Constitutive modelling of strain induced coupled phenomena in engineering materials applied at cryogenic temperatures

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Abstract

Design of modern scientific instruments (particle accelerators and detectors, superconducting magnets, NMR spectrometers, etc.) based on the principle of superconductivity generates ever increasing interest in development and mathematical description of materials suitable for extremely low temperatures. Many metals and alloys used in cryogenic applications undergo at low temperatures three coupled dissipative phenomena: discontinuous plastic flow (DPF), plastic strain induced phase transformation as well as evolution of micro-damage, including radiation induced damage.

Keywords: metastable materials, cryogenic applications, discontinuous plastic flow, radiation induced damage

1. Near 0K coupled dissipative phenomena

DPF (serrated yielding) is characteristic of low (LSFE) and high stacking fault energy (HSFE) materials strained at extremely low temperatures. It represents oscillatory mode of plastic deformation and reflects discontinuous nature of plastic flow (discontinuous in terms of d?/d?). Low temperature serrated yielding occurs below threshold temperature: T1 for LSFE materials and T0 for HSFE materials. Each threshold represents transition from screw to edge dislocations [1]. From the phenomenological point of view, serrated yielding consists in frequent abrupt drops of stress as a function of strain during kinematically controlled loading. There is enough experimental evidence to back the hypothesis that the mechanism of DPF is related to formation of dislocation pile-ups at the internal lattice barriers, such as the Lomer-Cottrell locks [2]. The microscopic analysis clearly shows that the back stresses of dislocation pile-ups substantially hinder motion of other dislocations. Accumulation of dislocations in the pile-up leads to gradual increase of the resolved shear stress at the head of pile-up, until the stress reaches the level of cohesive strength. As soon as the internal lattice barriers break, liberated glissile dislocations can freely glide away. Collective and massive character of this phenomenon leads to sudden drop of stress and heat production as a result of plastic power dissipation. The plastic deformation takes place locally, within deformation bands, often termed slip bands. General thermo-mechanical aspects of DPF are strictly linked to the so-called thermodynamic instability, which consists in strong oscillations of temperature due to heat accumulation in near adiabatic conditions, resulting from vanishing specific heat when the temperature approaches absolute zero. Another important phenomenon that occurs in metastable materials at extremely low temperatures is the phase transformation. It consists in the alteration of distance between neighbouring atoms and manifests itself as a change of crystallographic structure from face-centred-cubic parent phase to body-centred-cubic secondary phase. The strain-induced martensitic transformation is related to the TRIP (transformation-induced plasticity) effect, resulting in the uniform, unrecoverable, macroscopic strain, which occurs in the high-strength metastable austenitic steels. Finally, third important phenomenon is related to evolution of radiation induced damage fields accompanied by nucleation and evolution of mechanical damage. During irradiation, energetic particles penetrating lattice displace the atoms from their original positions. Exposure to a flux of particles leads inevitably to creation of clusters of defects in the material, provided that the energy of incident particles is large enough. As a result of cascade process, pairs of interstitial atoms and vacancies (the Frenkel pairs) are massively created. The vacancies, making part of the Frenkel pairs, often accumulate in clusters by means of diffusion. Each cluster may be qualified as a spherical or ellipsoidal void of the size of several nanometers. The nature of mechanically induced micro-damage, comprising micro-voids and micro-cracks, is different from the nature of irradiation induced micro-damage, comprising clusters of micro-voids resulting from interactions of particles with lattice atoms. All three phenomena discussed above are strongly coupled to each other.

2. Experimental evidence

The available studies of dynamics of plastic flow oscillations at extremely low temperatures are by far insufficient from the experimental point of view. For this reason, experimental identification of the strain localization phenomenon during discontinuous plastic flow in the near-0K regime has been carried out. It reveals an interesting feature of the plastic flow discontinuities consisting in strong localization in the form of slip bands travelling across the gauge length of the sample. Another interesting feature consists in coupling of plastic flow discontinuities with the phase transformation process, which makes the nucleation of slip bands and their free glide randomly redistributed over the gauge length of the sample. Specific tests were aimed at understanding the behaviour of austenite/martensite two-phase composite, obtained by plastic straining at cryogenic temperatures of the samples made of metastable materials.

3. Physically based multiscale constitutive model

Multiscale constitutive model of DPF [3] involves microscopic approach based on the analysis of evolution of dislocations density and formation of dislocation pile-ups at the lattice barriers. Moreover, average resolved shear stress in the lattice and average shear stress at the head of dislocation pile-up are included. The process of drop of stress during single serration is based on a criterion involving number of lattice barriers accompanied by dislocation pile-ups and the shear stress at the head of a pile-up. A completely new element of the model consists in defining the drop of stress in terms of the evolution of dislocation density rather than using an artificial phenomenological function. The model is defined by means of mesoscopic representative volume element (RVE), where all the important phenomena are embedded. Finally, by integrating the equations in the RVE and stretching them over a macroscopic continuum, the constitutive and the numerical models are developed. Formulation of the constitutive model of a material subjected to the plastic strain induced phase transformation is based on multiscale considerations. On one hand, it takes into account the micro-mechanical phenomena such as interactions of dislocations with martensitic inclusions or influence of hard inclusions on the soft matrix (the Eshelby approach used in the homogenisation). On the other hand, the model is defined on the mesoscopic level by means of the representative volume element (RVE), where all material properties are treated as uniform and their equivalent values are obtained via homogenisation process. The model involves the mechanism of strain hardening with two fundamental effects taken into account: interaction of dislocations with the inclusions of secondary phase, and evolution of tangent stiffness of two-phase continuum resulting from constantly evolving proportions between hard martensite and soft austenite. Interaction of dislocations with the inclusions of secondary phase affects the hardening modulus that becomes linear function of the volume fraction of martensite. On the other hand, the tangent stiffness operator representing two-phase continuum has been computed based on the Mori-Tanaka homogenisation scheme. Here, the local tangent stiffness operators were defined for both components of two-phase continuum, which follows the concept presented by Hill (1965). Combination of both above described effects results in strong nonlinear hardening as soon as the phase transformation threshold has been reached. Thus, the classical linear hardening model has been replaced by the volume fraction of martensite dependent nonlinear hardening model. For what concerns the evolution of radiation induced damage, it is combined with the evolution of mechanically induced damage within the common framework of Continuum Damage Mechanics. An additive formulation with respect to damage tensors has been postulated [4]. Multiscale constitutive model containing strong physical background related to the mechanism of generation of clusters of voids in the irradiated solids has been built. The model is based on the experimental estimation of concentration of lattice defects (interstitials, di-interstitials, interstitial clusters, vacancies, divacancies, vacancy clusters) as a function of dpa (displacement per atom), and comprises the relevant kinetics of evolution of radiation induced damage under mechanical loads. Two kinetic laws of damage evolution were taken into account: the Rice & Tracey model and - for comparison - the Gurson model. Coupling between all three phenomena has been mathematically described and numerically implemented [5].

References

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