Prediction of the Neutron Irradiation Effect on the Creep-Rupture Properties on the Basis of Physical-and-Mechanical Modeling of Fracture Process

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Abstract

The present report represents the mechanism of austenitic steels failure under creep and neutron irradiation and the developed models for prediction of the creep-rupture strength and strain and for the crack growth rate for different levels of neutron flax and irradiation temperature.

Introduction

Structural components of fast neutron reactor with sodium coolant of BN type work under high neutron flux and high temperatures when the creep processes occur. Critical event for these components is determined by fracture caused by long-term cyclic and static loading under creep and irradiation.

For assessment of strength and lifetime of structural components of BN reactor the creep-rupture and fatigue properties have to be determined for various neutron flux and time duration of $(3\div5)\cdot10^5$ hours. Two problems arise when obtaining these properties. Firstly, the creep-rupture properties differ for material after and during irradiation, and the properties of post-irradiated materials do not provide conservative estimation. Secondly, direct in-reactor experimental data are restricted to time of $t \leq 10^4$ h. Available extrapolation methods (Larson-Miller, Sherby-Dorn, Manson-Haferd) cannot be used for predicting the creep-rupture properties for long-term service under irradiation. The reason is that these methods convert the lifetime t_f and temperature T into a single parameter, however, the lifetime t_f is affected not only by T and by neutron flux Φ. Moreover, when increasing T the influence of neutron irradiation decreases and, as a result, the same damage cannot be modelled for less time at higher temperature.

If technological defects or stress concentrators are revealed in structural component the lifetime for crack growth stage may be significantly larger than for crack initiation stage and, hence, the lifetime of structural component is mainly determined by crack growth stage. It means that the crack growth rate has to be predicted for austenitic steels under creep and irradiation. Approach recommended in RCC-M Standard for description of the crack growth rate as a function of C*-integral may be used but has to be modified to take into account the properties of material under irradiation.

For assessment of the lifetime of structural components of BN reactor the lifetime has to be also predicted under cyclic loading that is accompanied by creep and neutron irradiation.

Intercrystalline Fracture Model: Development and Application

At long-term loading under creep, fracture usually happens on intercrystalline mode (Fig. 1). Therefore for long-term prediction of the above properties for austenitic steels, a physical-and mechanical model of intercrystalline fracture has been developed [1, 2].

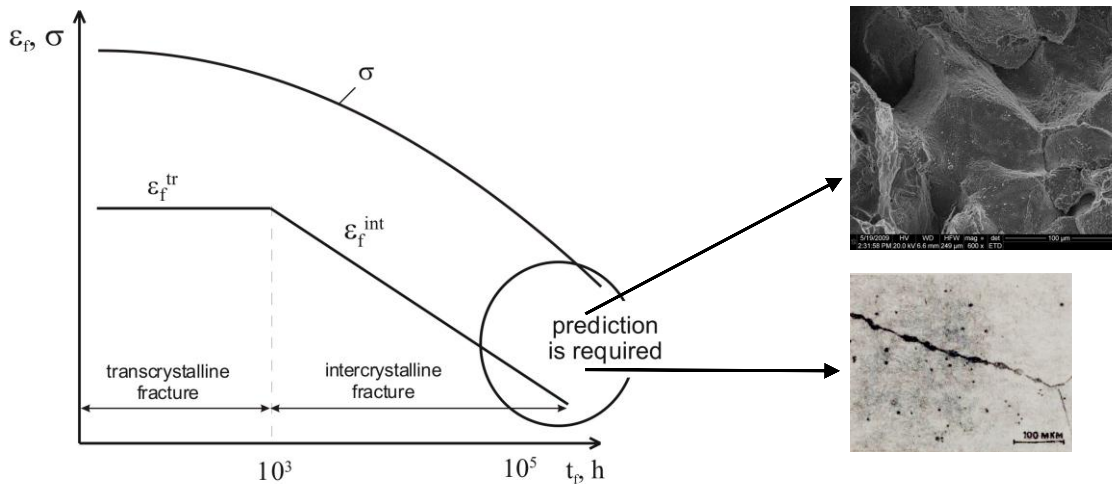

Fig. 1. The creep-rupture properties and fracture mode for austenitic materials

In this model the polycrystalline material is considered as conglomerate of unit cells, containing grain boundary with voids (Fig. 2). The model is based on the plastic collapse criterion of a unit cell and includes the equations for nucleation and growth of voids on a grain boundary caused by creep strain and vacancy diffusion allowing for the effect of neutron flux and fluence.

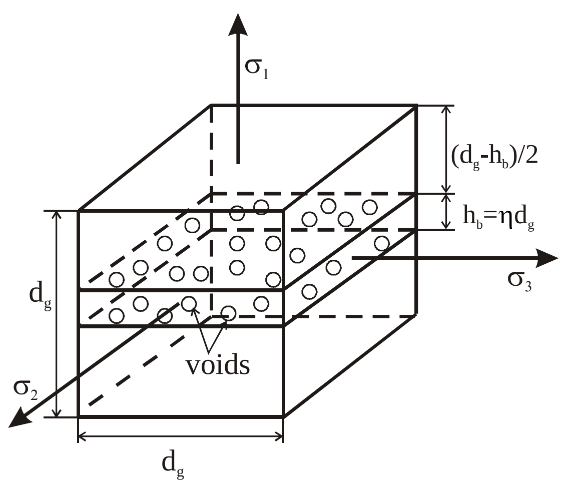

Fig. 2. A unit cell for the analysis of void growth on grain boundaries: d_g is grain size.

The effect of neutron irradiation on the creep-rupture properties may be illustrated with scheme shown in Fig. 3. It is seen that neutron irradiation accelerates integranular void evolution and decreases the creep-rupture properties by two mechanisms. As neutron dose increases (measured by displacement per atom or neutron fluence) a fraction of intercrystalline sliding in material deformation increases also and, hence, the intercrystalline void nucleation rate increases. Irradiation accelerates diffusion processes in a material that results in increasing the creep rate and void growth rate on vacancy mechanism. As s result, the void nucleation rate on grain boundary accelerates, and hence, the creep-rupture stress and strain decrease.

As followed from Fig. 3, the post-irradiated creep-rupture properties (the neutron flux Φ=0) are higher than properties obtained in-reactor tests when $\Phi \neq 0$ as for Φ=0 the void growth rate and creep rate do not increase as compared with unirradiated material.

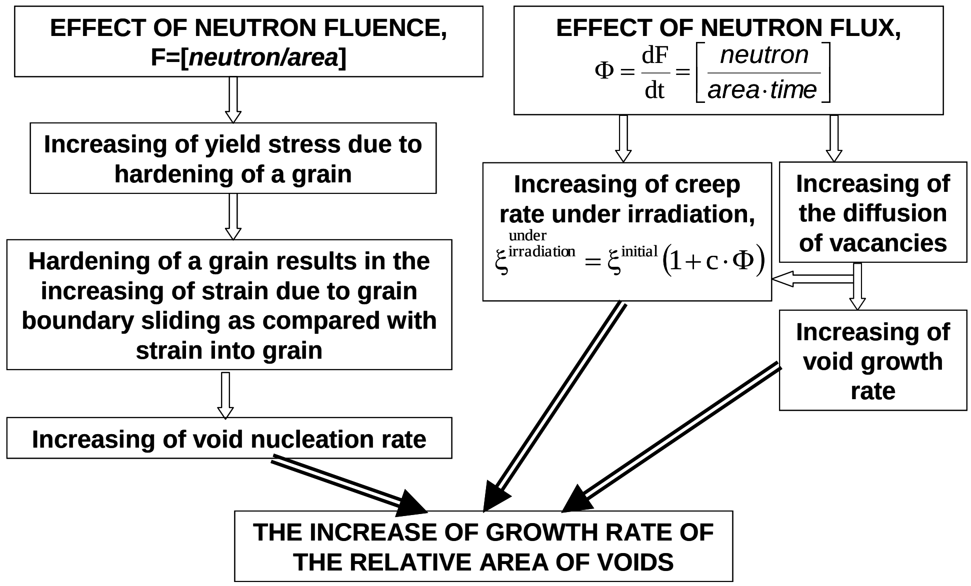

Fig. 3. Acceleration of integranular void evolution under creep due to neutron irradiation (scheme).

The intercrystalline fracture model [1 - 3] has been verified for unirradiated austenitic steels and for steels tested in reactor. Some examples are shown in Fig. 4 and 5.

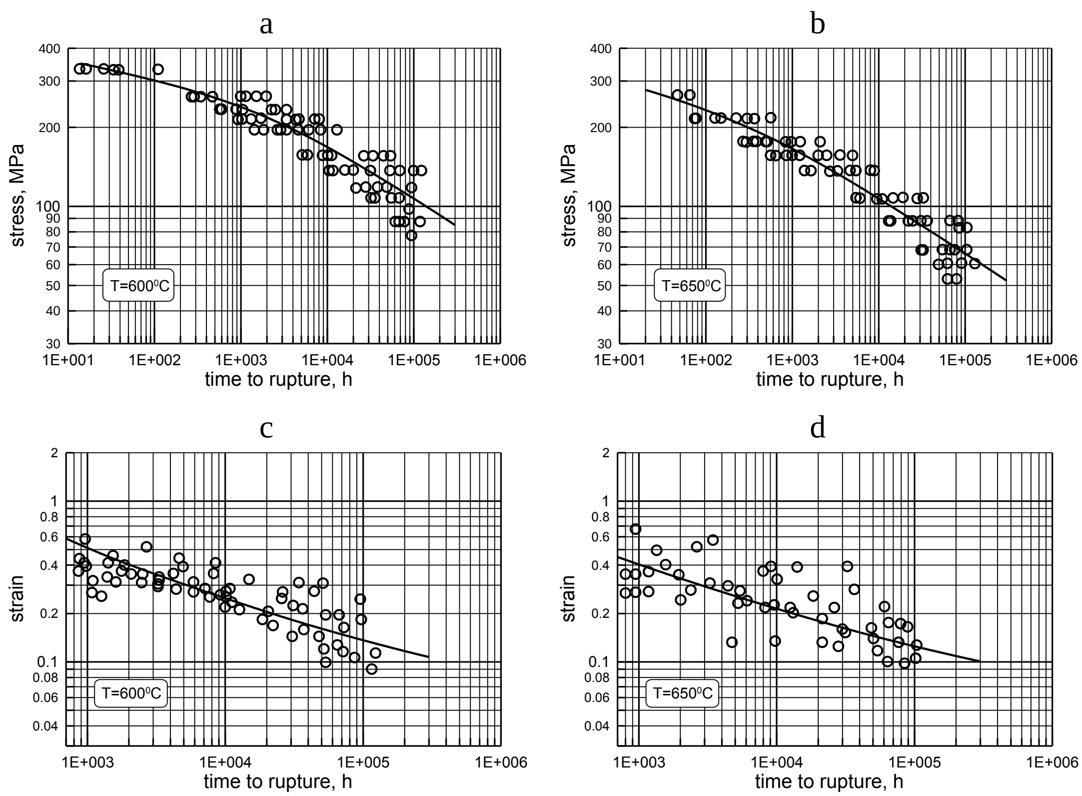

Fig. 4. The creep-rupture stress (a, b) and strain (c, d) for 18Cr-10Ni-Ti steel at T=600^{o}C (a, c) and T=650^{o}C (b, d): (——) – calculation by the model; (○) – experimental data.

In Fig. 4 the creep-rupture properties are represented for 18Cr-10Ni-Ti steel in initial conditions tested at different temperatures. It should be noted that for calibration of the model parameters the data are only used as obtained for time t $\leq 10^3$ hours at T=600°C. In Fig. 5 the creep-rupture properties are shown for 18Cr-10Ni-Ti and 18Cr-9Ni steels in unirradiated condition and for in-pile tests. As seen, the predicted curves are in good agreement with the test results.

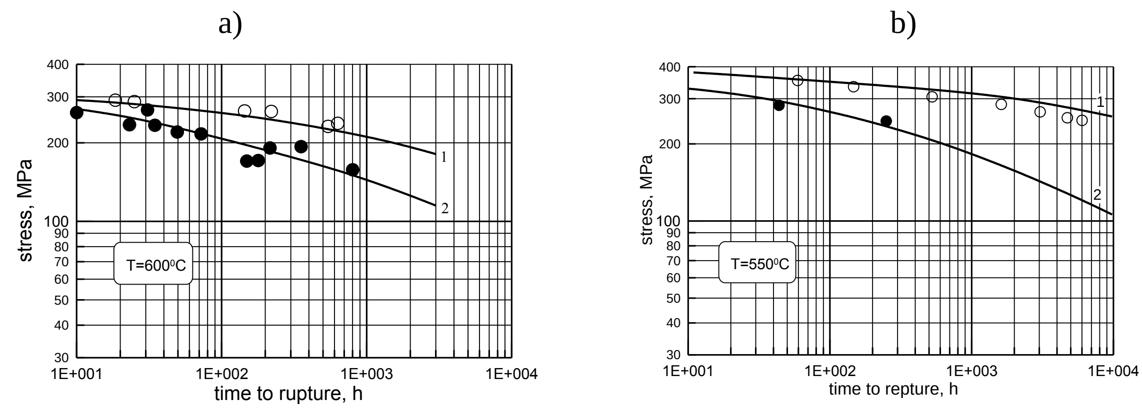

Fig. 5. Comparison of the calculated curves on creep-rupture stress with experimental data at T=600°C for 18Cr-10Ni-Ti steel (a) and 18Cr-9Ni (b) steel [4]: curves 1 and 2 – calculation by the model; O, ● - experimental data for material in initial condition and for in-pile tests ($\Phi=1\cdot10^{13}$ n/cm^{2}s (E>0.1 MeV)).

The dependences of creep-rupture strength for 18Cr-10Ni-Ti steel were calculated for different values of neutron fluxes Φ that varied over a range between $7\cdot10^{10}$ and $7\cdot10^{13}$ n/cm$^2\cdot$s (E>0.1 MeV). The data given in [1, 3] were used in the calculations. For verification let us represent the calculated creep-rupture strength in the form of isochronic curves σ(Φ) (Fig. 6).

It is seen from Fig. 6 that for $\Phi < 7\cdot10^{11}$ n/cm^{2}s irradiation has an insignificant effect on creep-rupture strength (the reduction of creep-rupture strength does not exceed 10%). This prediction is adequately confirmed by the experimental results given in [5, 6].

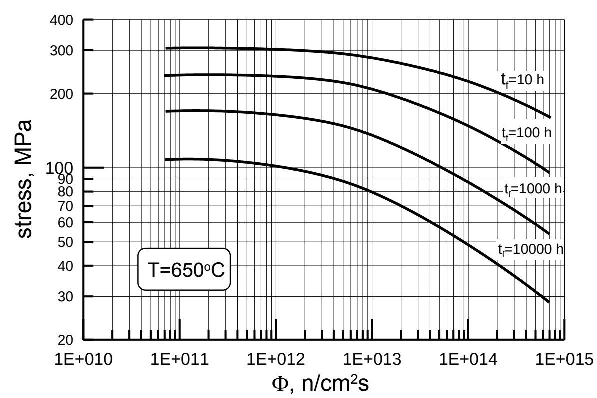

Fig. 6. The dependence of creep-rupture stress on neutron flux at T=650°C for different times to rupture.

The dependences of creep-rupture strength were also calculated for 18Cr-9Ni steel with different values of neutron fluxes Φ that varied over a range between $2\cdot10^{12}$ and $1\cdot10^{14}$ n/cm$^2\cdot$s (E>0.1 MeV). These dependences are presented in Fig. 7. From this figure it is seen strong influence of flux level on creep-rupture strength.

Thus, these examples show that the developed model allows the adequate prediction of the creep-rupture properties for various temperatures and neutron fluxes.

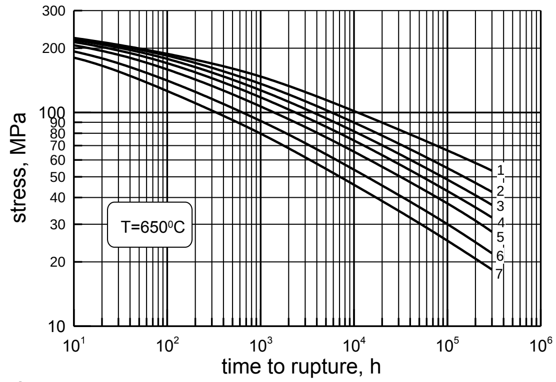

Fig. 7. The dependence of creep-rupture strength on time to rupture at T=650^{o}C for different neutron flux levels: 1 – initial condition; 2 – $\Phi=2\cdot10^{12}$ n/cm^{2}s; 3 – $\Phi=5\cdot10^{12}$ n/cm^{2}s; 4 – $\Phi=1\cdot10^{13}$ n/cm^{2}s; 5 – $\Phi=2\cdot10^{13}$ n/cm^{2}s; 6 – $\Phi=5\cdot10^{13}$ n/cm^{2}s; 7 – $\Phi=1\cdot10^{14}$ n/cm^{2}s (E>0.1 MeV).

Crack Growth Rate under Creep and Irradiation

The developed model allows also the prediction of material properties for various triaxial stress state that provides a possibility to use the model for prediction of the crack growth rate under creep and irradiation. The proposed procedure [7] is the following. Crack growth is schematized as consecutive fracture of unit cell near the crack tip. Then the crack growth rate $da/d\tau$ may be calculated by formula

$$\frac{da}{d\tau} = \frac{d\rho}{\tau_f^{uc}}, \tag{1}$$

where ρ_{uc} is unit cell size, τ_f^{uc} is rupture time for unit cell.

Then the coefficient of acceleration of crack growth rate ω may be calculated by formula

$$\omega \equiv \frac{\left(da/d\tau\right)^{irr}}{\left(da/d\tau\right)^{initial}} = \frac{\left(\tau_f^{uc}\right)^{initial}}{\left(\tau_f^{uc}\right)^{irr}}, \tag{2}$$

where the superscripts “initial” and “irr” are related to material tested in initial condition and tested under irradiation.

The parameter ω is calculated according to the scheme shown in Fig. 8.

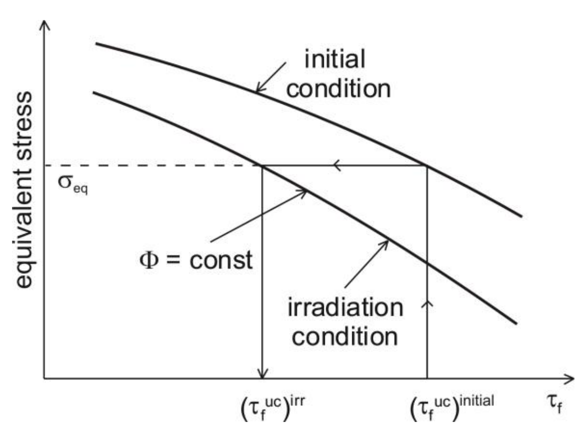

Fig. 8. Scheme for calculation of the crack growth rate under creep and neutron irradiation.

Creep-rupture strength for unit cell near the crack tip is calculated for stress-and-strain fields near the crack tip under creep with the intercrystalline fracture model [1, 2].

For unirradiated material the crack growth rate under creep is calculated according to [8] as

$$\left(\frac{da}{d\tau}\right)^{\text{initial}} = A_r\left(C^*\right)^{n_r}, \tag{3}$$

where A_r and n_r are material constants; C^* is so-called C^* - integral.

Then from (2) and (3) we have

$$\left(\frac{da}{d\tau}\right)^{\text{irr}} = \omega \cdot A_r\left(C^*\right)^{n_r}. \tag{4}$$

At common case the parameter ω depends on $\left(\frac{da}{d\tau}\right)^{\text{initial}}$ and neutron fluence F and flux Φ. Indeed, loading and irradiation of a material near the initial crack tip (shaded area 1 in Fig. 9) occur simultaneously. At the same time irradiation of a material in shaded area 2 occurs all time during crack growth from position 1 to 2 so that when the crack tip reaches position 2, simultaneous loading and irradiation near its tip occur for preliminary irradiated material (see Fig. 9).

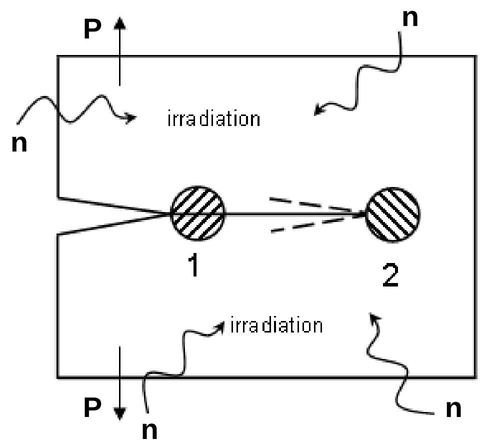

Fig. 9. The effect of neutron flux and neutron fluence on crack growth rate under creep.

Calculations performed by the model shows [7] that the curves describing creep-rupture strength of unit cell for initial condition and under irradiation are practically parallel. Hence, it is possible to assume that ω doe not depend on $\left(\frac{da}{d\tau}\right)^{\text{initial}}$. In [7] it has been shown that the parameter ω may be written as

$$\omega = \omega_1(\Phi) \cdot \omega_2(F) \tag{5}$$

The dependencies $\omega_1(\Phi)$ and $\omega_2(F)$ calculated with the model [1, 7] are shown in Fig. 10.

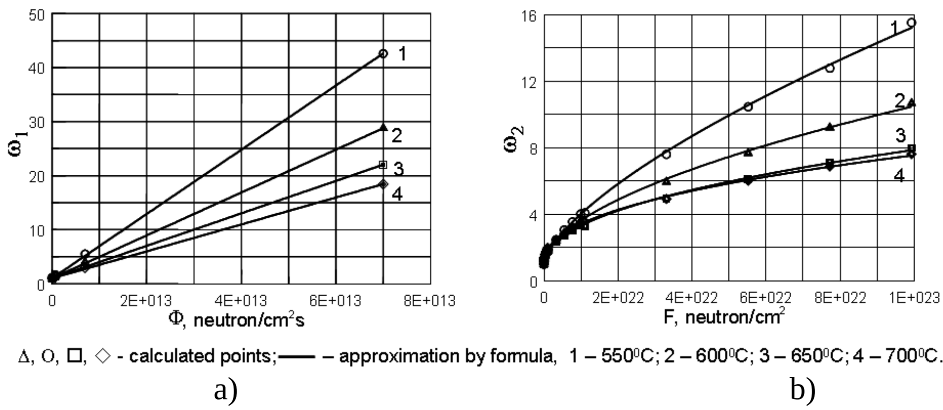

Fig. 10. The dependences of the parameter ω_1 on neutron flux (a) and the parameter ω_2 on neutron fluence (b) at various temperatures.

Lifetime Prediction under Cyclic Loading, Irradiation and Creep

The above procedure for prediction of the creep-rupture properties and the crack growth rate under creep is used for static loading. In this section a procedure is proposed for prediction of lifetime under cyclic loading. This procedure is based on the following considerations.

1) The Coffin-Manson equation is used in the form [9]

$$\Delta\varepsilon = \varepsilon_f (4N_f)^{-m} + \frac{2\sigma_{cr}}{E(4N_f)^{m_e}}, \tag{6}$$

where σ_{cr} is true fracture stress under creep; ε_f is fracture strain under creep, N_f is the number of cycles to failure; m and m_e are material constant.

2) The parameters σ_{cr} and ε_f depend on the strain rate ξ in loading cycle as well as on F, Φ and T [10]. The dependencies $\sigma_{cr}(\xi)$ and $\varepsilon_f(\xi)$ for given values of F, Φ and T may be determined from the creep–rupture properties according to the scheme shown in Fig. 11.

3) The creep-rupture properties for different values of F, Φ and T may be calculated by the model [1, 2].

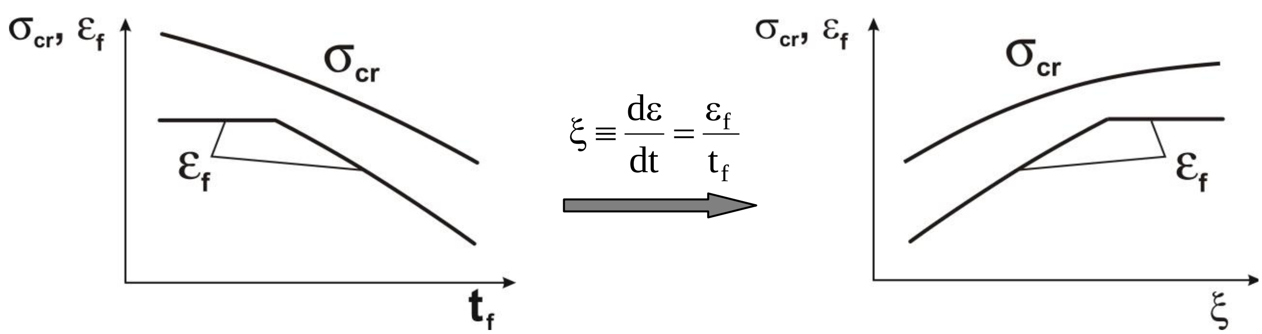

Fig. 11. Scheme for determination of $\sigma_{cr}(\xi)$ and $\varepsilon_f(\xi)$ on the basis of creep-rupture properties.

Comparison of the calculated curves with test results is shown in Fig. 12 for 18Cr-9Ni steel [10, 11]. As seen, the proposed procedure allows the adequate assessment the lifetime N_f for loading with various holds that result in various strain rates in cycle.

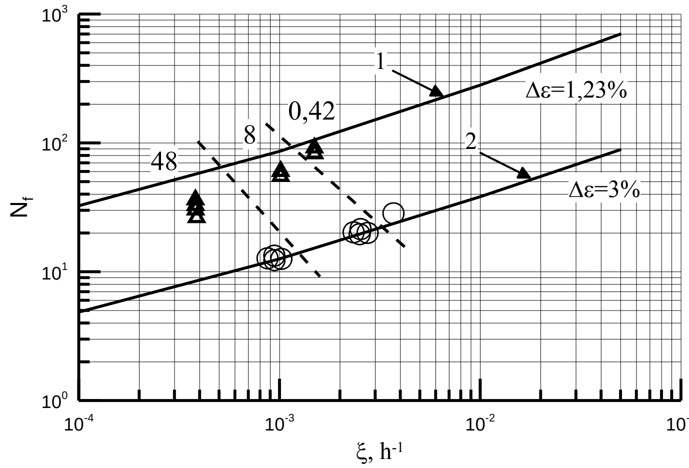

Fig. 12. The calculated curves 1 and 2 and test results (dots) for thermal-cyclic loading with hold at maximum temperature in cycle for the strain ranges $\Delta\varepsilon$=1.23 % and ε=3 %: Δ, O – tests for $\Delta\varepsilon$=3 % and $\Delta\varepsilon$=1.23 % respectively and different hold times in hours as shown near the dots; the dashed line separates the test results for different hold times [11].

Concluding Remark

The calculated results obtained with the intercrystalline fracture model, the methods proposed for prediction of mechanical properties and the formulated criteria of limit states for BN reactor components are a basis for new Russian Standard for calculation of strength and lifetime for BN reactor components: RD EO 1.1.2.09.0714-2011 “Method for structural integrity assessment of fast neutron reactor components with sodium coolant”.

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