The role of irradiation, hydrides and precipitates on strain localisation in a zirconium alloy

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Abstract.
During service, materials in the core of a nuclear reactor are subject to a harsh environment, which can change and degrade mechanical properties. In particular, zirconium alloy fuel cladding experiences irradiation by neutrons for years, which causes a reduction in ductility. Contact with water at elevated temperature leads to corrosion and the formation of hydrides, which can also reduce ductility. The effect of a combination of both irradiation and hydrides on deformation behaviour is less well understood. In this study, the effect of different simulated service conditions on sub-grain scale strain localisation are related to the microstructure and the importance of these observations in context of fuel cladding integrity is discussed.

Introduction

A prominent technique for investigating deformation behaviour at the sub-grain scale is high resolution digital image correlation (HRDIC) in a scanning electron microscope (SEM) using backscatter electron (BSE) imaging, which gives quantitative local strain maps, resolved at nanoscale resolution. This data is often combined with phase and grain orientation data from electron backscatter diffraction (EBSD) to relate microstructure to strain and slip system activity. This approach requires appropriate patterning, which was performed in the current study using gold sputtering and remodelling in a styrene vapour, allowing for spatial resolution of < 100 nm [1]. Investigation of neutron irradiated samples is slow, difficult, and expensive. Furthermore, specialised facilities are required for handling, limiting the experimental apparatus that can be used. Therefore the current study uses proton irradiation as a surrogate. Electrochemical hydrogen charging is used as an alternative to corrosion, allowing for control of hydrogen content.

Effect of irradiation

Irradiation causes a high density of nanoscale dislocation loops to form, leading to an increase in strength. Deformation causes channels of width ~100 nm to be cleared and further deformation is favoured along these paths [2]. Previous studies typically use TEM which limits the area studied and does not provide quantitative information. However, HRDIC provides strain maps over a large area, as shown Figure 1, which demonstrate that irradiation significantly increase heterogeneity, allowing greater slip transfer between grains [3,4]. Furthermore, this data has been used to validate a crystal plasticity model [5].

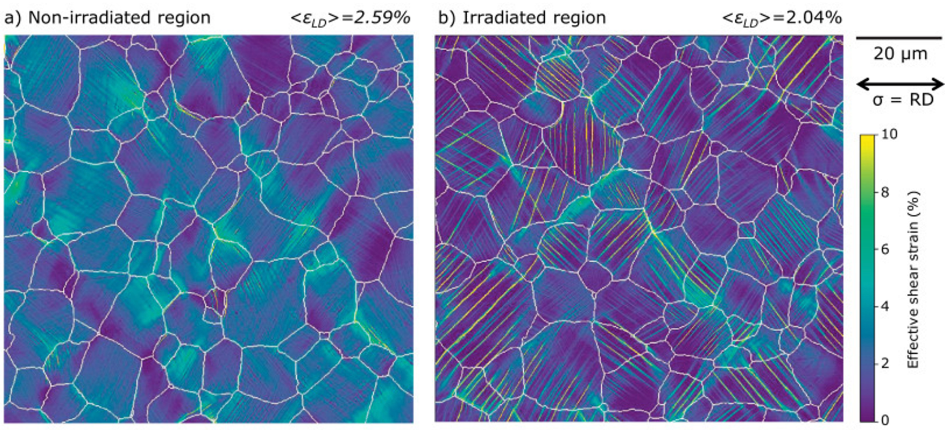

Figure 1. *Strain localisation in a) unirradiated Zircaloy-4, compared to b) Zircaloy-4 irradiated to 0.1 dpa [1].*

Effect of hydrides

Bulk zirconium hydrides are a brittle phase which show little ductility at room temperature. However, this phase is a minority constituent of in-service zirconium alloys. Figure 2 shows how phase and orientation information from EBSD is combined with HRDIC and BSE imaging to investigate where the largest strain localisation occurs in the microstructure, since these localisations are likely precursors to failure. It was found that hydrides significantly enhance heterogeneity in the matrix, especially near phase boundaries.

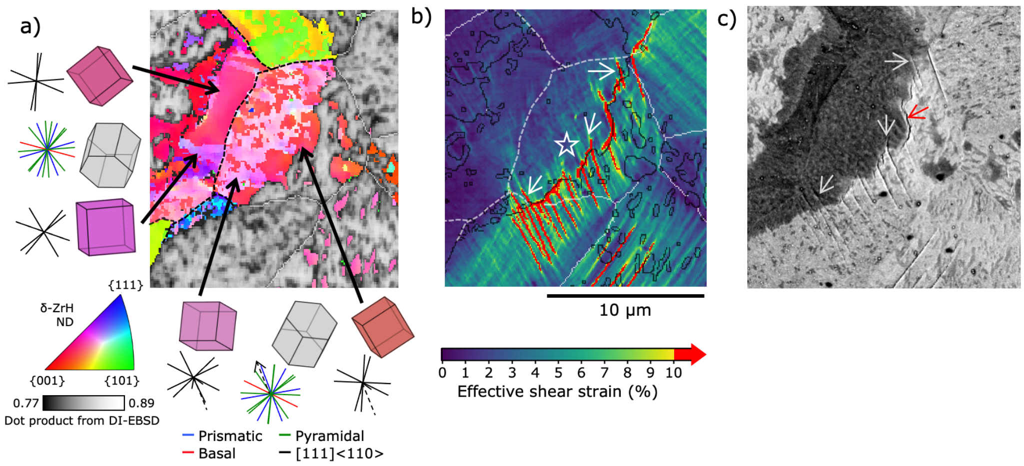

Figure 2. a) *Orientation map for the hydride phase, with unit cells and slip planes for the matrix and hydride phases. b) Effective shear strain map. c) BSE images from the final deformation step.*

Effect of precipitates and synergistic effects

Zirconium alloys also contain a small volume fraction of fine precipitates, which improve corrosion performance. Due to the high spatial resolution of the HRDIC technique, their effect on deformation behaviour is also quantified. Preliminary studies on a combination of irradiation and hydrides will also be presented.

Conclusion

Using a combination of speckle patterning, SEM-based HRDIC and EBSD; the effect of irradiation, hydrides and precipitates on deformation behaviour of a commercial zirconium alloys was studied.

- Diffuse, homogeneous slip was observed in the unirradiated zirconium alloy. In irradiated material, slip is confined to dislocation channels, containing high effective shear strains and relatively large spacings, increasing strain heterogeneity and reducing ductility.
- When loaded along RD, primarily planar prismatic and some pyramidal slip was observed. Wavy basal slip arising due to cross-slip and tension twins were additionally observed in the sample loaded along TD.
- Compared to unhydrided Zircaloy-4, deformation of the Zr matrix of hydrided material is more diffuse, wavy and heterogeneous because of the accommodation of deformation incompatibility.
- Large hydrides have a particularly deleterious effect on deformation behaviour, with large strain localisations and cracking observed at interfaces, which could be precursors to failure
- Precipitates exhibit a lower strain than the Zr matrix and undeformable particle behaviour is observed, with lobes of positive rotation on two sides of the precipitate and two alternate lobes of negative rotation.

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