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ScienceDirect
Journal of Nuclear Materials 372 (2008) 379–390
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Effect of irradiation-induced plastic flow localization on ductile crack resistance behavior of a 9%Cr tempered martensitic steel

R. Chaouadi [*,1]

Forschungszentrum Jülich, EURATOM Association, IEF-2, D-52425 Jülich, Germany

Received 29 November 2006; accepted 19 April 2007

Abstract

This paper examines the effect of irradiation-induced plastic flow localization on the crack resistance behavior. Tensile and crack resistance measurements were performed on Eurofer-97 that was irradiated at 300 °C to neutron doses ranging between 0.3 and 2.1 dpa. A severe degradation of crack resistance behavior is experimentally established at quasi-static loading, in contradiction with the Charpy impact data and the dynamic crack resistance measurements. This degradation is attributed to the dislocation channel deformation phenomenon. At quasi-static loading rate, scanning electron microscopy observations of the fracture surfaces revealed a significant change of fracture topography, mainly from equiaxed dimples (mode I) to shear dimples (mode I + II). With increasing loading rate, the high peak stresses that develop inside the process zone activate much more dislocation sources resulting in a higher density of cross cutting dislocation channels and therefore an almost unaffected crack resistance. These explanations provide a rational to all experimental observations.

PACS: 61.80.Hg; 62.20.Mk; 81.40.Np; 81.70.Bt

1. Introduction

Neutron irradiation damage produced in structural materials is very often monitored using a tensile test. Such a test is quite easy and allows the determination of the material flow behavior. Examination of the tensile properties usually shows an increase of the yield strength and a reduction of ductility. At high fluence levels, the strain hardening capacity can drastically be reduced, resulting from localized deformation that occurs shortly after the yield strength is reached. This phenomenon, result of a heterogeneous plastic deformation that occurs in localized slip planes within bands of easy glide, is called dislocation channel deformation [1–4]. Indeed, in these bands, defect clearing by the initial unpinned dislocations provides paths of easy glide for subsequent dislocations, promoting therefore a localized plastic deformation. This phenomenon was observed in bcc, fcc and hcp metals [2,5–8]. A number of investigations are being devoted to this phenomenon [6–15], from both macroscopic and microscopic aspects, i.e., tensile testing and transmission electron microscopy (TEM), respectively. The mechanical response of a material experiencing plastic flow localization is characterized by a softening shortly after the yield strength. The TEM observations clearly show narrow defect-free channels or bands is which plastic deformation occurs preferentially [6,9,12,13,16–19]. Recently, a number of computer simulations including molecular dynamics were also reported to better understand this phenomenon [20–24]. However, to the author's knowledge, there was no attempt to investigate the plastic flow localization ahead of a crack tip. More specifically, the critical question is how this channel deformation mode will affect the fracture toughness behavior. It is, therefore, very interesting to examine the deformation and fracture mechanism in such high triaxial stress–strain fields

* Tel.: +49 2461 614683; fax: +49 2461 613699 (until September 2007). *E-mail address:* r.chaouadi@fz-juelich.de

[1] On leave from SCK·CEN, Boeretang 200, 2400 Mol, Belgium. After September 2007, rchaouad@sckcen.be.

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2007.04.044

which are very different from those experienced during a standard tensile test.

2. Background

The present investigation was motivated by two considerations. First, there is a need of characterizing structural materials in their regime of operation conditions, namely at high temperature. Most irradiation studies directed towards irradiation effects on the mechanical properties concern the avoidance of the risk of brittle (catastrophic) failure. Therefore, the experimental data are usually reported in terms of ductile-to-brittle transition temperature (DBTT), either based on Charpy impact or fracture toughness data. However, the structural materials of the components are usually operated in a high temperature regime. Therefore, estimation of their crack resistance behavior is important in order to ensure adequate operation. Second, recent observations were reported on the disagreement between DBTT-shift as determined from Charpy impact tests in comparison to fracture toughness tests [25,26]. This disagreement could be explained in [27] by using the load diagram approach. Since part of the Charpy impact absorbed energy at the DBTT is spent in ductile fracture, it is important to understand how irradiation is affecting the flow and fracture behavior in the ductile regime. Therefore, the present work was initiated to provide better insight into the effect of plastic flow localization on the crack resistance behavior. More specifically, the subject of the present paper is the plastic flow localization induced by irradiation where dislocation channel deformation is the main deformation mechanism. Indeed, plastic instability can occur in a number of other conditions such as metals and alloys after quenching and subsequent heat treatment (ageing, tempering), predeformation or precipitation hardening [5,28]. However, the observation of a prompt necking after the yield strength that is usually observed on a tensile curve does not necessarily indicate a dislocation channel deformation mechanism. For example, at relatively high temperatures, plastic flow instability may occur without involving the dislocation channeling mechanism. This was observed in [26] for Eurofer-97 where plastic flow localization occurs above about 500 °C, but fracture toughness and crack resistance remain unaffected in comparison to room temperature. That's why it is preferred to define the phenomenon under investigation as irradiation-induced plastic flow localization involving specifically the dislocation channel deformation.

Before giving the experimental conditions, it is important to note that irradiation-induced plastic flow localization was long associated with low temperature embrittlement where typically a very significant hardening is observed when the irradiation temperature is below ~250 °C [7,8,29]. However, plastic strain localization is also found at higher irradiation temperature, 300 °C for example, although not as spectacular as observed in the low temperature range. In particular, the 9%Cr–1W ferritic/martensitic steel, Eurofer-97, was the subject of many investigations in Europe [26,30–38].

3. Experimental

The chemical composition of Eurofer-97 is given in Table 1. Some mechanical properties in the unirradiated condition are given in Table 2. Eurofer-97 was irradiated at SCK·CEN in the BR2 reactor at 300 °C up to about 2.1 dpa and was extensively characterized by Lucon [25,26,33] using tensile, Charpy impact and brittle fracture toughness tests. Because of the limited number of available specimens, the Charpy reconstitution technique was used to manufacture a few additional Charpy specimens from the broken ones. These were precracked to a crack length-to-width ratio close to 0.5 and further 20%-side grooved before testing at 300 °C in three-point bending at quasi-static loading.

The crack resistance curve was determined using the single specimen procedure based on the load–displacement test record. All specimens were tested using the unloading compliance method at 300 °C but the crack resistance curve determination was based on the load–displacement record according to a procedure detailed in [39]. After the crack has reached about 2.0 ± 0.5 mm crack extension, the specimens were unloaded, heat tinted (300 °C for 20 min), and further broken at low (liquid nitrogen)

Table 1
Chemical composition and heat treatment of Eurofer-97 (wt%)

C	Ni	Cr	Mo	Cu	Si	Nb	V	P	Mn	W	Ta	Fe
0.12	0.007	8.99	<0.001	0.022	0.07	<0.001	0.19	<0.005	0.44	1.1	0.14	Bal

Table 2
Tensile (at 25 °C), impact and fracture properties of unirradiated Eurofer-97

σ_y (MPa)	σ_u (MPa)	ε_u (%)	ε_t (%)	RA (%)	USE (J)	DBTT (°C)	$T_{100\,\mathrm{MPa}\sqrt{\mathrm{m}}}$ (°C)	J_Q at 25 °C (kJ/m^2)
557	670	5	20	80	251	−57	−115	300

σ_y is the yield strength, σ_u is the tensile strength, ε_u is the uniform elongation, ε_t is the total elongation, RA is the reduction of area, USE is the Charpy upper shelf energy, DBTT is the ductile-to-brittle transition temperature measured at 50% of the USE, $T_{100\,\mathrm{MPa}\sqrt{\mathrm{m}}}$ is the static fracture toughness transition temperature and J_Q is the ductile initiation toughness evaluated at 0.2 mm crack extension.