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On the viscous and strain rate dependent behavior of polycrystalline NiTi

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Abstract

The viscous and rate dependent behavior of binary, pseudoelastic NiTi is investigated. The main focus is on the decoupling of thermal and viscous effects on the transformation stress level as the specimen material is subject to heating and cooling due to latent heat generation and absorption during phase transition. On this account, an active temperature control is proposed to account for swift temperature variations. In addition to uniaxial testing of the shape memory sample, two-dimensional tension/torsion experiments are conducted in order to generalize the uniaxial findings. Therefore, a two-dimensional strain measuring device is realized, which is capable of measuring large angle strains. Furthermore, the relaxation behavior of the examined NiTi alloy is explored as well.

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Keywords: NiTi; Pseudoelasticity; Isothermal process; Multidimensional; Viscous material behavior; Rate dependence; Strain control

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1. Introduction

Throughout the last years, more and more experimental data on shape memory alloys and especially NiTi have been accumulated. In this context, dog bone shaped tubular specimens are frequently used when complex tension/torsion tests are considered. Extensive studies have been performed by Helm (2001), Helm and Haupt (2002), and Helm and Haupt (2003) in connection to material modeling. Referring to medical applications and the behavior of nano-grained stents in particular, Sun et al. have advanced the investigation of nano-grained microtubes (see, e.g., Li and Sun, 2002; Sun and Li, 2002; Ng and Sun, 2006; Feng and Sun, 2006). Here, one focus is on the formation and development of macroscopic domains during the transformation process, frequently referred to as Lüders bands. Imbeni et al. (2003) and McNaney et al. (2003) concentrate on the path

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dependence of the material behavior of NiTi. It is shown that the simple concept of equivalent von Mises stress and strain is not sufficiently elaborate to capture the complicated interaction of the microstructure.

Furthermore, the thermomechanical coupling of the material behavior is also intriguing. Detailed examinations have been performed with reference to the connection between specimen temperature and transformation stress, which can be defined as the critical stress that is needed for the triggering of a stress-induced transformation of the microstructure. The description of these phenomena using the Clausius–Clapeyron relation is meanwhile well accepted (see, e.g., Ortín and Planes, 1989).

Moreover, as a large amount of mechanical experiments is performed under strain control, multiple works have been dedicated to the characterization and determination of the strain rate effect on the stress–strain behavior. Mukherjee et al. (1985) have been among the first to report a direct connection between higher strain rates and higher transformation stress levels. Similar findings have been made by Shaw and Kyriakides (1995), Leo et al. (1993), and McCormick et al. (1992). Herein, it is shown that a rise of the specimen temperature is observed during the loading process, which depends on the magnitude of the strain rate. Furthermore, Shaw and Kyriakides (1995), McCormick et al. (1992) present experimental data for different ambient media, thus, resulting in different heat transfer conditions, i.e., different specimen temperatures and different stress–strain curves due to the temperature dependence of the transformation stress (cf. Ortín and Planes, 1989). Quite recently Nemat-Nasser et al. (2005) examined the rate dependence of NiTi shape-memory alloy at low and high strain rates and at room temperature. Although the main focus in this work is on high strain rates up to $10^3\ \mathrm{s}^{-1}$, they also observed a moderate rate sensitivity of their material in the range of small rates from $10^{-4}\ \mathrm{s}^{-1}$ to $1\ \mathrm{s}^{-1}$.

It is well accepted today that the transformation process results in the production of latent heat leading to an exchange of heat between the specimen and the environment. Hence, the specimen temperature is changed. Consequently, different specimen geometries and different surrounding media may lead to different experimental results. Finally, the outcome of the experiments strongly depends on the particular setup, which renders experimental data from distinct experimental setups incomparable. This is why it is highly important to realize an experimental setup, which is independent of the specific geometry and the external conditions, thus, allowing for a decoupled examination of strain rate and temperature effects on the material behavior. Moreover, due to the heterogeneity of the phase transformation process resulting in a heterogeneous release of latent heat (Shaw and Kyriakides, 1995; Li and Sun, 2002; Sun and Li, 2002) and heat conduction phenomena within the specimen material as described by the heat diffusion equation, the transformation process shows an intrinsically pseudo-viscous behavior.

Referring to the modeling part of material characterization, Leo et al. (1993) and McCormick et al. (1993) use a one-dimensional material model, which incorporates heat transfer due to conduction, convection, and radiation, yielding a satisfactory agreement between modeled and material behavior observed on wire. Lexcellent and Rejzner (2000) arrive for a three-dimensional model and two-dimensional experiments conducted by Lim and McDowell (1999) at a similar result.

Although these modeling efforts give a first lead concerning the rate dependence of the mechanical material behavior, together with the awareness that part of the increase of the transformation stress can be attributed to the increase of the specimen's temperature, the reverse, implying that the material behavior is independent of strain rate, is far from being a stringent conclusion. Moreover, it is questionable to what extent it is possible to render a material model the "true" model by the fact that a certain effect can be fitted well.

On this account, temperature controlled experiments are imperative. Some first experiments of that kind were conducted by the research group around Tobushi and Lin (Lin et al., 1996b,a; Tobushi et al., 1998; Tobushi et al., 1999) on 0.1 mm wire. Consequently, only uniaxial tension tests were possible and the actual strain state is deduced just from the movement of the clamping. The specimen temperature is measured using one single thermocouple, which is pressed on the central part of the specimen. Based on the results of these tests, it is reported that the material behavior is independent of strain rate. By contrast, Helm arrives in his recent paper (Helm, 2007) at an approach utilizing a Perzyna-type inelastic multiplier, thus, realizing a rate-dependent theory.

In order to generalize these findings and to determine whether this holds true even for bulk material, isothermal multidimensional experiments are to be carried out on three-dimensional specimens. Some preliminary results were published in Grabe and Bruhns (2006, in press).

Throwing a glance at a different field of viscous material behavior, some non-isothermal relaxation experiments have been recently presented by Helm (2001). Similar to the experimental data published by Lim and