COUPLED STRAIN INDUCED PHENOMENA IN DUCTILE MATERIALS AT EXTREMELY LOW TEMPERATURES

B. Skoczeń
Institute of Applied Mechanics, Cracow University of Technology, Cracow, Poland

1. Thermodynamic instability in the proximity of absolute zero

In the proximity of absolute zero several thermodynamic parameters like specific heat, thermal conductivity, thermal contraction coefficient or state functions like entropy tend to zero. This fact remains consistent with the third law of thermodynamics which states that the entropy of perfect crystal at absolute zero is equal to zero. Such a statement has fundamental consequences for the behavior of single and poly-crystals at extremely low temperatures, including coupled dissipative phenomena related to inelastic deformation in the lattice. It is assumed that the heat transport in the lattice is based on two mechanisms: the phonon mechanism and the free electrons. Given the assumptions of Debye model, the specific heat takes the following form:

(1) $$C_V = \left(C_{el}\right)_V + \left(C_{ph}\right)_V \sim aT + bT^3$$

Based on the known definition of specific heat capacity (heat increment is related to mass, specific heat and temperature increment), the following relation can be derived:

(2) $$C_V\big|_{T\to 0} \to 0 \Rightarrow dT/dQ\big|_{T\to 0} \to \infty$$

This means that in the proximity of absolute zero an arbitrarily small dissipation of energy in the lattice will produce significant increase of temperature. Such energy dissipation can be induced by plastic deformation consisting in the motion of dislocations in the lattice. The plastic work is partially converted to heat, thus contributing to strong temperature oscillations, which has fundamental meaning for thermo-mechanical coupling in the weakly excited lattice near 0K.

2. Coupled phenomena in metals and alloys loaded at cryogenic temperatures

Ductile materials (metals, alloys) strained at very low temperatures undergo generally three dissipative phenomena: discontinuous plastic flow (DPF), strain induced phase transformation (SIPT) from the parent to the secondary phase, and evolution of micro-damage (EMD). All of them cause irreversible degradation of lattice and accelerate the process of material failure. Discontinuous yielding represents oscillatory deformation mode and occurs below specific temperature that represents transition from screw to edge dislocations. Plastic strain induced fcc-bcc phase transformation occurs in metastable LSFE metals and alloys within broad temperature range (practically from 0K to ambient). Finally, strain and radiation driven nucleation and evolution of micro-damage represents a dissipative and irreversible process consisting in creation of micro-cracks and micro-void clusters. All three phenomena are coupled to each other. In addition, thermo-mechanical coupling, resulting from near 0K thermodynamic instability, constitutes strong thermodynamic background for the occurrence of the above mentioned coupled effects.

3. Experimental evidence for coupled effects during straining in liquid helium

Experiments performed in liquid helium clearly indicate strong thermo-mechanical coupling that leads to temperature oscillations during serrated yielding. DPF is attributed to the mechanism of local catastrophic failure of internal lattice barriers (e.g. Lomer–Cottrell locks), under the stress fields related to the accumulating edge dislocations. Failure of internal barriers leads to massive motion of released dislocations, accompanied by step-wise increase of the strain rate (macroscopic slip) and drastic drop of stress. Recent experiments indicate strong strain localization in the form of shear bands propagating along the sample. The plastic power dissipated in the shear band is partially converted to heat, which results in local drastic increase of temperature promoted by thermodynamic instability. Spatio-temporal correlation indicates smooth shear band propagation, as long as the process of phase transformation remains on hold. However, as soon as the fcc-bcc phase transformation begins, the occurrence of shear bands becomes irregular. Inclusions of secondary phase form obstacles for shear bands and free path of shear band is limited to average distance between the obstacles. Also, DPF is accompanied by observable evolution of micro-damage of mechanical or radiation origin. The evolution of micro-damage affects loading and unloading moduli within each serration. In addition, the micro-damage evolution is strongly affected by the phase transformation process due to compressive stress fields produced by inclusions of new phase.

4. Physically based constitutive models including coupled phenomena

4.1 Discontinuous plastic flow versus phase transformation

Coupling between DPF and phase transformation is reflected by the appropriate modification of the shear band concept. Free path of shear band is limited to average distance between obstacles, that evolves as a function of the accumulated plastic strain. Distance between the inclusions of secondary phase is extracted from the constitutive model of fcc-bcc phase transformation, including strain hardening due to interaction of dislocations with the inclusions and evolution of stiffness of two-phase continuum caused by changing proportions between the phases (M-T homogenization).

4.2 Phase transformation versus evolution of micro-damage

Constitutive model of two-phase continuum affected by damage is based on the assumption that primary phase (matrix) is subjected to plastic deformation and ductile damage, whereas, the inclusions show purely brittle response. Current damage state is described by using second-order damage tensors. Rule of mixture is applied to estimate the average level of damage in the RVE. Evolution of micro-damage of mechanical and radiation origins is highly affected by the phase transformation process. During the first stage of damage evolution, before the phase transformation threshold is reached, purely ductile damage develops. This stage exhibits constant or increasing damage rate. With the appearance of fcc-bcc phase transformation, significant drop of damage rate is observed. It has been assumed that brittle damage in the secondary phase depends only on the current state of stress, and does not inherit the state of ductile damage existing in the parent phase before transformation.

4.3 Evolution of micro-damage versus discontinuous plastic flow

DPF constitutive model has been corrected by involving loading and unloading moduli, affected by propagation of micro-damage. Each serration cycle during DPF is composed of four stages: elastic loading (1), smooth plastic flow (2), drop of stress at constant total strain (3), and thermally assisted relaxation (4). It has been assumed that each fast drop of stress occurs at constant value of total strain, which means that a redistribution of the elastic and the plastic parts of strain takes place. Thus, loading and unloading moduli, associated with stages 1 and 3 of each serration, are modified to account for micro-damage evolution. This yields coupled DPF/damage response.

5. References

[1] B. Skoczeń, J. Bielski and J. Tabin (2014). Multiaxial constitutive model of discontinuous plastic flow at cryogenic temperatures, *International Journal of Plasticity*, **55**, 198-218.

[2] H. Egner, M. Ryś and B. Skoczeń (2015). Constitutive and numerical modeling of coupled dissipative phenomena in 316L stainless steel at cryogenic temperatures, *International Journal of Plasticity*, **64**, 113-133.

[3] B. Skoczeń and A. Ustrzycka (2016). Kinetics of evolution of radiation induced micro-damage in ductile materials subjected to time-dependent stresses, *International Journal of Plasticity*, **80**, 86-110.