International Journal of Refractory Metals & Hard Materials 72 (2018) 349–366

Contents lists available at ScienceDirect

International Journal of Refractory Metals & Hard Materials

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

The research on vacuum isothermal bloom for powder metallurgy V-5Cr-5Ti alloy guiding by the constitutive models and the error analysis

F.S. Qu[a,*], X.F. Dong[a], J.Y. Liu[a], D.M. Chen[a], Z.H. Wang[a], J. Zhou[b]

[a] *Institute of Materials, China Academy of Engineering Physics, 9 Huafeng Street, Jiangyou, Mianyang 621908, China*
[b] *College of Material Science and Engineering, Chongqing University, 174 Shazheng Street, Chongqing 400030, China*

A R T I C L E I N F O

Keywords:
V-5Cr-5Ti alloy
Hot deformation
EBSD
Constitutive equation
Flow stress

A B S T R A C T

For studying the vacuum isothermal cogging technology for V-5Cr-5Ti alloy, the isothermal hot compression tests are conducted in the deformation temperature ranging from 1150 °C(1423 K) to 1400 °C(1673 K) with an interval of 50 °C, strain rate ranging from 0.001 to 1 s^{-1} and height reductions of 55% on a computer controlled thermal simulation machine. The three kinds of constitutive equations of V-5Cr-5Ti alloy are deduced based on the true stress–strain curves. The analysis is carried out for the error for constitutive models and the optimum deformation condition. Isothermal hot cogging in vacuum is carried out guiding by the constitutive models and the optimum deformation conditions. Warm rolling is adopted for sheet manufacture of the cogging billet. The test results show that strain-compensated Arrhenius constitutive model is the most accurate and modified Johnson Cook constitutive model is the most efficient among them; by the solution steps, microstructure with metallographic and EBSD technology and other factors, the error reasons generated at lower strain rate of 0.001 s^{-1} and 0.01 s^{-1} in the modified Johnson-Cook and Zerilli-Armstrong models are explicit to some extent; the optimum deformation condition is at the temperature of 1250–1400 °C and the strain rate is 0.001–0.02 s^{-1}, which are determined through strain rate sensitivity coefficients(m), deformation activation energy(Q) and the processing map; the mechanical properties of the sheet by warm rolling are the yield of 400 MPa, the tensile strength of 535 MPa and the elongation rate of 35%. And the material utilization rate is high up to 90%.

1. Introduction

V-5Cr-5Ti alloy is considered as one of the candidate structural materials for fusion reactors because of their attractive properties such as low radiation-induced activation, high thermal conductivity, low thermal expansion, excellent high temperature performance and superior resistance against radiation-induced swelling [1–4]. V-5Cr-5Ti alloy is usually prepared by vacuum consumable arc melting(VAR) or electron beam melting(EBM). The researches for the properties of V-5Cr-5Ti alloys prepared by VAR or EBM process have been reported under the different conditions [5–6]. However, there are few researches on the properties of V-5Cr-5Ti alloy fabricated by powder metallurgy. Compared with VAR and EBM processing, V-5Cr-5Ti alloy prepared by powder metallurgy have the advantages of accurate composition control, uniform distribution of alloy elements and moreover, this method is more conducive to the study of the influence on the mechanical properties of alloys by impurities just like O, N, C etc. The microstructure of V-5Cr-5Ti alloy prepared by powder metallurgy is uneven and the mechanical properties are poor, which requires the reasonable hot forging, rolling to improve the microstructure and performance to meet engineering requirements of the fusion reactor. Thermo-mechanical processing has been considered as the applicable fabrication approach owing to the couple influence from plastic forming and microstructural evolution [7]. But even at the high temperature, the deformation ability of V-5Cr-5Ti alloy is limited. In addition, when the temperature is higher than 450 °C, vanadium alloys are oxidized and the dense oxide film cannot be produced just like aluminum alloys etc. Therefore, the cogging of V-5Cr-5Ti alloy during high temperature in the atmospheric environment is performed by using the stainless canning [5–6]. Because of the low melting point of stainless steel, the cogging temperature of V-5Cr-5Ti alloy is usually at about temperature of 1200 °C, which makes the edge crack easily generated during free upsetting [5–6]. And there are many steps, long cycle and low material utilization ratio in the processing of the canning blooming method. At present, there are few reports on the new blooming methods with the characteristic of high efficient, short cycle and high utilization rate. Vacuum isothermal cogging is a new kind of free upsetting method which is developed on the basis of hot pressing sintering. In this

* Corresponding author.
E-mail address: qufengsheng@caep.cn (F.S. Qu).

https://doi.org/10.1016/j.ijrmhm.2018.01.007
Received 12 October 2017; Accepted 7 January 2018
Available online 11 January 2018
0263-4368/

process, the cogging of V-5Cr-5Ti alloy can be carried out by free upsetting in the condition of high temperature and vacuum. This method has obvious advantages for the cogging of vanadium alloys which are the characteristic of the oxidation, high resistance and easy cracking in the high temperature. This method can make the processing cycle shortened obviously and improve the utilization rate of the material by removing the canning steps and reducing the edge cracking of alloy. However, there are few researches on the technology of vacuum isothermal blooming of V-5Cr-5Ti alloy at the present. And the best technology parameters for vacuum isothermal cogging of V-5Cr-5Ti alloy are still unknown. Therefore, it is necessary to study the relevant parameters of this technology. But the research object by using the actual size of V-5Cr-5Ti alloy will result the high cost and the long cycle. Therefore, a preliminary study can be conducted by the small size samples on the thermos-physical simulator. And based on the experimental results, the constitutive equations of the thermal deformation for V-5Cr-5Ti alloy are derived, which can determine the time–pressure curve of the actual cogging for V-5Cr-5Ti alloy and simulate hot forming of alloys. Through analyzing the cause of the error for the constitutive models from the solving process and the microstructure evolution, the optimal constitutive equation and deformation condition can be determined, which is very important to the actual cogging and simulation. Especially the optimal deformation condition for V-5Cr-5Ti alloy is determined from the analysis of the error of the equation. Unfortunately, the research efforts on V-Cr-Ti alloys have mainly been focused on the irradiation properties [8–9], the thermal creep properties [10–12], the welding performance [13–15], effects impurity such as oxygen on properties of vanadium-based alloys [16–18] etc. So the purpose of this research is to establish the physical and phenomenological constitutive equations for V-5Cr-5Ti alloy. Through analyzing the solving processing of constitutive equation and the microstructure evolution in the process of thermal deformation, the causes of the error are analyzed to some extent. And the optimum conditions of the hot deformation in the experimental range are pointed out at the same time. On the basis of the above research, the process of vacuum blooming of V-5Cr-5Ti alloy and the subsequent warm rolling experiments are carried out. The feasibility and superiority of the process were illustrated by the material utilization rate and the mechanical properties of the rolled sheets.

2. Experimental details

V-5Cr-5Ti alloy rod used in the hot compression experiment is obtained by powder metallurgy technology. The chemical composition of V-5Cr-5Ti alloy is shown in Table 1. The metallographic structure and SEM photos of the powder metallurgy sample are shown in Fig. 1. In order to be in line with the actual processing, V-5Cr-5Ti alloy is homogenized with temperature of 1200 °C and holding time of 40 min before the hot deformation test. The alloy is machined as Φ10mm × 12 mm cylindrical test specimen. The compression tests corresponding to a height reduction 55% are carried out six temperatures of 1150 °C(1423 K), 1200 °C(1473 K), 1250 °C(1523 K), 1300 °C(1573 K), 1350 °C(1623 K) and 1400 °C(1673 K) and four strain rates of 0.001 s^{-1}, 0.01 s^{-1}, 0.1 s^{-1} and 1 s^{-1}. The high purity argon was used to protect the specimen during the compression process. At the end of the experiment, the specimens with rapid water are for retention of the microstructure of high temperature deformation.

During the compression process, the variations of stress and strain are monitored continuously by a personal computer equipped with an automatic data acquisition system. The true stress and true strain are derived from the measurement of nominal stress–strain relationship according to the following formula: $\sigma_T = \sigma_N(1 + \varepsilon_N)$, $\varepsilon_T = \ln(1 + \varepsilon_N)$, where σ_T is true stress, σ_N is nominal stress, ε_T is true strain and ε_N is nominal strain [19]. In the condition of the strain rate of 0.005 s^{-1} and the temperature of 1350 °C, the isothermal cogging process of the alloy is carried out with the billet size of 100 × 145 mm. The prediction result by the most accurate equation is used for the compression curve for the cogging process. When the true strain reaches 0.7, the deformation temperature and pressure will keep 30 min for making the microstructure uniform. The billet after the isothermal cogging is undergone by warm rolling and recrystallization annealing, which is for observing the effect on the subsequent processing by the isothermal hot cogging technology.

The microstructures are characterized by metallography and EBSD techniques. The alloy sample is grinded and polished by standard metallographic specimen. The EBSD measurements and analyses are performed by using TSL system (OIM 6 software) attached to a Quanta 200FEG scanning electron microscope. The mechanical properties of warm rolled sheet are tested by the uniaxial tensile.

Table 1
Chemical composition of V-5Cr-5Ti alloy.

Cr(wt%)	Ti(wt%)	O(wppm)	N(wppm)	C(wppm)	V
5.03 ± 0.05	5.02 ± 0.05	450	50–60	60–70	Bal.

3. Results and discussion

3.1. The constitutive models for V-5Cr-5Ti alloy

3.1.1. The phenomenological constitutive models

3.1.1.1. Modified Johnson cook model. The original Johnson-Cook model [20] can be expressed as:

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \tag{1}$$

where σ is the equivalent flow stress, ε is the equivalent plastic strain, A is the yield stress at reference temperature and reference strain rate, B is the coefficient of strain hardening, n is the strain hardening exponent, C and m are the material constants which represent the coefficient of strain rate hardening and thermal softening exponent, respectively, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless strain rate ($\dot{\varepsilon}$ is the strain rate, while $\dot{\varepsilon}_0$ is the reference strain rate), and T^* is the homologous temperature and expressed as $T^* = (T - T_r)/(T_m - T_r)$. Here, T is the absolute temperature, T_m is the melting temperature and T_r is the reference temperature.

As mentioned before, because it cannot account for the coupling effects of temperature, strain rate and strain on the flow behavior, the original Johnson Cook model results in a decrease in the accuracy of predication. So, in this study, a modified Johnson-Cook model [21] is adopted for V-5Cr-5Ti alloy, as shown in Eq. (2):

$$\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2)(1 + C_1\ln\dot{\varepsilon}^*)\exp[(\lambda_1 + \lambda_2\ln\dot{\varepsilon}^*)T^*] \tag{2}$$

where A_1, B_1, B_2, C_1, λ_1, λ_2 are material constants, σ is the flow stress, ε is the equivalent plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless strain rate with $\dot{\varepsilon}$ being the strain rate and $\dot{\varepsilon}_0$ the reference strain rate, $T^* = (T - T_{ref})$ with T and T_{ref} being the current and reference temperatures.

In this paper, 1423 K is taken as the reference temperature and 1 s^{-1} the reference strain rate to evaluate the material constants.

When the deformation temperature is 1423 K and strain rate is 1 s^{-1}, Eq. (2) can be expressed as:

$$\sigma = (A_1 + B_1\varepsilon + B_2\varepsilon^2) \tag{3}$$

Substituting the corresponding experimental flow stress data into Eq. (3), the relationship between σ and ε can be obtained, as shown in Fig. 2. Then the values of A_1, B_1 and B_2 can be obtained from the fitting curve.

When the deformation temperature is 1423 K, Eq. (2) can be written as: