FRACTURE BEHAVIOR AND DEFORMATION MECHANISMS UNDER FAST NEUTRON IRRADIATION

J.L. Boutard and J.M. Dupouy

Department of Technology
S.R.M.A.
Centre d'Etudes Nucléaires de Saclay
B.P. N°2 - 91190 GIF SUR YVETTE, France

ABSTRACT

We have established the out-of-pile and in-pile deformation mechanism maps of a 316 stainless steel irradiated in a fast reactor. The knowledge of the dominating deformation mechanism either in post irradiation creep experiments or during the in-pile steady state operating conditions allows to rationalize the apparent discrepancy between the very low out-of-pile ductility and the rather high plastic diametral strains which are obtained in the fast reactor environment without fracture.

KEYWORDS

316 stainless steel; irradiation creep; creep fracture; deformation mechanism map; fast reactor.

INTRODUCTION

After irradiation in the conditions of neutron flux and temperature of a fast reactor, very low ductilities (less than 0.5 %) are obtained in out-of-pile creep tests on 316 stainless steel specimens (Dupouy, 1977; Harries, 1979). This can be understood, at least qualitatively, for temperature below or equal to 650°C, in terms of stress concentrations inducing "r" or "w" cracks (Ashby, 1975; Williams, 1975) in an embrittled grain boundary. The presence of irradiation produced helium is probably the most important fact that acts on nucleation of the cracks by decreasing the Zener-Stroh initiation stress (Harries, 1979) and also helps their growth (Grossbeck, 1977).

On the other hand, quite high plastic deformation (as high as 6 %) can be sustained by the same 316 stainless steel when submitted to the stress in the neutron flux of the reactor itself. Under irradiation, other mechanisms exist (Heald, 1974; Martin, 1971; Gittus, 1972; Mansur, 1979). They are of diffusion or of dislocation glide type. Their stress exponent is generally rather low ($n = 1$ or 2) compared to that of the out-of-pile dislocation creep ($n \sim 10$). As Koeller has already pointed out (Koeller, 1978) these additional mechanisms may relax the stress concentrations and thus enhance the ductility. The existence of these mechanisms may therefore explain the apparent discrepancy between the high plastic diameter strain observed on fuel pin cladding without fracture and the poor ductility measured out of pile on the irradiated material (Boutard, 1979)

We propose to set up the deformation maps of a solution treated 316 stainless steel in both environments : under irradiation and out of pile, after irradiation. We will thus be able to determine which deformation mechanism is preponderant in pile under nominal operating conditions of the reactor and out of pile in a pressurized tube creep experiment.

DEFORMATION MECHANISM MAPS

Out of Pile Map for an Irradiated Material

Two mechanisms are operating.

Dislocation creep. Such a dislocation creep can be expressed by a classical power law with a high stress exponent (n ∿ 10).

Diffusion creep. There are two contributions depending upon whether the grain boundary (Coble creep) or the volume diffusion (Herring Nabarro creep) is controlling. Experimental results show that below 500 °C Coble creep dominates whereas at 600°C and above it seems to be inhibited as is often found in austenitic steels (Crossland, 1977), thus, in this temperature range Herring Nabarro creep is dominant.

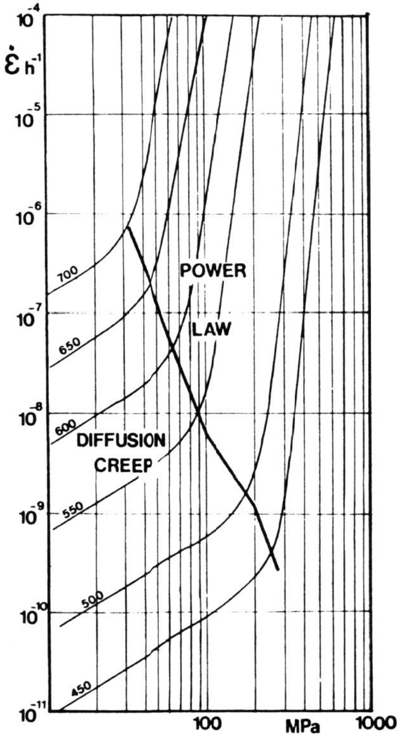

Fig. 1. Total creep rate versus the applied stress of an irradiated solution annealed 316 tested out of pile.

Figure 1 shows the total creep rate $\dot{\varepsilon} = \dot{\varepsilon}_{pl} + \dot{\varepsilon}_{diff.}$ as a function of stress between 450 and 750 °C.

Stress and strain are equivalent ones. The solid line represents the values of temperature, stress and strain rate for which $\dot{\varepsilon}_{pl}$ and $\dot{\varepsilon}_{diff}$ are equal.

We can also draw the more classical deformation mechanism map in the stress temperature plane (Ashby, 1972); it is presented on Figure 2.

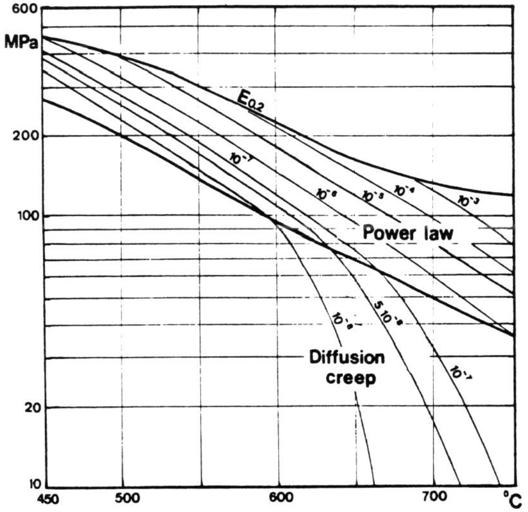

Fig. 2. Deformation mechanism map of an irradiated solution annealed 316 tested out of pile in the creep range. The strain rates indicated are in h^{-1}.

The conventional yield limit $E_{0.2}$ as measured in hot cells on the irradiated material has been taken as an upper bound for the stresses.

In-Pile Mechanism Map

Theoretical approaches show that irradiation does not affect the Herring Nabarro creep rate (Duffin, 1972). Therefore it was assumed that diffusion creep rate was unchanged. Although some evidence of point defect hardening has been published (Gilbert, 1977) we assume that at sufficiently high stress, dislocation source operation, gliding and piling up processes are unchanged by irradiation. That is to say, the power law creep rate adopted in the last paragraph is also considered to be unaffected by the presence of the neutron flux.

However, under this flux other contributions to the creep rate become possible. Three types of theoretical mechanisms have been proposed and it has been shown that (Boutard, to be published) the diametral plastic strains of the Rapsodie fuel clads can be consistently described with them.

SIPA creep. (Heald, 1974) This mechanism is of diffusion type. It is due to the fact that the volume containing a point defect has a shear modulus different from that of the surrounding matrix; the strain rate is proportional to the damage rate ϕ and the stress σ :

$$\dot{\varepsilon}_{SIPA} = K \cdot \phi \cdot \sigma \qquad (1)$$

The K coefficient is constant up to ∿ 550°C and thermally activated above, in satisfactory agreement with theoretical calculations (Wolfer, 1977).

I-creep. (Martin, 1971; Gittus, 1972) It is a climb-enabled glide mechanism. The climb rate is produced by the net flux of interstitials absorbed by the dislocation network because of the swelling; thus it is proportional to the swelling rate

$$\frac{dS}{dt}$$

The stress exponent is given by the type of obstacles and is low in any case. The data can be reasonably fitted with a linear stress dependance :

$$\dot{\varepsilon}_I = \alpha \cdot \frac{dS}{dt} \cdot \sigma \qquad (2)$$

α being inversely proportional to the density of obstacles is consistently found to increase with temperature.

PAG creep (Mansur, 1979). It is of the same type as the previous one but the climb rate is given by the SIPA mechanism itself and is therefore linear in stress. The strain rate is then quadratic in stress :

$$\dot{\varepsilon}_{PAG} = 2\alpha \cdot K \cdot \sigma^2 \qquad (3)$$

The figure 3 shows the total in-pile creep rate versus stress :

$$\dot{\varepsilon} = \dot{\varepsilon}_{diff} + \dot{\varepsilon}_{pl} + \dot{\varepsilon}_{SIPA} + \dot{\varepsilon}_I + \dot{\varepsilon}_{PAG} \qquad (4)$$

The irradiation creep contribution ($\dot{\varepsilon}_{SIPA} + \dot{\varepsilon}_I + \dot{\varepsilon}_{PAG}$) largely dominates the low stress region where diffusion creep is quite negligible in the temperature range investigated. It must be noted that in this range, the creep rates are about two orders of magnitude higher than out-of-pile (cf. Fig. 1)

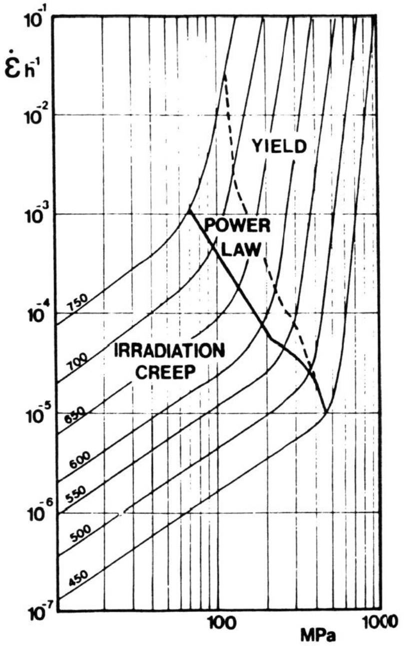

Fig. 3. Total strain rate vs stress of a solution annealed 316 under irradiation.

The figure 4 shows the deformation mechanism map in the temperature stress coordinates.

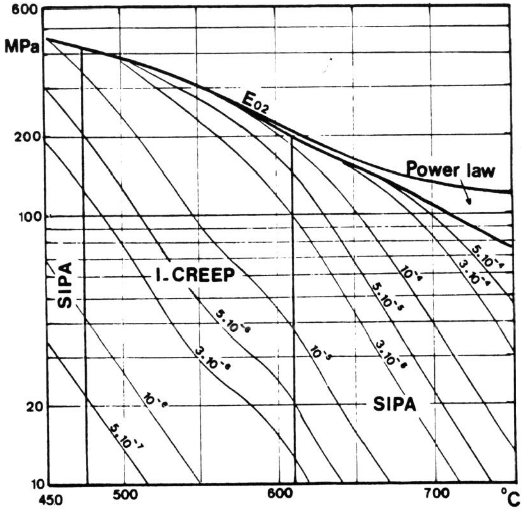

Fig. 4. Deformation mechanism map of a solution annealed 316 under irradiation. The strain rates indicated are in h^{-1}.

DISCUSSION

The in-pile deformation mechanism map is in good agreement with the previously published one (Matthews, 1979). The principal features are the shrinkage of the power law creep domain (see Fig. 2 and 4) and the very much higher creep rates in the irradiation creep field than in the corresponding diffusion creep one (see Fig. 1 and 3).

The claddings irradiated at 650°C, tested in biaxial creep experiments at the same temperature in the 100-150 MPa hoop stress range lie in the power law creep domain with the damaging consequences we briefly mentioned in the introduction.

Under irradiation, the loading conditions are more complicated. For the purpose of our demonstration, we only consider the steady state operating conditions, ruling out of the scope of this article any operational power change or transient overpower ramp. There are two types of stresses to consider, the primary and the secondary ones.

Secondary stresses come from the temperature and the swelling gradient within the thickness of the clad and from the ovalization due to interaction between the pins in the bundle. Swelling gradients give rise to an imposed strain rate close to $10^{-6}\ h^{-1}$, hence to secondary stresses σ_S that can be determined from figure 3 (see point A). The variation of σ_S along the fissile column is shown on Fig. 5.

be modelled like a hindered swelling in the direction of a diameter. At 600°C, where the swelling is maximum along the clad and where there is bundle interaction a maximum strain rate of ∿ $5.10^{-6}h^{-1}$ can be calculated implying a secondary stress σ_{ov} of 20 MPa (see Fig. 5)

Figure 5 shows the profile of secondary stress ($\sigma_S + \sigma_{ov}$) along the fuel column and one can determine the equivalent primary stress P that a clad can tolerate without crossing the line marked L which corresponds to the limit of significant power law creep ($\dot{\varepsilon}_{pl} = 10^{2}\dot{\varepsilon}_{irr}$). P is close to 100 MPa which corresponds to a hoop stress of 115 MPa.

Such a high value of the primary stress is in general not reached even at the highest burn ups in the commercial breeder reactors. Therefore, the irradiation creep mechanisms are largely dominating in the steady state operating conditions of a breeder reactor clad. We can expect a very effective relaxation of the stress concentrations due to boundary sliding and a superplastic behaviour resulting in high plastic strain without fracture.

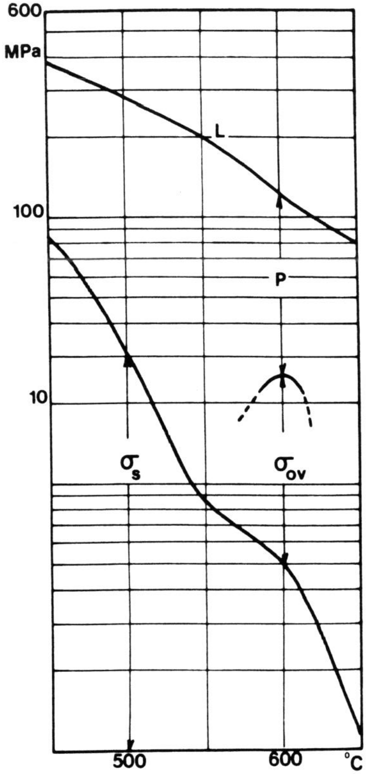

Fig. 5. Secondary and primary equivalent stresses along the fissile column.

CONCLUSION

The discrepancy between in pile and out of pile fracture behaviour of an irradiated 316 stainless steel may be understood with the help of the very different deformation mechanisms that occur in the two environments. The same qualitative conclusion certainly applies to other materials, at least of the same crystal structure as 316. Consequently, if the out of pile creep experiments allow to study the fast neutron irradiation embrittlement of the grain boundary, they can give information on the in pile fracture behaviour only if the stress or strain rate are sufficiently high so that the representative point lies in the power law creep range of the in pile deformation mechanism map.

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