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Effect of martensite reorientation and reorientation-induced plasticity on multiaxial transformation ratchetting of super-elastic NiTi shape memory alloy: New consideration in constitutive model

Chao Yu [a,b], Guozheng Kang [a,b,*], Di Song [b], Qianhua Kan [b]

[a] State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu, Sichuan 610031, PR China
[b] School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu, Sichuan 610031, PR China

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ABSTRACT

Experimental results show that the martensite reorientation and reorientation-induced plasticity play critical roles on the non-proportional multiaxial transformation ratchetting of super-elastic NiTi shape memory alloy (SMA) (Song et al., 2014b). In this paper, the multiaxial transformation ratchetting of the NiTi shape memory alloy is described by developing a new constitutive model in the framework of crystal plasticity. Besides the well-known inelastic mechanisms of NiTi shape memory alloys, such as the martensite transformation, martensite reorientation, transformation-induced plasticity and accumulated residual martensite, a new inelastic deformation mechanism, i.e., reorientation-induced plasticity is included in the proposed model to address its effect on multiaxial transformation ratchetting. The constitutive model is constructed in the single crystal scale and extended to a polycrystalline version by adopting an explicit scale-transition rule. By comparing the predicted results with the corresponding experimental ones, it is verified that the proposed model describes the non-proportional multiaxial transformation ratchetting of super-elastic NiTi shape memory alloy more reasonably by considering the martensite reorientation and reorientation-induced plasticity simultaneously.

1. Introduction

Owing to the solid to solid diffusionless thermo-elastic martensite transformation, NiTi shape memory alloy (SMA) can exhibit the unique super-elasticity, shape memory effect and high damping capacity (Morgan, 2004). Based on these characteristics, the NiTi SMA has been widely used in aeronautic, microelectronic and biomedical applications.

The NiTi SMA exhibits different thermo-mechanical properties at various temperatures. When the test temperature T is higher than the austenite finish temperature A_f, the NiTi SMA consists of a high symmetric austenite phase originally. The austenite phase will transform to the martensite phase when the applied stress is higher than its martensite transformation stress, and a transformation strain is produced. The transformation strain will be fully recovered during the unloading. This is the well-known super-elasticity of the NiTi SMA. When the test temperature T is lower than the martensite finish

* Corresponding author at: School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu, Sichuan 610031, PR China. Tel.: +86 28 87603794; fax: +86 28 87600797.

E-mail addresses: guozhengkang@home.swjtu.edu.cn, guozhengkang@126.com (G. Kang).

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temperature M_f, the alloy consists of a low symmetric twinned martensite phase originally. Martensite reorientation and detwinning will occur when the applied stress is high enough, and an inelastic strain is produced. The inelastic strain can be recovered during the subsequent heating process. This is the shape memory effect of the NiTi SMA.

In practice, super-elastic NiTi SMA ($T > A_f$) is widely used in structural components such as intravascular stents, spectacle frames and dampers. The structural components made from super-elastic NiTi SMA are often subjected to cyclic thermo-mechanical loading. Thus, the cyclic deformation 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. In the last two decades, many experiments were performed to investigate the cyclic thermo-mechanical responses of super-elastic NiTi SMA under uniaxial loading condition (Miyazaki et al., 1986; Sehitoglu et al., 2001; Eggeler et al., 2004; Nemat-Nasser and Guo, 2006; Otsuka and Ren, 2005; Yawny et al., 2005; Kang et al., 2009, 2012; Delville et al., 2011; Morin et al., 2011b; Song et al., 2014a). It is reported that the martensite transformation and its reverse result in a progressive increase in the peak and valley strains, and the accumulation rates of the peak and valley strains tend to be zero after few cycles; the start stress of martensite transformation and the dissipation energy decrease, but the transformation hardening increases with the increasing number of cycles. These features have been denoted as transformation ratchetting by Kang et al. (2009), and reflect a super-elasticity degeneration of NiTi SMA during the cyclic deformation (Eggeler et al., 2004). The cyclically accumulated axial strains of NiTi SMA during the cyclic heating–cooling at constant uniaxial stresses were also observed by Lagoudas and Bo (1999) and Benafan et al. (2014). Similarly, Eggeler et al. (2004) demonstrated that the residual strain would accumulate during cyclic deformation, which reflected a functional fatigue of super-elastic NiTi SMA.

However, the experimental observations on the transformation ratchetting of super-elastic NiTi SMA under non-proportional multiaxial cyclic loading conditions are much fewer than that under the uniaxial ones, and only a few recent works (Wang et al., 2010; Saleeb et al., 2013; Song et al., 2014b) can be referred to. As discussed by Song et al. (2014b), martensite reorientation plays a critical role in the non-proportional multiaxial transformation ratchetting of super-elastic NiTi SMA: firstly, martensite reorientation is one of the main inelastic deformation mechanisms occurred in the NiTi SMA under non-proportional multiaxial loading condition; secondly, reorientation-induced plasticity promotes the accumulation of peak and valley strains and then make the transformation ratchetting presented under the non-proportional multiaxial loading condition much higher than those obtained under the uniaxial one. At the microscopic scale, the uniaxial cyclic deformation of NiTi SMA at temperatures lower than M_f was observed by Xie et al. (1997) and Liu et al. (1998). The microscopic observations by the transmission electronic microscope showed that a lot of defects were caused at the martensite–martensite interfaces after the cyclic deformation. Since the main inelastic deformation mechanisms of the NiTi SMA at the temperature lower than M_f are the martensite reorientation and detwinning, it can be concluded from the microscopic observations that the martensite reorientation can also induce the occurrence of plasticity, as does the martensite transformation discussed by Kang et al. (2009). In this paper, the plasticity caused by the cyclic martensite reorientation is named reorientation-induced plasticity, similar to the transformation-induced plasticity denoted by Kang et al. (2009). Therefore, in order to describe the non-proportional multiaxial transformation ratchetting of super-elastic NiTi SMA more accurately, the effects of martensite reorientation and reorientation-induced plasticity should be considered in the proposed constitutive model.

Based on experimental observations, many macro-phenomenological constitutive models were constructed in the last two decades to describe the thermo-mechanical deformation of NiTi SMA, and the representative works can be referred to Lagoudas et al. (2006, 2012), Panico and Brinson (2007), Zaki and Moumni (2007a), Hartl and Lagoudas (2009), Arghavani et al. (2010, 2011), Thamburaja (2010), Chemisky et al. (2011, 2014), Morin et al. (2011a), Sedlák et al. (2012), Zaki (2012), Teeriaho (2013), Auricchio et al. (2014) and Xiao (2014). However, these models cannot be used to describe the cyclic deformation of NiTi SMA, since the transformation ratchetting features are not considered by them. Modified constitutive models of NiTi SMA have been proposed by Lagoudas and Entchev (2004), Auricchio et al. (2007), Zaki and Moumni (2007b), Hartl et al. (2010), Saint-Sulpice et al. (2009), Kan and Kang (2010), Morin et al. (2011b) and Saleeb et al. (2011), and the uniaxial transformation ratchetting can be reasonably predicted. The macro-phenomenological models are very suitable for the finite element implementation and then can be readily used in the structural analysis, but the microscopic physical nature of macroscopic deformation just can be indirectly reflected by the introduction of internal variables and their evolution rules here.

On the other hand, to reflect the microscopic physical natures of thermo-mechanical deformation of NiTi SMA in the constitutive model more directly, some micro-mechanical constitutive models have been constructed (e.g., Sun and Hwang, 1993a,b; Peng et al., 2008; and so on). Among of them, the crystal plasticity based constitutive models are popular (Huang and Brinson, 1998; Gao et al., 2000; Huang et al., 2000; Anand and Gurtin, 2003; Patoor et al., 2006; Wang et al., 2008; Manchiraju and Anderson, 2010). The crystal plasticity based models are constructed in the single crystal scale, and can be used to describe the thermo-mechanical deformation of polycrystalline alloy with the help of finite element method (FEM) or scale-transition rule. However, only a martensite transformation mechanism is considered in the crystal plasticity based models mentioned above. Recently, Thamburaja (2005) and Thamburaja et al. (2005) proposed a new crystal plasticity model to describe the shape memory effect of NiTi SMA by considering the martensite reorientation and detwinning. Also, the martensite reorientation mechanism is adopted by Yu et al. (2014) to describe the thermo-mechanical deformation of super-elastic NiTi SMA under the non-proportional multiaxial loading condition. However, the crystal plasticity based constitutive models (Huang and Brinson, 1998; Gao et al., 2000; Huang et al., 2000; Anand and Gurtin, 2003; Thamburaja, 2005; Thamburaja et al., 2005; Patoor et al., 2006; Wang et al., 2008; Manchiraju and Anderson, 2010; Yu et al., 2014) only focus on the thermo-mechanical behavior of NiTi SMA within one loading–unloading cycle, and then