International Journal of Plasticity 71 (2015) 170–194

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Strain localization and failure in irradiated zircaloy with crystal plasticity

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ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form 31 March 2015
Available online 21 May 2015

Keywords:
B. Crystal plasticity
B. Cyclic loading
A. Dislocations
C. Finite elements
Zircaloy

ABSTRACT

This paper presents a micromechanical and mechanistic study of irradiation-induced crystallographic softening known to accelerate failure in irradiated zircaloys typically used as cladding material in pressure water nuclear reactors. The irradiation is known to lead to an increase in yield strength, and reduced ductility is anticipated to result from the progressive reduction in slip system strength. Extensive studies using transmission electron microscopy (TEM) show the formation of <a> type dislocation channels in irradiated zircaloys anticipated to affect basal and prismatic systems. A crystal plasticity approach is established to incorporate basal and prismatic crystallographic softening, both of which are shown to be required in order to capture independent experimental observations for irradiated zircaloy.

Representative irradiated zircaloy textures subjected to cyclic loading regimes were modelled to provide an understanding of the failure processes during in-service conditions. Under both strain and stress-controlled cyclic loading, irradiation softening led to the development of strain localization, and the formation of slip banding and its coalescence. This was found to lead to localized ratcheting and macroscale softening, and in strain-controlled loading, ultimately to plastic shakedown. Stress-controlled cyclic loading, however, especially with non-zero mean applied stress, led to pronounced local and macroscale ratcheting, influenced profoundly by the irradiation softening, and hence finally to ductile failure. It was also observed that local strain hardening due to GND development was small compared to irradiation-induced softening processes, supporting the notion that slip system softening dominates shear band formation.

1. Introduction

This paper addresses the mechanisms affecting the structural integrity of zircaloy subjected to irradiation during in-service nuclear application. The consequences of neutron irradiation-induced slip system softening in reactor cladding material (often zircaloys) are investigated to understand the deformation mechanisms and the nature of irradiation-accelerated strain localization. Some work to explain the micromechanical mechanisms of deformation resulting from irradiation has been undertaken using computational plasticity and supported by experimental observation and has been reported in the literature. So far, the numerical studies used employ self-consistent models (Boyne and et al., 2013; Onimus

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http://dx.doi.org/10.1016/j.ijplas.2015.05.008
0749-6419/

and Bechade, 2009) which are known to be useful for addressing macroscopic material response based on average ensembles of material orientations, but equally are less good in understanding local, grain-by-grain, slip system based-deformation. This is because of the simplifications involved in abandoning either equilibrium or compatibility (or both) requirements, and because they do not represent the details of grain morphology and interaction fully. However, the crystal plasticity framework adopted here overcomes these limitations and offers the possibility of a better understanding of slip-based deformations, and particularly strain localization, in Zr alloys resulting from slip system softening known to result from neutron irradiation.

Material reliability and safety are crucial to industrial practices and hence, it is no coincidence that extensive interest exists in understanding deformation mechanisms in hexagonal close packed (HCP) metals such as zircaloys, given their range of applications in critical and highly sensitive environments. Zircaloys are important materials used for cladding in nuclear reactors and are subjected to high levels of irradiation, or fluence. Experiments have shown that changes in material crystallographic-level structure arise due to fluence thereby raising safety concerns (Onimus et al., 2012; Wei et al., 2009; Onimus and et al., 2004).

The effect of fluence on zircaloys can be macroscopic and microscopic. Macroscopically, fluence leads to an increase in yield strength of the material (Boyne and et al., 2013; Wei et al., 2009) and lowering in the ductility, i.e. strain to failure, shown experimentally in Fig. 1. Microscopically, it affects the differing classes of slip systems found in zircaloys (Boyne and et al., 2013). Zircaloys have four classes of slip systems illustrated in Fig. 2 which are basal, prismatic, <a> pyramidal and <c+a> pyramidal types with differing critical resolved shear stresses (CRSS) on each system detailed in Table 1 for a particular zircaloy of interest. The CRSS determines the ease of achieving slip on that particular slip system and in zircaloys, the basal and prismatic systems generally have lower CRSS compared to the pyramidal systems (Onimus and Bechade, 2009). The CRSS for prismatic systems is usually lower than that for basal systems (Wei et al., 2009). Experiments on zircaloys, however, strongly suggest that the CRSS on these slip systems change by varying degrees with fluence and the increase can be estimated (Boyne and et al., 2013; Onimus and Bechade, 2009). There are also indications that the CRSS for prismatic systems after irradiation is higher than that for basal systems i.e. a strength reversal compared to the unirradiated material.

Transmission electron microscopy (TEM) analysis shows that pronounced slip localization along dislocation channels, illustrated in Fig. 3, is observed in irradiated zircaloys compared to unirradiated samples (Onimus et al., 2012; Wei et al., 2009; Onimus and et al., 2004; Onimus et al., 2013). This has been attributed to the efficient clearing of dislocation channels leading to increased slip activity along these channels (Wei et al., 2009). A further consequence of such channels is the increased susceptibility of the irradiated material to stress corrosion cracking (SCC), especially where the channels intersect with surfaces (Lee and Adamson, 1977).

Furthermore, irradiation-induced softening on active slip systems promotes accelerated localization and consequently, lower strain to failure (Adamson and Bell, 1986). This phenomenon is suggested to affect basal slip systems, but also prismatic systems to a lesser extent, but it remains unclear at what rate the softening on each system type occurs (Onimus and Bechade, 2009; Garde et al., 1996). Slip system softening however, manifesting as a decrease in CRSS, is thought to be bounded (Onimus and Bechade, 2009) and does not decrease beyond the CRSS of the unirradiated material.

This paper attempts to understand two key issues. It addresses (i) the onset and rate of softening on individual slip systems, and perhaps more importantly, (ii) the strain localization effects resulting from irradiation-induced softening. The former involves the development of a slip-system dependent softening model in order to reproduce the experimentally observed mechanical response for representative irradiated zircaloy textures. The latter entails the nucleation and growth of strain localization and slip bands in the irradiated model material, utilizing the softening model developed, and their consequences for deformation behaviour under representative in-service loading regimes.

An assessment of a number of possible slip system weakening mechanisms contributing to softening responses is presented in §2, together with a brief summary of the crystal plasticity modelling adopted. Sections §3 and §4 address the effects of neutron irradiation-induced softening in single and polycrystal zircaloys with differing textures, and this is followed by an

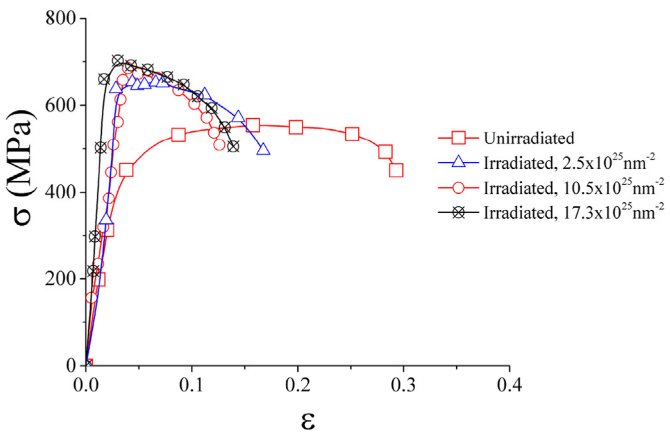

Fig. 1. Typical σ-ε curves of the irradiated/unirradiated zircaloy at a test temperature of 23 °C reproduced from Wei et al. (2009).