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Constitutive equation and processing map of equiatomic NiTi shape memory alloy under hot plastic deformation

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Abstract: In order to describe the deformation behavior and the hot workability of equiatomic NiTi shape memory alloy (SMA) during hot deformation, Arrhenius-type constitutive equation and hot processing map of the alloy were developed by hot compression tests at temperatures ranging from 500 to 1100 °C and strain rates ranging from 0.0005 to 0.5 s^{-1}. The results show that the instability region of the hot processing map increases with the increase of deformation extent. The instability occurs in the low and high temperature regions. The instability region presents the adiabatic shear bands at low temperatures, but it exhibits the abnormal growth of the grains at high temperatures. Consequently, it is necessary to avoid processing the equiatomic NiTi SMA in these regions. It is preferable to process the NiTi SMA at the temperatures ranging from 750 to 900 °C.

Key words: NiTi alloy; shape memory alloy; hot plastic deformation; constitutive equation; hot processing map

1 Introduction

NiTi shape memory alloy (SMA) is a promising candidate for biomedical, control engineering and aerospace applications due to its excellent shape memory effect, superelasticity, corrosion resistance and mechanical properties [1−4]. Because of poor plasticity at room temperature, most high-quality products made from NiTi SMA should be subjected to hot deformation. It is very critical to reasonably control the process parameters in the case of hot deformation, so that high-quality products of NiTi SMAs are able to be obtained. Therefore, it is increasingly important to investigate the hot workability of NiTi SMA.

Over the recent decades, the concern for NiTi SMAs has been focusing on the thermo-mechanical processing, such as ausforming, marforming, severe plastic deformation and cold working followed by heat treatment [5−8]. Only a few literatures which involve hot deformation of NiTi SMAs can be found. In this regard, JIANG et al [9] investigated the hot deformation behavior of Ni−49.1%Ti (mole fraction) alloy and established the corresponding constitutive equation by hot compression tests. YEOM et al [10] optimized the hot forging process of Ni−49.6%Ti alloy by combining hot processing map with finite element method and obtained a sound NiTi billet without forging defects. SHAMSOLHODAEI et al [11] examined the constitutive behavior of Ni−49.9%Ti alloy through modified Zerillie−Armstrong and Arrhenius type models. MORAKABATI et al [12] developed the processing map of Ni−50.2%Ti alloy and determined the process parameters of NiTi alloy according to processing map.

However, all the above investigations are concerned with the near-equiatomic NiTi SMAs, which are either Ni-rich NiTi alloys or Ti-rich NiTi alloys. So far, few literatures which deal with constitutive equation and hot workability of the equiatomic NiTi SMA (Ti−50%Ni) have been found. Therefore, in the present study, the constitutive equation of hot deformation for the equiatomic NiTi SMA was investigated according to the compression tests, and the corresponding hot workability was studied on the basis of the hot processing map, which lays the foundations for obtaining the appropriate process parameters during hot deformation of equiatomic NiTi SMA.

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2 Experimental

The equiatomic NiTi SMA bar, which possessed nominal composition of Ni−50%Ti (mole fraction), was prepared by vacuum induction melting and subsequent hot rolling at 850 °C. Based on differential scanning calorimetry (DSC), the phase transformation temperatures of the NiTi alloy were determined as M_s=33.6 °C, M_f=10.8 °C, A_s=44.4 °C and A_f=70.7 °C. In order to obtain homogenous martensite structure, the NiTi alloy bar was held at 850 °C for 2 h and then quenched into the ice water. All the NiTi specimens used for experimental analysis were taken from the NiTi bar subjected to heat treatment along the longitudinal direction. The NiTi specimens for metallographic observation were etched in a solution with the composition of $V(HF):V(HNO_3):V(H_2O)$=1:2:5, and subsequently characterized by an OLYMPUS311 optical microscope. The NiTi specimens for TEM observation were thinned by twin-jet polishing in an electrolyte consisting of 34% $CH_3(CH_2)_3OH$, 6% $HClO_4$ and 60% CH_3OH by volume fraction. Subsequently, the NiTi specimens were characterized by TEM using an FEI TECNAI G2 F30 microscope. Figure 1 illustrates the microstructures of the NiTi bar subjected to heat treatment, where the equiaxed grains and the twin substructures can be observed. Twenty NiTi samples with the diameter of 4 mm and the height of 6 mm were used for compression tests. The tests were carried out on a INSTRON−5500R universal material testing machine. The samples were compressed by the deformation degree of 70% at the temperatures ranging from 500 to 1100 °C and the strain rates ranging from 0.0005 to 0.5 s^{-1}.

3 Results and discussion

3.1 Deformation behavior

Figure 2 illustrates the true stress–strain curves of the equiatomic NiTi SMA under compression at various temperatures and strain rates. It can be concluded that the true stress–strain curves exhibit the following characteristics. In the initial stage of the deformation, the true stress increases rapidly with the increase of the true stain. However, when the strain amounts to a certain value, the stress varies very slowly. Some of the curves decrease continuously, while others increase with the increase of the true strain and are followed by a period of decrease. The phenomenon is attributed to the competition between work hardening and dynamic softening of NiTi SMA. In the case of a constant deformation temperature, the true stress increases with the increase of the strain rate, which indicates that the equiatomic NiTi SMA is sensitive to the strain rate. Furthermore, the sensitivity at high temperatures is higher than that at low temperatures. In the case of a constant strain rate, the true stress decreases with the increase of the deformation temperature.

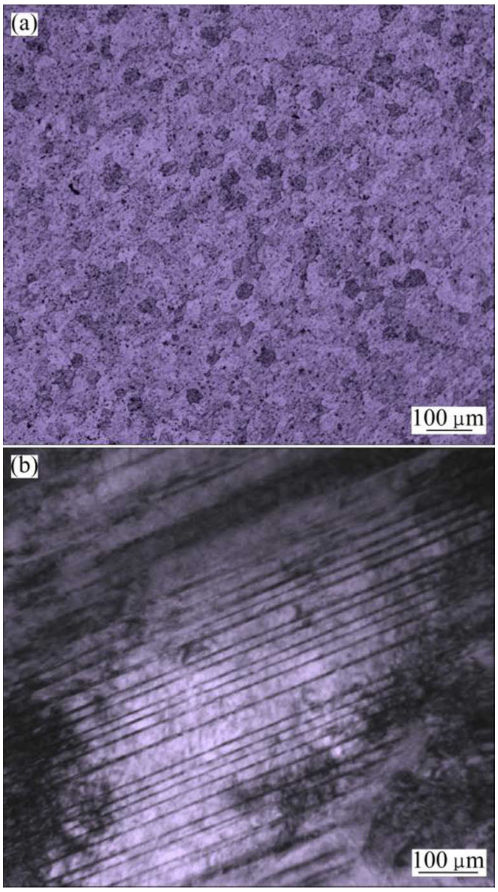

Fig. 1 Optical micrograph (a) and TEM image (b) of equiatomic NiTi SMA subjected to heat treatment

3.2 Constitutive equation

According to the true stress−strain curves of NiTi SMA at elevated temperature, the constitutive equation of NiTi SMA is established on the basis of the Arrhenius type equation [13,14]:

$$\dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, σ is the flow stress which is taken as the peak stress in the present study, R is the mole gas constant (8.314 J/(mol·K)), T is the thermodynamic temperature, Q is the activation energy, and α, A and n are the material constants.

In order to further obtain the aforementioned material constants on the basis of the experimental data, it is convenient to simplify Eq. (1) mathematically [9].

When the low stress level leads to $\alpha\sigma \le 0.8$, $\sinh(\alpha\sigma)=\alpha\sigma$ is approximately satisfied. As a consequence, Eq. (1) can be simplified as