International Journal of Plasticity 59 (2014) 152–179

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Micromechanics based constitutive modeling of martensitic transformation in metastable materials subjected to torsion at cryogenic temperatures

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ARTICLE INFO

Article history:
Received 15 August 2013
Received in final revised form 28 February 2014
Available online 20 March 2014

Keywords:
Cryogenic temperatures
A. Phase transformation
B. Constitutive behavior
C. Analytical functions
C. Mechanical testing

ABSTRACT

Special class of multi-phase structural members with graded microstructure can be obtained at cryogenic temperatures as a result of controlled transition from the parent phase to the secondary phase. The required features are obtained via the mechanism of diffusionless plastic strain induced phase transformation from purely austenitic to martensitic lattice ($\gamma \rightarrow \alpha'$). Many ductile materials are known to behave in metastable way when strained at extremely low temperatures. Among them the austenitic stainless steels are often used to construct components of superconducting magnets, cryogenic transfer lines and other cryogenic systems. The multiscale constitutive model developed to describe the plastic strain induced phase transformation at very low temperatures involves plastic hardening where two important effects play fundamental role: (1) interaction of dislocations with martensite inclusions and (2) increase of resultant tangent stiffness due to the evolution of harder martensite within the softer austenite. The micro-mechanism of interaction of dislocations with martensite inclusions is based on the Orowan scenario. The other mechanism takes into account constantly evolving proportion between the primary and the secondary phase and involves the relevant homogenization scheme. Both effects contribute to strong nonlinear hardening that occurs as soon as the phase transformation process begins. The constitutive model has been used in order to obtain a new closed form analytical solution for the case of torsion of round bars at extremely low temperatures. Moreover, numerous experiments involving quasistatic and cyclic loads were carried out in order to trace the profile of phase transformation. An ultimate proof is presented that a functionally graded structural member, characterized by the required profile of volume fraction of both phases, can be obtained. The profile of volume fraction of secondary phase (martensite) is checked by means of 2 independent methods: hardness measurements and verification by using a ferritscope (magnetic induction).

1. Introduction

Special class of multi-phase structural members with highly graded microstructure can be obtained at cryogenic temperatures (for instance in liquid nitrogen, 77 K) as a result of controlled transition from the parent phase (γ) to the secondary

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http://dx.doi.org/10.1016/j.ijplas.2014.03.006
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phase (α'). The required microstructural features are obtained by means of the mechanism of diffusionless plastic strain induced phase transformation from purely austenitic to martensitic lattice ($\gamma \rightarrow \alpha'$). It is well known that the martensitic transformation can be either spontaneous (thermally activated), stress assisted (for instance in shape memory alloys) or can be triggered by inelastic strains (for example TRIP steels). The diffusionless plastic strain induced martensitic transformation consists in rapid change of the distance between the neighboring atoms which leads to evolution of crystallographic structure from face-centered-cubic parent phase to body-centered-cubic product phase. The strain induced phase transformation is often observed at cryogenic temperatures in the so-called TRIP (transformation-induced plasticity) alloys, causing occurrence of uniform, unrecoverable, macroscopic strain due to the fact that the volume of product phase exceeds the volume of parent phase. One of possible practical applications of martensitic transformation consists in using kinematically controlled strain fields in order to create functionally graded microstructure of anticipated mechanical properties. Thus, it is possible to obtain various distributions of mechanical properties, generated by two-phase microstructure of the material, depending on the distribution of plastic strain fields as a function of imposed loads (Skoczen, 2007). The author obtained theoretical distribution of the α' phase in the cross-section of round bar loaded by torsion in the liquid nitrogen temperature. In the present work this idea has been experimentally verified. A cylindrical bar made of austenitic 304 stainless steel was subjected to torsion at 77 K and 293 K.

Many attempts have been made to describe the plastic strain induced martensitic transformation and the related TRIP effects. Both the kinetics of phase transformation and the relevant constitutive frameworks are constantly improved based on modified formulations (thermodynamic potentials, micromechanical approaches, effective properties, etc.). Application of numerical methods, especially finite elements, offers an opportunity to implement even more complex constitutive models, simulate the mechanical behavior of materials and cross-check the results with the experimental data in order to validate the models. A brief overview of the constitutive models describing the phase transformation from the microstructural and phenomenological point of view will be presented in the following section.

The basis for constitutive models has been forged in the past by means of known analytical solutions. A theoretical basis describing continuum containing inclusions was derived by Eshelby (1957), who solved typical nonhomogenity problem well known in the theory of elasticity. The results of his study were of fundamental meaning for all theories regarding modeling of multi-phase continua. Another useful instrument to describe the resultant stiffness of two-phase continuum is the mean field approach, represented by the so-called homogenization algorithms. The idea of homogenization postulates essentially replacing a heterogeneous portion of the continuum, contained in the representative volume element (RVE), by a quasi-homogeneous portion, response of which is determined from suitable averaging procedure. The well-known homogenization schemes for two-phase continua are the rule of mixtures, the self-consistent scheme (Hershey, 1954; Hill, 1965) as well as the Mori–Tanaka algorithm (Mori and Tanaka, 1973). The homogenization schemes, to large extent based on the Eshelby solution, perform correctly under the assumption that the elastic inclusions embedded in the elastic matrix are ellipsoidal or spherical in shape.

Complex problem of homogenization of rate-independent elastic–plastic composites has been already solved by Hill (1965), who linearized the constitutive equations and defined the local elastic–plastic tangent stiffness moduli. Based on these moduli any homogenization scheme (for instance the self-consistent model) can be applied at each load step. In view of this fact, the elastic–plastic analysis of heterogeneous multi-phase continuum consists in performing a sequence of homogenization operations on the step-by-step basis, including tangent stiffness moduli of all components of the composite and evolving proportion between the phases. Similar approach has been applied by Garion and Skoczen, 2002, to derive equivalent tangent stiffness of the elastic–plastic matrix containing elastic inclusions. The Mori–Tanaka scheme has been used. Broad overview of the homogenization methods has been done by Dvorak, 2013. Numerical methods applied especially for composite and other polycrystalline materials have been presented.

In the present paper the kinetics of the phase transformation is proposed, allowing further integration together with the equations of plasticity. Next, full multiaxial constitutive model is presented taking into account plastic strain, phase transformation as well as the averaged properties of the mixture of austenite and martensite. In the subsequent section, the 3D model is applied to one dimensional torsion of a cylindrical bar. Assuming some simplifications, a closed form analytical formula has been obtained for the stress versus strain as well as the torque versus the angle of twist. The following sections reflect extensive experimental results, including mechanical test of torsion at 77 K and at 293 K as well as the micro-hardness measurements, the microstructural observations and the martensite content measurements in the cross-sections of the bar. Finally, all the constants of the proposed constitutive model have been calibrated by means of the experimental data obtained during the campaign of tests. Then, the theoretical and the experimental results are compared.

2. Phase transformation oriented constitutive models

As already indicated in the previous section, the plastic strain induced phase transformation is often observed at cryogenic temperatures in the so-called TRIP (transformation-induced plasticity) alloys. Typical examples of such alloys are stainless steels, massively used to construct superconducting magnets or cryogenic systems.

Phase transformation in the austenitic stainless steel have been very extensively studied in the past decades. This phenomenon leads to extraordinary mechanical properties, especially high strength connected with high ductility. For this reason, the stainless steels are extensively exploited, including at extremely low temperatures. Their enhanced mechanical