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Constitutive modelling and identification of parameters of the plastic strain-induced martensitic transformation in 316L stainless steel at cryogenic temperatures

Cédric Garion [a,*], Błażej Skoczeń [b], Stefano Sgobba [a]

[a] CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland
[b] CUT, Cracow University of Technology, Al. Jana Pawla II 37, Krakow, Poland

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Abstract

The present paper is focused on constitutive modelling and identification of parameters of the relevant model of plastic strain-induced martensitic transformation in austenitic stainless steels at low temperatures. The model used to describe the FCC → BCC phase transformation in austenitic stainless steels is based on the assumption of linearization of the most intensive part of the transformation curve. The kinetics of phase transformation is described by three parameters: transformation threshold (p_ξ), slope (A) and saturation level (ξ_L). It is assumed that the phase transformation is driven by the accumulated plastic strain p. In addition, the intensity of plastic deformation is strongly coupled to the phase transformation via the description of mixed kinematic/isotropic linear plastic hardening based on the Mori–Tanaka homogenization. The theory of small strains is applied. Small strain fields, corresponding to phase transformation, are decomposed into the volumic and the shear parts. The grade AISI 316L, stainless steel often used in cryogenic applications, has been chosen as a good example of the austenitic structure. The magnetic permeability of fine gauge stainless steel sheets (thickness 0.15–0.25 mm) subjected to monotonic straining was measured as a function of strain. The detailed methodology of relevant measurements is presented in the paper. Tuning of the constitutive model is described and the relevant parameters are identified. The model has been applied in the design of thin-walled

* Corresponding author.
E-mail address: Cedric.Garion@cern.ch (C. Garion).

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bellows expansion joints for the large Hadron Collider (LHC), at present under construction at CERN.

Keywords: A. Phase transformation; A. Strengthening mechanisms; B. Elastic–plastic material; B. Constitutive behavior; C. Mechanical testing

1. Introduction

1.1. General

The present paper is focused on constitutive modelling and identification of the parameters of a consistent model of austenitic stainless steels (SS) for cryogenic applications. The model describes one out of three phenomena, driven by the plastic strains, that occur in metastable stainless steels at low temperatures: the phase transformation, from the FCC to BCC lattice. The other two phenomena of dissipative nature: the discontinuous yielding and the evolution of microdamage, are not taken into account in the present paper. The martensitic transformation yields the initially homogeneous material strongly heterogeneous as a result of the presence of martensite platelets embedded into the austenitic matrix. Since the BCC α'-martensite is much more rigid than the FCC γ-austenite, its presence influences the plastic flow and the process of hardening. The intensity of phase transformation affects the level of stress for a given total strain imposed on a sample. In the present paper, the elastic–plastic material with mixed kinematic-isotropic linear hardening is taken into account (Garion and Skoczeń, 2001, 2002, 2003). The volume fraction of martensite affects both the parameters of kinematic and isotropic hardening. The hardening process of two-phase material has been described on the basis of the Mori–Tanaka homogenization (Garion and Skoczeń, 2002). The kinetic law of phase transformation has been presented in a convenient linearized form, where the rate of transformation is proportional to the rate of the accumulated plastic strain. One of the possible applications for such a model are thin-walled corrugated shells called bellows, subjected to kinematically controlled expansion/compression cycles between room and cryogenic temperatures. SS bellows, often used at cryogenic temperatures as compensation elements (Skoczeń, 2004), develop strong plastic strain fields in the convolutions. Such fields contribute to the strain-induced martensitic transformation that modifies the FCC γ-austenite into the BCC α'-martensite. The γ–α' transformation, usually localised at crest and at root of convolutions, has an impact on the local evolution of ductile damage and fatigue life of bellows but also on the magnetic permeability of the shell. Since the α' martensite is known to be ferromagnetic, an intensive phase transformation yields the structure highly susceptible to magnetic field. This has a crucial impact on the performance of the expansion joints applied in the construction of particle accelerators for high energy physics. The bellows, designed for particle accelerators, are often located in close proximity of the superconducting magnets and in their stray field. High magnetization of the bellows convolutions may affect the correct functioning of the accelerator. Therefore, a correct choice of material, oriented towards maximum stability at cryogenic temperatures (minimum phase transformation), is an important issue. In order to minimize the amount of the γ–α' phase transformation due