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Physical and mechanical modeling and prediction of fracture strain and fracture toughness of irradiated austenitic steels

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ABSTRACT

A physical-and-mechanical model of ductile fracture has been developed to predict fracture toughness and fracture strain of irradiated austenitic stainless steels taking into account stress-state triaxiality and radiation swelling. The model is based on criterion of plastic collapse of a material unit cell and takes into account deformation voids nucleation, growth of deformation and vacancy voids, and their coalescence controlled by strain hardening of a material.

For justification of the model experimental data on fracture strain and fracture toughness of austenitic stainless steel 18Cr–10Ni–Ti grade irradiated up to 46–49 dpa with various swelling were used. Experimental data on fracture strain and fracture toughness are compared with the results predicted by the model. It has been shown that for prediction of the swelling effect on fracture toughness the dependence of process zone size on swelling should be taken into account.

1. Introduction

A lot of experimental data on the mechanical properties of highly irradiated austenitic stainless steels has been obtained by now. Processing this data array allowed one to reveal some peculiarities of the neutron irradiation effect on fracture of these materials.

The results obtained point to a much more considerable decrease in the fracture toughness of a material under irradiation as compared to that in the fracture strain of a tensile cylindrical specimen $\varepsilon_f = -\ln(1 - Z)$ where Z is the reduction of area. Indeed, with neutron irradiation doses above 20 dpa the fracture strain decreases by 40–50% with reference to the initial state [1]. At the same time, the material fracture toughness with such doses in terms of the critical value of J-integral, J_c, decreases 5–6 times in comparison with the material in the initial state [2].

Such a behavior of materials may be due to a strong effect of the stress state triaxiality (SST) on the ductility decrease under irradiation.

Another peculiarity of the irradiation effect on the properties of austenitic materials is a decrease in ductility due to vacancy voids leading to radiation swelling. Taking into consideration the strong effect of stress triaxiality on the ductility decrease, a considerable swelling effect on fracture toughness should be expected. But, there is only limited experimental data on the swelling effect on fracture toughness [3].

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Nomenclature

ε_f	fracture strain of material for tensile cylindrical specimen
ε_{f_crack}	fracture strain of material near the crack tip
J_c	critical value of J-integral (N/mm)
D	neutron irradiation dose, displacement per atom (dpa)
T_{irr}	irradiation temperature (°C)
T_{test}	test temperature (°C)
S	swelling
ρ_v^{def}	concentration of deformation voids (mm^{-3})
ρ_v^{vac}	concentration of vacancy voids (mm^{-3})
ρ_v^{max}	maximum concentration of deformation void nucleation sites (mm^{-3})
σ_d	effective local strength of matrix–inclusion interphase (MPa)
σ_{nuc}	stress controlling deformation voids nucleation (MPa)
$\bar{\varepsilon}_{eq}^p = \int d\varepsilon_{eq}^p$	Odquist parameter where $d\varepsilon_{eq}^p$ is the equivalent of a plastic strain increment
σ_{eq}	equivalent stress (MPa)
σ_Y	yield strength of material (MPa)
σ_{ul}	ultimate tensile strength of material (MPa)
σ_f	true fracture stress (MPa)
σ_{nuc}^{th}	threshold stress for deformation voids nucleation (MPa)
A	parameter of stress–strain curve (MPa)
n	exponent of stress–strain curve
d_{def}	deformation void diameter (mm)
d_{vac}	vacancy void diameter (mm)
l_{def}	distance between deformation voids (mm)
l_{vac}	distance between vacancy voids (mm)
r_f	process zone size under ductile fracture (mm)
SST	stress state triaxiality
SSC	stress–strain curve

It should be noted that the above trends are observed in case of transgranular ductile fracture of irradiated austenitic steels when a leading fracture mechanism is the evolution of deformation and vacancy voids. In the general case fracture of irradiated austenitic steels may occur by such mechanisms as channel fracture due to shearing of voids under channel deformation [2] and intergranular fracture due to twinning or channel deformation when swelling is absent but the strength of grain boundaries is weakened by neutron irradiation [4–6].

Intergranular fracture occurs under specific conditions, namely, at low temperatures and a high strain rate (for example, under impact tests) or at a slow strain rate and test temperatures T_{test} of about 300 °C [4]. Moreover, this type of fracture is observed in materials irradiated in PWRs where the generation of transmutation helium and hydrogen is much higher than that in fast neutron reactors for the same neutron dose.

The aim of this paper is the physical-and-mechanical modeling of transgranular ductile fracture and prediction of fracture strain and fracture toughness of irradiated austenitic steels for different stress states, neutron irradiation doses and irradiation swelling values. The predicted results are compared with the experimental data obtained.

2. Main considerations of the physical-mechanical ductile fracture model

The main considerations of the proposed model are as follows:

(a) Fracture proceeds by the mechanism of nucleation, growth and coalescence of voids. Two void populations are considered: vacancy voids and deformation voids. Vacancy voids are nucleated during irradiation and deformation ones are nucleated during deformation.
(b) Polycrystalline material is presented as an aggregate of unit cells in the form of cubes with homogeneous properties of a material.
(c) The deformation void concentration rate $\frac{d\rho_v^{def}}{d\sigma_{nuc}}$ is presented in the form

$$\frac{d\rho_v^{def}}{d\sigma_{nuc}} = \frac{\rho_v^{max} - \rho_v^{def}}{\sigma_d}, \tag{1}$$

where ρ_v^{def} is the concentration of deformation voids per unit volume of the material, ρ_v^{max} is the maximum concentration of void nucleation sites, σ_{nuc} is the stress resulting in void nucleation, σ_d is the effective local strength of matrix–inclusion interphase. In the general case the parameter σ_d depends on the particle shape.