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Arrhenius-type constitutive model and dynamic recrystallization behavior of V−5Cr−5Ti alloy during hot compression

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Abstract: To clarify the high temperature flow stress behavior and microstructures evolution of a V−5Cr−5Ti (mass fraction, %) alloy, the isothermal hot compression tests were conducted in the temperature range of 1423–1573 K with strain rates of 0.01, 0.1, and 1 s^{-1}. The results show that the measured flow stress should be revised by friction and the calculated values of friction coefficient *m* are in the range of 0.45−0.56. Arrhenius-type constitutive equation was developed by regression analysis. The comparison between the experimental and predicted flow stress shows that the R^2 and the average absolute relative error (AARE) are 0.948 and 5.44%, respectively. The measured apparent activation energy Q_a is in the range of 540–890 kJ/mol. Both dis-continuous dynamic recrystallization (DDRX) and continuous dynamic recrystallization (CDRX) mechanisms are observed in the deformed alloy, but dynamic recovery (DRV) is the dominant softening mechanism up to a true strain of 1.5.

Key words: V−5Cr−5Ti alloy; constitutive model; flow stress; dynamic recrystallization

1 Introduction

In recent years, V−Cr−Ti alloy has been investigated as a potential constructive material for the first wall blanket of the fusion reactor [1]. It is well documented that V−Cr−Ti ingot produced by vacuum melting is subjected to various thermomechanical processes, such as forging, extrusion and rolling to refine the grain size [2−6]. The alloy fabrication is also prevalent during recent years (2012−2013) [5,6] despite that different products can be fabricated successfully in 1990s [2,3]. However, the corresponding constitutive model of the alloy is not sufficient to characterize the dependence of flow stress on temperature, strain rate and strain. LENNON and RAMESH [7], VOYIADJIS and ABED [8] and NASSER and GUO [9] constructed some physically-based models to investigate the dynamic response of pure V from 77 to 800 K. Moreover, CHEN et al [10] and CAI et al [11] developed ambient temperature Johnson-Cook model for V−5Cr−5Ti alloy under high strain rate impact and quasi-static tensile state, respectively. DONAHUE et al [12] evaluated a physically-based model for V−4Cr−4Ti alloy from 77 to 373 K. However, the above mentioned models are not suitable to describe the formation process of alloy under hot working conditions. Recently, YU et al [13] have developed a mathematical constitutive model for a coarse-grained V−5Cr−5Ti alloy under hot compression conditions, however, that is not systematical.

As we all know, in metal-forming processes, the control parameters are temperature (*T*), strain rate ($\dot{\varepsilon}$) and strain (ε). To establish precise relationships among the three variables and to investigate their influence on the flow stress(es) and microstructure, tests are usually performed at constant temperature and strain rate [14−17]. These relationships in combination with finite-element methods (FEM) make possible to analyze the process. Therefore, to achieve this objective, the first step is to obtain a constitutive equation describing the evolution of flow stress under specified conditions [18–20]. Constitutive equations involving evolution and estimation of flow stress have been extensively studied, and among these, Arrhenius-type model has been extensively used under simulated hot working conditions [17, 21–26].

On the other hand, investigations on the microstructure of V−Cr−Ti alloy during the

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thermomechanical process mainly focus on the cold work, static recrystallization (SRX) and artificial aging [27−31]. The detailed microstructure research of hot-deformation is scarce. HOELZER and ROWCLIFFE [32] and HINS and THRESH [2] reported the occurrence of dynamic recrystallization (DRX) during hot extrusion, and YU et al [13] mentioned that there is DRX behavior during the uniaxial compression. However, none of them gave more details.

The objective of this study is to investigate the influence of strain, strain rate and temperature of formation on the uniaxial compressive deformation flow stress and the microstructures of a nominal V−5Cr−5Ti alloy. A phenomenological Arrhenius-type model is developed firstly, and then the deformed grain features are investigated preliminarily.

2 Experimental

2.1 Materials

First, a piece of vertical section disk (d~120 mm) was cut from an annealed and hot isostatic pressed (HIP-ed) V−5Cr−5Ti ingot (~25 kg). Its chemical composition is V−5.12Cr−4.87Ti−0.056O (mass fraction, %). A series of cylindrical specimens, d9 mm × 12 mm, were sliced from the disk by an electrical discharge machine. The typical grain feature is shown in Fig. 1. The grain size of specimen is in the range of 0.7−1.1 mm and the mean value is about 860 μm (by intercept method based on ASTM E112-12). There are some plate-like Ti−(CNO) phase in the alloy, as shown in Fig. 1(b), and some unwell developed sub-grains in the huge matrix grains. The compression axial (CA) direction is along the axial of ingot.

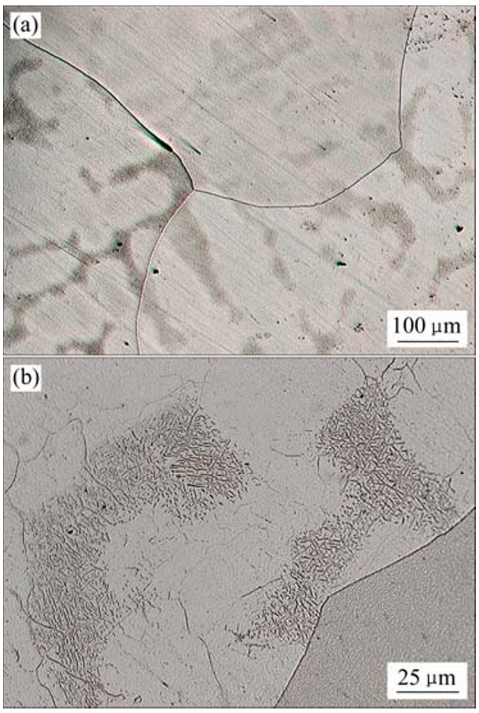

Fig. 1 Microstructures of as-received V−5Cr−5Ti alloy (Compression axial (CA) direction is vertical to screen): (a) Grain features; (b) Plate-like Ti−(CNO) phase

2.2 Experimental procedure

All cylindrical compression specimens were machined to d 8 mm × 12 mm to remove the surface oxidation layer. Subsequently, both the ends of each specimen were mechanically polished. The hot compression test was performed on a Gleeble-3800 system (Dynamic Systems Inc., USA) at three strain rates (0.01, 0.1 and 1 s^{-1}) and four temperatures (1423, 1473, 1523 and 1573 K) in an argon atmosphere (99.999%, ~0.09 MPa). Pure tungsten was adopted as compression anvil after testing. Tantalum, graphite foil and nickel-based lubricant were employed for lubrication. As shown in Fig. 2, the specimen was heated to 100 K over the deformation temperature (T_{deform}) at a heating rate of 10 K/s and held for 1 min, and cooled at a rate of 2 K/s to the deformation temperature and held for another 0.5 min, which was then compressed and quenched in water within 2−3 s.

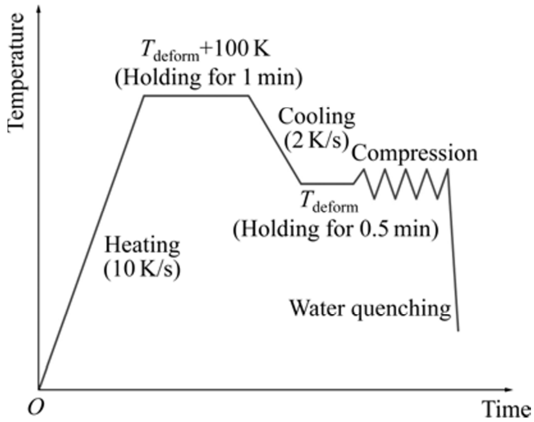

Fig. 2 Experimental procedure for hot compression test

Repeated tests were performed under similar condition until the difference between the two peak stresses (true stress vs. true strain curve) was within 5%−7%. The height and diameter of specimen before and after test were recorded. After test, the specimens were sectioned into two parts along the CA direction to observe the microstructures.

3 Results and discussion

3.1 Flow stress behavior and correction

The measured true stress–true strain curves are shown as solid lines in Fig. 3. It exhibits that the flow stress of isothermal compressed V−5Cr−5Ti alloy is sensitive to both strain rate and deformation temperature.