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The role of deformation mechanisms in flow localization of 316L stainless steel

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Abstract

Type 316 SS is widely used as a structural material in a variety of current accelerator driven systems and designs as well as in a number of current and advanced fission and fusion reactor concepts. The material is found to be very sensitive to irradiation damage in the temperature range of 150–400 °C, where low levels of irradiation exposure, as little as 0.1 dpa, can substantially reduce the uniform elongation in tensile tests. This process, where the plastic flow becomes highly localized resulting in very low overall ductility, is referred to as flow localization. The process controlling this restriction of flow is related to the difference between the yield and ultimate strengths such that dramatic irradiation-induced increases in the yield strength results in very limited plastic flow until necking. In this study, the temperature dependence of this process is examined in light of the operating deformation mechanisms. It is found that twinning is an important deformation mechanism at lower temperatures but is not available in the temperature range of concern since the stress to activate twinning becomes excessively high. This limits the deformation and leads to the flow localization process.

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1. Introduction

During the past several decades, there has been a long and continuing effort to understand the influence of irradiation exposure on reactor structure materials. In the spallation neutron source (SNS) and other advanced nuclear applications, type 316L (LN) and 304L (LN) stainless steel have been selected as components and structure materials, particularly because of their relatively high strength and good capacity to resist brittle fracture. However, under the condition of irradiation exposure, 316L SS will suffer a severe reduction of ductility. This loss of ductility typically is exhibited through following features: elevated yield strength accompanied by a very low uniform elongation under tensile loading conditions. The damage microstructure developed during irradiation restricts dislocation flow so that the plastic deformation is confined to very small volumes or regions of materials in the tensile load. Under this circumstance, premature necking at yield often followed by brittle fracture. This process is characterized as *flow localization*. Due to its importance in many applications, numerous studies have been performed to investigate the relationship among ductility loss, radiation-induced

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microstructure change and testing temperature. Previous studies [1–3] show that regardless of the irradiation level, the true stress for the onset of plastic instability (necking) is approximately constant, defined as the '*critical stress*'. In other words, the true stress to failure is an inherent material property rather than a function of irradiation-induced defect microstructure or strain hardening behavior. Limited studies of the tensile behavior of 300-series stainless steels following irradiation exposure have been carried out at intermediate temperatures in the past. A major conclusion by Pawel et al. [4] is that the 316L SS could suffer a minimum ductility in the range of 150–350 °C even at the irradiation levels as low as 1 dpa. This temperature range and irradiation conditions are typical of several current nuclear systems including spallation neutron source (SNS), current light water reactors (LWRs) and some Generation IV reactor concepts designs. Past efforts to understand flow localization concentrated primarily on dislocation pinning and channeling effects. Several models based on the 'barrier' mechanism have been proposed to explain the large increase in yield strength. However, current research shows that the flow localization process is more closely associated with the final stage of tensile deformation instead of the initial stage. This fact is indicated in Fig. 1, in which the true stress–strain curves of 316L SS irradiated to different dose level and tested at 50 °C are shifted to superpose at the point of plastic instability. It can be observed that the plastic flow exhibits a uniform behavior for various irradiation levels before the onset of plastic instability for all irradiation conditions. Therefore, the controlling microstructural mechanism for flow localization should be working for both unirradiated and irradiated materials and could include deformation-induced twinning and large scale planar slip in addition to the cleared channel flow due to the irradiation-induced defect microstructure. This insight provides an advantage in studying the final stages of flow localization, since the point of instability occurs at the same true stress level for both irradiated and unirradiated materials. Thus the controlling mechanism can be studied directly from unirradiated material.

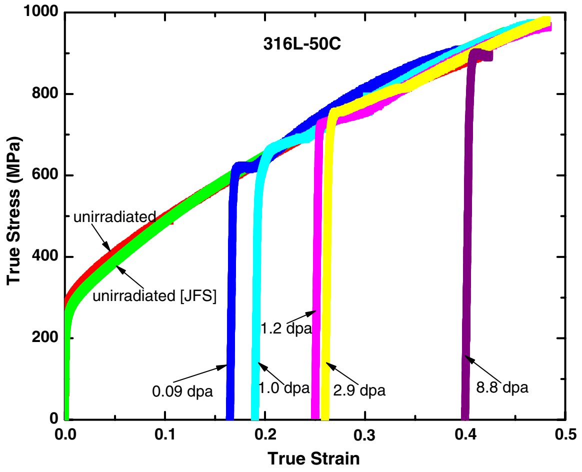

Fig. 1. True stress–strain curves for 316L SS tested at 50 °C.

2. Experiments

The material studied in this investigation was fully annealed 316L stainless steel with nominal composition given in Table 1. A series of tensile tests were performed on this material at temperatures ranging from RT to 400 °C. The tests were stopped at various strain levels to investigate the microstructural evolution during tensile loading. After testing, specimens were sliced from the center of specimen and polished. They were then examined using a JEOL 7000F SEM with electron backscattering diffraction (EBSD) capabilities. The results and details are discussed in the following sections.

3. Analysis

Recent work [1–3] shows the existence of a critical stress for the flow localization of face-centered cubic metals and alloys. This critical stress is a direct consequence of the post yield hardening properties of the materials, which seem to be independent of irradiation conditions. The observations show that,

Table 1
Composition for 316L stainless steel

Material	Composition (wt%)										
	C	Co	Cr	Cu	Mn	Mo	N	Ni	P	S	Si
316L SS	0.20	0.155	16.847	0.322	1.755	2.214	0.039	10.234	0.027	0.002	0.388