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Micromechanical analysis of the effect of void swelling on elastic and electric properties of irradiated steel

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ABSTRACT

The paper focuses on changes in mechanical and electrical properties of austenitic steel due to radiation swelling. Various micromechanical models for the electrical conductivity and elastic moduli are assessed based on the experimental data available in literature. We show that, in the considered case, the effective field method provides the best prediction for both elastic and conductive properties. Comparing the two sets of experimental data, the cross-property connections that relate changes in the elastic and electrical conductivity of a material due to radiation swelling has been verified. It is shown that analytical cross-property connection is in a good agreement with experimental data and can be used to estimate changes in electrical resistivity of a material from the changes in Young's modulus or vice versa.

1. Introduction

Prediction of material behavior of structural elements of nuclear reactors is a critical task for both nuclear safety and increase of the structural elements service life. The present paper focuses on micromechanical modeling of changes in the elastic and conductive properties of austenitic steel due to radiation swelling. For this goal, we use the concept of the quantitative characterization and express radiation-induced changes in microstructure with changes in elastic and electric properties. We also show that the cross-property connections that relate the mentioned properties' changes are in a good agreement with experimental data available in literature.

Formation and evolution of radiation defects attracted attention of the researchers from the beginning of 1950s. The swelling due to irradiation found in stainless steels was first reported by Fulton and Cawthorne [1]. A further discussion, primarily focused on impact of radiation induced swelling on fast reactor cores, was given by Shewmon [2], and electrical resistivity R and showed that the primary change in these properties is due to the void swelling that occurs during irradiation. The following phenomenological dependences have been obtained by matching the experimental data:

It is related to the overall porosity p as

Shcherbakov et al. [3] measured electrical resistivity and elastic moduli of specimens obtained from the BN-600 reactor and discussed the changes in the said properties. The observed changes, however, were negligible in this case, staying within experimental error. Neustroev and Garner [4] discussed the shortening of service life of the structural elements made of austenitic steel due to the high void swelling that occurs during irradiation. The effects of swelling on mechanical properties are seen in an initial hardening followed by a decrease in the elastic modulus. These effects accompanied by formation and growth of internal cracks lead ultimately to a shortened service life for the steel.

Effect of irradiation on elastic and electric properties of austenitic steel has been studied by Balachov et al. [5]. They measured effective Young's modulus E, shear modulus G Sagisaka et al. [6] discussed the problems related to measurement of the electrical resistivity of small specimens. The problem appears due to the heat generation created during the standard measurement methods. To avoid this difficulty, they proposed to use Eddy-current method instead of four-point method. As a result, working on the same specimens as Balachov et al. [5], they obtained different matching relation between relative resistivity changes and swelling parameter (1.1):

$$\frac{R - R_0}{R_0} = \frac{3S}{2} \tag{1.1}$$

Below, we show that results of Sagisaka et al. [6] are in agreement with exact micromechanical estimates (like Hashin–Shtrikman bounds) while the data of Balachov et al. [5] noticeably violate the bounds.

Generally, as pointed out by Kozlov [7], the present level of knowledge in the area of quantitative characterization of microstructural changes associated with accumulation of the radiation damage is insufficient to accurately predict the behavior of materials especially in the case of variable external conditions. The existing models of influence of radiation defects on physical and mechanical properties of materials in most cases have either a qualitative character or represent empirical relations valid for a

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narrow range of the service conditions that cannot be extrapolated. In the present paper we use micromechanical approach to the problem. Analysis of the effect of radiation induced void swelling on the elastic and conductive properties of metals is based on the concept of property contribution tensors [8]. We compare several micromechanical schemes with experimental data of Sagisaka et al. [6]. and Balachov et al. [5] and explore the possibility to use cross-property connections [9–11] to link the changes observed in elastic and electric properties of metals subjected to radiation damage.

2. Quantitative characterization of microstructure and property contribution tensors

The quantitative characterization of a microstructure means identification of the *microstructural parameters* in whose terms the physical property of interest is to be expressed. Such parameters are generally different for different physical properties [8]. The main requirement to the proper microstructural parameters is that they must represent individual inhomogeneities in accordance with the inhomogeneities' contributions to the physical property considered. Otherwise, the property cannot be uniquely expressed in their terms.

Strictly speaking, the individual inhomogeneity contributions to the overall property are affected by *interactions* between them and interactions should be incorporated into the proper microstructural parameter, since they affect compliance contributions of individual inhomogeneities. Such a parameter would depend on mutual positions of inhomogeneities in the way that is relevant for the interaction mechanics. The effective property would then be a linear function of such a parameter (as implied by summation of the individual compliance contributions).

However, incorporating interactions into the micromechanical parameter amounts to solving the interaction problem, and hence is not attempted: contributions of individual inhomogeneities are taken by treating them as *isolated, non-interacting* ones (in particular, the parameters do not reflect mutual positions of inhomogeneities). In various approximate schemes (self-consistent, differential, etc.) the effect of interactions is addressed through a non-linear dependence of the effective property on the parameter. Since the latter is defined in the non-interaction approximation (NIA), this approach is not perfectly logical; however, there is no simple alternative.

In the context of the effective elastic properties of heterogeneous materials, property contribution tensor has been first proposed by Kachanov et al. [12] for a porous material. For general composites, these tensors were introduced and calculated for a number of shapes by Sevostianov and Kachanov [13,9]

We consider a homogeneous isotropic linear elastic material (matrix), with the compliance tensor $\boldsymbol{S}^0$. It contains an inhomogeneity, of volume V^*, of a different material with the compliance $\boldsymbol{S}^1$. The contribution of the inhomogeneity to the overall strain, per representative volume V (the extra strain, as compared to the homogeneous matrix) is given by the fourth-rank tensor $\boldsymbol{H}$ – the compliance contribution tensor of the inhomogeneity – defined by

$$\Delta\varepsilon = (V^*/V)\boldsymbol{H} : \boldsymbol{\sigma}^0 \tag{2.1}$$

where $\boldsymbol{\sigma}^0$ represents the homogeneous boundary conditions [14,15], i.e. tractions on ∂V have the form $\boldsymbol{t}|_{\partial V} = \boldsymbol{\sigma}^0 \cdot \mathbf{n}$ where $\boldsymbol{\sigma}^0$ is a constant tensor; $\boldsymbol{\sigma}^0$ can be viewed as a far-field, or remotely applied, stress.

In the case of multiple inhomogeneities, $\Delta\varepsilon^{(k)} = \boldsymbol{H}^{(k)}{:}\boldsymbol{\sigma}^0$ for each one and the extra compliance is given by

$$\Delta\boldsymbol{S} = \frac{1}{V}\sum V^{(k)}\boldsymbol{H}^{(k)} : \boldsymbol{\sigma}^0 \tag{2.2}$$

The compliance contribution tensor is determined by the shape of the inhomogeneity, as well as properties of the matrix and of the inhomogeneity material. Formula (2.2) highlights the fundamental importance of this tensor as the one that has to be summed up (averaged), in the context of the effective elastic properties. The sum

$$\sum \boldsymbol{H}^{(k)} \tag{2.3}$$

properly reflects compliance contributions of individual inhomogeneities and constitutes the *general microstructural parameters* in whose terms the effective compliance should be expressed.

For a general ellipsoid, components H_{ijkl} are expressed in terms of elliptic integrals. The $\boldsymbol{H}$ – tensor of a *spheroidal pore* (x_3 is the axis of symmetry) is expressed in terms of elementary functions and has the following components [13]

$$G_0(H_{1111}+H_{1122}) = \frac{\kappa(f_0-f_1)}{(4\kappa-1)\left[2\kappa(f_0-f_1)-(4\kappa-1)f_0^2\right]};$$

$$G_0(H_{1111}-H_{1122}) = \frac{1}{2[1-2f_0+\kappa(f_0-f_1)]};$$

$$G_0H_{1133} = \frac{-(2\kappa(f_0+f_1)-f_0)}{4(4\kappa-1)[2\kappa(f_0-f_1)-(4\kappa-1)f_0^2]};$$

$$G_0H_{1313} = \frac{1}{4[f_0+4\kappa f_1]};$$

$$G_0H_{3333} = \frac{4\kappa-1-6\kappa f_0+2f_0-2\kappa f_1}{4(4\kappa-1)\left[2\kappa(f_0-f_1)-(4\kappa-1)f_0^2\right]} \tag{2.4}$$

where G_0 and ν_0 is shear modulus and Poisson's ratio of the virgin material,

$$\kappa = \frac{1}{2(1-\nu_0)}, \quad f_1 = \frac{\gamma^2}{4(\gamma^2-1)^2}[(2\gamma^2+1)g-3] \tag{2.5}$$

and the shape factor g is expressed in terms of the aspect ratio γ as follows

$$g(\gamma) = \begin{cases} \frac{1}{\gamma\sqrt{1-\gamma^2}}\arctan\frac{\sqrt{1-\gamma^2}}{\gamma}, & \text{oblate shape } (\gamma<1) \\ \frac{1}{2\gamma\sqrt{\gamma^2-1}}\ln\frac{\gamma+\sqrt{\gamma^2-1}}{\gamma-\sqrt{\gamma^2-1}}, & \text{prolate shape } (\gamma>1) \end{cases} \tag{2.6}$$

For a spherical void [17]

$$H_{ijkl} = \frac{3(1-\nu_0)}{2(7-5\nu_0)E_0}[5(1+\nu_0)(\delta_{ik}\delta_{jl}+\delta_{il}\delta_{jk})-(1+5\nu_0)\delta_{ij}\delta_{kl}] \tag{2.7}$$

(δ_{ij} is the Kronecker delta)

In the context of electric conductivity, we consider a reference volume V of an infinite three-dimensional solid (with the isotropic electrical conductivity k_0) containing a pore (insulating inhomogeneity). Assuming a linear conduction law (linear relation between the gradient of electric field $\boldsymbol{E}$ and remotely applied electric current density $\boldsymbol{J}^0$), the resistivity contribution tensor of an inhomogeneity $\boldsymbol{H}^R$ is defined by the following relation [14]:

$$\boldsymbol{E} = \frac{1}{k_0}\boldsymbol{J}^0 + \Delta\boldsymbol{E} = \frac{1}{k_0}\boldsymbol{J}^0 + \frac{V^*}{V_0}\boldsymbol{H}^R\cdot\boldsymbol{J}^0 \tag{2.8}$$

Similarly to the elastic properties, in the case of multiple inhomogeneities

$$\Delta\boldsymbol{E} = \frac{1}{V}\sum V^{(k)}\boldsymbol{H}^{R(k)}\cdot\boldsymbol{J}^0 \tag{2.9}$$

For a spheroidal pore of aspect ratio γ,