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A macro-constitutive model of polycrystalline NiTi SMAs including tensile–compressive asymmetry and torsion pseudoelastic behaviors

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ABSTRACT

Experimental results show that material component and loading modes may affect the properties of shape-memory alloys (SMAs) markedly. In order to investigate the influence of loading modes on pseudoelasticity behaviors fully, some experiments of NiTi specimens under pure tension, compression and torsion with the same material component are investigated. In terms of the phenomena observed in experiments, a macro-constitutive model is presented for considering the tension–compression asymmetry of polycrystalline NiTi SMAs. In this study, the macroscopic strain is taken account of elastic strain, macro-transformation strain and macro-temperature strain. The volume fraction of martensite is governed by the reduction in Gibbs' free energy of the system. In the present model, the fewer experimental data which are used to determine model parameters are needed. The model is not only simple but also fit for using in engineering. The theoretical results are found to be in good agreement with experimental data.

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1. Introduction

Shape-memory alloys (SMAs) have been proposed as sensors and large strain actuators for use in intelligent composites and structures. This is because SMAs have native abilities to undergo reversible thermoelastic martensitic phase transformation under external thermomechanical loading.

In the past decades, many experiments and theoretical analysis have been developed to investigate the potential properties of SMAs. There are tension–compression tests [1–7], torsion experiments [8–12], bending experiments [13–15], proportional and nonproportional loading experiments [16–19], and so on. Experimental results show that the influence on properties of SMA resulting from material component and loading modes is much larger. For example, shape-memory alloy presents an asymmetric behavior under tensile or compressive loads [1–7]. Polycrystalline NiTi, deformed under compression, presents smaller recoverable strain levels, higher critical transformation stress levels, and steeper transformation stress–strain slopes [4,5]. The martensitic/austenitic transformation temperatures, the transformation critic stress are markedly affected by compositional changes.

However, most of these experiments considered the influence of two loading modes on specimens with the same material component, such as tension versus compression, tension versus torsion. A few papers performed three loading modes with the same material component [16,20,21]. Lim and McDowell [16] performed pure tension, pure compression, and pure torsion loading strain control experiments. However, the full transformation did not develop. Grabe and Bruhns [20] investigated the influence of the loading sequence and the combined loading paths on pseudoelasticity and the one-way effect.

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Thamburaja and Anand [21] performed pseudoelasticity experiments in tension, compression, and shear on initially textured polycrystalline TiNi alloys. Until now there are few papers investigating the pseudoelasticity stress–strain relations with full martensite transformation of polycrystalline TiNi alloys with the same material component in pure tension, compression, and torsion.

There are some constitutive models to describe the thermomechanical behavior of shape-memory alloys. And, they probably are classified as four classes, namely models using plastic concepts, models using single crystal theory, micromechanics models, macroscopic phenomenological models. The models using plastic concepts [22,23] could analyze transformation and deformation behaviors. Due to the more complex function relation, it is difficult to be used in engineering situation. The models using single crystal theory [24,25] were based on Landau theory, and the corresponding free energy function was obtained by introducing shear strain as a new order parameter. These models were fit for shear deformation of single crystal. The macroscopic phenomenological models [26–28] were developed by making use of thermodynamic laws and phase transformation kinetics. The model firstly developed by Tanaka and coworkers [26] was originally conceived to describe three-dimensional problems involving SMAs. Nevertheless, its implementation became restricted to the one-dimensional context. Liang and Rogers [27] presented an alternative evolution law for the volumetric fraction. Boyd and Lagoudas [28] rewrote Tanaka's original model, for a three-dimensional theory construction. Numerical simulations show that the model could capture the general behavior of SMAs, such as phase transformations. However, there are so many materials parameters in the model, and the usage process is complex. Micromechanics models of SMAs [29–31] relied heavily on the detailed knowledge of the deformation/transformation processes, which was difficult to be used in engineering.

Recently, some macroscopic models of SMA were proposed [32–34]. Peultier et al. [32] proposed a SMA constitutive law based on a thermodynamical approach of the martensitic phase transformation, and implemented in a finite element code. However, tensile–compressive asymmetry was not considered. Auricchio et al. [33] proposed a one-dimensional model with taking into account tension–compression asymmetries. Thamburaja and Nikabdullah [34] developed a non-local and thermo-mechanically-coupled constitutive model for polycrystalline shape-memory alloys. The theory was developed in the isotropic metal-plasticity setting using fundamental thermodynamic laws and the principle of micro-force balance. However, there were visible difference between the simulation curves and the experiments.

It is well known that the main object of studying SMA model is to exploit its potential features and promote its wide application in engineering. So, the SMA model should be accurate, simple, and fit for using in engineering.

So, we propose in this work to investigate the influence of loading modes of stress on the pseudoelasticity behavior of NiTi SMA namely pure tension, compression and torsion with the same material component. A three-dimensional macro-constitutive model is presented for polycrystalline shape-memory alloy. In this study, the tension–compression asymmetry of SMA is taken into account. We take the view that macroscopic strain includes elastic strain, macro-transformation strain and macro-temperature strain. The volume fraction of martensite is governed by the reduction in Gibbs' free energy of the system. Likewise, there is a resistance force associated with the nucleation. At a given level of applied mechanical stress, the driving force must be sufficient to overcome the resistance force. The fewer material constant which are used to determine model parameters are needed. It is easy to use and enable quick computations.

2. Experimental tests

In order to fully investigate the mechanical behaviors of SMA in different loading modes, the material component for the all specimens is the same with 50.8 at.% NiTi which can exhibit pseudoelastic behavior at room temperature. The tensile specimen is flat dog-bone shape with a gage length of 60.13 mm length and a 7.89 mm×2.93 mm gage cross-section. The compressive specimen is round shape with a gage length of 9.46 mm length and a 5.10 mm diameter. The torsion specimen is tubular stock. The radius-to-wall-thickness ratio is approximately 5:1 with a gage length of 40.23 mm, an inner/outer diameter of 9.70 mm, 5.12 mm, respectively. After machining, these specimens were subjected to a heat treatment involving solution annealing at 400 °C for 15 min, followed by water quenching. This treatment is known to result in good superelastic material properties.

The transformation temperatures for the Ti–Ni, determined by using differential scanning calorimetric (DSC) techniques, are: $M_s = -40.8$ °C, $M_f = -72.4$ °C, $A_s = -10.6$ °C, $A_f = 22.0$ °C, where M_s, M_f, A_s, and A_f are the martensite start, martensite finish, austenite start, and austenite finish temperatures, respectively.

All the tests were performed at room temperature about 26 °C. Within the regime of quasi-static processes at isothermal conditions, the mechanical behavior of NiTi polycrystalline is independent of the applied strain rate [35]. The low applied strain rate is commonly regarded as quasi-static. In this paper, strain rate 10^{-4}/s were used for tension and compression tests. The Mises equivalent strain is defined by $\varepsilon_{eq} = \gamma'/\sqrt{3}$. Here, γ' is the engineering shear strain of thin walled gage section. The strain rate in torsion is the equivalent shear strain rate, $\dot{\varepsilon}_{eq}$. The equivalent strain rate $\dot{\varepsilon}_{eq} = 10^{-4}$/s was used for torsion test.

The loading–unloading pseudoelasticity stress–strain hysteresis loops for all the tests were obtained, seen in Fig. 1. For compression the absolute values of stress and strain are plotted. Fig. 1a shows pseudoelastic responses of polycrystalline NiTi SMAs under uniaxial tension and compression. As seen in Fig. 1a, NiTi SMA macroscopic behaviors present asymmetry under tensile–compressive loads including also in yield stress level as well as in loop width and length, and transformation stress–strain slopes. Fig. 1b shows a superelastic stress–strain response under torsion load. By comparison the tension and torsion

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