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Phase transformation behavior of pseudoelastic NiTi shape memory alloys under large strain

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Abstract

Although it is known that the plastic deformation after transformation could stabilize martensite and make the transformation irreversible, there lacks a systematic research on the effect of plasticity on phase transformation behavior of NiTi shape memory alloys (SMAs). Therefore, the present study focuses on this aspect of NiTi SMAs. A series of tensile cycling experiments are performed on a NiTi SMA at room temperature. Attention has been paid to the characteristics of the phase transformation stresses, the residual and recoverable strain and the dissipated and recoverable energy density as functions of deformation cycles and maximum strain amplitude. With the increasing of plastic strain amplitude at the first loading cycle, the stress–strain curves reach a stable state sooner during cycling. It is concluded that a small amount of plastic strain at the first loading cycle is helpful to get good stable mechanical properties.

Keywords: NiTi shape memory alloys; Pseudoelasticity; Plasticity; Phase transformation

1. Introduction

Shape memory alloys (SMAs) are well known for its shape memory effect and pseudoelasticity. These behaviors are due to intrinsic solid to solid, diffusionless, displacive thermoelastic martensitic phase transformation at different temperatures. The near equiatomic Ni–Ti alloys are the most important practical SMAs because they combine superior shape memory and superelastic properties with excellent long fatigue life, good corrosion resistance and biocompatibility. Thermomechanical properties of NiTi shape memory alloys have been studied extensively [1–4].

The failure property is equally important in the use of NiTi SMA structures. The failure characteristics have become a popular topic recently. In order to investigate a non-linear drilling device, Takahiro et al. studied the structural fatigue of superelastic Ni–Ti wires using bending–rotation–fatigue (BRF) tests [5]. McKelvey and Ritchie carried out a series of experimental study on the growth of fatigue cracks in NiTi alloys [6,7]. The fracture mechanisms in single crystal and polycrystalline NiTi SMAs containing Ti_3Ni_4 precipitates were studied under tensile loading using the scanning electron microscope by Gall et al. [8]. Similar tensile fracture tests in polycrystalline NiTi SMAs were also carried out with detailed analysis of fracture surfaces by Chen et al. [9].

To study the failure property of NiTi SMA, it is important to understand their plastic deformation behavior. Plastic strain development during cyclic loading in stress induced phase transformation behavior of NiTi alloys has been investigated by Strnade et al. [10], Sehitoglu et al. [11] and Gall and Maier [12]. Brinson et al. observed localized plastic deformation after a few loading cycles via *in situ* optical microscopy [13]. Miller and Lagoudas studied the influence of plastic strain on the two-way shape memory effect [14]. In ref. [7], McKelvey and Ritchie have studied the influence of plasticity on superelastic properties of a NiTi SMA experimentally and found that plastic deformation after forward transformation could stabilize martensite and hinder the reverse transformation. It is acknowledged that after the stress-induced martensitic transformation plastic deformation of martensite via dislocation slip or deformation twinning takes place [15–17]. However, there are no systematical researches about the effect of plastic deformation after the stress induced

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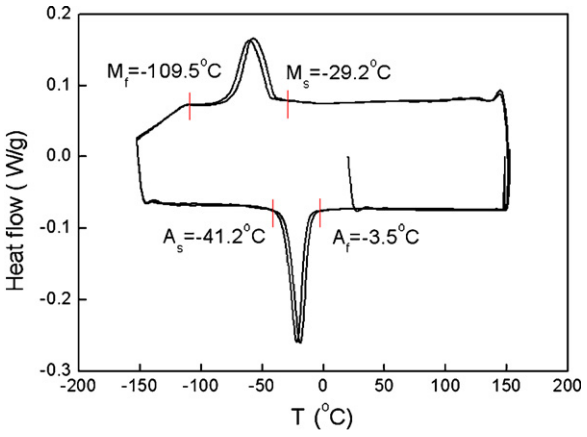

Fig. 1. DSC curves to determine the phase transformation temperatures.

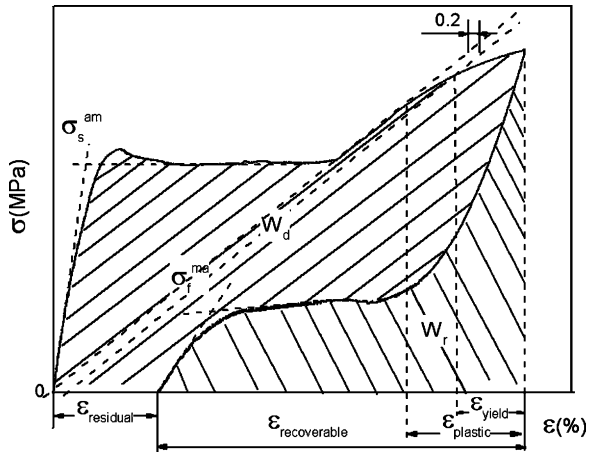

Fig. 2. Schematical drawing of stress–strain diagram showing σ_s^{am}: forward transformation start stress; σ_f^{ma}: reverse transformation finish stress; $\varepsilon_{residual}$: residual strain; $\varepsilon_{recoverable}$: recoverable strain; $\varepsilon_{plastic}$: plastic Strain; ε_{yield}: strain at yield strength w_d: dissipate energy; w_r: recoverable energy.

phase transformation on the mechanical behavior of NiTi shape memory alloys which is important not only to the functional property but also to the failure mechanism.

In the present study, tensile experiments are performed on polycrystalline NiTi SMAs with different maximum strains. The influences of plastic deformation after phase transformation as well as cycling on the mechanical properties of NiTi SMAs are investigated systematically.

2. Material and experiments

The composition of the studied material in this paper is 49.94 at.% Ni (55 wt.%). All the tensile experiments were carried out at room temperature of $T = 23\,^{\circ}C$ in an open testing environment.

The transformation behavior of the material was firstly assessed in terms of differential scanning calorimetry (DSC). Small piece of specimen (about 100 mg) was heated to 100 °C and held for 3 min to reach thermal equilibrium. Then, the specimen was heated and cooled at rates of 10 °C/min for two cycles. The DSC curve is shown in Fig. 1. The four characteristic phase transformation temperatures are: martensite phase transformation starting at $M_s = -29.2\,^{\circ}C$, martensite phase transformation finishing at $M_f = -109.5\,^{\circ}C$, austenite phase transformation starting at $A_s = -41.2\,^{\circ}C$, austenite phase transformation finishing at $A_f = -3.5\,^{\circ}C$. The DSC curve shows that there is no third phase (R phase typically) during the phase transformation. The low temperature of A_f guarantees the material in austenite phase at room temperature.

The specimen geometry for the tensile experiments is in plate form. After the manufacture of the specimens, they were held for 15 min at 350 °C and then quenched in water. This procedure is to eliminate the residual stress and the fraction of the martensite phase during machining.

Mechanical testing was performed using an Instron 8871 universal testing machine. All experiments were carried out under strain controlled cycling with different fixed maximum strain (from 5% to 12%). The strain rate $d\varepsilon/dt$ was $2 \times 10^{-4}\,s^{-1}$. Each test was taken trough to 30 cycles to arrive at a stable stress–strain hysteresis.

3. Results and discussion

Several characteristic elements in the stress–strain curves are defined in Fig. 2, namely, phase transformation stresses σ_s^{am} and σ_f^{ma}, residual strain $\varepsilon_{residual}$, recoverable strain $\varepsilon_{recoverable}$, plastic strain $\varepsilon_{plastic}$, strain amplitude corresponds to plastic yield strength ε_{yield}, dissipated work per unit volume w_d and recoverable strain energy density w_r. σ_s^{am} is the stress where the austenite to martensite transformation starts. σ_f^{ma} is the stress where the martensite to austenite transformation finishes. Plastic strain $\varepsilon_{plastic}$ refers to the plastic deformation of martensite phase after the phase transformation at the first cycle. ε_{yield} is defined the same as the plastic strain in ref. [7], which is corresponding to the 0.2% offset plastic yield stress of martensite phase.

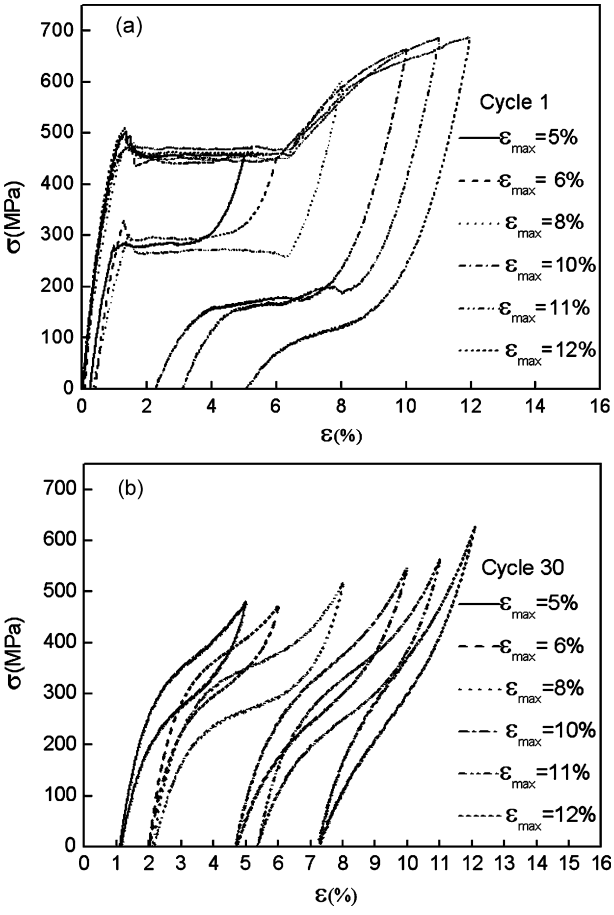

Fig. 3. Stress–strain curves during loading-unloading cycling with different maximum strain amplitude at (a) cycle 1 and (b) cycle 30.