Physical and mechanical modelling of fracture and prediction of fracture strain and fracture toughness

Boris Margolin[1,a], Alexander Sorokin[1]

[1]Central Research Institute of Structural Materials "Prometey", Saint-Petersburg, Russia

[a]margolin@prometey2.spb.su

Keywords: ductile fracture model, fracture strain, fracture toughness, swelling, stress state triaxiality, austenitic steel, neutron irradiation.

Abstract. The model of ductile fracture has been developed to predict fracture toughness and fracture strain of irradiated austenitic steels taking into account stress-state triaxiality and irradiation swelling. Comparison of experimental data on fracture strain of irradiated austenitic weld metal with predicted results by the model has been performed.

Introduction

According to the experimental data [1], fracture strain of smooth cylindrical specimens $\varepsilon_f = -\ln(1-Z)$ (where Z is reduction of area) decreases by approximately 1.5-2 times under a neutron dose of 25 dpa relative to the initial condition. On a further increase of a neutron dose a decrease of ε_f practically does not happen. Unlike the relatively insignificant decrease of ε_f, the fracture toughness of austenitic steels decreases under the influence of irradiation more significant. For example under a neutron dose D=15-20 dpa the critical value of J_c integral decreases by approximately 5-6 times relative to the material in the initial condition [2].

Taking into account the approximate dependences $\delta \sim \frac{J}{\sigma_{flow}}$ where δ is a crack opening and $\varepsilon^p \sim \frac{\delta}{r}$ where r is the distance from a crack tip the value J_c under ductile fracture may be presented in the form similar to the proposed in [3, 4]:

$$J_c = \eta \cdot \sigma_{flow} \cdot r_f \cdot \varepsilon_{f\_crack}, \tag{1}$$

where J_c is the critical value of J-integral, r_f is a process zone size, ε_{f_crack} is a fracture strain near the crack tip determined with regard to stress-strain triaxiality (SST) typical for a crack, η is some numerical coefficient, σ_{flow} is the flow strength

$$\sigma_{flow} = \frac{\sigma_Y + \sigma_{ul}}{2}, \tag{2}$$

where σ_Y is yield strength, σ_{ul} is ultimate tensile strength.

Let us assume that SST effect on ε_f is the same for a different value of D. Then we may write that $\varepsilon_{f\_crack} = const \cdot \varepsilon_f$. Considering that with D=25 dpa value of ε_f decreases by one half, while σ_{flow} increases by approximately 2.5 times [1] we obtain that with D=25 dpa J_c increases by 1.25 times according to Eq. 1. The experimental value of J_c decreases by more than 5-6 times. Consequently, the influence of SST on ε_f increases with increasing degree of material irradiation.

The aim of this paper is to develop a physical-mechanical model allowing one to predict fracture strain on neutron dose for different stress states, as well as to predict the influence of irradiation and radiation swelling on material fracture toughness.

The main considerations of the physical-mechanical ductile fracture model

The main considerations of the proposed model are following:

a) Fracture proceeds by the mechanism of nucleation, growth and coalescence of voids. Two void populations are considered: vacancy voids and deformation voids, i.e. voids nucleating during the process of material 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 rate of change of void volume concentration $\frac{d\rho_v^{def}}{d\sigma_{nuc}}$ is presented in the form

$$\frac{d\rho_v^{def}}{d\sigma_{nuc}} = \frac{\rho_v^{max} - \rho_v^{def}}{\sigma_d}, \tag{3}$$

where ρ_v^{def} is the concentration of deformation voids in a unit of volume of a material matrix, ρ_v^{max} is the maximum volume concentration of void nucleation sites.

Integrating Eq. 3 and assuming that voids start nucleating only at stresses $\sigma_{nuc} \geq \sigma_{nuc}^{th}$ we obtain

$$\rho_v^{def} = \begin{cases} 0, \text{ for } \sigma_{nuc} < \sigma_{nuc}^{th} \\ \rho_v^{max}\left[1 - \exp\left(-\frac{\sigma_{nuc} - \sigma_{nuc}^{th}}{\sigma_d}\right)\right], \text{ for } \sigma_{nuc} \geq \sigma_{nuc}^{th} \end{cases}. \tag{4}$$

In Eq. 4 σ_{nuc} is stress controlling nucleation of discontinuity near some barriers [5, 6]. For void nucleation this barriers are inclusions of second phase or coarse carbides and others. According to papers [5,6] σ_{nuc} can written in the form

$$\sigma_{nuc} = \sigma_1 + m_{T\varepsilon} \cdot \sigma_{eff}. \tag{5}$$

where the parameter $m_{T\varepsilon}$ is concentration coefficient of local stress near dislocation pile-up; σ_1 is maximum principal stresses; $\sigma_{eff} = \sigma_{eq} - \sigma_Y$ is effective stress; σ_{eq} is equivalent stress; σ_d is a local strength of matrix-inclusion interface.

In general case σ_d depends on neutron dose and does not depend on test temperature [5,6]. It is necessary to note that equation for σ_{nuc} is similar to equation proposed in paper [7].

From Eq. 5 it follows that as a neutron dose D increases, σ_{nuc} will increase at the expense of an increase of σ_Y and, correspondingly, σ_1. According to papers [5, 6], as a dose D increases, σ_d decreases. Then from Eq. 4 it follows that irradiation results in an increase of void concentration. This conclusion following from the considered equations is confirmed by the experimental data. It is shown in paper [8] that dimple concentration on a specimen surface in an irradiated condition is higher than that in the initial one.

d) When analysing the growth of vacancy and deformation voids the Huang's equation [9] used. It should be noted that Huang's equation is valid for a single void in an infinite body. In the case when the distance between voids is comparable with their sizes the rate of a void growth increases at the expense of an additional deformation concentration in the vicinity of voids. To describe a void growth under conditions of their interaction an additional factor into Huang's equation was introduced in the form $\frac{1}{1-f}$

$$\frac{dV_{void}}{V_{void}} = \frac{3\alpha}{1-f} \cdot d. \tag{6}$$

where

$$\alpha = 0.427\left(\frac{\sigma_m}{\sigma_{eq}}\right)^k \cdot \exp\left(\frac{3}{2}\frac{\sigma_m}{\sigma_{eq}}\right);\ k = \begin{cases} 0{,}25,\ \text{for}\ \dfrac{\sigma_m}{\sigma_{eq}} \le 1 \\ 0,\ \text{for}\ \dfrac{\sigma_m}{\sigma_{eq}} > 1 \end{cases}, \tag{7}$$

$æ = \int d\varepsilon^p_{eq}$ is the Odquist's parameter (the length of a deformation path); $d\varepsilon^p_{eq}$ is equivalent of a plastic strain increment, f is material void volume fraction

$$f = \frac{V_\Sigma}{V + V_\Sigma}, \tag{8}$$

In Eq. 8 V_Σ is the total volume of vacancy and deformation voids in a material matrix of the volume V.

e) The criterion of a unit cell plastic collapse or, in other words, the criterion of plastic instability is used as fracture criterion [10,11]

$$\frac{dF_{eq}}{dæ} = 0, \tag{7}$$

where $F_{eq}=\sigma_{eq}\cdot(1-\overline{A}_\Sigma)$, σ_{eq} is equivalent stresses related to a material matrix (without voids), $\overline{A}_\Sigma$ is a relative void area, i.e. void cross-section area related to the cross-section area unit of a unit cell with voids. It should be noted that when analysing conditions (7) stress state triaxiality is taken to be constant [10].

The parameter $\overline{A}_\Sigma$ is calculated on the basis of following considerations. In the general case α in Eq. 6 depends on æ and does not depend on a void volume. Then an increase in the volume of vacancy and deformation voids taking into account Eq. 4 and 6 may be calculated by the equation:

$$d\overline{V}_\Sigma = \frac{3\cdot\alpha}{1-f}\cdot\overline{V}_\Sigma\cdot dæ + V^{def}_{nuc}\cdot\left[\rho^{def}_v(æ+dæ) - \rho^{def}_v(æ)\right], \tag{8}$$

where V^{def}_{nuc} is the volume of a nucleus deformation void.

When integrating Eq. 8 the initial condition is formulated in the form:

$$\left(\overline{V}_\Sigma\right)_0 = S_w + V^{def}_{nuc}\cdot\left[\rho^{def}_v(æ)\right], \tag{9}$$

where $\left(\overline{V}_\Sigma\right)_0$ is the value of a relative void volume with æ=0, S_w is material swelling.

The average void area will be determined as

$$A_{void} = \left(\frac{\overline{V}_\Sigma}{\rho^{def}_v + \rho^{rad}_v}\right)^{2/3}, \tag{10}$$

where ρ^{rad}_v is a vacancy voids concentration.

Considering that the total area of voids per unit of area of a material matrix is calculated by the formula

$$\overline{A}^*_\Sigma = A_{void}\left(\rho^{def}_v + \rho^{rad}_v\right)^{2/3}, \tag{11}$$

we obtain

$$\overline{A}^*_\Sigma = \overline{V}_\Sigma^{\,2/3}, \tag{12}$$

The volume of a unit cell increases by $(1+\overline{V}_\Sigma)$ times at the expense of vacancy and deformation voids.

Then the void area related to the cross section area of a unit cell, whose volume increased by $(1+\overline{V}_\Sigma)$ times, can be calculated by the formula

$$\overline{A}_{\Sigma} = \overline{A}_{\Sigma}^{*} \cdot \left(\frac{1}{1+\overline{V}_{\Sigma}} \right)^{2/3}, \qquad (13)$$

Taking into account Eq. 12 and Eq. 13 we obtain

$$\overline{A}_{\Sigma} = \left(\frac{\overline{V}_{\Sigma}}{1+\overline{V}_{\Sigma}} \right)^{2/3}. \qquad (14)$$

Simulation of fracture under different conditions of irradiation and testing of material.

Investigated material. The weld metal of 18Cr-10Ni-Ti steel in the initial and irradiated conditions was chosen as an object for the use of the model. Welding was performed with the use of 19Cr-11Ni-3Mo welding wire without subsequent heat treatment.

Weld metal specimens were irradiated in the BOR-60 reactor by neutron doses in the range from 6-7 to 46 dpa at a temperature T_{irr}=320-340°C [1].

Analysis of the test temperature effect. The authors considered a weld metal irradiated by up to 46 dpa at T_{irr}=320-340°C and tested in the temperature range from 80°C to 495°C.

The model parameters were chosen from the following considerations:

1) Values of σ_Y and parameters of stress-strain curves (SSC) for σ_{eq} determination at different values of T_{test} were calculated according to equations, presented in [1].
2) The radiation swelling according to measurements of specimens is close to zero. Therefore when simulating fracture under the indicated irradiation condition the effect of vacancy voids on ε_f was neglected.
3) The parameter $m_{T\varepsilon}$ was taken as independent of T_{irr} and an irradiation dose. The value $m_{T\varepsilon}$ based of paper [7] was taken as 1.0. The value σ_{nuc}^{th} in Eq. 4 was taken as zero.
4) The pair of parameters σ_d and ρ_v^{max} was formed in such a way that the calculated critical strain ε_f^{calc} at T=80°C was equal to the value ε_f^{exp} determined by the regression dependence presented in paper [1]. As a result of the performed calculations, the following parameter values were chosen: σ_d = 4874 MPa, ρ_v^{max} = $1.2 \cdot 10^7$ mm^{-3}. Parameters σ_d and ρ_v^{max} were taken as independent of T_{test}.

As the criterion of fracture of a smooth cylindrical specimen the fracture of the central fibre of a specimen neck was taken. To describe the dependences characterizing SST in the central fibre of a specimen neck, $q_m(æ) \equiv \frac{\sigma_m}{\sigma_{eq}}$ and $q_1(æ) \equiv \frac{\sigma_1}{\sigma_{eq}}$ the Bridgman's formulas [12] were used.

Over the range of T_{test}=80-495°C the values of critical strain ε_f^{calc} were calculated on the basis of the plastic collapse condition (7).

Fig. 1 shows the experimental data and the dependence $\varepsilon_f^{calc}(T_{test})$. As input data generalized SSC, calculated by equations presented in [1] were used.

Additional calculations ε_f^{calc} were performed for each temperature taking into accounts individual SSC, obtained from test of each specimen. Results of performed calculations and strain hardening curves for each test temperature presented on the Fig. 2.

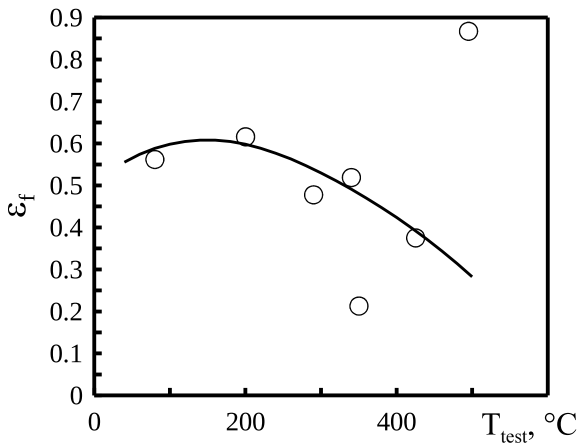

Fig. 1. Experimental data (○) of the critical strain for different test temperatures of the material irradiated by the dose D=46 dpa at T_{irr}=330-340°C and curve calculated by the model with regard for generalized stress-strain curves [1];

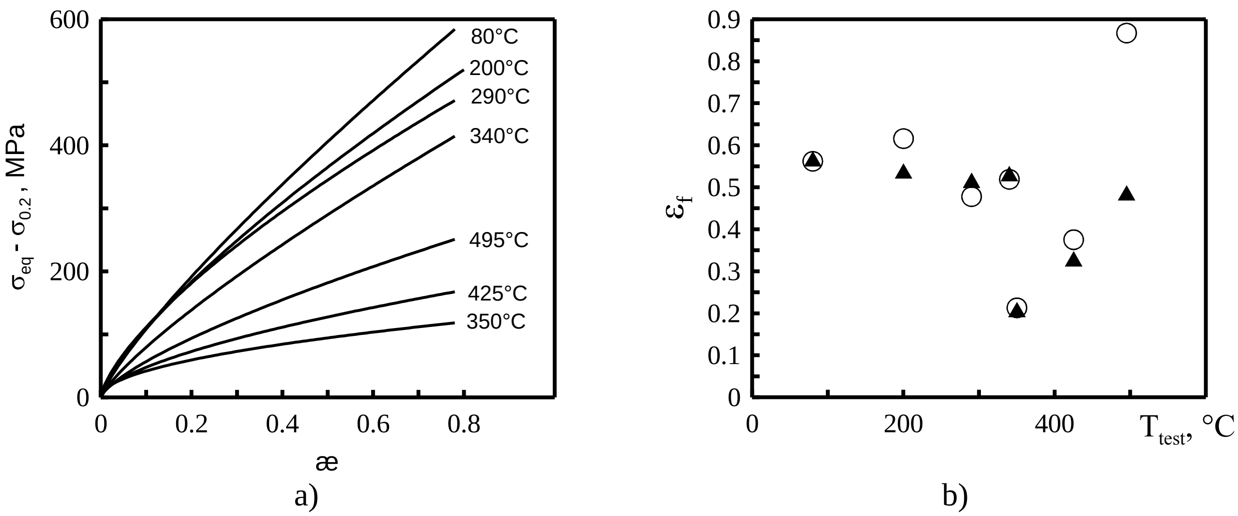

Fig. 2. Strain hardening (a) and temperature dependence of the critical strain (b) of the material irradiated by the dose D=46 dpa at T_{irr}=330-340°C: ○ - experimental data; ▲ - points calculated by the model on the basis of individual SSC.

As is seen from Fig. 1 and Fig. 2, a good agreement between the experimental data and results calculated by the model is observed. The conservative calculated value (relative to the experimental one) at T_{test}=495°C is evidently connected with annealing of radiation defects occurring at $T_{test} > T_{irr}$, which resulted in an increase of the parameter σ_d. When making calculation this parameter was taken as a constant one and was calibrated from the value of critical strain for unannealed irradiated material.

The presented data shows that with invariant values of σ_d and ρ_v^{max} the model makes correct predictions of the value ε_f^{exp} at different T_{test} especial with taking into account the peculiarities of individual stress-strain curves for each T_{test}. The effect of T_{test} on ε_f is determined by the influence of strain hardening on the realization condition of a plastic collapse of a unit cell.

Analysis of the effect of an neutron dose on the parameter $\boldsymbol{\sigma_d}$. We considered weld metal irradiated in the neutron dose range from 0 to 46 dpa at T_{irr} = 320-340°C tested at T_{test}=80°C.

The parameter σ_d for each neutron dose was chosen in such a way that the calculated value ε_f for a given dose coincided the experimental one. Fig. 3 shows the values σ_d and dependence $\Delta\sigma_Y$ for different neutron doses, taken from [1].

As is seen from the figure, the dependence σ_d(D) correlates well with the dependence $\Delta\sigma_Y$(D).

On changing a neutron dose from 0 to 6 dpa a rapid change of σ_d and $\Delta\sigma_Y$ occurs. On a further increase of a neutron dose σ_d and $\Delta\sigma_Y$ practically do not change. The obtained result is confirmed by the physical laws on the influence of radiation defects on σ_d. [5, 6].

Thus, the obtained results point to the model possibility to describe the influence of a neutron dose on critical strain ε_f , if the influence of D on σ_d is taken into account.

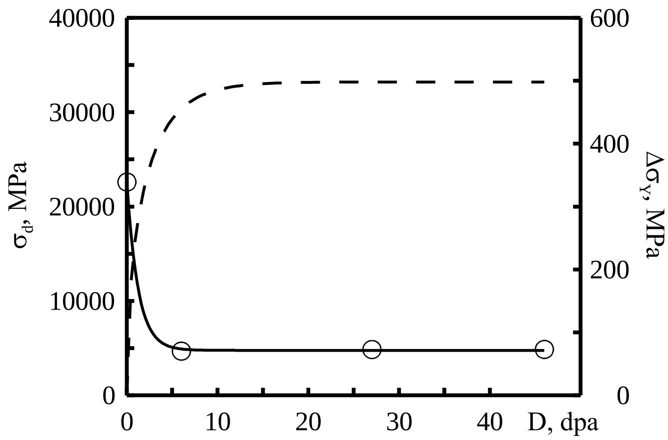

Fig. 3. Decrease of the value σ_d with an increasing neutron dose:
○ and ——— - calculated values σ_d;
— — — - dependence of yield strength increment on dose D, according to [1];

Influence of swelling on the value of critical strain. In the preceding divisions the analysis of the model parameters was made on the basis of the experimental data obtained with specimens irradiated in the range of temperatures at which swelling is practically absent.

Let us consider possibility of developed model to predict the influence of swelling on the value of critical strain. For this purpose the test data of the weld metal specimens irradiated by a dose of 49 dpa at T_{irr}=400-450°C [13] was used. Swelling of these specimens varies from 3 up to 7%.

Numerical simulation of the influence of vacancy void volume fraction on critical strain is based on the following propositions:

1) the SSC for a material matrix, i.e. material without vacancy and deformation voids is invariant to swelling and irradiation temperature and depends only on a neutron dose and test temperature;
2) when calculating critical strain for each temperature the individual values of swelling for each specimen [13] were used;
3) the values of the parameters σ_d and ρ_v^{max} are determined from the equality condition $\varepsilon_f^{exp} = \varepsilon_f^{calc}$ at T_{irr}=320-340°C (i.e. without swelling [1,13]) and T_{test}=80°C, i.e. the same way as described for analyzing of test temperature effect.

The results of the calculation of critical strain in the absence and existence of swelling are shown in Fig. 4. It is seen from the figure that there is a close coincidence of the experimental and calculated data for specimens without and with swelling (for specimens without swelling comparison of ε_f^{exp} and ε_f^{calc} was shown above in Fig. 1).

The obtained results suggest that a decrease of ε_f at T_{irr}=400-450°C compared with ε_f at T_{irr}=320-340°C is connected exclusively with vacancy void volume fraction that determines material radiation swelling. It should be noted that nonmonotony of the dependence $\varepsilon_f^{exp}(T_{test})$ at T_{irr} =400-450°C is evidently determined by the inhomogeneity of specimens swelling. At the same time the average value of fracture strain $\bar{\varepsilon}_f$ over a temperature range of 80-425°C obtained experimentally approaches the calculated value: $\bar{\varepsilon}_f^{exp}=0.26$, $\bar{\varepsilon}_f^{calc}=0.25$.

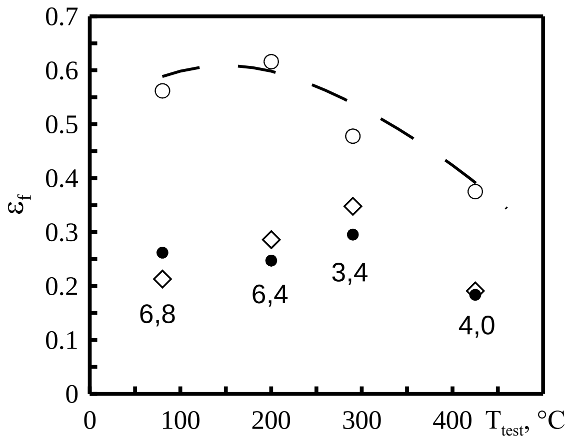

Fig. 4. Temperature dependences ε_f^{exp} and ε_f^{calc} for weld metal with and without swelling; the digitals denote swelling of specimens as a percentage:
○ - fracture strain of weld metal without swelling (experiment);
◇ - fracture strain of weld metal with swelling (experiment);
● - calculated value of fracture strain of weld metal with swelling;
— — — - calculated temperature dependence of critical strain of weld metal without swelling.

The close coincidence of the experimental and calculated values of ε_f in figure 4 indicates the invariance of σ_d to T_{irr}, since the value σ_d obtained at T_{irr}=320-340°C was used as input information for predicting ε_f at T_{irr}=400-450°C.

Determination of the model parameters. Based on the performed analysis the following procedure of determining the model parameters may be proposed.

SSC are determined on the basis of processing of smooth tensile specimen test results.

The values ρ_v^{max} and σ_d can be determined by a tensile test of specimens of two types: a smooth cylindrical specimen and a specimen with a circumferential notch. The values ε_f for these specimens will be different and, hence, when comparing the calculated and experimental results the pair of parameters ρ_v^{max} and σ_d can be determined. A similar approach was used in paper [11].

Analysis of an irradiation effect on fracture toughness

The influence of stress state triaxiality on the dependence $\varepsilon_f(D)$. To estimate the influence of SST in the dependence $\varepsilon_f(D)$ let us compare the dependence $\frac{\varepsilon_f}{\varepsilon_f^0}(D)$ obtained on the basis of test data processing of smooth cylindrical tensile specimens and the dependence $\frac{\varepsilon_{f\_crack}}{\varepsilon_{f\_crack}^0}(D)$ calculated by the model. For ε_{f_crack} let us take ε_f^{calc} calculated for the stress state typical for a material near a crack tip on the line of its extension. The ε_f^0 and $\varepsilon_{f\_crack}^0$ is fracture strain of material in initial condition with regard to corresponding SST.

The dependences characterizing SST - $q_m(æ)$ and $q_1(æ)$ for tensile specimens and a material near a crack tip are shown in Fig. 5. Calculation of $q_m(æ)$ and $q_1(æ)$ for tensile specimens was made according to Bridgeman's formulas [12], while calculation for a material near a crack tip was made by the dependences proposed in [14].

The calculation by the model $\frac{\varepsilon_{f\_crack}}{\varepsilon_{f\_crack}^0}(D)$ was made for T_{test}=290°C. The choice of such temperature is connected with the available representative data on $J_c(D)$ for T_{test} = 290-350°C [2].

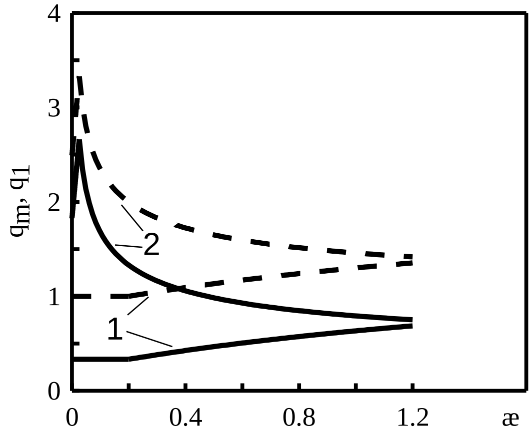

Fig. 5. Dependence of stress state triaxiality on plastic strain in a tensile specimen neck with D=0 (1) and near a crack tip with D=0 [14] (2):
——— - stress state triaxiality in terms of q_m; – – – - stress state triaxiality in terms of q_1;

Following parameters was used as input information for model: SSC calculated by equations presented in [1], $\rho_v^{max} = 1.2 \cdot 10^7$ mm^{-3} and $\sigma_d(D)$ presented in Fig. 3.

Table 1 presents the calculation results of $\frac{\varepsilon_f}{\varepsilon_f^0}$ by equation presented in [1] and $\frac{\varepsilon_{f\_crack}}{\varepsilon_{f\_crack}^0}$ calculated by the model.

Table 1. The values $\frac{\varepsilon_f}{\varepsilon_f^0}$, $\frac{\varepsilon_{f\_crack}}{\varepsilon_{f\_crack}^0}$ and $\frac{J_c}{J_c^0}$ at different doses and for the same T_{test}=290°C.

D, dpa	Stress state			σ_{flow}, MPa	$\frac{J_c}{J_c^0}$ (calc)	$\frac{J_c}{J_c^0}$ (exp)
	in the centre of a tensile specimen neck	near the crack tip				
	$\frac{\varepsilon_f}{\varepsilon_f^0}$	ε_{f_crack}	$\frac{\varepsilon_{f\_crack}}{\varepsilon_{f\_crack}^0}$			
0	1	0.0671	1	413	1	1
27	0.480	0.0055	0.082	883	0.175	0.169
46	0.480	0.0056	0.083	883	0.177	0.164

On the basis of above calculations it is possible to estimate a fall of J_c with an increasing dose. Assuming that process zone size r_f is invariant to material condition calculation of a relative decrease of J_c may be determined on the basis of the following expression

$$\frac{J_c}{J_c^0} = \frac{\varepsilon_{f\_crack}}{\varepsilon_{f\_crack}^0} \cdot \frac{\sigma_{flow}}{\sigma_{flow}^0}, \qquad (15)$$

where J_c is a critical value of the J-integral for irradiated material, J_c^0 is the critical value of the J-integral for material in the initial condition, σ_{flow} is flow stress for a material calculated according Eq. 2 and dependencies presented in [1].

The calculation performed by the model at T_{test}=290°C was compared with the calculation results on the dependence obtained on the basis of processing of the experimental data presented in [2,3]. The calculation results are presented in Table 1.

As it seen from the presented results, a decrease of ε_f with an increasing dose is considerably enhanced with increasing stress state triaxiality. Thus, for the triaxiality typical for a tensile specimen with D=46 dpa ε_f decreases by half compared to an unirradiated condition, while for the triaxiality typical for material near a crack tip a decrease of ε_f reaches 12 times. In other words, the influence of SST increases with a growth of a neutron dose. Calculation of ε_f with regard to the influence of SST on dependence ε_f(D) makes possible to describe adequately the change of material fracture toughness under irradiation.

It should also be indicated that with the obtained low values of $\frac{J_c}{J_c^0}(D)$ material fracture, according to the performed fractographic investigations happened by the mechanism of void coalescence. Therefore the conclusion drawn in paper [15] on the fact that a low value of the relation $\frac{J_c}{J_c^0}(D)$ suggests a channel fracture is not a general one.

Influence of swelling on fracture toughness J_c

In order to investigate the influence of radiation swelling on J_c we determined the dependences $\varepsilon_{f\_crack}(S_w)$ for different neutron doses from 6 to 46 dpa. The same parameters as in previous divisions were used as an input information for the model.

The value of a relative decrease of $\bar{J}_c$ resulted from the value S_w was calculated by the formula

$$\bar{J}_c = \frac{J_c(S_w)}{J_c(S_w=0)} = \frac{\varepsilon_{f\_crack}(S_w)}{\varepsilon_{f\_crack}(S_w=0)} \cdot \frac{\sigma_{flow}(S_w)}{\sigma_{flow}(S_w=0)}, \qquad (16)$$

According to [1], $\sigma_{flow}(S_w)$ can be calculated by the formula

$$\sigma_{flow}(S_w) = \sigma_{flow}(S_w=0)\cdot\left(1-\left(\frac{S_w}{1+S_w}\right)^{2/3}\right), \qquad (17)$$

Fig. 6 shows the dependence $\bar{J}_c$ (S_w) for different neutron doses. It is seen from the figure that the value $\bar{J}_c$ does not practically depend on a neutron dose, but depends only on the value of swelling S_w.

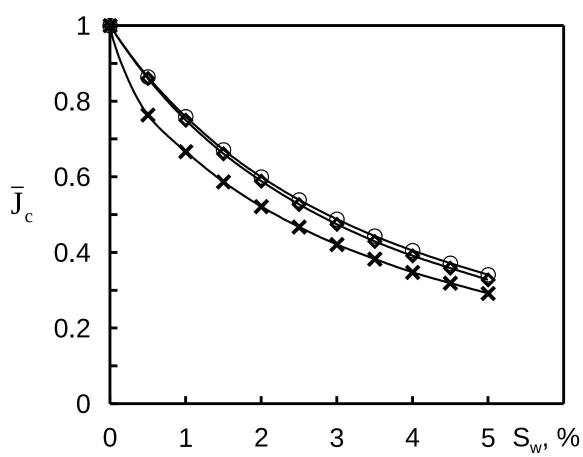

Fig. 6. Calculative dependence of relative fracture toughness on radiation swelling for different neutron doses:

○, ———— - D=6 dpa, ◇, — — — - D= 27 dpa, ×, — · — · — - D =46 dpa.

A considerable decrease of J_c, for material with radiation swelling follows from the experimental data [16]. It is shown there that with a dose D=100 dpa and T_{irr}=420-460°C J_c for 316 cold-worked steel ≈1.5 N/mm, which is by 10 times lower than the minimum value J_c for irradiated materials without swelling. According to our estimation swelling of this steel was no less than 10-15%. Hence calculation presented in Fig. 6 agree with available experimental data.

Nevertheless, the model requires further experimental confirmation.

Conclusions

1. The model of ductile fracture was developed, which makes it possible to describe the influence of stress state triaxiality, neutron irradiation and radiation swelling on the critical parameters controlling fracture: fracture strain ε_f and the critical value of J-integral J_c.

2. Predictions were made on the influence of a neutron dose on ε_f and fracture toughness J_c. It was shown that as stress state triaxiality increases the degree of the irradiation influence on ε_f increases.

The calculation results of J_c showed that this parameter with D ≥6 dpa decreases by ~6 times. This prediction is in complete agreement with the experimental data.

3. The model predicts a severe decrease of J_c with a growth of swelling in relation to J_c of a material irradiated under the condition when radiation swelling is absent. This result is confirmed by the available experimental data.

4. It was shown that the influence of T_{test} on ε_f is determined exclusively by the influence of a test temperature on a stress-strain curve. The parameter ρ_v^{max} does not depend on T_{test} and a neutron dose. The parameter σ_d depends only on a neutron dose and does not depend on T_{test} at $T_{test} \le T_{irr}$, i.e. in the case when radiation defects are not annealed during test processes.

5. The obtained dependence of σ_d on a neutron dose corresponds to the regularities determined earlier on the basis of the analysis of radiation defect influence on microcrack initiation. The parameter σ_d is invariant to T_{irr} at least over the range T_{irr}=320-450°C.

6. The procedure of determining the model parameters was proposed. These parameters can be determined based on the tensile test results of smooth cylindrical specimens and cylindrical specimens with a circumferential notch.

7. Based on the general regularities of a stress-strain curve change resulted from a neutron dose, test temperature and dependence $\sigma_d(D)$ obtained from testing smooth cylindrical tensile specimens, the model makes it possible to predict the influence of an neutron dose on fracture toughness as well as predict crack initiation in structure components with different stress concentrators.

References

[1] A.A. Sorokin, B.Z. Margolin, I.P. Kursevich et al.// Voprosy Materialovedenia (Problems of Material Science) . – 2011, №2(66), pp. 131-152 (in Russian).

[2] V.I. Smirnov, B.Z. Margolin, A.N. Lapin et al.// Voprosy Materialovedenia (Problems of Material Science) . – 2011, №1(65), pp. 167-183 (in Russian).

[3] B.Z. Margolin, A.I. Minkin, V.I. Smirnov et al.// Voprosy Materialovedenia (Problems of Material Science) . – 2008, №1(53), pp. 123-138 (in Russian).

[4] B.Z. Margolin, V.I. Kostylev, A.V. Ilyin et al. //Int. J. Pres. Ves. & Piping. – 2001. –V. 78. – pp.715-725.

[5] Margolin B.Z., Shvetsova V.A., Gulenko A.G., and Kostylev V.I. Prometey local approach to brittle fracture: development and application // Eng. Fract. Mech. – 2008. – V. 75. – P. 3483 – 3498

[6] B.Z. Margolin, V.A. Shvetsova, A.G. Gulenko et al.// Strength of Materials. – 2010, Vol. 42, №5, pp 506-527.

[7] F.M. Beremin, Cavity formation from inclusions in ductile fracture of A508 Steel, Met. Trans. 12A, 1981, pp. 723-731

[8] E.A. Little. Fracture mechanics evaluation of neutron irradiated type 321 austenitic steel // J. of Nuc. mat. – 1986, V. 139, pp 261-276

[9] Huang Y. Accurate dilatation rates for spherical voids in triaxial stress fields // Transaction of the ASME, Ser. E, Journal of Applied Mechanics. – 1991. – V. 58. –pp. 1084-1086

[10] B.Z. Margolin, G.P. Karzov, V.I. Kostylev et al.// Fatigue Fract. Eng. Mater. Struct. – 1998. – V.21. – P. 123-137.

[11] B.Z. Margolin, V.I. Kostylev, A.V. Il'in et al.// Int. J. Pres. Ves.& Piping. – 2001, Vol. 78, Issue 10, pp. 715-725.

[12] Bridgman PW. Studies in large plastic flow and fracture. New York: McGraw-Hill, 1952.

[13] B.Z. Margolin, I.P. Kursevich, A. A. Sorokin et al.// Strength of Materials.– 2009, Vol. 41, №6, pp. 593-602.

[14] Margolin B.Z., Gulenko A.G., Shvetsova V.A. Improved probabilistic model for fracture toughness prediction based for nuclear pressure vessel steels// Int J Pres Ves Piping. – 1998, Vol. 75, pp. 843-855.

[15] G.E. Lucas et al. //Journal of Nuclear Materials. – 1996. - Vol. 233-237. – pp.207-212.

[16] Effect of Irradiation on water reactors internals. Paris, CEA, TECNATOM, VTT, AMES Report N 11, June 1997.