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Modeling the constitutive relationship of powder metallurgy Al–W alloy at elevated temperature

Lafeng Guo [a,b,*], Zhimin Zhang [a], Baocheng Li [a], Yong Xue [a]

[a] School of Materials Science and Engineering, North University of China, Taiyuan 030051, China
[b] School of Mechatronics Engineering, North University of China, Taiyuan 030051, China

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ABSTRACT

The deformation behavior of Al–W alloy was researched with isothermal compression tests at various deformation temperatures and strain rates to evaluate the deformation activation energy and to develop the constitutive relationship equation, which is in pursuit of revealing the dependence of the flow stress on the strain, strain rate and deformation temperature. The compression tests were conducted in the temperature range between 420 and 570 °C and at strain rates between 0.001 and 5.0 s^{-1}. With the help of determination of related material constants (such as A, β and α) and activation energy Q (451.15 kJ mol^{-1}), the Arrhenius-type constitutive relationship equation of Al–W alloy is developed. It was found that the correlation coefficient R and the *AARE* is 0.997% and 4.08%, respectively. The results show that the Arrhenius-type model, which considers the combined influence of strain rate and deformation temperature, is able to provide the accurate prediction of high temperature flow stress for the researched alloy.

1. Introduction

Aluminum and its alloys are characterized by their favorable comprehensive properties such as low density, good appearance and corrosion resistance, which have been extensively applied in different fields of marine [1,2], aviation [3,4] and automotive industry [5,6]. However, with the progress of science and technology, the national defense development and the improvement of people's living standards, aluminum alloys are experiencing an increasing demand to obtain higher mechanical properties at room temperature and maintain reliability at elevated temperature, including the desired performances of wear-resisting, corrosion resistance, resistance to fatigue, etc. As a novel type of structure material, Al–W alloy is considered as a kind of special aluminum alloy, which possesses the combination advantages of tungsten and aluminum. Therefore, such alloys have great application potential in terms of golf club head, medical apparatus and instruments and the automobile motor piston, etc. More importantly, Al–W alloy is quite possible to become a new generation of armor materials and aerospace engine structure materials due to its superior performance. However, because of quite large difference between the melting points of tungsten (3410 °C) and aluminum (660 °C), as well as also the density of tungsten (19.25 g cm^{-3}) and aluminum (2.70 g cm^{-3}), the alloying of such incompatible chemical elements by melting probably cause considerable problems. Fortunately, the mechanical alloying (MA) method is able to deal with the mentioned drawbacks. Compared with other techniques, the most obvious advantages of mechanical alloying is that it is a kind of solid state technique and thus the issues associated with melting and solidification can be ignored [7], which has been applied to fabricate the composites with immiscible components, especially useful for those compounds which are difficult to prepare by the traditional processes due to high vapor pressure and/or the large differences in melting points of components [8].

Previously, a number of beneficial researches regarding the research alloy in this work were soundly addressed and well documented by some materials scientists. For instance, Tang et al. [9] synthesized W_{1-x}–Al_x (x = 0–0.86) alloys by mechanically alloying the pure metal powder mixtures at designated compositions on the basis of high-energy ball milling. Ouyang et al. [10] prepared the Al–W powders based on the mechanical alloying in a planetary ball mill, and calculated the solubility of aluminum in tungsten using the embedded-atom method. Rafieia et al. [11] suggested the characterization and formation mechanism of nanocrystalline Al–W alloy which was prepared by mechanical alloying. However, few scientific reports involving the hot deformation behavior and constitutive relationship concerning the present alloy is involved. Basically, the constitutive relationship of metals and alloys is

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* Corresponding author at: School of Materials Science and Engineering, North University of China, Taiyuan 030051, China. Tel./fax: +86 0351 3557452.

E-mail address: guolafeng@nuc.edu.cn (L. Guo).

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considered as the basic function of flow stress and hot processing parameters. It can express the internal correlation of the dynamic material properties with hot processing parameters of strain, strain rate and deformation temperature [12]. During the hot deformation process, the flow behavior of Al–W alloy is a quite complicated process involving the combination of work-hardening and dynamic softening. The relationship between these processing parameters and the flow stress presents highly non-linear. More importantly, establishment of accurate constitutive relationship model which is available to present the instantaneous responses of materials during hot processing is inevitable for the research on the numerical simulation. Therefore, the clear understanding of constitutive relationship of materials is a foundation in theory and beneficial to the finite element simulation under the condition of various hot processing parameters. Some helpful contributions in this aspect have been dedicated to the conventional aluminum alloys in recent years, such as commercial purity aluminum [13], AA7085 aluminum alloy [14], cast A356 aluminum alloy [15] and 7075 aluminum alloy [16]. But there are almost not investigations about Al–W alloy being reported publically. As a result, in the present paper, the isothermal compression tests at different hot processing parameters have been conducted. Based on the obtained experimental data, the influences of deformation temperature, strain rate and strain on the flow stress in the isothermal compression of an Al–W alloy are discussed systematically. The deformation activation energy Q and other material constants for deformation at fixed strain were determined, which was subsequently employed to establish the constitutive relationship equation to model the flow behavior of Al–W alloy.

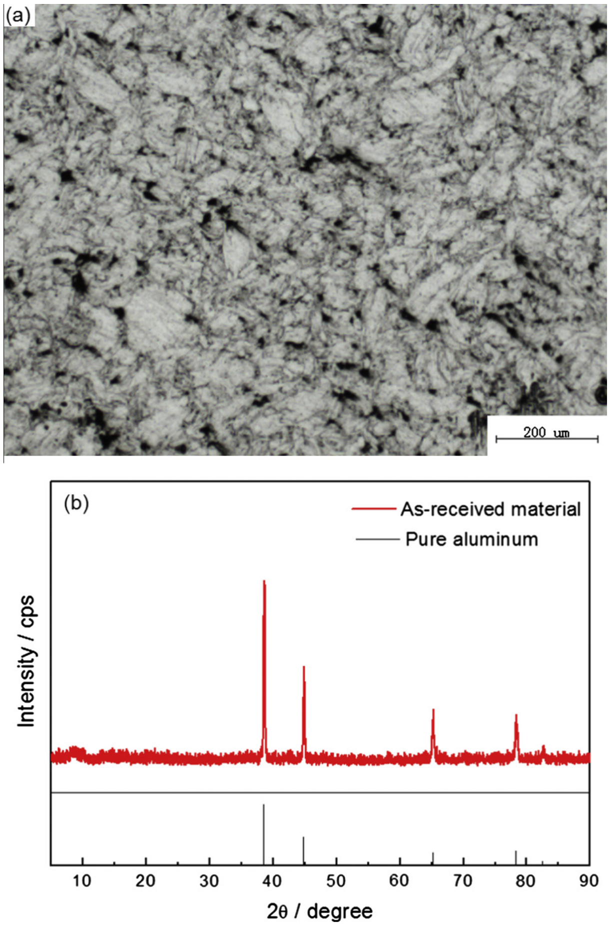

Fig. 1. The initial microstructure (a) and the X-ray diffraction pattern (b) of the as-received material.

2. Materials and experimental procedure

The research Al–W alloy was produced by using the elemental powder metallurgy route. Based on the mixed powders of aluminum and tungsten, the cold compaction was prepared after being compressed on the 6300 kN forging press. The initial microstructure and the X-ray diffraction pattern of the as-received material are shown in Fig. 1. It can be seen from this figure that the white part in the microstructure is aluminum, and the dark spots in the aluminum is tungsten. In addition, almost no tungsten was found based on the XRD result because of little concentration of tungsten, or no new phase was formed between aluminum and tungsten in the cold compaction. The detail chemical composition of this alloy (wt.%) is listed in Table 1. The cylindrical compressive specimens were machined into the size of $\varnothing 10 \times 15$ mm with their cylinder axes parallel to the axial line direction of the bar with the diameter of 116 mm. Isothermal compressing tests were conducted on the Gleeble-1500D thermo-simulation machine in the temperature range of 420–570 °C with the interval of 30 °C. Five typical strain rates were determined from 0.001 s^{-1} to 5 s^{-1}. Prior to the compression, the specimens were heated at 10 °C/s up to deformation temperature, held for 3 min to homogenize the temperature in the sample. In order to minimize the deformed friction, a graphite lubricant was performed as lubricant. All of the testing specimens were deformed up to a total true strain of approximately 0.7. During the compression process, the temperature was controlled and measured with a thermocouple welded to the mid-height of the sample. The variations of stress and strain were monitored continuously by a personal computer equipped with an automatic data acquisition system. The true stress and true strain were derived from the measurement of the nominal stress–strain relationship.

3. Results and discussion

3.1. Flow stress behavior and microstructure

The typical true stress–true strain curves of Al–W alloy which were obtained at various deformation temperatures (420–570 °C) and different strain rates (0.001, 0.01, 0.1, 1 and 5 s^{-1}) with strain of 0.7 through the isothermal compression tests are illustrated in Fig. 2. It can be revealed from this figure that the shapes of the flow curves are typical of aluminum alloys produced by powder metallurgy [17] and most of them exhibit the similar characteristics in general. At the initial stage, the curves increase sharply at the beginning of the plastic deformation with increasing strain till a peak stress reaches, which is because the work hardening resulted from the continuous accumulation of dislocations plays a leading role in this stage [14]. Then the flow stress decreases gradually into a steady state stress by increasing the strain ascribed to the flow softening. Finally, the flow stress reaches to a steady state, which means that a good balance between work hardening and dynamic

Table 1
The chemical composition of Al–W alloy (wt.%).

Al	W	Fe	Si	Cu	Mn	Mg	Zn	Ti	Ga	Cr	V
99	0.81	0.111	0.042	0.003	0.0005	0.0014	0.0015	0.0023	0.012	0.001	0.0153