International Journal of Solids and Structures 51 (2014) 4386–4405

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Study on the rate-dependent cyclic deformation of super-elastic NiTi shape memory alloy based on a new crystal plasticity constitutive model

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ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form 14 April 2014
Available online 18 September 2014

Keywords:
NiTi shape memory alloy
Crystal plasticity
Cyclic deformation
Rate-dependence
Internal heat production

ABSTRACT

In this paper, a crystal plasticity based constitutive model (Yu et al., 2013) is extended to describe the rate-dependent cyclic deformation of super-elastic NiTi shape memory alloy by considering the internal heat production. Two sources of internal heat productions are included in the proposed model, i.e., the mechanical dissipations of inelastic deformation and the transformation latent heat in the NiTi shape memory alloy. With an assumption of uniform temperature field in the alloy specimen, a simplified evolution law of temperature field is obtained by the first law of thermodynamics and the heat boundary conditions. An explicit scale-transition rule is adopted to extend the proposed single crystal model to the polycrystalline version. The capability of the extended polycrystalline model to describe the rate-dependent cyclic deformation of super-elastic NiTi shape memory alloy is verified by comparing the predictions with the corresponding experimental ones. The comparison demonstrates that the proposed constitutive model considering the internal heat production predicts the rate-dependent cyclic deformation of super-elastic NiTi shape memory alloy fairly well.

1. Introduction

NiTi shape memory alloys exhibit unique super-elasticity, shape memory effect and high damping capacity due to their thermo-elastic martensite transformation, and have been widely used in the aeronautic, microelectronic and biomedical industries (Morgan, 2004). In services, the structural components made by the NiTi shape memory alloys are often subjected to a cyclic thermo-mechanical loading. The cyclic deformation of the NiTi shape memory alloys is a key issue which should be discussed in advance in order to predict the fatigue life and assess the reliability of such components reasonably and precisely. However, during the cyclic deformation of the NiTi alloys, two features have been observed by many experiments, which must be taken into account in the construction of theoretical model:

- *Transformation ratchetting:* During the cyclic deformation of super-elastic NiTi shape memory alloys, the repeated martensite transformation and its reverse result in a cyclically accumulated residual strain i.e., the transformation ratchetting (Lagoudas and Bo, 1999; Sehitoglu et al., 2001; Nemat-Nasser and Guo, 2006; Zaki and Moumni, 2007a; Kang et al., 2009, 2012; Morin et al., 2011b), and the accumulation rate of residual strain tends to be zero after certain cycles. During the transformation ratchetting deformation, the start stress of the transformation from austenite to martensite phase and the dissipation energy per cycle decrease, but the transformation hardening increases with the number of cycles. The mechanisms of transformation ratchetting are explained by the transformation-induced plasticity occurred at the austenite–martensite interfaces and the accumulation of residual martensite together (Gall and Maier, 2002; Brinson et al., 2004; Kang et al., 2009, 2012). It should be noted that all the experiments mentioned above were preformed actually under the non-isothermal condition due to the internal heat production during the cyclic loading.
- *Rate-dependence:* During the cyclic deformation, the internal heat production of super-elastic NiTi shape memory alloys coming from the mechanical inelastic dissipation and transformation latent heat competes against the heat transfer/convection, and the transformation stress depends strongly on the test temperature, which leads to a rate-dependent thermo-mechanical cyclic deformation of the NiTi shape memory alloys, as discussed by the existing literature (Shaw and Kyriakides, 1995; Grabe and Bruhns, 2008; Christ and Reese,

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http://dx.doi.org/10.1016/j.ijsolstr.2014.09.006
0020-7683/

2009; Zhang et al., 2010; He and Sun, 2010a,b, 2011; He et al., 2010; Morin et al., 2011a, 2011b; Sun et al., 2012; Yin and Sun, 2012; Peigney and Seguin, 2013; Yin et al., 2013, 2014). For example, the additional transformation hardening and the number of macroscopic domains during the martensite transformation increase with the increasing loading rate (Zhang et al., 2010). However, the stress hysteresis varies non-monotonically with the varying loading rate (Zhang et al., 2010; He and Sun, 2010a,b, 2011; He et al., 2010; Morin et al., 2011a, 2011b; Yin et al., 2013). It should be noted that the rate-dependent cyclic deformation of NiTi shape memory alloys is caused mainly by the internal heat production, which is different from the rate-dependent deformation of ordinary metals caused by the viscosity.

Thus, a theoretical model describing the rate-dependent transformation ratchetting of NiTi shape memory alloys is needed. Based on the experimental results, many constitutive models had been established in the last two decades to describe the thermo-mechanical deformation of NiTi shape memory alloys. The established models can be classified into two groups, i.e., the macro-phenomenological and micromechanical models. The macro-phenomenological models do not concern the complicated microstructures of the NiTi shape memory alloys and their evolutions during the thermo-elastic martensite transformation and its reverse; while they are very suitable for the numerical implementation and then can be easily applied in the structure analysis. The representative models can be referred to those proposed by Bo and Lagoudas (1999a,b,c), Lexcellent et al. (2000), Auricchio et al. (2003, 2007), Lagoudas and Entchev (2004), Lagoudas et al. (2006), Zaki and Moumni (2007a) and Kan and Kang (2010). Recently, Morin et al. (2011b) extended a macroscopic phenomenological thermo-mechanical constitutive model proposed by Zaki and Moumni (2007a) to describe the rate-dependent transformation ratchetting of super-elastic NiTi shape memory alloys by considering the hysteresis dissipation and latent heat simultaneously. The full-coupled governing equations in the proposed model were solved by finite element method (FEM) and rate-dependent transformation ratchetting can be described by the extended model reasonably.

It is well-known that, the macro-phenomenological models cannot reasonably reflect the microscopic physical nature of thermo-mechanical deformation of the NiTi shape memory alloys. Thus, in the last decades, many micromechanical constitutive models (Sun and Hwang, 1993a,b; Levitas and Ozsoy, 2009a,b; Levitas, 2013; Guthikonda and Elliott, 2013) were developed to describe the super-elasticity and shape memory effect of NiTi shape memory alloys. Among them, the crystal plasticity based constitutive models are popular, since 24 martensite variants with different morphological features and their evolutions during the thermo-mechanical deformation of NiTi shape memory alloys can be reasonably considered in such models. With the help of FEM or homogenization methods such as the self-consistent method and so on, a single crystal model can be extended into a polycrystalline version. Although the crystal plasticity based constitutive model is time-consuming, it is an attractive approach due to its solid physical background. The representative models can be referred to those developed by Patoor et al. (1996, 2006), Huang and Brinson (1998) Huang et al. (2000), Gall et al. (2000), Gao et al. (2000), Thamburaja and Anand (2001, 2003), Anand and Gurtin (2003), Nae et al. (2003), Thamburaja et al. (2005, 2009), Wang et al. (2008), Manchiraju and Anderson (2010), and Yu et al. (2012, 2014). However, the crystal plasticity based micromechanical constitutive models addressed above cannot describe the transformation ratchetting of super-elastic NiTi shape memory alloys observed by Kang et al. (2009), since the physical mechanisms of transformation ratchetting have not been considered yet in these models.

More recently, Yu et al. (2013) constructed a crystal plasticity based constitutive model to describe the transformation ratchetting of super-elastic NiTi shape memory alloys by introducing 24 friction slip systems at the austenite–martensite interfaces (Lagoudas and Entchev, 2004; Kan and Kang, 2010; Kang et al., 2012) and considering the accumulation of residual martensite during the cyclic deformation (Gall and Maier, 2002; Brinson et al., 2004). The predictions agreed with the corresponding experiments well at one specific loading rate. However, the internal heat production in the cyclic deformation of NiTi shape memory alloys was neglected in the proposed model. It means that the crystal plasticity based micromechanical constitutive model proposed by Yu et al. (2013) cannot describe the rate-dependent cyclic deformation of the NiTi shape memory alloys observed by Shaw and Kyriakides (1995), He and Sun (2010a,b, 2011), He et al. (2010), Morin et al. (2011a, 2011b), Yin and Sun (2012) and Yin et al. (2014), in which the rate-dependence of cyclic deformation has been proved to be caused by the internal heat production of the NiTi alloy.

Therefore, in this work, the crystal plasticity based constitutive model proposed by Yu et al. (2013) is extended to describe the rate-dependent cyclic deformation of super-elastic NiTi shape memory alloys. Two sources of internal heat productions (i.e., mechanical inelastic dissipation and transformation latent heat) are considered in the extended model. With the assumption of uniform temperature field in the deformed NiTi alloy specimen (Nae et al., 2003; Zhu and Zhang, 2007; He and Sun, 2010b, 2011; Yin and Sun, 2012; Yin et al., 2014), a simplified evolution law of the temperature field is proposed from the first law of thermodynamics. An explicit scale-transition rule considering the inelastic accommodation of single crystal grains is also employed to obtain the polycrystalline constitutive model from the single crystal version. The extended model is firstly verified by comparing the predictions with the corresponding experiments of polycrystalline NiTi shape memory alloy obtained under the uniaxial cyclic loading conditions and at different strain rates (Morin et al., 2011b). Then, the effects of mechanical dissipation and transformation latent heat on the cyclic deformation of the NiTi alloy are discussed by comparing the predictions with the experiments done by Sun et al. (2012). Finally, the effect of initial texture on the rate-dependent transformation ratchetting and some heterogeneous deformation details of the polycrystalline NiTi alloy in the inter-grain scale are discussed.

2. Outline of original model

As mentioned above, the crystal plasticity based constitutive model proposed by Yu et al. (2013) to describe the transformation ratchetting of super-elastic NiTi shape memory alloys will be extended to describe the rate-dependent cyclic deformation of the NiTi alloys further by considering the internal heat production. Therefore, the original constitutive model (Yu et al., 2013) is first outlined in this section to keep the integrity of the content.

2.1. Definitions of inelastic strain

Based on the hypothesis of small deformation, total strain tensor $\boldsymbol{\varepsilon}$ in a representative volume element (RVE) of a single crystal can be decomposed into three parts, i.e., the elastic strain tensor $\boldsymbol{\varepsilon}^e$, transformation strain tensor $\boldsymbol{\varepsilon}^{tr}$ and transformation-induced plastic strain tensor $\boldsymbol{\varepsilon}^p$. It yields:

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^{in} \tag{1-a}$$

$$\boldsymbol{\varepsilon}^{in} = \boldsymbol{\varepsilon}^{tr} + \boldsymbol{\varepsilon}^p \tag{1-b}$$