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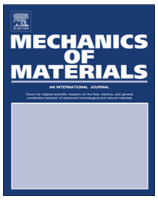

A physical mechanism based constitutive model for temperature-dependent transformation ratchetting of NiTi shape memory alloy: One-dimensional model

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ABSTRACT

In this paper, the effect of test temperature on the transformation ratchetting of super-elastic NiTi shape memory alloy was first investigated in the cyclic tension-unloading tests. It is shown that all the residual strain, dissipation energy, the start stress of martensite transformation and their evolutions during the cyclic loading depend greatly upon the test temperature. Based on the experimental observations, a new one-dimensional constitutive model is constructed by considering two different inelastic deformation mechanisms (i.e., martensite transformation and transformation-induced plasticity). The proposed model employs a new evolution rule of transformation-induced plasticity which considers the physical mechanism of the plastic deformation, i.e., the dislocation slipping in the austenite phase near the austenite–martensite interfaces. Furthermore, the interaction between dislocation and martensite transformation is also taken into account in the proposed model. The capability of the proposed model to predict the uniaxial temperature-dependent transformation ratchetting of NiTi shape memory alloy is verified by comparing the predictions with the experimental data.

1. Introduction

NiTi shape memory alloy (SMA) has been widely used in aerospace, mechanical, electronic and medical fields due to its unique shape memory and super-elastic effects. Often, the structural components and devices manufactured by the NiTi SMA are subjected to a cyclic loading. Therefore, the cyclic deformation of NiTi SMA is a key issue should be investigated in advance. Many experimental investigations have been done in the last few decades. In the macroscopic scale, during the cyclic deformation of super-elastic NiTi SMA, the repeated martensite transformation and its reverse result in a cyclically accumulated residual strain; and the start stress of the transformation from austenite to martensite (simply, the start stress of martensite transformation) and the dissipation energy per cycle decrease, but the transformation hardening increases with the increasing number of cycles (Miyazaki et al., 1986; Kang et al., 2009; Saint-Sulpice et al., 2009; Song et al., 2014). These phenomena are defined as transformation ratchetting (Kang et al., 2009). In the microscopic scale, the dislocation slipping has been observed in the austenite phase near the austenite–martensite interfaces during the cyclic deformation; however, the density of dislocation increases remarkably in the first beginning of cyclic loading and tends to be saturated after a certain number of cycles (Gall and Maier, 2002; Simon et al., 2010; Delville et al., 2011). Unlike the plastic

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deformation of ordinary metal materials, the dislocation slipping in the austenite phase of NiTi SMA can be activated during the repeated martensite transformation and its reverse, even the applied stress is much lower than the yield stress of austenite (about 700 MPa) and martensite phases (about 1200 MPa), and the resulted plastic deformation is called as transformation-induced plasticity. Moreover, the cyclic deformation behaviors of NiTi SMA under the repeated cyclic tension-unloading conditions at different test temperatures have been investigated by Miyazaki et al. (1986), Nemat-Nasser and Guo (2006), and it is shown that the residual strain increases with the increasing test temperature. However, the temperature-dependent transformation ratchetting of NiTi SMA has not been discussed in detail yet.

Based on the experimental observations, many phenomenological constitutive models have been constructed to describe the thermo-mechanical behavior of NiTi SMA and can be classified into two groups: (1) macroscopic models (Lagoudas and Entchev, 2004; Auricchio et al., 2007; Panico and Brinson, 2007; Zaki and Moumni, 2007; Chemisky et al., 2011); (2) micromechanical models (Sun and Hwang, 1993a,b; Thamburaja et al., 2005, 2009; Patoor et al., 2006; Lagoudas et al., 2006). In these models, the evolution equations of internal variables are set as the exponent functions of the accumulated martensite volume fraction. They can describe the transformation ratchetting of NiTi SMA very well just in some specific loading conditions; however, they cannot model the dependence of transformation ratchetting on the applied stress levels. In order to overcome these shortcomings, modified constitutive models have been proposed by Saint-Sulpice et al. (2009), Kan and Kang (2010), and Yu et al. (2013), but they are still phenomenological and no physical mechanism is included. For example, in order to describe the temperature-dependent transformation ratchetting of NiTi SMA (as shown in Figs. 1–4), the evolution equations of internal variables adopted in the modified phenomenological models (Kan and Kang, 2010; Yu et al., 2013) should be set as the functions of accumulated martensite volume fraction and temperature simultaneously, and then a large number of material parameters will be used, which limits the applications of the models.

Therefore, in this work, a series of uniaxial strain loading-stress unloading cyclic tests (simply, cyclic tension-unloading tests) were first performed at various test temperatures to investigate the temperature-dependent transformation ratchetting of super-elastic NiTi SMA. Then, a new one-dimensional constitutive model was constructed by considering two inelastic mechanisms, i.e., martensite transformation and transformation-induced plasticity. In the proposed model, a new evolution

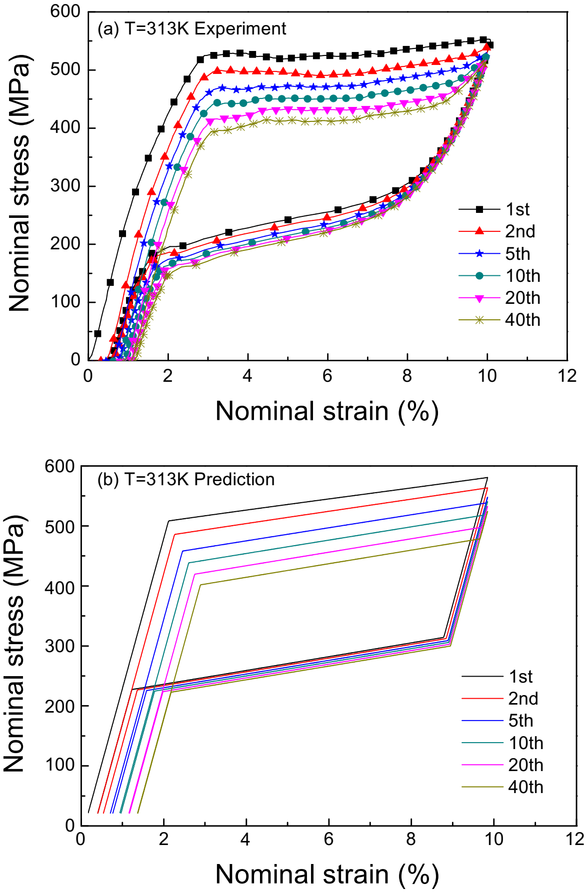

Fig. 1. Stress–strain curves at 313 K: (a) Experiment (b) Prediction.

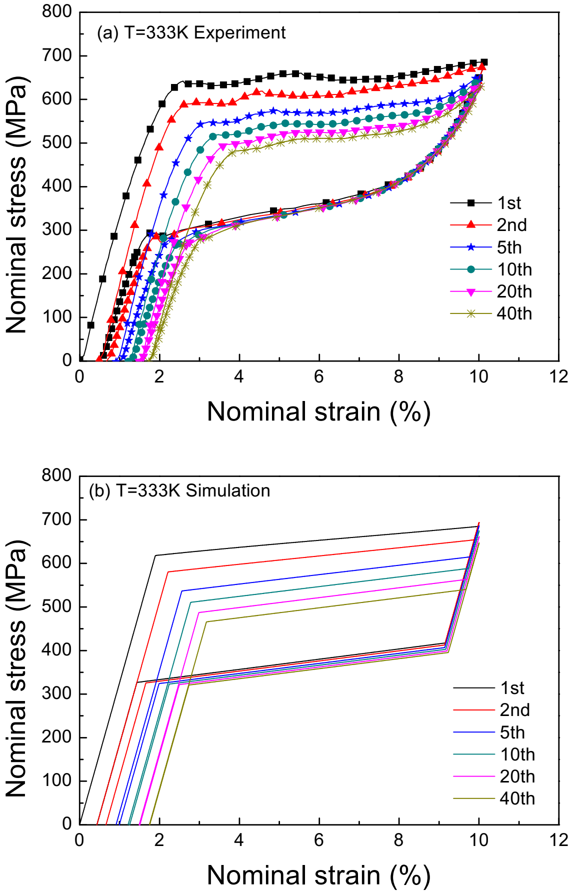

Fig. 2. Stress–strain curves at 333 K: (a) Experiment (b) Simulation.