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Thermal activation parameters of V−5Cr−5Ti alloy under hot compression

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Abstract: In order to well understand the elementary mechanisms that govern the hot working process of a V−5Cr−5Ti alloy (mass fraction, %), thermal activation parameters under compression were measured in a temperature range of 1373−1673 K by a Gleeble−3800 system. The results show that the stress exponent n is 4.87 and the activation energy Q is 375.89 kJ/mol for the power law equation. The activation energy is determined as 288.34 kJ/mol, which is close to the self-diffusion energy of alloy (270−300 kJ/mol) by introducing a threshold stress(σ_0) variable. The typical values of physical activation volume (V_p) and strain rate sensitivity (m) are measured as (120−700) b^3 and 0.075−0.122, respectively, by the repeated stress relaxation tests. These activation parameters indicate that the rate controlling mechanism for V−5Cr−5Ti alloy compressed in ranges of 1373−1673 K and 0.001−1.0 s^{-1} is the dislocation climb by overcoming of forest dislocations.

Key words: V−5Cr−5Ti alloy; hot compression; thermal activation; dislocation climb

1 Introduction

Researches on the high temperature deformation mechanism of V−Cr−Ti alloy, which has been investigated as the potential fusion reactor first-wall blankets over several years, are mainly on the thermal creep [1−6]. The thermal activation parameters, such as activation energy and activation volume, are very important to understand the elementary mechanisms. It is well accepted that the predominant creep mechanism in V−(4−5)Cr−(4−5)Ti alloy between 600−850 °C is climb-assisted glide of dislocations [1−4]. The reported activation energy Q is 180−326 kJ/mol [1−3,5,6] and the stress exponent n is in the range of 2.7−8.0 [1,3,5], depending on the materials and testing methods used. On the other hand, LI et al [7], GUBBI and ROWCLIFFE [8] measured the activation energies of static recrystallization for V−(4−5)Cr−(4−5)Ti alloy are 261.91−289.67 kJ/mol and 576 kJ/mol, respectively.

It is believed that both creep and hot working can share the same dislocation motion mechanism which governs plasticity. The temperature dependent flow stress reflects the interaction of dislocations with energy barriers, which are mostly thermal activated [9]. While, insufficient data are available in the temperatures of 1373−1573 K, which are the typical temperatures for the hot working of V−Cr−Ti alloy [10]. In order to well understand the elementary mechanisms that govern the hot working process of alloy, it is necessary to determine thermal activation parameters of V−5Cr−5Ti alloy during hot working.

The present paper is intended to determine the activation energy Q and activation volume V of a V−5Cr−5Ti alloy in the range of 1373−1673 K by hot compression experiments, including constant strain rate test and transient test.

2 Experimental

A piece of vertical section disk (d120 mm × 50 mm) was cut from a hot isostatic pressed (HIP-ed) V−5Cr−5Ti ingot. Its chemical composition is V−5.12Cr−4.87Ti−0.056O (mass fraction, %). A series of cylindrical specimens, d8 mm × 12 mm, were cut from the sheet by electrical discharge machine and lathe [11]. The mean grain size of specimen is about 860 μm. The hot compression test was performed on a Gleeble−3800 system (Dynamic Systems Inc., USA) in an argon atmosphere (99.999%, ~0.09 MPa).

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Two kinds of experiment were carried out. The first kind of test is the constant strain rate compression at three strain rates (0.01, 0.1, and 1 s^{-1}) and five temperatures (1423, 1473, 1523, 1573, 1673 K) to a true strain level of 0.5. The second experiments are transient test, including strain rate jump and stress relaxation at four temperatures (1373, 1473, 1573 and 1673 K), which were performed near the yield point. For the strain rate jump tests, the applied strain rate was changed from 0.001 to 0.01 s^{-1}. For the repeated stress relaxation tests, two applied strain rates (0.001 and 0.01 s^{-1}) were performed for comparison, and the relaxation time of each cycle is 30 s and 5−6 cycles were adopted in each test. The compression axial (CA) direction is along the axial of specimen.

Transmission electron microscopy (TEM, FEI TF 20) was used to identify the Ti-(CNO) phase. The as-received sheet was machined, polished and cut to *d*3 mm foils. The foil specimen was final thinned by electronic two-jet method under DC 20 V, 20 mA. The composition of solution is 15% H_2SO_4 + 85% H_2O (volume fraction).

3 Results and discussion

3.1 Activation energy and stress exponent

3.1.1 Apparent constitutive analysis

For hot working, the phenomenological hyperbolic sine constitutive model combined with Zenner−Hollommon parameter (Z), Eq. (1), is well known to predict the flow stress and to evaluate the apparent activation energy [11−14]. In general, Eq. (1) can be simplified to Eqs. (2) and (3) for low stress level (power law) and high stress level (exponential law), respectively.

$$Z = \dot{\varepsilon}\exp[Q_a/(RT)] = A\sinh(\alpha\sigma)^n \quad (1)$$

$$\dot{\varepsilon}\exp[Q_a/(RT)] = A_1\sigma^{n_1} \quad \text{for} \quad \alpha\sigma < 0.8 \quad (2)$$

$$\dot{\varepsilon}\exp[Q_a/(RT] = A_2\exp(\beta\sigma) \quad \text{for} \quad \alpha\sigma > 1.2 \quad (3)$$

where $\dot{\varepsilon}$ is the strain rate (s^{-1}), R is the universal gas constant, T is the thermodynamic temperature (K), Q_a is the apparent activation energy for hot deformation (kJ/mol), σ is the flow stress (MPa) for a given strain, A, A_1, A_2, $\alpha=\beta/n_1$, n, n_1 and β are the material constants.

It should be noted that the nature of materials constants and equations are dependent on the characteristic stress used to derive them. In general, the peak stress is the most widely accepted one to find the hot working constants [13]. The peak stresses, obtained by constant strain rate compression experiments and revised by friction coefficient [11], were used in the present work (Fig. 1). Following the well established procedures [11−14], the mean values of α and n are determined to be 0.007635 and 6.02, respectively.

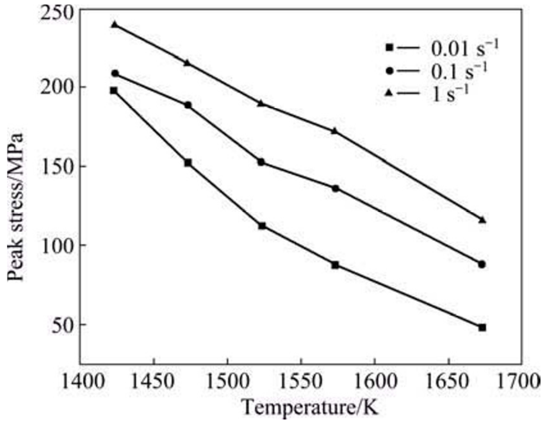

Fig. 1 Peak stress dependent on temperature and strain rate revised by friction coefficient

The slope of the plots of ln[sinh($\alpha\sigma$)], lnσ and σ against the reciprocal of thermodynamic temperature can be used to obtain the value of Q_a [12]. The values of Q_a are calculated as 637.13, 883.48 and 737.42 kJ/mol based on Eqs. (1)–(3), respectively, by averaging the values under different strain rates. The correlation coefficients (R^2) of these regression values are 0.9894, 0.9756, and 0.9869, for Eqs. (1)−(3), respectively, which reveals that Eq. (1) has a slightly better fit to the experimental data. Therefore, the apparent activation energy Q_a of hot working can be taken as 637.13 kJ/mol.

It can be seen that the Q_a (637.13 kJ/mol) is higher than that for creep (180−326 kJ/mol [1−3,5,6]), because it is without any specific physical meaning (and may be the sum of several thermal activation processes) and is common for many metals [15].

3.1.2 Physical-based approach

As we all know, the n value should be 5 and the Q value should be close to the self-diffusion energy as long as the deformation mechanism is controlled by the glide and climb of dislocations [12]. Moreover, Eq. (2) is also well known for thermal creep equation [1−6]. Usually, Eq. (4) is used to fit the experimental data to get the actual values [12,13]:

$$\ln[\dot{\varepsilon}/D(T)] = n\ln[\sigma/E(T)] \quad (4)$$

where $D(T) = D_0\exp[-Q_{sd}/(RT)]$ is the self-diffusion coefficient and $E(T)$ is the elastic modulus, and D_0 is 3×10^{-5} m^2/s, Q_{sd} is 300 kJ/mol and $E(T)$=125.2×[1−7.69×10^{-5}(T−20)] GPa for V−4Cr−4Ti alloy [1,6,16].

Taking data into Eq. (4), the n value can be evaluated from the slope of plots shown in Fig. 2. It can be seen that the entire n value is 6.47 for all data. While, the n value varying from 23.49 to 4.87 depends on the used stress. Following Eq. (2), the Q value can be determined as 499.89 and 375.89 kJ/mol for n of 6.47 and 4.87, respectively, by linear fitting the plot of ln(σ/E)−1/T.