International Journal of Plasticity 56 (2014) 219–231

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Strain localization at dislocation channel–grain boundary intersections in irradiated stainless steel

M.D. McMurtrey [a,*], G.S. Was [a], B. Cui [b], I. Robertson [b], L. Smith [c], D. Farkas [c]

[a] Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109, United States
[b] Department of Materials Science and Engineering, University of Illinois, Urbana, IL 61801, United States
[c] Department of Materials Science and Engineering, Virginia Tech, Blacksburg, VA 24061, United States

ARTICLE INFO

Article history:
Received 11 September 2013
Received in final revised form 19 November 2013
Available online 13 January 2014

Keywords:
A. Dislocations
A. Grain boundaries
B. Metallic material
A. Irradiation effects

ABSTRACT

The interaction of dislocation channels with grain boundaries in irradiated stainless steel was observed on multiple length scales using scanning electron microscopy (SEM) digital image correlation (DIC) and confocal microscopy (micro-scale), *in situ* straining and transmission electron microscopy (TEM) (nano-scale), and atomistic modeling (atomic scale). Interactions were divided into three classifications; slip transmission, discontinuous slip, and discontinuous slip that induced grain boundary slip. DIC and confocal microscopy were used to quantify the plastic strain at dislocation channel–GB intersections. *In situ* TEM was used to image dislocations inside of channels as they interacted with the grain boundary. Slip in the dislocation channels, as observed by TEM, was found to involve cross slip between different slip planes, as well as the possibility of different slip systems activated on parallel slip planes. Atomistic simulations agreed well with experiments on the nature of channel-grain boundary interactions and also showed elevated levels of elastic stress at DC–GB intersections where slip was discontinuous with no slip transmission. The two distinct classifications of discontinuous slip are significant, suggesting two possible cracking mechanisms that both lead to the rupture of the oxide over the grain boundary.

1. Introduction

The occurrence of stress corrosion cracking susceptibility of austenitic stainless steels under irradiation is known as irradiation assisted stress corrosion cracking (IASCC), and is a major concern for light water reactor component integrity, in particular as the lifetime of reactors is extended (Zinkle and Was, 2013; Fukuya, 2013). Irradiation alters the microstructure of stainless steel, causes radiation-induced segregation of elements, dislocation loop and precipitate formation, increased hardness, and a transformation of the deformation mode from relatively homogeneous slip to heterogeneous slip in the form of coarse dislocation channels. The complexity of the irradiation effects on stainless steel makes it difficult to determine the cause of IASCC, however, there appears to be a connection between the localization of deformation into dislocation channels and cracking (Zinkle and Was, 2013; Fukuya, 2013; Jiao and Was, 2011; Onchi et al., 2005; West and Was, 2013; McMurtrey et al., 2011; Le Millier et al., 2011). Recent results show that the degree of slip in dislocation channels correlates with cracking severity (Jiao and Was, 2011), but the mechanism still is not clear. This study seeks to better understand the interactions between dislocation channels and grain boundaries through a multi-length scale approach.

Dislocation channels are formed when the resolved shear stress reaches a magnitude sufficient to propagate dislocations through the damaged lattice. As the dislocation travels along the slip planes, small defects pin it temporarily and are

* Corresponding author. Tel.: +1 7349360266.
E-mail address: mdmcm@umich.edu (M.D. McMurtrey).

0749-6419/$ - see front matter
http://dx.doi.org/10.1016/j.ijplas.2014.01.001

eventually annihilated when the dislocation passes through, creating less resistance for subsequent dislocations to follow. As more dislocations travel through the channel, defects are progressively removed and the ease of slip in the channel increases. Typically, dislocation channels consist of parallel slip planes totaling 50–200 nm in thickness (Edwards et al., 2005), and spaced one to three micrometers apart, though both spacing and thickness are dependent on straining temperature and irradiation dose (Howe, 1974). Due to the high concentration of plastic deformation, it is possible to reach very high plastic strains within the channels at low average macroscopic strains. Jiao et al. (2005) used atomic force microscopy (AFM) measurements of the height of the channels protruding from the surface to estimate the average shear strains at nearly 100% in the channels of an irradiated steel strained to a macroscopic tensile strain of 3%.

While height measurements of surface steps provide out-of-plane strain values for the dislocation channels, the in-plane strain is more difficult to measure. Heterogeneous plastic strain has been studied in both unirradiated and irradiated alloys using digital image correlation (DIC) (Le Millier et al., 2011; Gioacchino and Quinta da Fonseca, 2012). DIC compares pre-strain and post-strain digital images of a region. With a speckle pattern made of nano-scale particles, sub-micron spatial resolution has been achieved. By using gold nano-particles on the order of 30–150 nm in size, Gioacchino and Quinta da Fonseca (2012) were able to measure strain within slip bands, as well as visualize areas of strain localization in an unirradiated stainless steel.

The interaction of dislocation channels with grain boundaries is an area of active investigation. Using scanning electron microscopy (SEM) imaging of indentations near grain boundaries, Wo and Ngan (2004) found that slip transmission was related to a misorientation factor based on the orientations of the closest {1 1 1} slip planes and ⟨1 1 0⟩ directions of the two neighboring grains. When slip does not transmit across the boundary, a dislocation pileup may form. Britton and Wilkinson (2012) used high resolution EBSD to measure the stress caused by a pile-up of screw dislocations at the grain boundary and found a stress field ahead of the dislocation pile-up which decayed at a rate proportional to one over the square root of the distance from the pileup, similar to the model proposed by Eshelby et al. (1951).

Transmission electron microscopy (TEM) has also been used to observe the interactions between dislocations and grain boundaries. Dislocations observed to absorb into the grain boundary may either be glissile or sessile and retain the lattice Burgers vector or decompose into grain boundary dislocations (Lagow et al., 2001). In cases of slip transmission, except the special case of direct transmission, which occurs only for screw dislocations with a line direction parallel to the slip plane intersection in the grain boundary, the dislocations are absorbed into the grain boundary, and a new dislocation is nucleated in the grain boundary and ejected. By conducting *in situ* TEM straining experiments, it has been possible to develop a set of criteria to predict which slip system is activated to enable slip transmission across the grain boundary (Shen et al., 1988; Lee et al., 1989). It was found that the magnitude of the Burgers vector of the residual grain boundary dislocation was a dominating factor in predicting slip transmission with the magnitude of the local resolved shear stress playing a minor role.

Only recently have *in situ* TEM straining experiments been conducted on the interaction between dislocations and grain boundaries in irradiated materials. Briceño et al. (2011) found that dislocation motion within a irradiated 304 stainless steel was different from that observed in the unirradiated state. Dislocation motion became irregular and jerky, and required higher levels of stress to push the dislocation through the grain. This was evident through the formation of dislocation pile-ups against invisible barriers in the grain interior and the tendency of dislocations to pile-up at the grain boundary dislocation source. When dislocations traverse the grain and reach the other grain boundary, a pile-up is formed. Initially, the dislocations in the pileup are evenly spaced, unlike the unirradiated case where the distance between dislocations rapidly decreases near the grain boundary. Eventually, as stress is increased, the dislocation pile-up in the irradiated sample develops into a more conventional pileup, similar to those seen in the unirradiated case. This evolution of the pile-up structure is another manifestation of the need for higher stresses to push dislocations through the irradiation induced obstacle field.

Plastic deformation of a polycrystalline sample has been studied using different simulation and modeling techniques over various length scales (Lim et al., 2011; McDowell, 2010; Warner et al., 2006). In particular, atomistic studies are important as they can shed light on the details of fundamental atomistic mechanisms, such as dislocation/grain boundary interactions, at a length scale that is not accessible to experimental techniques. Atomistic techniques have been used to study the interaction of dislocations with specific special grain boundaries (Couzinié et al., 2005), as well as the shearing of the interface when a dislocation arrives at a grain boundary (Chu et al., 2013).

To provide a sound statistical basis for identifying commonalities in dislocation interactions with grain boundaries in irradiated steels and at the same time understand the atomistic processing involved, a multi-scale experimental and simulation approach is employed in this study. Digital image correlation (DIC) and confocal microscopy are used to create a detailed image of the strain field at 23 dislocation channel-grain boundary (DC–GB) intersections on a 10–1000 nm scale, using scanning electron microscopy to provide a large sample area and more DC–GB intersections to examine. This allows for a quantitative description of the strain in the dislocation channel, the grain boundary, and the area surrounding the intersection. To understand the interactions at the dislocation level, *in situ* TEM straining was employed to observe the interactions dynamically. These interactions were characterized in terms of the intersection angle, local resolved shear stress, and residual dislocation Burgers vector using methods described by Lee et al. (1989). Details of the specific interactions are described by Cui et al. (2014). Atomistic simulations of interactions at specific grain boundaries, identified experimentally, were employed to understand the processes and mechanism of strain transfer at the atomistic level. In particular, the modeling activity provide insight on the local elastic stress in the lattice at dislocation-grain boundary intersections, which is difficult to determine experimentally. The objective of this work is to couple these multi-scale methods to obtain an understanding of channel interactions at grain boundaries to provide the basis for linkage to IASCC.