New Characteristics of Radiation Defects Evolution and Interaction

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ABSTRACT: *Evolution of radiation defects appearing as a result of irradiation was considered. It was shown that swelling rate (dS/dD) (i.e. the derivative of swelling with respect to dose) is a power-law function of an R-parameter suggested which characterizes the swelling in different irradiation conditions and determines the stages and mechanisms of this process. It was found that cumulative number of defects* (N_Σ) *is connected with their sizes (d) by a power-law relation* ($N_\Sigma = Ad^{-b}$) *which remains unchanged at different hierarchical levels of damage accumulation process development. Coalescence of defects leads to a decrease in the b-exponent by its absolute value.*

INTRODUCTION

Processes of damage accumulation and development in solid exhibit some common peculiarities in various loading conditions. Thus, they usually manifest a stable stage of initiation and development of defects, stage of their coalescence and transition to the accumulation of next level defects. Analysis of defect distribution geometric picture shows that it remains unchanged (in statistical sense) at the stage of multiple damage accumulation before the beginning of defect coalescence and serves as evidence of multiple fracture process self-similarity at this stage [1]. These common peculiarities allow for describing multiple fracture processes various by their nature by similar relations and, in particular, the Kachanov - Rabotnov relation connecting damage accumulation rate ($d\omega/dt$) with the damage itself (ω) and acting factors. To describe size distribution of defects one may use the dependence ($N_\Sigma \sim d^{-b}$) of cumulative defect number (N_Σ) on their sizes (d) which is analogous to the well-known in seismology Gutenberg - Richter relation connecting the number of seismic events to their energy proportional to the length of arising fault. In this study, it will be shown that the above-mentioned relations well describe the radiation defects development process.

SELF-SIMILARITY OF RADIATION DEFECTS EVOLUTION

Swelling of materials is connected to increase in specimen volume and decrease in material density as a result of multiple process of defect formation at irradiation. It is influenced by many factors: temperature (T), stress (σ), preceding cold deformation (ε), concentration of alloying (C_{AE}) or trace elements (C_{TE}) [2].

In damage mechanics the Kachanov-Rabotnov equation is used to describe a multiple fracture process [3]:

$$d\omega/dt = f(\omega, t, T, \sigma, ...), \tag{1}$$

where ω is the damage measure, t is the time, T is the temperature, σ is the stress.

If radiation swelling (S) is taken as a damage measure, and the swelling rate is written as dS/dD [4] (so far as a dose is a function of a time), then the Eq. 1 for swelling under action of the above-mentioned factors is:

$$dS/dD = f(S, D, T, \sigma, \varepsilon, C_{AE}, C_{TE}) \tag{2}$$

In order to investigate this function in terms of self-similarity theory, let us present the parameters of Eq. 2 in dimensionless form:

$$dS/dD = f(C_{AE}, C_{TE}, T/T_m, \sigma/\sigma_y, \varepsilon, D, S) \tag{3}$$

where T_m is the melting point and σ_y is the yield stress.

The self-similarity of the function dS/dD means that its dependence on each of the arguments in Eq. 3 is of a power-law type:

$$\acute{S} = dS/dD = A(S/C_{AE})^{\alpha}\ (S/C_{TE})^{\beta}\ (ST/T_m)^{\gamma}\ (S\varepsilon)^{\delta}\ (S\sigma/\sigma_y)^{\mu}, \tag{4}$$

where $A, \alpha, \beta, \gamma, \delta, \mu$ are constants.

In accordance with the analysis of self-similar processes [5], self-similar function *dS/dD* (4) tends to a limiting value as each of it's arguments approaches zero or infinity.

Indeed, when swelling (*S*) and, accordingly, each of the above-mentioned parameters decreases to zero, the swelling rate *dS/dD* tends to zero or a finite limit.

Investigation of damage rate changes versus each of the indicated parameters in Eq. 4 is usually performed under conditions where the other parameters are kept constant. Therefore, we shall equate the exponents corresponding to these parameters to zero.

Then, the relation (4) for swelling under conditions of a changing concentration of the alloying elements looks as follows:

$$\acute{S} = dS/dD = A(S/C_{AE})^{\alpha} \qquad (5)$$

If the graphs of this power-law function (5) in log-log coordinates are linear, then we can assume that the above-mentioned condition of self-similarity is fulfilled [5]. Thus, it is possible to consider the function described by Eq. 5 as obeying the self-similarity conditions.

For verification of this supposition, the swelling rate dependencies on each governing parameter were plotted. Initial *S-D* curves were taken from literature [6-11]. Such initial swelling curves obtained for aluminum irradiated at different temperatures are shown in Figure 1, a. Using these curves the dependencies of swelling rate *dS/dD* on dimensionless similarity parameter $R_T = (T/T_m)\ S^{1/3}$ were plotted for each temperature. For different irradiation temperatures the swelling rate curves either coincide or are almost parallel and can be brought to a single curve by normalization to the coordinates of the curve's knee points which correspond to the end of a stable stage of swelling. It can be seen that this normalization enables us to obtain a unified universal kinetic swelling diagram which is described by power-low dependence of the swelling rate on the relative parameter R_T^* (Figure 1, b). The swelling diagram is similar by the shape to the well-known fatigue fracture diagram and is described in its linear middle part by the power law function.

Similar relationships were obtained for the swelling rates in steels 09Cr16Ni15Mo3Nb and AISI 316 after preceding cold plastic deformation (ε), in steels AISI 316 and SA 304 irradiated in tension conditions at various stresses (σ), in steel Fe-15Cr-XNi with different concentration of nickel (C_{Ni}) and in steel AISI 316 with different concentration of trace elements:

phosphorus (C_P), zirconium (C_{Zr}) and titanium (C_{Ti}). To describe the swelling process under these conditions the following R-parameters were used: $R_\varepsilon = (1+\varepsilon)S^{1/3}$; $R_\sigma = S^{1/3}/(1+\sigma/\sigma_y)$; $R_{Ni} = S^{1/3}/C_{Ni}$; $R_P = S^{1/3}/C_P$; $R_{Zr} = S^{1/3}/C_{Zr}$ and $R_{Ti} = S^{1/3}/C_{Ti}$ [12].

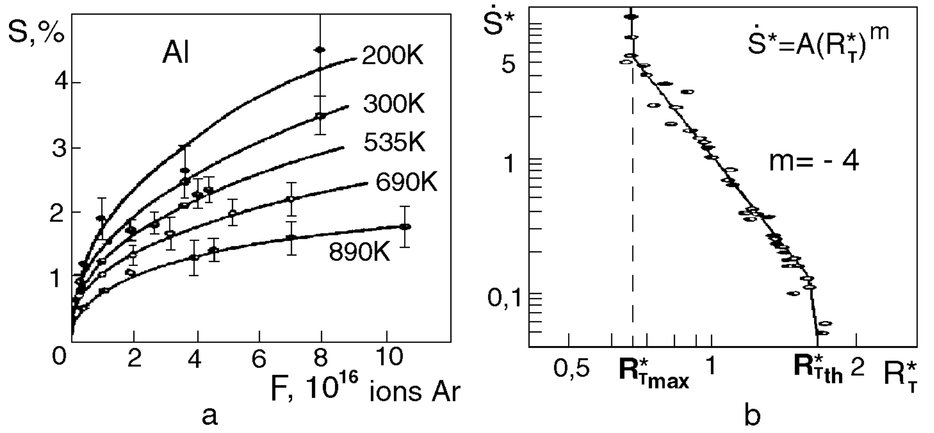

Figure 1: Initial swelling curves for aluminum at different temperatures of irradiation [6] (a); plotted kinetic diagram of swelling in universal coordinates (b) [12].

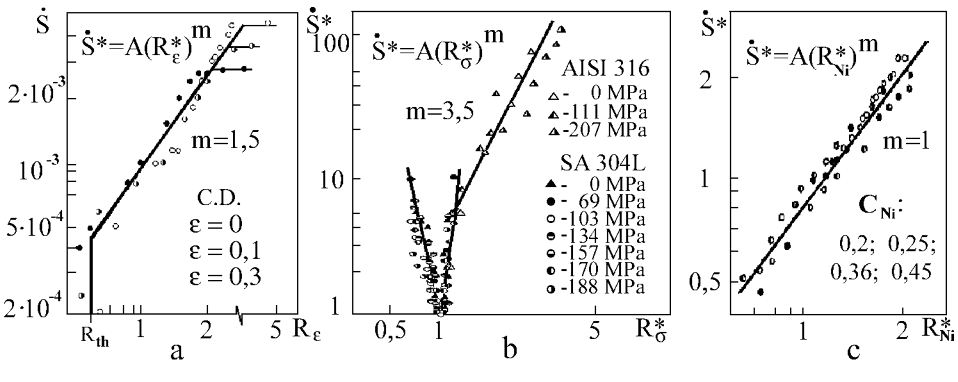

Figure 2: Kinetic swelling diagrams obtained for steel 09Cr16Ni15Mo2Nb at different values of preceding cold plastic deformation (a), steels AISI 316 and SA 204L at different stress level (b) and steel Fe-15Cr-XNi with different concentration of nickel (c).

As can be seen from Figure 2, the swelling diagrams for all the studied factors influencing damage accumulation may be described by power law functions characterizing process development at its extended stage. It allows for considering this process as self-similar. The *R*-parameter changes during irradiation from the threshold (R_{th}) to the maximum critical value (R_{max}), corresponding to the maximum swelling rate. Accordingly, the *R*-parameters suggested may be used to choose and compare materials resistant to the radiation damage.

Thus, the analysis conducted have shown that swelling process development at its extended stage and under different irradiation conditions may be considered as self-similar described by power law relations connecting the swelling rate to the *R*-parameter characterizing the governing factor and swelling itself:

$$dS/dD = AR^m \tag{6}$$

ANALYSIS OF SIZE DISTRIBUTION CURVES OF RADIATION DEFECTS

The dependencies of the cumulative number of radiation defects were used for analysis of defect distribution by their sizes, although literature data on defect accumulation are usually presented in coordinates: the current defect number versus defect size (Figure 3, a) [13].

The distribution curves in Figure 3 correspond to different irradiation doses. In Figure 3, b the cumulative size-frequency distributions of radiation defects in aluminium plotted using the data in Figure 3, a were presented. These curves were described by straight line pieces in log-log coordinates with angular coefficients b_1 and b_2 characterising the cumulative number of small, predominant and large radiation defects correspondingly. As can be seen from Figure 3, b, the defect distribution curves 1-5 are displaced with increasing irradiation doses to the side of larger defect sizes, but they remain similar to each other. Moreover, these curves coincide being normalised by the coordinates of the points corresponding to the end of horizontal curve section. It means that curves obtained at different doses are scale invariant, and damage accumulation process is a self-similar.

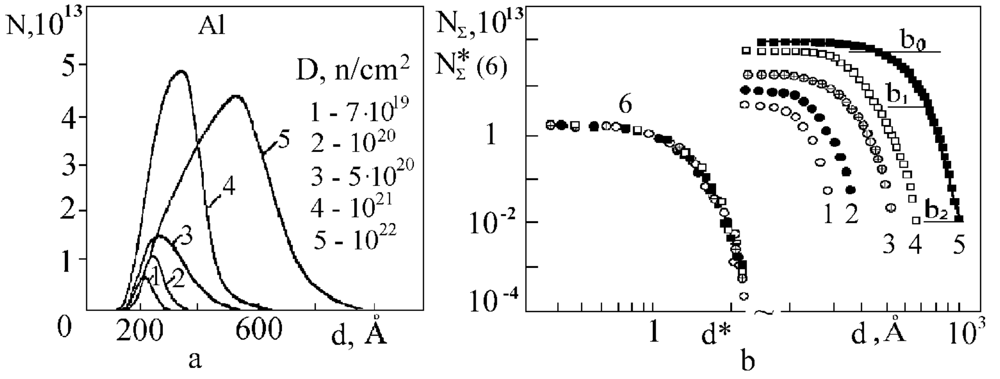

Figure 3: Initial size distribution of voids in aluminum irradiated by different neutron doses *D* [13] (a), curves of void cumulative number (1-5) and universal size distribution curve in normalized coordinates (6) (b).

At reaching the critical spacing between defects providing for possibility of their interaction, such a self-similar regime of defect development is completed and a stage of defect's coalescence starts. Dynamics of defect accumulation at this stage may be analysed on a evolution of gaseous bubbles into voids in alloy Al-Li irradiated by neutron flux and then annealed at temperatures 200-600°C [14].

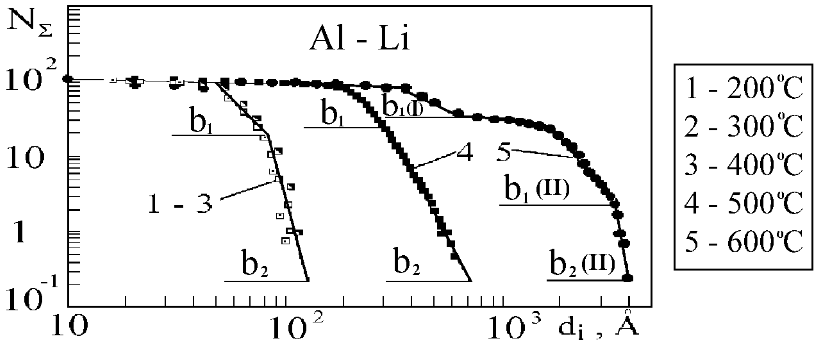

Figure 4: Damage accumulation curves for bubbles and voids in Al-Li alloy irradiated by neutron flux and annealed at different temperatures.

Annealing at 200-400°C almost does not change the average diameter, total volume and density of defects. The curves of defects accumulated at these temperatures (1-3 in Figure 4) practically coincide and are similar to the curves 1-5 in Figure 3, b. It means that accumulation and growth of gaseous bubbles in this alloy is self-similar. Sharp growth of the average diameter and total volume of bubbles and decrease in their density at 500°C testify on beginning of defect's coalescence. The angular coefficients (b_1, b_2) of damage accumulation curve (curve 4 in Figure 4) decrease at this temperature. At 600°C a step appears on the damage curve 5. Part of this curve following the step is similar by shape to the curves 1-3 and corresponds to a stable accumulation stage of defects of a new hierarchical level.

Thus, analysis of a development of radiation damage in different metals and alloys showed that damage process in these conditions includes two stages of stable and accelerated accumulation of defects, alternation of which leads to formation of a defects picture preceding to initiation of the main crack.

Results of analysis of the size distribution curves plotted using experimental data on creep and thermal fatigue allowed us to conclude that the above mentioned peculiarities of damage accumulation are probably common, inherent to many processes of multiple fractures occurring at different loading conditions [15]. Thus, the accumulation process of defects with sizes changing on 5 orders (from sizes of gaseous bubbles to those of thermal fatigue microcracks) manifests two stages at each hierarchical level. The first stage is characterized by a stable development of defect's system and described by the power law

$$N_{\Sigma} = Ad^{-b}$$

with the power exponent equal to 1.8 - 2.0 for materials and test conditions studied. The second stage is connected with defect coalescence and decrease in power exponent leading to formation of defects of the next level.

CONCLUSIONS

1. The analysis performed has shown that swelling process under different irradiation factors satisfies self-similarity conditions and is described by power-law relations connecting the swelling rate with the proposed radiation damage parameters.
2. It was found out that the size distribution of cumulative number of radiation defects may be described by the power-law relation with the power

exponent decreasing at the stage of defect coalescence. This relation is kept unchanged at various scale levels of defect evolution.

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