour, capturing the effects of texture, grain size and shape, and manufacturing processes on the material response [4].

Methodology

In-situ time-of-flight neutron diffraction measurements were performed at the Engin-X beamline at the ISIS Neutron and Muon Source [5]. The neutron diffraction fatigue test was conducted at room temperature, and during the testing, the specimen was positioned at a 45° angle to the incident neutron beam, with two detector banks fixed at $2\theta = \pm 90°$ as shown in Figure 1. This scattering geometry allowed one detector to collect diffraction data along the loading direction (axial strain) and the other to capture data normal to the loading direction (transverse strain). The gauge volume was 4 x 4 x 4 mm^3 to capture a sufficient number of grains within the neutron beam. The LCF tests were performed using a 50 KN Instron loading rig under fully reversed loading conditions of a strain ratio of R = -1 at a strain range of 0.6% at room temperature.

Diffraction data were collected at different fatigue cycles, specifically the first 4 cycles, and gradually increased to 8, 12, 30, 40, 50, 100, 250, 500, 1000, 1500 and 2000 with a loading frequency of around 1 Hz. To track the evolution of lattice strain throughout the fatigue cycle, neutron scans were performed at six key points, shown in Figure 2, within a loading cycle. These measurement points were selected to capture the critical stages of cyclic deformation. The experiments were conducted on both as-drawn samples and samples annealed at 450°C. This approach enables the investigation of how microstructural conditions influence the activation of grain families that dominate plastic deformation during cyclic loading.

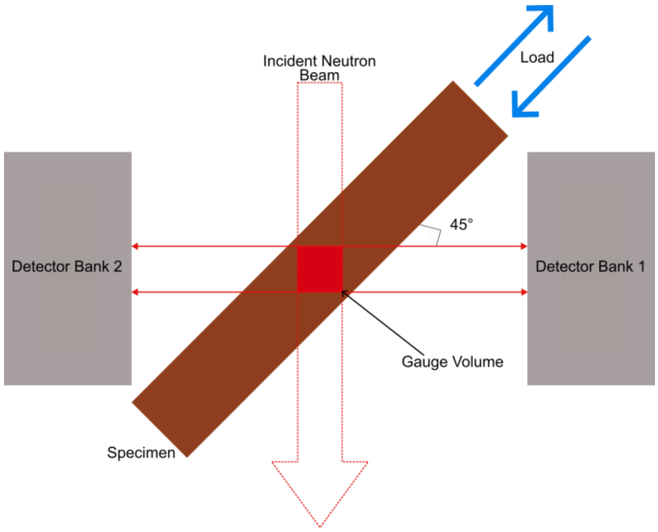

Figure 1: Schematic view of the in-situ neutron diffraction measurements set-up.

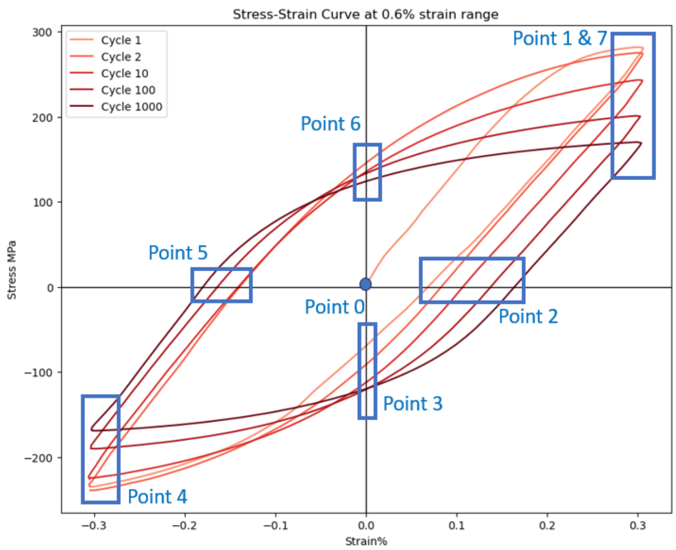

Figure 2: The cyclic-loading sequence for neutron scan.

Conclusion

This study demonstrates that in-situ neutron diffraction effectively captures grain-resolved strain evolution during cyclic of OFHC copper. The results show that thermal history strongly influences cyclic softening and hardening, and that intergranular stresses develop due to local strain partitioning between grains. These findings provide knowledge for validating mesoscale models and improving fatigue life predictions for fusion components.

References

[1] G. J. Butterworth and C. B. A. Forty, 'A survey of the properties of copper alloys for use as fusion reactor materials', *Journal of Nuclear Materials*, vol. 189, no. 3, pp. 237–276, Aug. 1992.

[2] H. Roirand, N. Saintier, A. Hor, and B. Malard, 'Understanding of additively manufactured material cyclic behavior at the grain scale by neutron diffraction and crystal plasticity modeling', *Materials Science and Engineering: A*, vol. 918, p. 147380, Dec. 2024, doi: 10.1016/j.msea.2024.147380.

[3] C. Allen *et al.*, 'Prediction of multiaxial deformation of 316H stainless steel at high temperature using a multiscale crystal plasticity approach', *Materials Science and Engineering: A*, vol. 931, p. 148160, Jun. 2025, doi: 10.1016/j.msea.2025.148160.

[4] D. Agius *et al.*, 'Microstructure-informed, predictive crystal plasticity finite element model of fatigue-dwells', *Computational Materials Science*, vol. 183, p. 109823, Oct. 2020, doi: 10.1016/j.commatsci.2020.109823.

[5] J. R. Santisteban, M. R. Daymond, J. A. James, and L. Edwards, 'ENGIN-X: a third-generation neutron strain scanner', *J Appl Cryst*, vol. 39, no. 6, pp. 812–825, Dec. 2006, doi: 10.1107/S0021889806042245.