Materials and Design 35 (2012) 184–193

Contents lists available at SciVerse ScienceDirect

Materials and Design

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

Constitutive equation for elevated temperature flow behavior of TiNiNb alloy based on orthogonal analysis

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ARTICLE INFO

Article history:
Received 13 June 2011
Accepted 20 September 2011
Available online 28 September 2011

Keywords:
A. Non-ferrous metals and alloy
F. Constitution
F. Plastic behavior

ABSTRACT

The high-temperature deformation behaviors of as-cast and as-forged TiNiNb shape memory alloy under compression in the temperature range of 923–1323 K and strain rate range of 0.01–10 s^{-1} have been investigated with the view to acquiring the optimum hot deformation processing parameters. By the application of orthogonal experiment and variance analysis, the significance of the effects of strain, strain rate, deformation temperature as well as interaction between strain rate and deformation temperature on flow stress are evaluated, and the results indicate that the effect of interaction between strain rate and deformation temperature can be neglected in comparison with other factor. Thereafter, on the basis of the conclusions of orthogonal analysis, a new constitutive equation incorporating the effects of strain, strain rate and deformation temperature has been established. The developed constitutive equation enables to predict the flow stress accurately throughout the entire domain of temperature and strain rate, excepting at 973 K in 0.1 s^{-1} and 10 s^{-1} for as-cast TiNiNb alloy and at 923 K in 0.1 s^{-1} and 1 s^{-1} for as-forged TiNiNb alloy.

1. Introduction

TiNiNb alloys as the most well-known shape memory alloys have been paid considerable attention on during recent years, since it can exhibit excellent mechanical properties and a wide transformation hysteresis, which makes them highly attractive for many engineering applications such as sealing and pipe coupling [1–5]. Zhao et al. [6] have studied NiTiNb alloys with 4.5 at.% Nb and pointed out that the addition of Nb dissolved in NiTi matrix is the major reason for the wide hysteresis. Moreover, parts made of TiNiNb alloys can be conveniently stored and transported at ambient temperature in the martensitic condition without the use of liquid nitrogen [2,3]. TiNiNb alloys also possess a better ductility at elevated temperature. Yang et al. [7] revealed that as the deformation temperature comes up to 673 K or even above, its tensile strength will rapidly decrease and its elongation rate will sharply increase. Nevertheless, it could be found that the earlier studies about TiNiNb alloys were rarely focused on their high-temperature flow behavior. Therefore, with the purpose to improve the forging technology of TiNiNb alloys and accurately control the deformation processes, flow behaviors of TiNiNb alloys at elevated temperature should be studied in detail.

High temperature flow behavior, as the macro-reflection about the mechanisms of microscopic deformation and microstructure evolution, is often represented by making use of constitutive model. In the past recent years, several phenomenological and physically-based constitutive models have been proposed, and that phenomenological models mainly consist of Arrhenius model, Zerilli–Armstrong model and Johnson–Cook model and so on [8]. Amongst the phenomenological models, the sine-hyperbolic law in Arrhenius equation has been widely applied for engineering application. Such as a modified sine hyperbolic Arrhenius equation considering the compensation of strain and strain rate, which had been employed to predict high temperature flow behavior of 42CrMo steel by Lin et al. [9]. In the meantime, Lin et al. [10] have also proposed a modified Johnson–Cook model which takes into account the coupled effects of strain, strain rate and deformation temperature to describe the tensile behaviors of typical high-strength alloy steel. However, the physically-based models involve a large number of unidentified material constants so that they are not preferred to the user [11].

The objective of this investigation is to construct the constitutive model amongst flow stress, strain, strain rate and deformation temperature to predict high temperature flow behaviors of as-cast and as-forged TiNiNb shape memory alloy. To achieve this aim, a series of isothermal hot compression tests have been conducted in several different strain rates and temperatures. On the basis of orthogonal experiment and variance analysis, the comprehensive

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doi:10.1016/j.matdes.2011.09.044

Table 1
Chemical composition of as-cast and as-forged TiNiNb alloys (mass fraction in %).

Ti	Ni	C	O	Nb
36.08	51.20	0.004	0.022	Bal.

constitutive equation for as-cast and as-forged TiNiNb shape memory alloys incorporating the effects of strain, strain rate and deformation temperature have been derived from the experimental stress–strain data, respectively. Finally, the validity of descriptive results calculated from the proposed constitutive equation has also been checked.

2. Experimental procedures

Two states TiNiNb alloy employed in this study, as-cast TiNiNb alloy and as-forged TiNiNb alloy, have the same chemical composition which has been given in Table 1. In addition, the original microstructures of these two states TiNiNb alloy are exhibited in Fig. 1.

Cylindrical specimens with a diameter of 8 mm and a height of 12 mm were machined to carry out compression testing. Before this, as-cast TiNiNb alloy had been conducted three hours annealing treatment at temperature of 1173 K. In order to minimize the friction between specimens and die during the compression tests, the flat ends of the specimens were recessed a depth of 0.2 mm groove to entrap the lubricant such as graphite or machine oil.

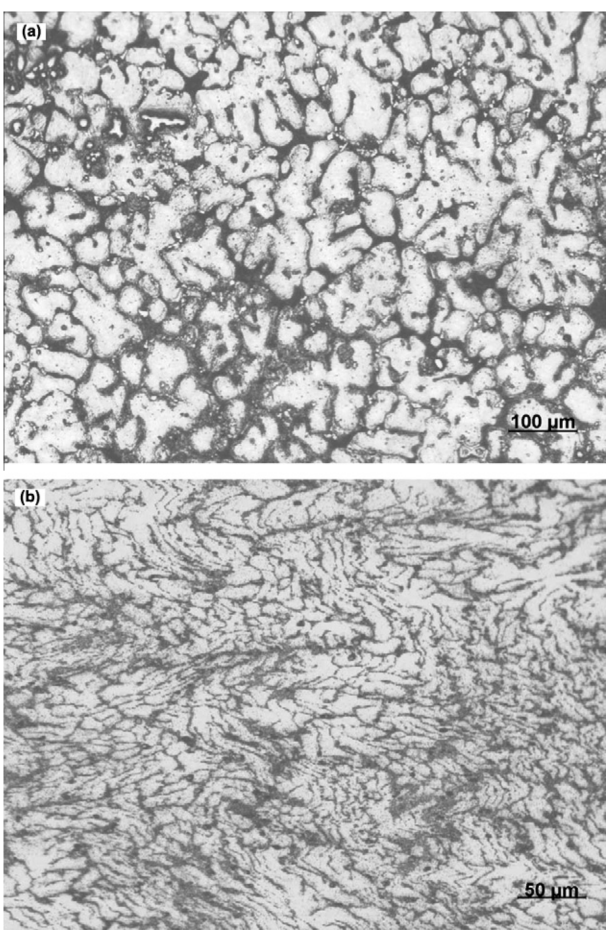

Fig. 1. The original microstructure of (a) as-cast TiNiNb alloy, (b) as-forged TiNiNb alloy.

The isothermal hot compression experiments were performed on a Gleeble-1500D thermo-simulation machine in the temperature range of 973 K-1323 K and the strain rate range of 0.01–10 s^{-1} for as-cast specimens, as well as in the temperature range of 923–1323 K and the strain rate range of 0.1–10 s^{-1} for as-forged specimens. Each specimen was heated to deformation temperature at a rate of 10 K/s^{-1} and held for 3 min at isothermal condition so as to obtain a uniform temperature. After testing, the height of compressed specimens reduced by range from 10% to 50% and the specimens were blown rapidly to room temperature.

3. Experimental results and analysis

3.1. Flow stress

The experimental flow stress curves of as-cast and as-forged TiNiNb shape memory alloy at different strain rates are shown in Figs. 2 and 3, respectively. It could be observed from Figs. 2 and 3 that the flow curves of these two states TiNiNb alloy have similar characteristics. In the initial stage, the flow stress increases quickly with the increasing of strain and then reaches a peak value. Subsequently, the flow stress sharply decreases to a steady state under some deformation conditions, whereas the others descend up to high strains. Prasad et al. [12] have given insight into the hot deformation flow behavior of as-cast nickel aluminide alloy and indicated that the occurrence of steady flow implies that the dynamic softening effect is sufficient to counteract the work hardening effect in these two states alloy. On the other side, that the flow stress declines to the last may be attributed to dynamic recrystallization, cracking and flow instability happened during the deformation process. During the isothermal compression tests of as-cast TC21 titanium alloy, Zhu et al. [13] also observed a rapid drop in flow stress with strain under all deformation temperatures and proclaimed that it was attributed to adiabatic heating, dynamic recrystallization or flow instability. Additionally, it also can be found in Figs. 2 and 3 that the flow stress increases with the increasing of strain rate at certain deformation temperature, and decreases with the increasing of deformation temperature at certain strain rate.

As illustrated in Fig. 4a and b, it can be seen that dynamic recrystallization phenomenon has been occurring in as-cast TiNiNb specimen at 1323 K and 10 s^{-1} with deformation degree of 30% as well as at 1323 K and 0.01 s^{-1} with deformation degree of 50%, as shown at the arrow; however, it is unable to find out any distinct microstructures of dynamic recrystallization in Fig. 4c. Similarly, Fig. 5a suggests that as-forged TiNiNb specimen gets a complete dynamic recrystallization at 1323 K and 0.1 s^{-1} with deformation degree of 50%. Moreover, it can be seen from Fig. 5b that as-forged TiNiNb sample is undergoing dynamic recrystallization under the deformation condition of 1223 K and 1 s^{-1} with deformation degree of 30%. Nevertheless, there is no obvious dynamic recrystallization grains emerged in Fig. 5c.

3.2. Orthogonal analysis

In order to estimate the significance of the effect of strain, strain rate, temperature and interaction between strain rate and temperature, some values of flow stress corresponding to the deformation conditions shown in Table 2 about two states TiNiNb alloy have been introduced to support the orthogonal experiment. A orthogonal test table (L32($8^1 * 4^8$)) has been adopted, and the impact factors as well as the program of orthogonal experiment are separately given in Tables 2 and 3. Moreover, Table 3 also provides the values of flow stress responding to the relevant deformation conditions, and flow stress will be taken as objective function to