MULTISCALE MODEL OF HARDENING IN METASTABLE MATERIALS WITH RADIATION INDUCED POROSITY

B. Skoczeń

Institute of Applied Mechanics, Cracow University of Technology, Poland
e-mail: blazej.skoczen@pk.edu.pl

1. Introduction

Metastable materials, like stainless steels, are massively used in the construction of scientific instruments, operating at extremely low temperatures (e.g. superconducting particle accelerators). The components operating in the proximity of a source of primary or secondary particles are subjected to irradiation that induces an enhanced level of porosity, accompanied by the presence of inclusions of secondary phase resulting from the plastic strain induced phase transformation [1]. Therefore, the primary phase (austenitic matrix) contains two types of microstructural imperfections: the porosity in the form of clusters of micro-voids, and the inclusions of secondary phase. Both of them strongly affect hardening, in particular due to the Orowan mechanism of interaction between the dislocations and the lattice defects (voids, cavities, interstitials, inclusions, etc.). On the other hand, the presence of porosity affects the stiffness of two-phase continuum, leading to the material softening. Both mechanisms, hardening and softening, are contradictory and their multiscale description is essential for correct prediction of the behaviour and the lifetime of components operating at very low temperatures.

2. Irradiation induced porosity and softening

Exposure to irradiation (flux of particles) leads to creation of clusters of defects in the material [2]. The so-called atomic displacement damage process correlates with the evolution of porosity. Energy brought by the incident particles is dissipated mainly by the elastic collisions with the lattice atoms. These nuclear interactions lead to creation of atoms moving inside the lattice, and to the production of defects (interstitials and vacancies). The vacancies form clusters and grow into the so-called cavities, often filled with helium at high pressure. It is shown that the actual pressure is function of the overall strain, that leads to the evolution of size of the clusters according to the Rice-Tracey kinetics. The increase of porosity is expressed by the following formula:

$$\Delta\xi_p = \xi_{p0}\left(e^{3C\Delta p} - 1\right)$$

where ξ_{p0} is the initial porosity, C is function of triaxiality, and Δp denotes accumulated plastic strain. The pressurized cavities form spaces subjected to internal pressure and characterized by specific value of surface energy. The cavities form Eshelby type ellipsoidal entities that reduce the tangent stiffness of the matrix. As the porosity evolves with plastic strain, the resultant tangent stiffness is function of the increase in porosity.

3. Plastic strain induced fcc-bcc phase transformation

Plastic flow in the metastable alloys (e.g. stainless steels) is usually accompanied by dynamic evolution of the microstructure, resulting from the phase transformation. In the course of plastic strain induced phase transformation, that occurs in the LSFE materials at extremely low temperatures, the γ-austenite (fcc microstructure) is transformed into α’-martensite (bcc microstructure). The martensite platelets (lenticular martensite), embedded in the austenitic matrix, affect the surrounding fcc lattice and induce local distortions. Therefore, the plastic strain induced fcc-bcc phase transformation results in significant evolution of the material properties, and strong nonlinear hardening. The classical sigmoidal curve, representing the volume fraction of secondary phase, is essentially valid for wide range of temperatures. However, at extremely low temperatures the phase transformation rate is less temperature dependent, and a simplified linearized kinetics can be applied:

$$\dot{\xi}_t = A(T, \underline{\underline{\sigma}})\, \dot{p} H\big((p - p_\xi)(\xi_{tL} - \xi_t)\big)$$

where ξ_t denotes volume fraction of secondary phase, and H is the Heaviside function.

4. RVE based multiscale model of irradiated metastable continuum

Formulation of the constitutive model of elastic-plastic continuum subjected to the plastic strain induced phase transformation in the presence of radiation induced porosity is based on multiscale approach. In particular, it takes into account the micromechanical phenomena such as the interactions of dislocations with the inclusions and the pressurized cavities (micro-level), or the influence of hard inclusions and "soft" cavities on the resultant tangent stiffness of two-phase continuum (meso-level). The model is defined on the mesoscopic level by means of the representative volume element (RVE), size of which should be large enough to contain representation of all microstructural phenomena (lattice defects and inhomogeneity), but small enough to justify the local approach. The final constitutive model, defined at the macroscopic level, comprises the model of mixed plastic hardening consisting of the kinematic hardening component, represented by the position of the centre of yield surface expressed by the second rank tensor $\underline{\underline{X}}$, and the isotropic hardening component, described by a scalar parameter R. The proportion between them is defined by the appropriate value of the Bauschinger parameter.

5. Hardening due to the evolution of secondary phase

When crossing a pair of inclusions or pressurized cavities of the average size d, much smaller than the average distance between them ($d<<l$), a dislocation driven by the enhanced shear stress leaves around each inclusion or cavity a closed loop (the Orowan mechanism). This mechanism, described by means of the micromechanical analysis, leads to substantial increase of hardening parameter. Moreover, the evolution of material micro-structure induces strain hardening related to the increase of the equivalent tangent stiffness as a result of evolving proportions between both phases, each characterised by different stiffness. The corresponding hardening model is based on the Hill concept (1965), supplemented by the Mori-Tanaka (1973) homogenisation algorithm. As soon as the phase transformation threshold is reached, combination of both the above described effects results in nonlinear hardening, that is only to some extent compensated by the softening related to the presence of pressurized cavities [3].

6. Closed form analytical solutions

The above presented new model takes into account two contradictory phenomena in metastable alloys: softening due to the presence of radiation induced porosity, and hardening due to the phase transformation. The model contains relatively small number of parameters and is suitable for the temperatures ranging from absolute zero to the room temperature. New closed form analytical solutions were obtained for the uniaxial cases, and the results were cross-checked directly with the available experiments.

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References

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