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Creep Behaviour of T6 Treated Mg-4Al-5.1Y-2.5LPC Alloy

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The compressive creep curves of Mg-4Al-5.1Y-2.5LPC alloy in T6 condition were tested under different stresses and temperatures using an electronic creep testing machine. The results show that the stress exponent of Mg-4Al-5.1Y-2.5LPC alloy at 250℃ is 3.38, indicating the creep mechanism of Mg-4Al-5.1Y-2.5LPC alloy is dislocation climb. When the creep stress is 117.1MPa, the creep activation energy ($Q_{200\text{-}250℃}$) of Mg-4Al-5.1Y-2.5LPC alloy is 145.7 kJ/mol, approximately being equal to self-diffusion activation energy of Mg, which also shows that the dislocation climb plays an important role in the creep process of Mg-4Al-5.1Y-2.5LPC alloy.

1. Introduction

Magnesium alloys are considered the most promising lightweight structure materials in the 21st century because of their low density, high specific strength and stiffness, superior damping capacity, good electromagnetic shielding characteristics, good castability and machinability (Celikin et al. 2012; Kim et al. 2011; Petterson et al. 1996; Ziogou et al. 2013). Therefore, a great many of kinds of magnesium alloys are expected to be used in automotive, aerospace and other fields (Unigovski et al. 2005; Wu et al. 2016). However, some magnesium alloys can not be used in commercial applications due to their poor strength or low creep properties at elevated temperature.

Rare earth (RE) elements, as important alloying elements, have been widely used in magnesium alloys and efficiently improve the mechanical properties and creep properties of magnesium alloys at high temperature. For example, Meshinchi Asl et al.(2009) reported that Mg-Al alloys containing lanthanum-praseodymium-cerium (LPC) and neodymium rare earth could significantly improve creep properties of these alloys. Smola et al. (2004) reported that Mg alloys including yttrium (Y) could remarkably improve the mechanical properties of these alloys at high temperature owing to the precipitation strengthening and the solution strengthening. However, the cooperative effect of Y and LPC rare earth on the creep properties of Mg alloy at elevated temperature has rarely been reported.

In this work, compressive creep behaviour of Mg-4Al-5.1Y-2.5LPC alloy in T6 condition was investigated.

2. Materials and Methods

2.1 Preparation of Mg-4Al-5.1Y-2.5LPC alloy

Mg, Al, Y and LPC rare earth (85wt%La, 10wt%Pr, 5wt%Ce) were used to prepare Mg-4Al-5.1Y-2.5LPC alloy. A vacuum induction melting furnace was used to melt Mg-4Al-5.1Y-2.5LPC alloy, and the melt was poured at 740℃ into a magnesia crucible.

2.2 Heat treatment process of Mg-4Al-5.1Y-2.5LPC alloy

The T6 heat treatment process parameters were 520℃ quenching temperature for 8 hours and 200℃ aging temperature for 16 hours.

2.3 Creep test of Mg-4Al-5.1Y-2.5LPC alloy in T6 condition

Creep tests were conducted in CSS-3902 electronic creep testing machine. The creep temperature was 150~300℃, the creep stress was 85.9~117.1MPa and the creep time was 0~80 hour.

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Microstructures were examined by a H-7650 transmission electron microscope (TEM) equipped with energy dispersive X-ray spectroscopy(EDX).

3. Results and Discussion

3.1 Creep curves

The compressive creep behaviour of T6 treated Mg-4Al-5.1Y-2.5LPC alloy at 150℃, 200℃, 250℃ and 300℃ under 117.1MPa creep stress is presented in Figure 1 . It can be seen that the creep rate is very small at 150℃~250℃, while the creep temperature rises to 300℃, the creep rate increases rapidly. When creep temperature is 250℃ and creep stresses are 85.9MPa, 97.3MPa and 117.1MPa, respectively, the compressive creep curves of Mg-4Al-5.1Y-2.5LPC alloy by T6 treatment are shown in figure 2.

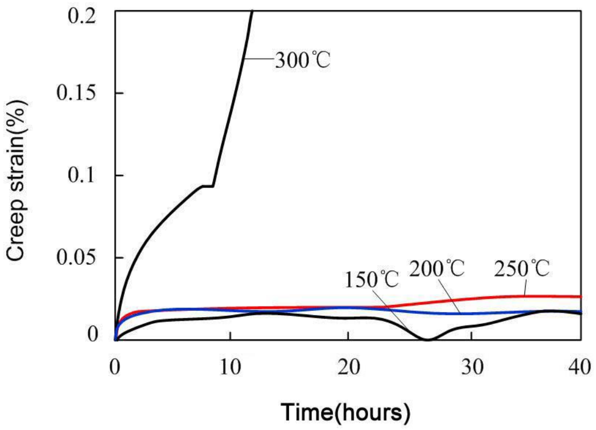

Figure 1 : Compressive creep curves of Mg-4Al-5.1Y-2.5LPC alloy after T6 treatment at different temperatures and 117.1MPa.

3.2 Creep mechanism

Table 1 gives the steady creep rate of T6 treated Mg-4Al-5.1Y-2.5LPC alloy under different temperatures and stresses. It can be seen that the steady creep rate increases with the temperature and stress increasing.

$ln\varepsilon$-$ln\sigma$ curve of T6 treated Mg-4Al-5.1Y-2.5LPC alloy at 250℃ is shown in Figure 3. It can be seen that a linear relationship can be drawn between the steady creep rate and creep stress. The stress exponent of T6 treated Mg-4Al-5.1Y-2.5LPC alloy is 3.38 at 250℃, that is, n =3.38.

Table 1: Steady creep rate of Mg-4Al-5.1Y-2.5LPC alloy after T6 treatment at different temperatures and stresses

Temperature / ℃	Stress/ MPa	Steady creep rate/S^{-1}
150	117.1	4.55×10-11
200	117.1	7.90×10-10
	85.9	9.11×10-9
250	93.7	1.48×10-8
	117.1	2.73×10-8

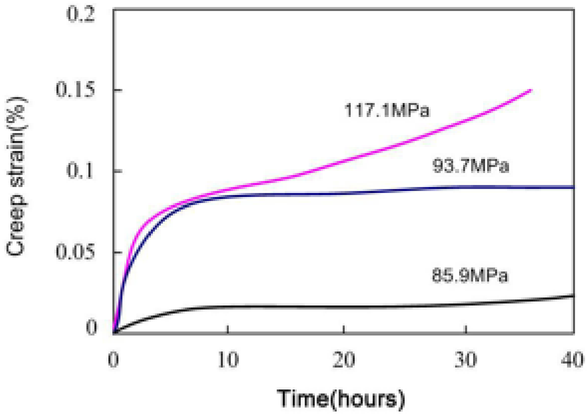

Figure 2: Compressive creep curves of Mg-4Al-5.1Y-2.5LPC alloy after T6 treatment at 250℃ and different stresses.

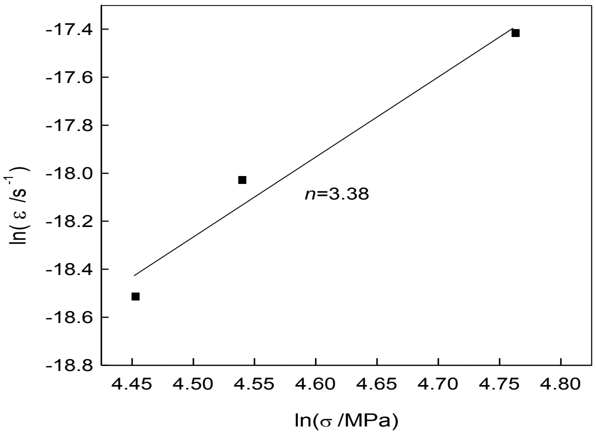

Figure 3: lnε-lnσ curve of Mg-4Al-5.1Y-2.5LPC alloy after T6 treatment at 250 ℃

Some studies (Yi et al. 2011; Liu et al. 2014; Mordike 2002; Rokhlin et al. 2003; Wei et al. 1996) have indicated that during the creep of magnesium alloy, creep rate is the smallest in the steady creep stage, the deformation mechanism of magnesium alloy is relatively simple, and the steady creep rate can be described the function of temperature and stress. The conventional Power-Law equation relating the steady creep rate to the temperature and the applied stress is:

$$\dot{\varepsilon} = A\sigma^{n} \exp[-{}^{Q}\!/_{(RT)}] \tag{1}$$

Where $\dot{\varepsilon}$ is the steady creep rate, A is a constant related to materials, σ is the applied stress, n is the stress exponent, Q is the creep activation energy, R is the molar gas constant and T is the thermodynamic temperature.
At a constant temperature, the stress exponent in equation (1) can be calculated using the following equation.

$$n = [\frac{\partial(\ln \dot{\varepsilon})}{\partial(\ln \sigma)}] \tag{2}$$

It can be known by the equation (2) that the stress exponent is the slope of *lnε-lnσ* curve. Therefore, by plotting the steady creep rate versus the applied stress, the stress exponent of magnesium alloy at a constant temperature can be obtained through fitting $ln\varepsilon$-$ln\sigma$curve. Different stress exponent corresponds to the different creep mechanism for magnesium alloys.

Yi et al. (2011) have reported that when the stress exponent n is equal to 2, the creep mechanism of magnesium alloy is grain boundary sliding, and when n is in the range of 3~7, creep mechanism of magnesium alloy is dislocation climb controlled creep, however, n being beyond 7 indicates the equation (1) is invalid, that is to say, the conventional Powder-Law equation relating the steady creep rate to the temperature and the applied stress may no longer hold. According to the stress exponent n, the creep mechanism of T6 treated Mg-4Al-5.1Y-2.5LPC alloy at 200~250℃ is dislocation climb.

The creep activation energy Q is an important parameter indicating magnesium alloy creep mechanism. The reasons causing magnesium alloys creep can be judged in light of value of the creep activation energy.

Under a constant stress, the creep activation energy Q can be calculated based on the following equation:

$$Q = R\frac{T_1T_2}{T_1 - T_2}\ln\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right) \tag{3}$$

Where T_1 and T_2 are the thermodynamic temperatures, R is the molar gas constant, $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are steady creep rates at T_1 and T_2 temperature, respectively.

Table 2: Creep activation energy of Mg-4Al-5.1Y-2.5LPC alloy after T6 treatment at different temperatures

Temperature / ℃	Stress/ MPa	Creep activation energy/ (kJ.mol^{-1})
150-200	117.1	95.0
200-250	117.1	145.7

The creep activation energy of Mg-4Al-5.1Y-2.5LPC alloy by T6 treatment can be calculated based on the equation (3), and the result is shown in Table 2. It can be found that under a constant creep stress, the creep activation energy of Mg-4Al-5.1Y-2.5LPC alloy by T6 treatment increases as the creep temperature elevates. When the creep stress is 117.1MPa and the creep temperature is 200~250℃, the creep activation energy of Mg-4Al-5.1Y-2.5LPC alloy is 145.7 kJ/mol, close to the self-diffusion activation energy of Mg (Q =138 kJ/mol). Rokhlin et al.(2003); Nie et al.(200); Socjusz et al.(2003) have reported that when the creep activation energy of magnesium alloy is close to the grain boundary diffusion activation energy of Mg (Q =80 kJ/mol), the creep behaviour of magnesium alloy is controlled by grain boundary sliding, and the creep behaviour of magnesium alloy is controlled by dislocation climb when the creep activation energy of magnesium alloy is close to self-diffusion activation energy of Mg (Q =138 kJ/mol). Therefore, it can be known that under 117.1MPa creep stress and 200~250℃ creep temperature, the creep of Mg-4Al-5.1Y-2.5LPC alloy by T6 treatment is controlled by dislocation climb, which is consistent with the conclusion drawn by stress exponent of T6 treated Mg-4Al-5.1Y-2.5LPC alloy.

TEM images of T6 treated Mg-4Al-5.1Y-2.5LPC alloy after creep are presented in Figure 4 and Figure 5. It can be seen that there are some creep cracks in matrix (Figure 4) and two small particle chains near grain boundary(Figure 5). In addition, it can be also observed that creep cracks are perpendicular to the particle chain and cease to extend at the particle chain. The particle chain is Al_{11} RE_3 compound based on the EDX. Meshinchi Asl et al. (2009) have reported that $Al_{11}RE_3$ compound has high melting point and distributes along grain boundaries, and $Al_{11}RE_3$ compound can pin grain boundaries and hinder both grain boundary migration and sliding during high temperature creep. Therefore, $Al_{11}RE_3$ compound can prevent the creep cracks from extending and improve the creep properties of Mg-4Al-5.1Y-2.5LPC alloy.

Figure 4: The microstructure in matrix of Mg-4Al-5.1Y-2.5LPC alloy after T6 treatment and after creep (creep temperature 250℃, creep stress 117.1MPa)

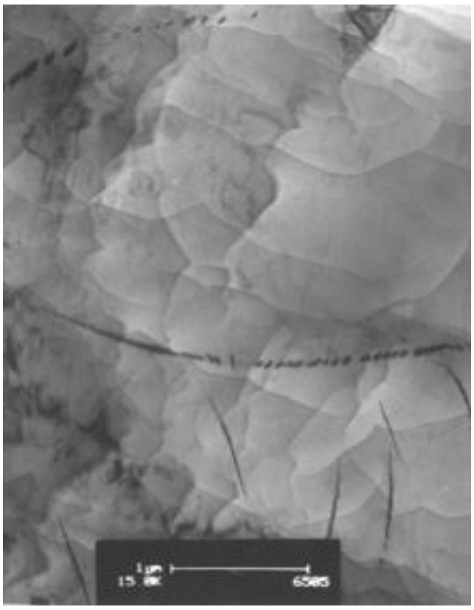

Figure 5: The microstructure near grain boundary of Mg-4Al-5.1Y-2.5LPC alloy after T6 treatment and after creep (creep temperature 250℃, creep stress 117.1MPa)

4. Conclusion

The compressive creep behaviour of Mg-4Al-5.1Y-2.5LPC alloy in T6 condition was investigated. Under 117.1MPa creep stress and 200~250℃ creep temperature, the creep activation energy of Mg-4Al-5.1Y-2.5LPC alloy is equal to 145.7kJ/mol, approximately being equal to self diffusion activation energy of Mg. At 250℃ creep temperature, the stress exponent n of Mg-4Al-5.1Y-2.5LPC alloy is 3.38, indicating the creep mechanism of Mg-4Al-5.1Y-2.5LPC alloy is dislocation climb controlled creep.

Acknowledgments

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