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Constitutive behavior of Ni-Ti shape memory alloy under hot compression

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Abstract: Constitutive behavior of nickel-titanium shape memory alloy (Ni-Ti SMA) under hot deformation was investigated by means of the compression tests and the linear fitting method. Based on the true stress–strain curves of Ni-Ti SMA under compression at the strain rates of 0.001–1 s^{-1} and at the temperatures ranging from 600 to 1 000 ºC, the constitutive equation of Ni-Ti SMA with respect to the Zener-Hollomon parameter was established according to the high stress level and the low stress level at various temperatures so as to more accurately describe the deformation behavior of Ni-Ti SMA during hot working. Dynamic recovery and dynamic recrystallization of Ni-Ti SMA occur under hot compression, which lays the theoretical foundation for understanding the constitutive behavior of Ni-Ti SMA.

Key words: Ni-Ti alloy; shape memory alloy; constitutive behavior; microstructural evolution; hot deformation

1 Introduction

The remarkable attractiveness of nickel-titanium shape memory alloy (Ni-Ti SMA) comes from its shape memory effect as well as superelasticity, which plays a significant role in application of Ni-Ti SMA in engineering fields [1]. It is well known that chemical composition, working history and heat treatment have an important influence on shape memory effect and superelasticity of Ni-Ti SMA [2–6]. In particular, hot working methods based on plastic deformation, such as hot rolling, hot forging, hot extrusion, and hot drawing, are the necessary means to cause as-cast Ni-Ti ingots to be made into Ni-Ti bar, sheet, strip, tube and wire. The profound understanding of flow rule and constitutive behavior of Ni-Ti SMA during hot plastic deformation is of great importance in obtaining the perfect workability and manufacturing the qualified product [7–10]. KHAMEI and DEHGHANI investigated constitutive behavior of Ni_{60}-Ti_{40} (mass fraction, %) alloy at the temperatures ranging from 950 ºC to 1 050 ºC and at the strain rates of 0.001–0.35 s^{-1}, and established the constitutive equation in terms of the Zener-Hollomon parameter, where the activation energy and the stress exponent were determined as 251 kJ/mol and 2.233, respectively [11–13]. MORAKABATI et al devoted themselves to obtaining the constitutive behavior of $Ni_{49.8}$-$Ti_{50.2}$ (molar fraction, %) alloy at the broader temperature ranging from 700 to 1 000 ºC and at the broader strain rate range from 0.001 to 1 s^{-1} and simultaneously established the constitutive equation expressed by the Zener-Hollomon parameter, where the activation energy is 261 kJ/mol, which approximates to the result by KHAMEI and DEHGHANI, but the stress exponent is determined as 7.33 and is rather higher [14–15].

In the present work, constitutive behavior of Ni-Ti SMA under hot deformation was investigated by means of the compression tests and the linear fitting method according to the true stress–strain curves under compression at the strain rates of 0.001–1 $s^{-1}$and at the temperatures ranging from 600 to 1 000 ºC.

2 Materials and method

The Ni-Ti alloy with a nominal composition of $Ni_{50.9}Ti_{49.1}$ (molar fraction, %) was prepared by means of vacuum induction melting method, and was then rolled at 800 ºC, and drawn to the Ni-Ti bar with the diameter of 12 mm at 400 ºC. The Ni-Ti bar was heated to 850 ºC and held for 2 h, followed by quenching into the ice water. The Ni-Ti samples with the diameter of 4 mm and the height of 6 mm which were cut from the solutionized Ni-Ti bar by means of electro-discharge machining (EDM) were used for the compressive tests at the various

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strain rates as well as at the various temperatures and then were quenched into water at room temperature. The compression deformation degree is 70%. The compressive tests were carried out on INSTRON-5500R in the atmosphere. The microstructures of the uncompressed and compressed Ni-Ti samples were observed by means of optical microscopy. All the specimens were etched in a solution consisting of 10%HF, 40%HNO_3 and 50%H_2O by volume fraction.

3 Results and discussion

3.1 Deformation behavior

Figure 1 illustrates the true stress–strain curves of Ni-Ti alloy under compression at the strain rates of 0.001–1 s^{-1} and at the temperatures ranging from 600 ºC to 1 000 ºC. It can be seen from Fig. 1 that the flow stresses of Ni-Ti alloy increase with the strain rates and decrease with the deformation temperatures, which indicates that Ni-Ti alloy is sensitive to the strain rates at high temperatures. Furthermore, it can be deduced from the features of the true stress–strain curves of Ni-Ti alloy that Ni-Ti alloy under compression at elevated temperatures is characterized by dynamic recovery or dynamic recrystallization.

3.2 Microstructural evolution

The knowledge of microstructural evolution lays the foundations for understanding the deformation behavior of Ni-Ti alloy under compression at high temperature. Figure 2 shows the microstructure of uncompressed Ni-Ti sample which exhibits a characteristic of the equiaxed grains. Figure 3 illustrates the microstructures of the compressed Ni-Ti samples at the strain rate of 0.01 s^{-1} at the temperatures of 600 ºC, 650 ºC, 800 ºC and 950 ºC, respectively. It can be seen from Fig. 3 that the microstructures of the compressed Ni-Ti samples at 600 ºC and 650 ºC are mainly dominated by dynamic recovery, where the grains are elongated considerably; but at 650 ºC, the recrystallized grains occur in the elongated grains, which reveals that dynamic recovery and dynamic recrystallization exist simultaneously. However, the complete dynamic recrystallization arises in the compressed Ni-Ti samples at 800 ºC and 950 ºC, and the recrystallized grains at 950 ºC are much larger than those at 800 ºC. In the present work, microstructural evolutions of Ni-Ti alloy under compression at several typical temperatures are selected to demonstrate that the constitutive behavior of Ni-Ti alloy is used for describing dynamic recovery and dynamic recrystallization.

3.3 Constitutive equation

It can be clearly seen from the true stress–strain curves of Ni-Ti alloy at elevated temperature that the flow behavior of Ni-Ti alloy under hot deformation depends on the strain rates as well as the deformation temperatures. It is necessary to establish the constitutive equation in order to obtain mathematical description of the constitutive behavior of Ni-Ti alloy at high temperature. The constitutive equation of Ni-Ti alloy is based on the Arrhenius type equation [16], namely:

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

where $\dot{\varepsilon}$ is the strain rate, σ is the flow stress, T is the absolute temperature, Q is the activation energy, R is the universal gas constant (8.314 $J\cdot mol^{-1}\cdot K^{-1}$), and A, α and n are the material constants.

In order to further obtain the material constants in Eq. (1) according to the experimental data, it is necessary to simplify Eq. (1) mathematically. Figure 4 shows the curves of such functions as Y=sinh(X), Y=X and Y=exp(X)/2. It can be seen from Fig. 4 that when X ranges from 0 to 1, $\sin(X) \cong X$; when X ranges from 1.2 to +∞, $\sin(X) \cong \exp(X)/2$. Therefore, Eq. (1) can be appropriately simplified according to the stress values.

When the low stress level leads to $\alpha\sigma$<1, Eq. (1) can be simplified as

$$\dot{\varepsilon} = A_1\sigma^n \exp(-\frac{Q}{RT}) \quad (2)$$

where A_1 remains the material constant and $A_1=A\alpha^n$.

When the high stress level results in $\alpha\sigma$>1.2, Eq. (1) can be approximately expressed as

$$\dot{\varepsilon} = A_2 \exp(\beta\sigma)\exp(-\frac{Q}{RT}) \quad (3)$$

where A_2 and β remain the material constant and $A_2 = A/2^n$, $\beta=n\alpha$.

Only if the values of A, α, n and Q can be determined according to the experimental data can the constitutive equation of Ni-Ti alloy be obtained.

According to the peak stress values as shown in Fig. 1, it is assumed that the flow stress belongs to the high level at 600 ºC, 650 ºC and 700 ºC, but the flow stress belongs to the low level at 900 ºC, 950 ºC and 1 000 ºC.

To obtain the value of n, the natural logarithm of Eq. (2) results in Eq. (4):

$$\ln\dot{\varepsilon} = \ln A_1 + n\ln\sigma - \frac{Q}{RT} \quad (4)$$

It can be seen from Eq. (4) that n is the linear proportion factor of $\ln\dot{\varepsilon}$ with respect to $\ln\sigma$ and thus can be determined by the slope of the lines which are obtained via linear fitting method in Fig. 5. The value

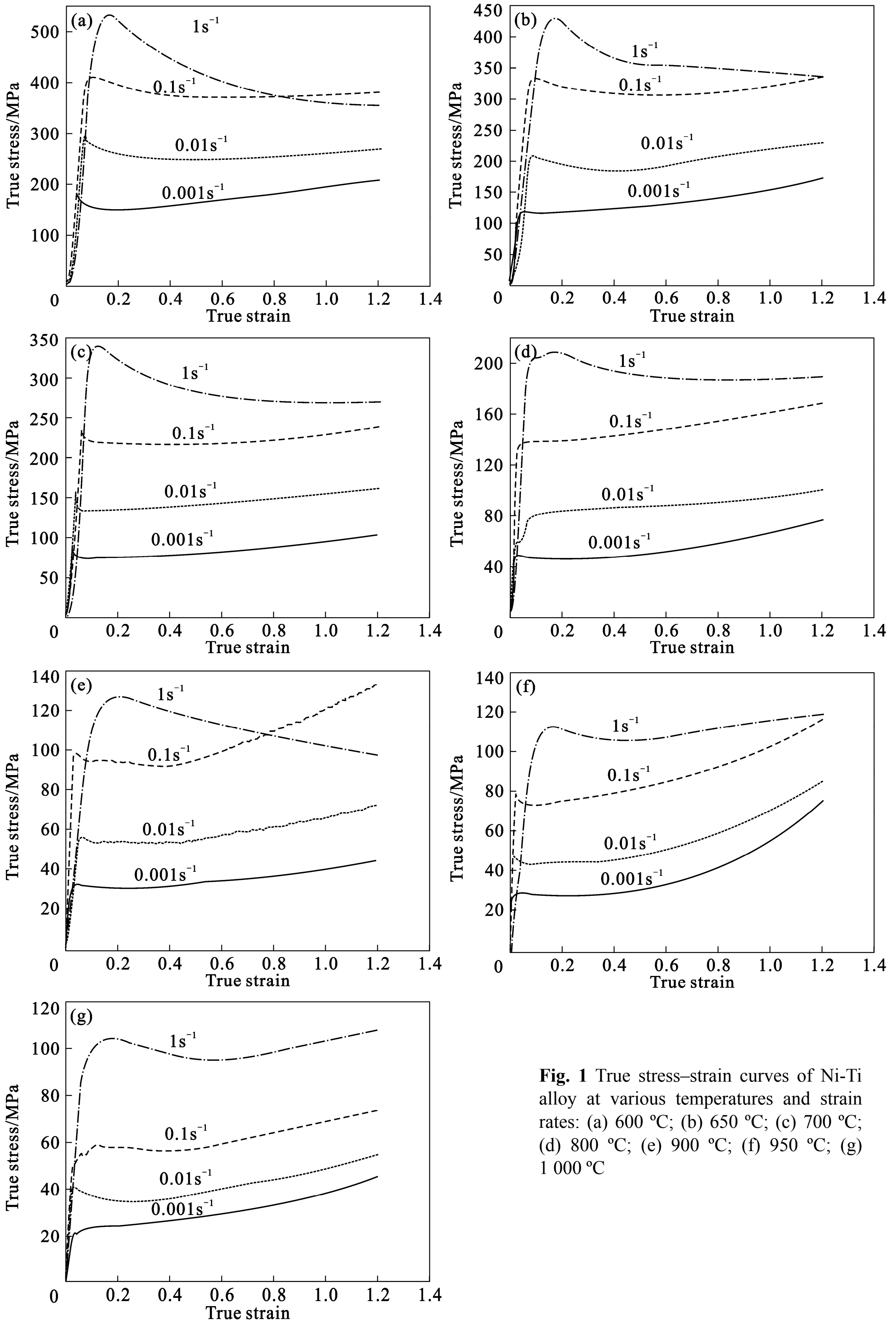

Fig. 1 True stress–strain curves of Ni-Ti alloy at various temperatures and strain rates: (a) 600 ºC; (b) 650 ºC; (c) 700 ºC; (d) 800 ºC; (e) 900 ºC; (f) 950 ºC; (g) 1 000 ºC

of n is calculated as the average values of slope of the lines at different deformation temperatures and thus is determined as 4.868 22.

In the same manner, in order to obtain the value of α, the value of β is firstly determined according to the natural logarithm of Eq. (3), which leads to Eq. (5):

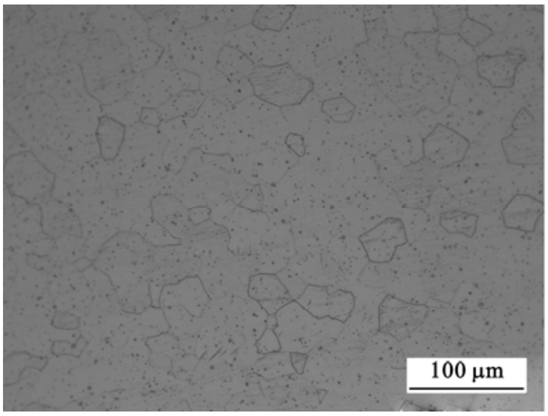

Fig. 2 Microstructure of uncompressed Ni-Ti sample

$$\ln\dot{\varepsilon} = \ln A_2 + \beta\sigma - \frac{Q}{RT} \tag{5}$$

Equation (5) indicates that β is the linear proportion factor of $\ln\dot{\varepsilon}$ with respect to σ which can be determined by the slopes of the lines which are obtained via linear fitting method in Fig. 6. The value of β is computed as the average value of slope of the lines at different deformation temperatures and thus is determined as 2.28×10^{-2} MPa^{-1}. As a result, the value of α can be obtained by combining the values of n and β, namely $\alpha = \beta / n = 4.7\times10^{-3}\,\text{MPa}^{-1}$.

To obtain the value of Q, the natural logarithm of Eq. (1) results in the following equation:

$$\ln\dot{\varepsilon} = \ln A + n\ln[\sinh(\alpha\sigma)] - \frac{Q}{RT} \tag{6}$$

Based on Eq. (6), the value of n is modified as the linear proportion factor of $\ln\dot{\varepsilon}$ with respect to $\ln[\sinh(\alpha\sigma)]$. The value of n is determined as 4.262 11 in accordance with the average value of slope of the lines at all the different deformation temperatures as shown in Fig. 7.

For the given strain rates, differentiating T^{-1} in Eq. (6) results in Eq. (7):

$$Q = nR\left(\frac{\partial \ln[\sinh(\alpha\sigma)]}{\partial T^{-1}}\right)_{\dot{\varepsilon}} \tag{7}$$

The value of Q can be calculated as $230.032\,45\times10^3$ J·mol^{-1} by combining the values of n and R with the average value of slope of all the lines at the different strain rates as shown in Fig. 8.

In general, the Zener-Hollomon parameter, Z, stands for the comprehensive influence of the strain rate and the temperature on the flow stress of the metal materials during hot deformation and is expressed as follows:

$$Z = \dot{\varepsilon}\exp(\frac{Q}{RT}) \tag{8}$$

Substitution of Eq. (8) into Eq. (1) results in

$$Z = A[\sinh(\alpha\sigma)]^n \tag{9}$$

The natural logarithm of Eq. (9) results in

$$\ln Z = \ln A + n\ln[\sinh(\alpha\sigma)] \tag{10}$$

According to Eq. (10), the value of ln$A$ is the intercept of the fitting line of ln$Z$ with respect to $\ln[\sinh(\alpha\sigma)]$ on the ln$Z$ coordinate axis as shown in Fig. 9 and thus is determined as 24.687 67, so the value of A is further determined as $5.268\,89\times10^{10}$ s^{-1}.

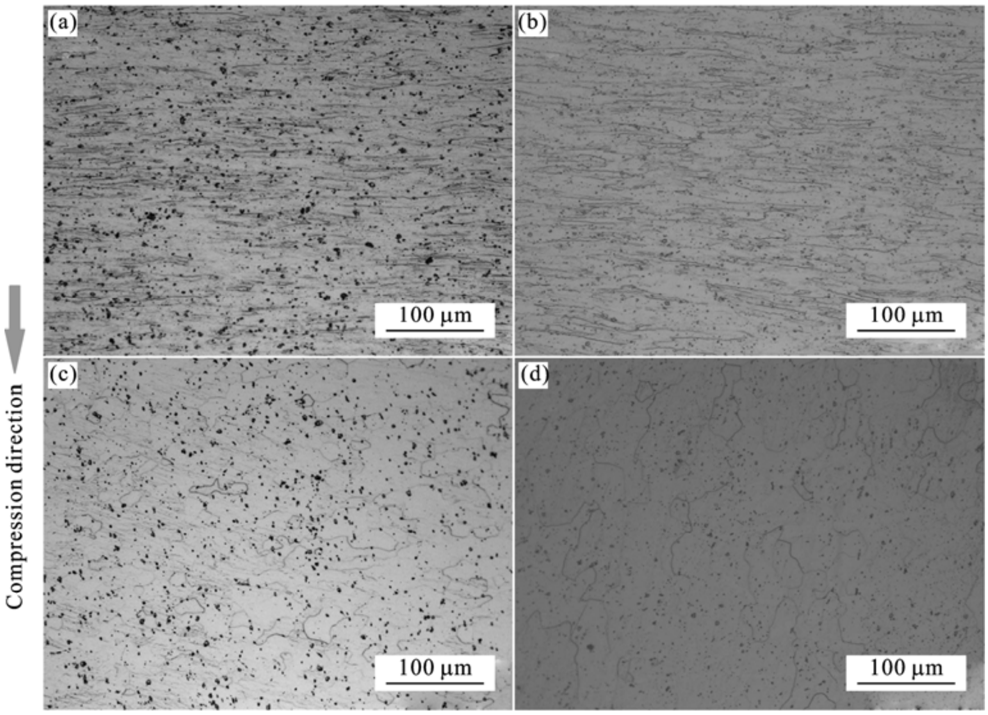

Fig. 3 Microstructures of compressed Ni-Ti samples at strain rate of 0.01 s^{-1}: (a) 600 ºC; (b) 650 ºC; (c) 800 ºC; (d) 950 ºC

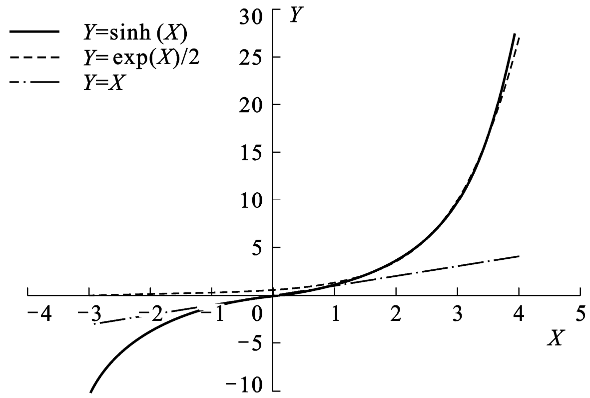

Fig. 4 Functional curves of Y=sin(X), Y=X, and Y=exp(X)/2

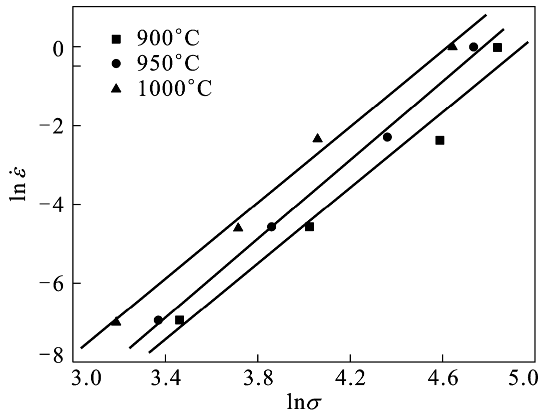

Fig. 5 Relationship between $\ln\dot{\varepsilon}$ and lnσ at low stress level

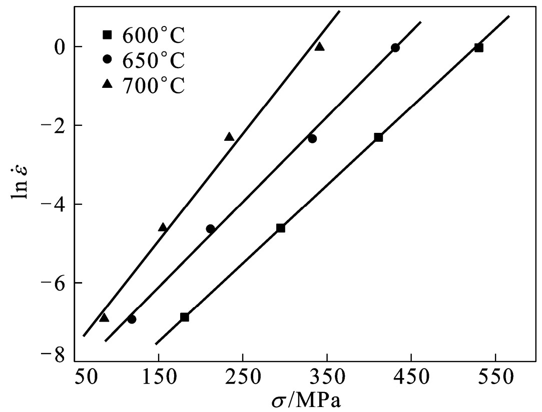

Fig. 6 Relationship between $\ln\dot{\varepsilon}$ and σ at high stress level

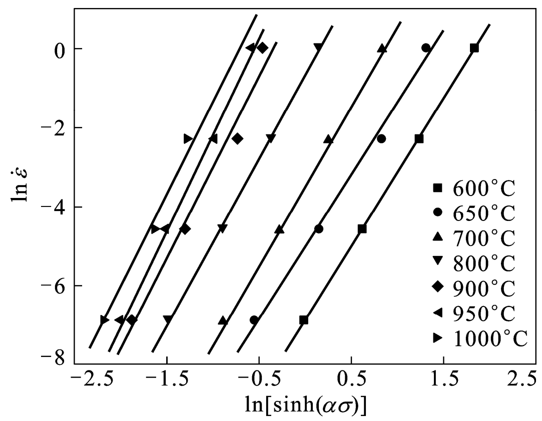

Fig. 7 Relationship between $\ln\dot{\varepsilon}$ and ln[sinh($\alpha\sigma$)] at all deformation temperatures

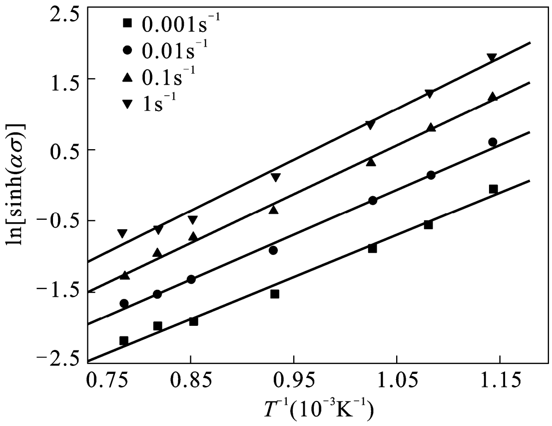

Fig. 8 Relationship between $\ln[\sinh(\alpha\sigma)$ and T^{-1} at different strain rates

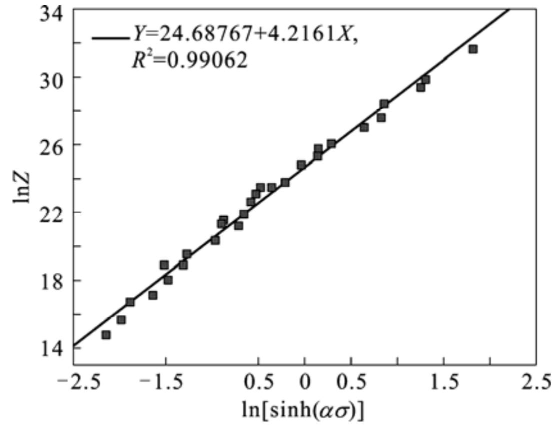

Fig. 9 Relationship between ln$Z$ and ln[sinh($\alpha\sigma$)]

By substituting the values of A, α, n and Q into Eq. (1), the constitutive equation of Ni-Ti alloy is expressed as follows:

$$\dot{\varepsilon}=5.268\ 89\times10^{10}[\sinh(4.7\times10^{-3}\sigma)]^{4.262\ 11}\times \exp\left(\frac{-2.300\ 324\ 5\times10^{5}}{RT}\right) \tag{11}$$

According to Eq. (9), the following formulation can be obtained:

$$\sinh(\alpha\sigma)=(\frac{Z}{A})^{1/n} \tag{12}$$

Furthermore, the hyperbolic sinh($\alpha\sigma$) can be transformed into the following expression:

$$\sinh(\alpha\sigma)=\frac{\exp(\alpha\sigma)-\exp(-\alpha\sigma)}{2}=\frac{[\exp(\alpha\sigma)]^2-1}{2\exp(\alpha\sigma)} \tag{13}$$

By combining Eq. (12) with Eq. (13), the following equation can be obtained:

$$[\exp(\alpha\sigma)]^2-2(\frac{Z}{A})^{1/n}\exp(\alpha\sigma)-1=0 \tag{14}$$

By referring to exp($\alpha\sigma$) as the variable, solving

Eq.(14) results in

$$\exp(\alpha\sigma)=\left[(\frac{Z}{A})^{1/n}+\sqrt{(\frac{Z}{A})^{2/n}+1}\right] \tag{15}$$

Equation (15) can be further expressed as follows:

$$\sigma=\frac{1}{\alpha}\ln\left[(\frac{Z}{A})^{1/n}+\sqrt{(\frac{Z}{A})^{2/n}+1}\right] \tag{16}$$

In terms of the Zener-Hollomon parameter Z, the constitutive equation of Ni-Ti alloy is expressed by

$$\sigma=212.765\ 96\ \ln\left\{\left(\frac{Z}{A}\right)^{1/4.262\ 11}+\sqrt{\left(\frac{Z}{A}\right)^{2/4.262\ 11}+1}\right\} \tag{17}$$

Compared to the results obtained by KHAMEI and MORAKABATI, the constitutive equation of Ni-Ti alloy in this work is established in the broader temperature range and the involved parameters are obtained according to the low stress level and the high stress level in Eq. (2) and Eq. (3), respectively. Furthermore, the value of the stress exponent is greater than that by KHAMEI, but is less than that by MORAKABATI. KHAMEI obtained a low value of stress exponent of 2.233, which better describes the dynamic recrystallization mechanism of Ni-Ti alloy. MORAKABATI obtained a high value of stress exponent of 7.33 which is greater than 5, which indicates that the dynamic recovery mechanism can be dominant during hot deformation of Ni-Ti alloy. In this work, the constitutive equation of Ni-Ti alloy with the value of stress exponent of 4.262 11 describes the flow behavior of Ni-Ti alloy during hot deformation based on dynamic recovery and dynamic recrystallization.

4 Conclusions

1) The true stress–strain curves of Ni-Ti alloy under compression at the strain rates of 0.001–1 s^{-1} and at the temperatures ranging from 600 to 1 000 ºC demonstrate that Ni-Ti alloy is sensitive to the strain rate and is characterized by dynamic recovery and dynamic recrystallization, which is validated by means of microstructural evolution as well.

2) Based on the experimental data and the linear fitting method, the constitutive equation of Ni-Ti alloy in hot deformation is established in terms of the Zener-Hollomon parameter by dividing the flow stress into the high stress level and the low stress level according to different temperatures. The constitutive equation lays the profound foundations for simulating hot plastic deformation of Ni-Ti alloy and investigating its hot workability.

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