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Creep mechanism of as-cast Mg-6Al-6Nd alloy

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Abstract

The creep mechanism of as-cast Mg-6Al-6Nd alloy was studied. The stress exponent for creep is 5.8 under the applied stresses of 50-70 MPa at 175°C. The activation energy for creep is 189 kJ·mol^{-1} under the applied stress of 70 MPa in the range of 150-200°C. The true stress exponent and threshold stress for creep are calculated as 4.96 and 10.2 MPa, respectively. The true stress exponent indicates that its creep mechanism belongs to the dislocation climb-controlled creep, which is in agreement with the microstructure changes before and after creep. The high value for stress exponent is attributed to the interaction of $Al_{11}Nd_3$ phase with dislocations. The activation energy is more than the self-diffusion activation energy of Mg, which is attributed to the load transfer taking place from the matrix to $Al_{11}Nd_3$ phase during creep.

Keywords: magnesium alloys; creep; creep resistance; neodymium

1. Introduction

The common Mg-Al alloys, such as AZ91 and AM60, are unsuitable for use at temperatures above 120°C because of the precipitating phase of $Mg_{17}Al_{12}$ with a low melting point and poor thermal stability. To improve the mechanical properties at elevated temperatures of Mg-Al alloys, the alloys containing the rare-earth Nd have been developed, in which $Mg_{17}Al_{12}$ phase is replaced by the thermally stable Al-Nd compounds. For example, Wang reported that $Al_{11}Nd_3$ phase was formed in Mg-5Al-0.4Mn-2Nd alloys prepared by metal mould casting method and the tensile strength was enhanced at 423 K [1]. Zhang noted that $Al_{11}Nd_3$ and Al_2Nd phases were formed in the die-cast Mg-4Al-0.4Mn-6Nd alloy and the tensile properties were improved at elevated temperatures [2]. Although both show that the addition of Nd is helpful to improve the strength of Mg-Al alloys, the effects of Nd on the creep mechanism have not been reported. In this paper, the creep mechanism of as-cast Mg-6Al-6Nd alloy is studied, and the reinforced effects of main precipitating phase are discussed.

2. Experimental

The nominal compositions of two studied alloys are Mg-6Al and Mg-6Al-6Nd. Commercially pure Mg and Al (>99.99%) were first melted in a crucible electric resistance furnace under a protection of flux cover, and then the rare-earth Nd was added to the melt in the form of Mg-20%Nd master alloy at 780°C. The melt was held at 780°C for 30 min and poured at 730°C into a steel mold that was kept at room temperature. The measured compositions of two studied alloys detected by inductively-coupled plasma (ICP) spectroscopy are Mg-6.1Al and Mg-5.8Al-5.7Nd, respectively. The creep samples were 25 mm in gauge length and 5.0 mm in diameter. The creep tests were performed by using a CSS-3902 creep testing machine under the applied stresses of 50, 60, and 70 MPa at 150, 175, and 200°C. The microstructures of the as-cast Mg-6Al-6Nd alloy before creep and precipitating phases were investigated using scanning electron microscopy (SEM), transmission electron microscopy (TEM) and electronic diffraction pattern (EDP). To clarify the effects of main precipitating phase on its creep mechanism more deeply, the microstructure after creep was further investigated by TEM.

3. Results and discussion

3.1. Creep curves

The creep curves of the as-cast Mg-6Al alloy under the applied stress of 70 MPa and the as-cast Mg-6Al-6Nd alloy under the applied stresses of 50, 60, and 70 MPa at 175°C are all shown in Fig. 1. There are usually three stages composed of primary creep, secondary creep, and tertiary creep

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in the creep deformation of metals and alloys, and the secondary creep is the most important for their applications. Fig. 1(a) indicates that the secondary creep rate of the Mg-6Al alloy under the applied stress of 70 MPa decreases from 4.5 $\times 10^{-7}$ to 5.0 $\times 10^{-8}$ s^{-1} with the addition of 6 wt.% Nd. The secondary creep rate of the as-cast Mg-6Al-6Nd alloy decreases with the decrease in applied stress and arrives at the lowest value of 9.8 $\times 10^{-9}$ s^{-1} under 50 MPa. The creep curves of the as-cast Mg-6Al-6Nd alloy under an applied stress of 70 MPa at 150, 175, and 200°C are shown in Fig. 1(b). It indicates that the secondary rate of the as-cast Mg-6Al-6Nd alloy decreases with the decrease in temperature and arrives at the lowest value of 2.3×10^{-8} s^{-1} at 150°C.

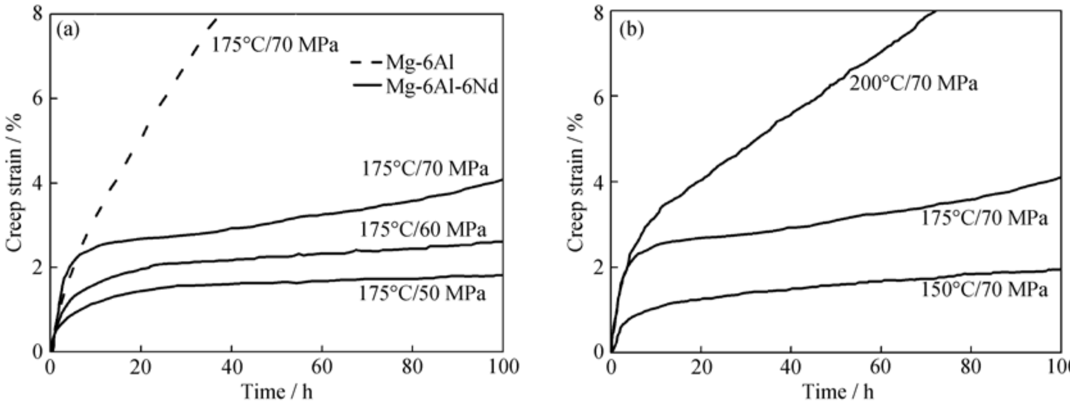

Fig. 1. Creep curves of the as-cast Mg-6Al-6Nd alloy: (a) under the applied stresses of 50, 60, and 70 MPa at 175°C; (b) under the applied stress of 70 MPa at 150, 175, and 200°C.

3.2. Creep mechanism

It is generally agreed that the secondary creep rate of magnesium and Mg-Al alloys is expressed as a power law equation in the applied stress σ and temperature T ranges of interest to automotive applications (i.e. σ = 50-70 MPa and T = 423-473 K) [3]:

$$\frac{d\varepsilon}{dt} = A\sigma^n \exp\left(\frac{-Q}{RT}\right) \quad (1)$$

where $d\varepsilon/dt$ is the secondary creep rate, A is a material-dependent constant, σ is the applied stress, n is the stress exponent, Q is the activation energy for creep, R is the gas constant, and T is the absolute temperature.

A plot of $d\varepsilon/dt$ against σ using logarithmic coordinates for the as-cast Mg-6Al-6Nd alloy is depicted in Fig. 2. It indicates that n is 5.8 under the stresses of 50-70 MPa at 175°C. A plot of the logarithm of $d\varepsilon/dt$ against $1/T$ for the as-cast Mg-6Al-6Nd alloy is depicted in Fig. 3. It indicates that Q is 189 kJ·mol^{-1} under the stress of 70 MPa at 150-200°C. In general, the different values of stress component or activation energy correspond to different creep mechanisms. The stress component n = 1-3 indicates that the creep is controlled by the grain boundary sliding [4]; n = 4-5 indicates that the creep is controlled by dislocation climb due to lattice diffusion [4-5]. The activation energy of creep in magnesium alloys, Q = 135 kJ·mol^{-1}, is for the self-diffusion activation energy of Mg, and Q = 80 kJ·mol^{-1} is for grain boundary diffusion [3].

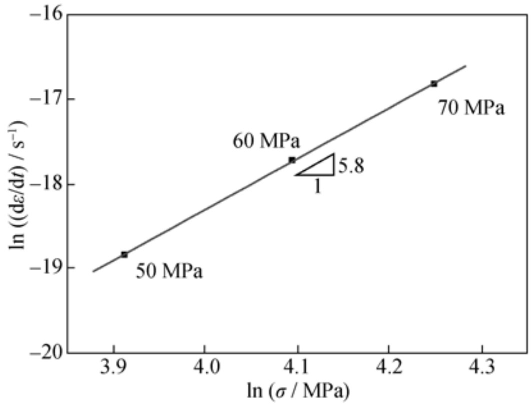

Fig. 2. Logarithm of secondary creep rate dependent on the logarithm of stress for the as-cast Mg-6Al-6Nd alloy at 175°C.

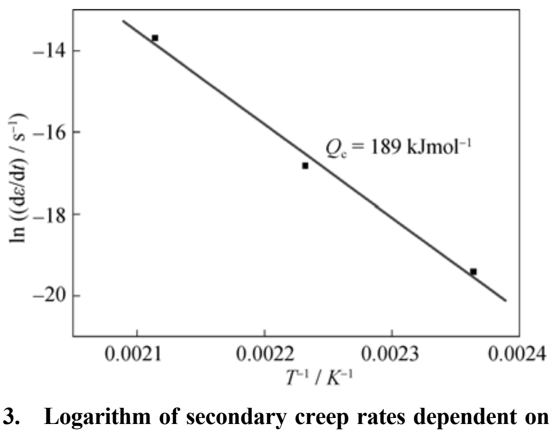

Fig. 3. Logarithm of secondary creep rates dependent on the reciprocal of creep temperature for the as-cast Mg-6Al-6Nd alloy under the stress of 70 MPa.

For the creep of the as-cast Mg-6Al-6Nd alloy, n = 5.8 and Q = 189 $kJ\cdot mol^{-1}$ are both higher than 4-5 and 135 $kJ\cdot mol^{-1}$. In General, the increases of stress exponent and activation energy for creep are considered to be induced by the reinforced effects of second phases in alloys. For example, the creep behaviors of alumina dispersion strengthened aluminium reinforced by silicon carbide particulates were investigated [6]. It was found that the increase of stress exponent was attributed to the interaction between the fine alumina particles and silicon carbide particulates and dislocations, which would lead to the threshold stress for creep. For the reinforced phases with a larger dimension, it was also proposed that the increase of activation energy should be related to the load transfer occurring from the matrix [7-8, 10]. To explore the creep mechanism, it is necessary to obtain the true stress exponent, n_0. After the stress σ is replaced by effective stress ($\sigma_e = \sigma - \sigma_{th}$), Eq. (1) can be rewritten as [7-8, 10]:

$$\frac{d\varepsilon}{dt} = A(\sigma - \sigma_{th})^n \exp\left(\frac{-Q}{RT}\right) \tag{2}$$

The calculation of σ_{th} can be done in the following way. A plot of $(d\varepsilon/dt)^{1/n}$ against σ in double linear scale with the known values for n shows a straight line when the value of n is chosen correctly. The value of σ_{th} can be obtained by the extrapolation of straight line to zero creep rate. When n = 5 is selected as the stress component for creep of the as-cast Mg-6Al-6Nd alloy, σ_{th} is calculated as 10.2 MPa. After incorporating the calculated threshold stress, the true stress component n_0 is calculated as 4.96. Its value indicates that the dislocation climb is the dominant creep mechanism.

To explore the creep mechanism and the reinforced effects of main precipitating phase more deeply, the microstructures of the as-cast Mg-6Al-6Nd alloy before and after creep were observed, which are listed in Fig. 4 and Fig. 5, respectively. In Fig. 4(a), the SEM analysis indicates that the irregular polygon-like and the other fiber-like phase are formed in this alloy. The irregular polygon-like phase is mainly located in the grains, and the fiber-like phase is mainly distributed in the dendrite and grain boundaries. In addition, the area fraction of the latter is much more than that of the former, which implies that the Nd element mainly exists in the fiber-like phase. In Figs. 4(b)-4(e), the TEM and EDP analyses indicate that the irregular polygon-like and fiber-like phases are Al_2Nd ($a = b = c$ = 0.800 nm) [9] and $Al_{11}Nd_3$ (a = 0.436 nm, b = 1.292 nm, c = 1.002 nm) [9], respectively. Consequently, it is found that the addition of Nd element into the Mg-6Al alloy is mainly in the fiber-like $Al_{11}Nd_3$ phase. In Fig. 5(a), the TEM analysis indicates that a great number of dislocations are aggregated in the intervals of fiber-like $Al_{11}Nd_3$ phase in the as-cast Mg-6Al-6Nd alloy after creep. On one hand, the dislocation motion proves that its creep mechanism is really controlled by the dislocations climb. On the other hand, the aggregation of dislocations indicates that $Al_{11}Nd_3$ phase hinders the dislocation motion, which would lead to the increase in the stress exponent. In Fig. 5(b), the TEM analysis indicates that the cracks occurred in some $Al_{11}Nd_3$ phase. It actually implies that a larger stress should be applied on the $Al_{11}Nd_3$ phase. In another word, the load transfer should take place from the matrix to some $Al_{11}Nd_3$ phase in the creep deformation. For the creep with the load transfer from alloy matrix to reinforced phase, Eq. (2) can be rewritten as [7-8, 10]

$$\frac{d\varepsilon}{dt} = (1-\alpha)^n A(\sigma - \sigma_{th})^n \exp\left(\frac{-Q}{RT}\right) \tag{3}$$

where α is the load transfer factor. Since α usually decreases with the creep temperature increasing, the activation energy for creep would increase according to Eq. (3) [7-8, 10]. It is the reason why the activation energy for creep of the as-cast

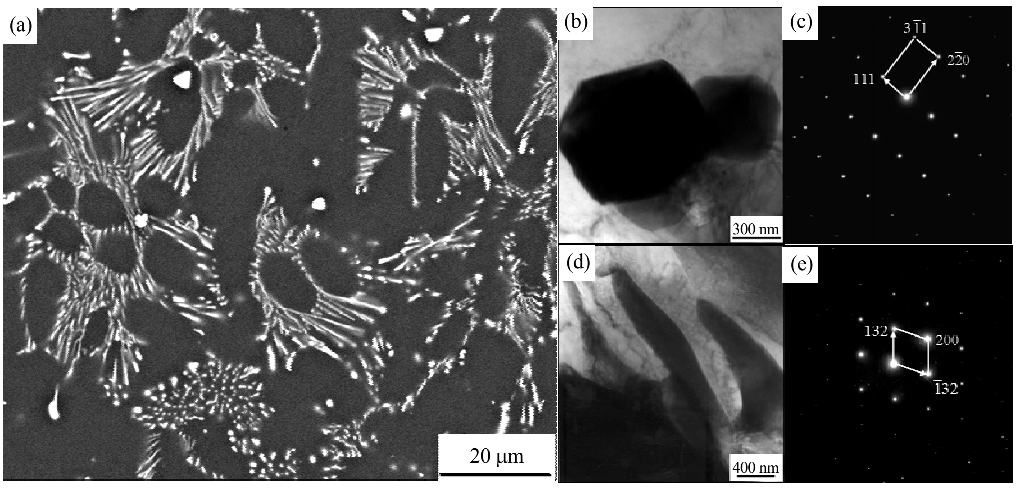

Fig. 4. Microstructures of the as-cast Mg-6Al-6Nd alloy before creep: (a) SEM image; (b) TEM image of Al_2Nd; (c) EDP of Al_2Nd; (d) TEM image of $Al_{11}Nd_3$; (e) EDP of $Al_{11}Nd_3$.

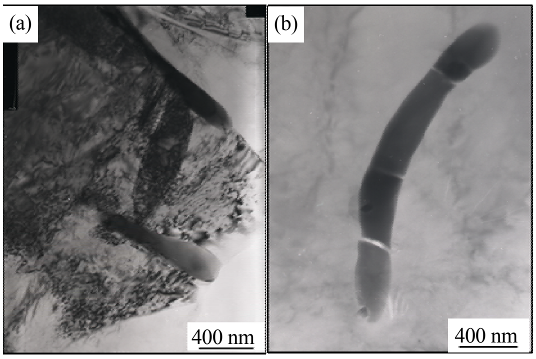

Fig. 5. Microstructures of the as-cast Mg-6Al-6Nd alloy after creep: (a) under the applied stress of 70 MPa at 175°C; (b) under the applied stress of 70 MPa at 150°C.

Mg-6Al-6Nd alloy is more than the self-diffusion activation energy of Mg. But it is difficult to identify the value of α precisely. It is affected by many factors such as the dimension, shape, distribution, and mechanical properties of second phase at different temperatures, so only qualitative discussion has been done in this paper.

4. Conclusion

The addition of Nd element into the Mg-6Al as-cast alloy improves its creep-resistant property effectively. The true stress exponent $n_0 = 4.96$ indicates that its creep mechanism belongs to the dislocation climb-controlled creep, which is in agreement with the microstructure changes before and after creep. The high value for stress exponent (n = 5.8) is attributed to the interaction of $Al_{11}Nd_3$ phase with dislocations. The activation energy is more than the self-diffusion activation energy of Mg, which is attributed to the load transfer taking place from the matrix to the $Al_{11}Nd_3$ phase during creep.

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