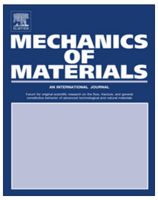
Mechanics of Materials 80 (2015) 67–86

Contents lists available at ScienceDirect

Mechanics of Materials

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



On the modeling of the thermo-mechanical responses of four different classes of NiTi-based shape memory materials using a general multi-mechanism framework

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ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form 4 August 2014
Available online 5 October 2014

Keywords:
NiTi shape memory alloys
Material modeling
Superelastic behavior
Pseudoplastic behavior
Evolution
Thermal cycles

ABSTRACT

The properties of a shape memory alloy (SMA) have been shown to be highly dependent on the chemical composition and thermo-mechanical processing applied to the material. These differences dictate the degree of superelasticity, pseudoplasticity, shape memory effect, and evolution under mechanical/thermal loading cycles, that is observed in the material. Understanding and utilizing these unique phenomena has become essential in many engineering applications. It is, therefore, important to provide two key ingredients in any SMA constitutive model; (i) a sufficiently comprehensive scope in the mathematical formulation to handle different classes of SMA materials; and (ii) a *general* model parameterization derived from fundamental tests that can be used for a specific SMA as intended for use in a given application. The present work is aimed at a detailed investigation of the interaction aspects between the above items (i) and (ii) in the context of using a recent three-dimensional, multimechanism-based SMA framework to model the experimentally measured responses of four different classes of SMA materials: (a) a commercial superelastic NiTi, (b) a powder metallurgically-processed NiTi-based SMA material, (c) a commercial $Ni_{49.9}Ti_{50.1}$ actuation material, and (d) a high-temperature $Ni_{50.3}Ti_{29.7}Hf_{20}$ alloy. To facilitate the parameterization task, the model parameters are classified into two groups, i.e., (1) fixed parameters that are designed to capture the non-linear, hysteretic response under any thermo-mechanical loading condition, and (2) a set of functionally dependent material parameters which account for a number of refinements including asymmetry in tension and compression responses, temperature- and stress-state dependencies, etc. The results of the work showed that the complexity of the characterization is dependent on the SMA feature exploited by the specific application intended, which in turn dictates the amount and type of test data required to accurately predict a given application response.

1. Introduction

It is well known that SMA materials are very sensitive to the chemical composition, thermo-mechanical processing (hot/cold working and heat treatment), and applied stress conditions (Otsuka and Wayman, 1998). For this reason, the metallurgical and experimental history of the SMA material plays a vital role in determining the unique properties that are observed, such as superelasticity, pseudoplasticity, shape memory effect, and evolutionary behavior.

The aforementioned sensitivity to processing/loading conditions can be used to one's advantage to obtain the most convenient properties for any specific application.

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http://dx.doi.org/10.1016/j.mechmat.2014.09.001

For instance, Ni-rich NiTi compositions (more than 50.5% at. Ni) have lower transformation temperatures than their Ti-rich counterparts. This lower transformation temperature facilitates the use of the superelastic property which is appropriate for biomedical stent applications at constant body temperature (Gall et al., 2005). Moreover, aging of a Ni-rich alloy enhances cyclic stability (Coughlin et al., 2012; Evirgen et al., 2012; Yawny et al., 2008). On the other hand, the NiTi-based ternary alloys with the addition of Hf exhibit a dramatic increase in the transformation temperature (Angst et al., 1995; Kockar et al., 2006), thus rendering this material suitable for high-temperature actuation applications in the aerospace field. As can be seen by the aforementioned, the different engineering or medical SMA-based applications are designed to exploit a specific shape memory behavior such as superelasticity (SE), one-way shape memory effect (OWSME), or stress-assisted two-way shape memory effect (TWSME).

The characteristic response of a particular SMA can only be unveiled through the comprehensive characterization of the SMA by conducting a detailed set of experiments under different mechanical as well as thermal loading scenarios. Due to constraints on time, cost, expertise, etc., access to such information is very rare. Hence, there is a need for a systematic, comprehensive set of experimental works that provides the appropriate information regarding the SMA behavior to be exploited in the application. Once the application based experiments are carried out, with relevant and appropriate test procedures, the designers/engineers face the dilemma of selecting an appropriate material model from the many choices available in the literature. As discussed in the recent publication by Hartl et al. (2010), this is particularly difficult since most of the available models require the use of test data for stabilized/trained materials but do not specify the nature of the training procedure. In particular, it is known that the behavior of a trained SMA material is dictated by the specific for a given load condition, and once that load condition is changed, the material will re-initiate stages of transient changes and subsequent evolution of deformation. Hence, there is a vital need for a general SMA material formulation, which once formulated, can be used by designers/engineers for the analysis of various intended applications using different classes of SMA materials, regardless of prior thermomechanical history. A general discussion of the different constitutive modeling approaches for SMA materials can be found in Lagoudas et al. (2006), Patoor et al. (2006), Kan and Kang (2010) and Saleeb et al. (2011).

In the work presented here, a general SMA modeling strategy (developed by Saleeb et al. (2011)) will be specialized to handle four different classes of SMA materials. Note that two of these materials (55NiTi ($Ni_{49.9}Ti_{50.1}$) and superelastic $Ni_{50.7}Ti_{49.3}$) are among the most-widely-used in applications and are commercially available. The other two material systems (i.e., ternary $Ni_{50.3}Ti_{29.7}Hf_{20}$ for aerospace applications and the powder metallurgically processed NiTi SMA system for biomedical applications) are representative of "state-of-the-art" materials being developed to enhance the material properties. Furthermore, the widely different response characteristic of these four materials presents an excellent setting to evaluate the viability of the developed modeling framework for use in applications. To facilitate the model parameterization for the four materials, we utilize the ability to activate or deactivate the temperature/stress functional dependency of the underlying inelastic mechanisms in the general framework. It will be shown that drastically different material responses, required to predict specific applications can be easily manifested through altering the framework's parameterization and that the complexity/simplicity of the parameterization is commensurate with the complexity of the deformation behavior being exploited. Hence, the parameterization will be shown to be quite complex for the applications requiring thermal actuation behavior (as in the cases of the commercially available $Ni_{49.9}Ti_{50.1}$ (at.%), and the high-temperature $Ni_{50.3}Ti_{29.7}Hf_{20}$ alloy (at.%)) but can be extremely simplified to handle simpler cases such as superelastic deformation of a stent.

To better place into perspective the scope, overall objectives, and practical utility of the present multimechanism model and its characterization presented here, we use the schematics of Fig.1. More specially, an application-driven approach is adopted, where the following observation is emphasized. Each technologically-significant application exploits one or more of the SMA response characteristics (see 1st row in Fig. 1), typically involving a complex initial/boundary-value problem (see 2nd row in Fig. 1), such as the cases of biomedical stents and different configurations of solid-state actuators. Hence, the *mathematical* formulations and assumptions made in the establishment of this model account for multi-axiallity and are sufficiently *comprehensive* in scope to treat *all* these different cases (see 3rd row in Fig. 1). However, for *practical* utility, the model *characterization* is *flexible* enough to allow the use of *reduced* sets of test data (4th row in Fig. 1), commensurate with the *limited* scope of a *specific* application (last row in Fig. 1).

2. Experimental measurements and observations

The investigation was carried out on four different NiTi-based, polycrystalline, SMA materials. These materials are; (a) a commercial $Ni_{49.9}Ti_{50.1}$ (at.%) actuation material, (b) a high-temperature $Ni_{50.3}Ti_{29.7}Hf_{20}$ alloy (at.%), (c) a powder metallurgically processed NiTi based material, and (d) a commercial superelastic NiTi. Details of the specific experimental results for each of these separate materials are given below.

2.1. $Ni_{49.9}Ti_{50.1}$ (at.%) SMA material

Here, an extensive number of isobaric, thermal cycling results for a $Ni_{49.9}Ti_{50.1}$ (at.%) material were utilized. Seven different bias stress levels (10, 50, 80, 100, 150, 200, and 300 MPa) were characterized over 100 thermal cycles (except only 88 cycles are available for 200 MPa) using a temperature range of 30 °C to 165 °C (Padula et al., 2013; Saleeb et al., 2013; Saleeb et al., 2013; Atli et al., 2013). Cylindrical, uniform-gage length tensile specimens with a diameter of 3.81 mm and a reduced gage length of 25.4 mm in the hot-rolled/hot-drawn and hot-straightened