Available online at www.sciencedirect.com
ScienceDirect
Journal of Nuclear Materials 358 (2006) 176–189
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Investigation of neutron radiation effects on the mechanical behavior of recrystallized zirconium alloys

F. Onimus [a,*], J.L. Béchade [a], C. Duguay [b], D. Gilbon [b], P. Pilvin [c]

[a] *Service de Recherches Métallurgiques Appliquées, CEA-Saclay, 91191 Gif-sur-Yvette, France*
[b] *Service d'Etudes des Matériaux Irradiés, CEA-Saclay, 91191 Gif-sur-Yvette, France*
[c] *Laboratoire de Génie Mécanique et Matériaux, Université de Bretagne-Sud, 56321 Lorient, France*

Received 20 March 2006; accepted 12 July 2006

Abstract

Neutron radiation induces important changes in the mechanical behavior of recrystallized zirconium alloys used as fuel cladding tube. The neutron radiation effects on the mechanical behavior for internal pressure tests performed at 350 °C have been investigated using a specific analysis in terms of isotropic hardening, kinematic hardening and viscous stress. A unified internal variables modeling has also been used in order to provide a consistent description of the radiation effects on the mechanical behavior. The impact of irradiation has been interpreted in terms of microscopic deformation mechanisms observed by transmission electron microscopy. Due to the localization of the plastic deformation inside channels and because of the only activation of basal channeling, the kinematic hardening is expected to be strong in irradiated zirconium alloys.

PACS: 61.80.Hg; 62.20.Fe

1. Introduction

Zirconium alloys cladding tubes containing the fuel of pressurized water reactors nuclear power plants constitute the first barrier against the dissemination of radioactive elements. In order to improve the material and guaranty the cladding integrity all along its life time, it is necessary to have a good understanding of the effect of neutron radiation on the mechanical properties and the related radiation-induced microstructure.

It is known that neutron radiation leads to a significant increase in strength [1–4]. This strengthening is usually attributed to the presence of a high density of small ⟨a⟩ prismatic loops induced by irradiation [5] which act as obstacles against dislocations glide [6,7]. However it is known that these loops can be swept up by gliding dislocations when a sufficient stress is applied leading to the creation of channels where dislocations can freely glide [8]. This mechanism has been reported by several authors in

* Corresponding author. Tel.: +33 1 69 08 44 29; fax: +33 1 69 08 71 30.
E-mail address: fabien.onimus@cea.fr (F. Onimus).

0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2006.07.005

irradiated Zr alloys [9–15]. Lately an extensive study [16,17] of this phenomenon has been performed on irradiated Zr alloys tested at 350 °C using transmission electron microscopy (TEM). It has been established that for the irradiated material strained during a tensile test performed in the transverse direction of a rolled sheet specimen or an internal pressure test performed on a cladding specimen at 350 °C, only basal channeling occurs whereas for the non-irradiated material, prismatic glide is mainly activated. The change in principal slip system activation has been attributed to the difference in junction reaction between loops and prismatic gliding dislocation and basal gliding dislocation. Indeed, as described in [16], in the hexagonal closed packed structure, the junctions created between a ⟨a⟩ loop and a ⟨a⟩ dislocation gliding in the basal plane are always glissile whereas in the case of a ⟨a⟩ dislocation gliding on the prismatic plane and interacting with a ⟨a⟩ loop, the junction is sessile in two cases over three. This leads to a lower ability for dislocation channeling in prismatic plane and therefore a change in principal slip system activation.

Nevertheless, the effect of this specific deformation mechanism on the mechanical behavior of irradiated zirconium alloys (for internal pressure test at 350 °C) is not yet clear.

In order to have a thorough understanding of the effect of dislocation channeling phenomenon on the mechanical behavior of neutron irradiated zirconium alloys, a detailed mechanical analysis has been performed. This specific analysis aims at characterizing the strain hardening behavior, the strain rate sensitivity as well as the stress relaxation behavior of the irradiated material and the non-irradiated material. A unified internal variables model is also used in order to confirm the analysis and provide a coherent description of the effect of neutron radiation on mechanical properties. The obtained results are then compared and discussed in terms of deformation mechanisms observed by TEM.

2. Materials and mechanical tests

Mechanical tests have been performed on three irradiated and non-irradiated recrystallized zirconium alloys: recrystallized Zy-4, M5™ alloy and a previous experimental grade alloy referred here as Zr–1%Nb–O. Chemical compositions are given in Table 1 and irradiation conditions are given in Table 2.

Mechanical tests have been conducted at 350 °C at various strain rates with internal pressure loading condition ($\sigma_{zz} \approx \sigma_{\theta\theta}/2$ and $\sigma_{rr} \approx 0$). In addition, in order to obtain detailed information on the mechanical behavior, several non-monotonic tests have been performed. All these mechanical tests can be divided into four types. The first type of test is a simple monotonic strain hardening test (at a given

Table 1
Zr alloys chemical composition (wt%)

Alloy	Sn	Nb	Fe	Cr	O	Zr
Zy-4	1.30	–	0.210	0.100	0.125	Bal.
M5™	–	1.00	0.035	–	0.130	Bal.
Zr–1%Nb–O	–	1.00	0.02	–	0.125	Bal.

Table 2
Irradiation conditions and testing conditions

Specimen	Material	Fluence, n/m^2	Irradiation temperature (°C)	Mechanical test	Test temperature (°C)	Strain rate, s^{-1}
NI1	M5™	0	–	Type 4 at $\varepsilon = 0.8\%$	350	2.5×10^{-4}
NI2	M5™	0	–	Type 4 at $\varepsilon = 0.8\%$	350	2.5×10^{-4}
NI3	M5™	0	–	Type 4 at $\varepsilon = 0.8\%$	350	2.5×10^{-4}
NI4	M5™	0	–	Type 2 at $\varepsilon = 1.5\%$	350	2.0×10^{-4}
NI5	M5™	0	–	Type 2 at $\varepsilon = 2.3\%$	350	2.0×10^{-4}
NI6	M5™	0	–	Type 1	350	2.0×10^{-5}
NI7	M5™	0	–	Type 1	350	2.5×10^{-6}
NI8	Zy-4	0	–	Type 2 at $\varepsilon = 1.2\%$	350	2.5×10^{-4}
IR1*	M5™	3.5×10^{25}	350	Type 4 at $\varepsilon = 0.8\%$	350	3.0×10^{-4}
IR2	M5™	2.3×10^{25}	350	Type 4 at $\varepsilon = 0.8\%$	350	3.0×10^{-6}
IR3*	M5™	3.5×10^{25}	350	Type 3 at $\varepsilon = 0.8\%$	350	3.0×10^{-6}
IR4*	Zr–1%Nb–O	12×10^{25}	350	Type 1	350	3.0×10^{-4}
IR5*	Zy-4	0.4×10^{25}	350	Type 2 at $\varepsilon = 0.7\%$	350	3.0×10^{-4}

* TEM investigations [16,17]: basal channels observed.