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The radiation swelling effect on fracture properties and fracture mechanisms of irradiated austenitic steels. Part I. Ductility and fracture toughness

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ABSTRACT

The radiation swelling effect on the fracture properties of irradiated austenitic steels under static loading has been studied and analyzed from the mechanical and physical viewpoints. Experimental data on the stress-strain curves, fracture strain, fracture toughness and fracture mechanisms have been represented for austenitic steel of 18Cr-10Ni-Ti grade (Russian analog of AISI 321 steel) irradiated up to neutron dose of 150 dpa with various swelling. Some phenomena in mechanical behaviour of irradiated austenitic steels have been revealed and explained as follows: a sharp decrease of fracture toughness with swelling growth; untypical large increase of fracture toughness with decrease of the test temperature; some increase of fracture toughness after preliminary cyclic loading. Role of channel deformation and channel fracture has been clarified in the properties of irradiated austenitic steel and different tendencies to channel deformation have been shown and explained for the same austenitic steel irradiated at different temperatures and neutron doses.

1. Introduction

The effect of neutron irradiation on mechanical properties of austenitic steels has been studied in many papers, for example, [1–8]. There are detailed studies of the effect of neutron irradiation on strength and ductility properties, and the dependencies of the stress-strain curves parameters on neutron dose and irradiation temperature have been obtained for austenitic steels of 18Cr-9Ni and 18Cr-10Ni-Ti grades [5] (Russian analogs of AISI 304 and 321 steels). The effect of neutron irradiation has been also studied on fracture toughness [7–11] and fatigue crack growth rate [10–16].

Neutron irradiation was ascertained to result in decrease of ductility and fracture toughness [4–9] and does not affect practically fatigue crack growth rate [10–16]. It has been found that the mechanical properties do not practically vary for neutron dose above 10÷20 dpa, i.e. some saturation in their dependences on neutron dose is observed [3,5,8]. This tendency is typical for neutron irradiation which is not accompanied with radiation swelling.

The effect of radiation swelling on plasticity, strength and fracture toughness reveals some distinctive features [6,8,17–22]. In particular, it has been shown that fracture toughness (in terms of critical value of J-integral, J_c) decreases sharply with no any saturation when radiation swelling increases [6,20,22]. It is of interest to note also that a decrease of J_c with radiation swelling growth is more intensive than a decrease of ductility that is defined as the relative area reduction of cross-section of tensile round bar at rupture. The rate of J_c decrease with swelling growth may differ not only for various steels but also for the same steel irradiated under different temperatures and with various neutron doses [20,22]. Reasons for the above features have not been found up to now.

In addition, as is found in the present study (Part II) radiation swelling affects weakly on fatigue crack growth rate as distinct from its effect on fracture toughness. There is no any explanation for so different effect of radiation swelling on fracture properties under static and cyclic loadings.

One more unexplained phenomenon is the effect of test temperature on fracture toughness of irradiated austenitic steels. It has been found in paper [23] that fracture toughness at test temperature of 20°C increases significantly as compared with fracture toughness at higher test temperature (above 80°C). Taking into account that fracture of irradiated steel happens on ductile mechanism over this temperature range and the critical parameters of ductile fracture do not depend practically on test temperature [24]

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the strong dependence of J_c on test temperature is not clear.

The above issues seem to be explained if the empirical properties are related to the physical features of plastic deformation and fracture of irradiated austenitic steels. Currently a lot of experimental data is accumulated on radiation-induced damage in austenitic steels, first of all, concerning radiation swelling and radiation-induced segregations [3,4,25,26]. Physical mechanisms of plastic deformation and fracture of irradiated austenitic steels are studied in detail, for example, [18,27–31]. At the same time, in spite of significant progress both in the mechanical and microstructural studies no clear relationship between the material behaviour on a macro-scale and on a micro-scale could be given. In particular, one of specific features of plastic deformation of irradiated austenitic steels is known to be channel deformation [1,28,29] and specific feature of fracture is channel fracture [30,31]. However a link of these specific mechanisms of deformation and fracture with empirical regularities of mechanical properties variation was studied to very restricted degree.

It should be emphasized that the above properties are typical for wide range of austenitic stainless chromium-nickel steels as well as the mentioned unexplained phenomena in their behaviour.

Thus, the main aim of the present paper is to study and analyze the processes of plastic deformation and fracture of irradiated austenitic steels under static and cyclic loading specially for finding a relationship of these processes with the features of the radiation swelling effect on mechanical properties such as ductility, fracture toughness and fatigue crack growth rate.

This aim is achieved through (i) experimental determination of mechanical properties such as the stress-strain curve, the fracture strain, fracture toughness and fatigue crack growth rate for irradiated austenitic steel with various radiation swelling; (ii) investigation of the fracture mechanisms, and (iii) the analysis of the features of the radiation swelling effect on mechanical behaviour and fracture mechanisms. To link the fracture characteristics on a macro-scale and material behaviour on a micro-scale the physical-and-mechanical model of ductile fracture of irradiated austenitic steel [19–22] is applied. Experimental research is carried out for austenitic stainless steel of 18Cr-10Ni-Ti grade (Russian analog of AISI 321 steel), and the performed analysis allows the generalization of the obtained results for wide range of austenitic chromium-nickel steels.

The present paper is represented in two parts. The first part considers the fracture properties of irradiated austenitic steels under static loading including the swelling effect on ductility and fracture toughness. The second part represents the study results of the fatigue crack growth rate for irradiated austenitic steels including the swelling effect.

2. Material and investigation methods

2.1. The investigated material and irradiation conditions

Material used in the present investigation is austenitic stainless steel of 18Cr-10Ni-Ti grade irradiated with various neutron doses and swelling.

The chemical composition of steel is given in Table 1 according to technical specification. Steel of this grade is used for Internals components of Russian WWER type reactors and for some components of fast neutron reactors, in particular, BOR-60 and BN-600 reactors.

Table 1
Chemical composition of the investigated steel according to technical specification.

Mass fraction of chemical elements, %							
C	Si	Mn	Cr	Ni	Ti	S	P
<0.12	<0.8	<2.0	17.0÷19.0	9.0÷11.0	5C-0.8	<0.020	<0.035

The microstructure of the steel in the as-received (unirradiated) condition is typical annealed microstructure with average size of grains is near 20÷25 μm. There are Ti carbonitride of cubic form with sizes which reach 2 μm, and spherical Ti carbides of 0.2÷1.0 μm in diameter. As a whole, the unirradiated microstructure is typical for austenitic stainless steels of 18Cr-10Ni-Ti composition (AISI 321 steel) [4,32,33].

For experimental investigation the irradiated material was taken from decommissioned shield assemblies of BOR-60 reactor. These shield assemblies were irradiated with great neutron dose at the irradiation temperature that varied along the assembly height from 320 to 450°C that covers the wide range of radiation swelling values [34].

The shield assemblies of BOR-60 reactor are hexagon casings in which there are either 7 rods of the same diameter or solid core with surface coil. For experimental investigation the assembly components were taken as follows: rods of 14.7 mm in diameter from the shield assembly BM-7 and solid core of 26 mm in diameter from the shield assembly E-65. The shield assembly BM-7 was in service during 15 years, and the irradiation temperature T_{irr} of rods was from 320 to 450°C, neutron dose D is 30÷46 dpa. The shield assembly E-65 was in service during 41 years, and the irradiation temperature T_{irr} of core was 320÷370°C and neutron dose D is 100÷150 dpa. Hereafter for shortness the irradiated materials taken from BM-7 and E-65 assemblies are often denoted as BM-7 and E-65 materials.

2.2. Experimental investigation methods

In the present study the mechanical properties of irradiated steel have been determined as follows: standard mechanical properties under uniaxial tension, the fracture strain under various stress triaxiality and fracture toughness. The fracture surfaces of all ruptured specimens have been examined to study the fracture mechanisms.

Standard mechanical properties have been determined by testing standard round bars with a gauge diameter of 3 mm. The effect of stress triaxiality on the fracture strain under tension has been studied by testing round bars with circular notches.

Sketches of standard round bar and round bar with circular notch are shown in Fig. 1.

Fracture toughness of the investigated steel has been determined by testing single-edge bending (SEB) specimens with side-grooves of 0.8 mm in depth. Sketch of SEB specimen is shown in Fig. 2. The width W of specimens was W = 10 mm and the thickness B is as follows: B = 10 mm for specimens machined from rods of BM-7 assembly and B = 9 mm for specimens machined from core of E-65 assembly. SEB specimens were pre-cracked in accordance with the requirements of ASTM E1820-09 Standard. Several SEB specimens were tested after testing on the fatigue crack growth rate therefore pre-cracking condition for these specimens differs from others. When representing the test results special note will be made.

Before tests the radiation swelling of every specimen of all three types (round bar, round bar with circular notch and SEB) was determined by a hydrostatic weighing method with error of 0.1%.

All the mechanical tests were carried out with Schenk PSB-100 test machine in “hot” laboratory at CRISM “Prometey”. Uniaxial tension tests of round bars were performed with the cross head speed of $(1.3 \div 1.7) \cdot 10^{-2}$ mm/c that corresponds to the strain rate of 10^{-3} c^{-1} for smooth bars. To measure the neck diameters of ruptured round bars a television-computer device was used that