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Effect of Zr on behavior of compressive creep in as cast ZA27 alloy①

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Abstract: The effect of Zr on the behavior of compressive creep in as cast ZA27 alloy was investigated in the temperature range of 20-160 ℃ and under different compressive stresses in the range of 50-137.5 MPa with special apparatus. The results show that the primary compressive creep strains and steady creep rates of ZA27-Zr alloy and ZA27 alloy increase with increasing temperature and stress. However, the primary compressive creep strain and steady creep rate of the ZA27-Zr alloy are lower than that of the ZA27 alloy below 100 ℃, but higher at 160 ℃. The compressive creep behaviors in both ZA27-Zr alloy and ZA27 alloy obey an empirical equation $\ln t = C - n\ln\sigma + Q/RT$, and the exponent stress n is 3.63 for ZA27-Zr alloy and 3.46 for ZA27 alloy, respectively, the activation energy Q is 87.32 kJ/mol for ZA27-Zr alloy and 81.09 kJ/mol for ZA27 alloy. Different material structural constants are associated with different compressive creep behaviors in the alloy. The compressive creep rate in the alloy is controlled by the lattice diffusion of zinc and dislocation limb.

Key words: as cast ZA27 alloy; Zr; compressive creep; stress exponent; activation energy
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1 INTRODUCTION

Among zinc-aluminum cast alloy, ZA27 alloy exhibits attractive physical and mechanical properties combined with good friction and wear resistance, making it a bearing alloy replacement of some copper alloys[1,2], also this alloy tends to be used widely. But some properties of this alloy which must be taken into account are comparatively low resistance to creep deformation, poor strength at moderately elevated temperatures[3-5]. Addition of some modifying elements, such as Zr, Mn, Li, can indeed improve tensile strength of the alloy at room and high temperature[4-7]. However, in the case of ZA27 alloy, the compressive loading is more common in the alloy applications. In automotive and other industries, many compressive components made of this alloy are used for service at temperatures in the range of 150-200 ℃. At this temperature the compressive creep properties are more important than the short-term tensile properties. Presently, the study on the compressive creep in the alloy is so scarce and nothing is known about the effect of Zr on the creep behavior of ZA27 alloy especially. Based on these, it is interesting to investigate this. Thus the objective of the present study is to establish an understanding of the effect of Zr on the compressive creep behavior of as cast ZA27 alloy in terms of creep kinetics and structure. It is essential for designers and will increase the scope for the development of this alloy.

2 EXPERIMENTAL

2.1 Materials

Some researches on the properties of ZA27 alloy show that the alloy has better room and high temperature tensile strength after adding about 0.2%Zr. Thus in this study work, addition of 0.2%Zr is used.

The alloys for testing specimens were prepared using commercial-purity Zn (99.99%), Al (99.88%), Cu (99.0%), Mg (99.85%) and master alloy Al-Zr in a resistance furnace (SRJG-3-9) and degassed with a commercial degasser ($ZnCl_2$). The melts of ZA27 and ZA27-Zr were poured into a Y-shaped permanent mould at 600 ℃ respectively, and then the specimens (8 mm diameter by 10 mm gauge length) were machined from the Y-shaped ingots.

2.2 Procedure

Compressive creep tests were carried out with special apparatus composed of constant pressurization, heating and temperature controller, data collecting and record devices. The temperature error could be maintained within ±0.5 ℃ and the compressive creep deformation parameters were obtained by displacement transducer, and then recorded by a computer for the whole period of the test. The precision of the compressive creep deformation could be up to

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0.0001 mm. Different temperatures (20, 60, 100 and 160 ℃) and various compressive stresses (50, 87.5, 100 and 137.5 MPa) were tested. All of the tests were done in triplicate in order to obtain satisfactory precision in measuring the compressive creep behavior of the alloys.

3 RESULTS

3.1 Curves of creep strain and primary creep deformation

Curves of creep strain versus time were obtained for various combinations of applied stress and testing temperature. From these the primary creep strain, secondary (or steady) creep rate and time to obtain total creep deformation of 0.2%, 0.6% and 1.0% were obtained. The typical creep curves of the specimens at 100 ℃ and 160 ℃ are shown in Fig. 1. The effect of Zr on primary compressive creep deformation of ZA27 alloy is shown in Fig. 2.

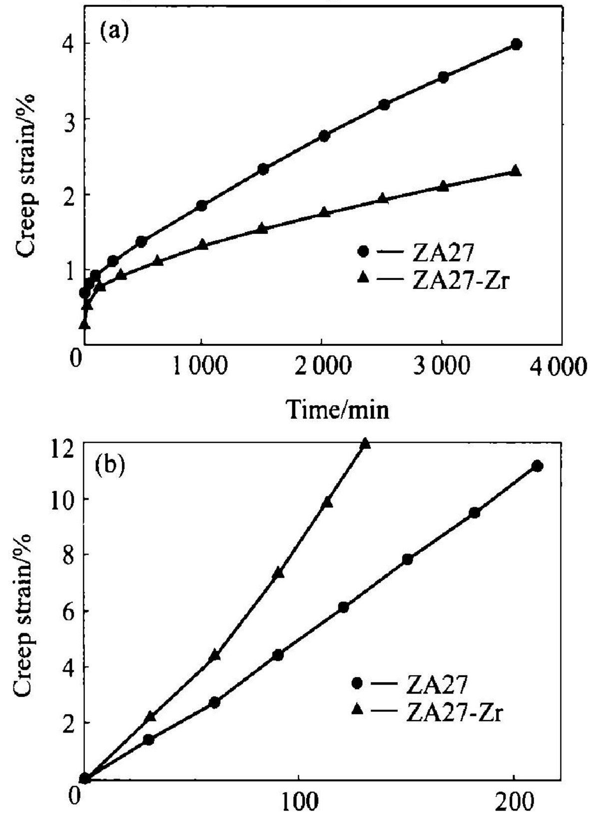

Fig. 1 Effect of Zr on compressive creep curves for ZA27 alloy
(a) —100 ℃, 100 MPa; (b) —160 ℃, 87.5 MPa

3.2 Effect of Zr on steady compressive creep rate

The steady compressive creep rate ($\dot{\varepsilon}_s$, averaged value of three specimens), in the linear portion of the creep curve which follows the primary stage, was calculated for each test over all of the stress and temperature range. The results are listed in Tabel 1, and plotted in form ln $\dot{\varepsilon}_s$ versus lnσ in Fig. 3. Table 1 and Fig. 3 show that the steady creep rate of ZA27-Zr alloy

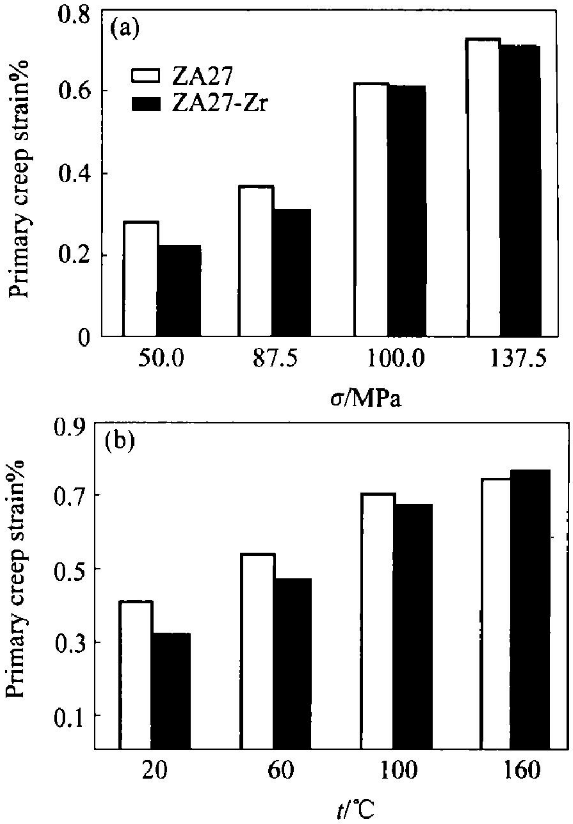

Fig. 2 Effect of Zr on primary compressive creep deformation of ZA27 alloy
(a) —Primary creep strain averaged over all temperatures for each stress;
(b) —Primary creep strain averaged over all stress level for each temperature

is lower than that of the ZA27 alloy below 100 ℃, but it is higher at

Table 1 Effect of Zr on steady compressive creep rate ($\dot{\varepsilon}_s$, %/s) of ZA27 alloy

Temperature/℃	Stress/MPa	ZA27-Zr	ZA27
20	50.0	4.34×10^{-9}	7.79×10^{-9}
	87.5	1.49×10^{-8}	6.05×10^{-8}
	100.0	8.31×10^{-8}	1.27×10^{-7}
	137.5	3.27×10^{-7}	6.41×10^{-7}
60	50.0	3.21×10^{-7}	7.30×10^{-7}
	87.5	1.04×10^{-7}	5.08×10^{-6}
	100.0	3.52×10^{-6}	1.44×10^{-5}
	137.5	1.65×10^{-5}	1.97×10^{-5}
100	50.0	6.72×10^{-6}	1.48×10^{-5}
	87.5	1.34×10^{-5}	5.49×10^{-5}
	100.0	8.67×10^{-5}	1.09×10^{-4}
	137.5	3.24×10^{-4}	4.18×10^{-4}
160	50.0	1.17×10^{-3}	9.03×10^{-4}
	87.5	2.13×10^{-3}	1.99×10^{-3}
	100.0	6.31×10^{-3}	6.04×10^{-3}
	137.5	2.24×10^{-2}	1.81×10^{-2}

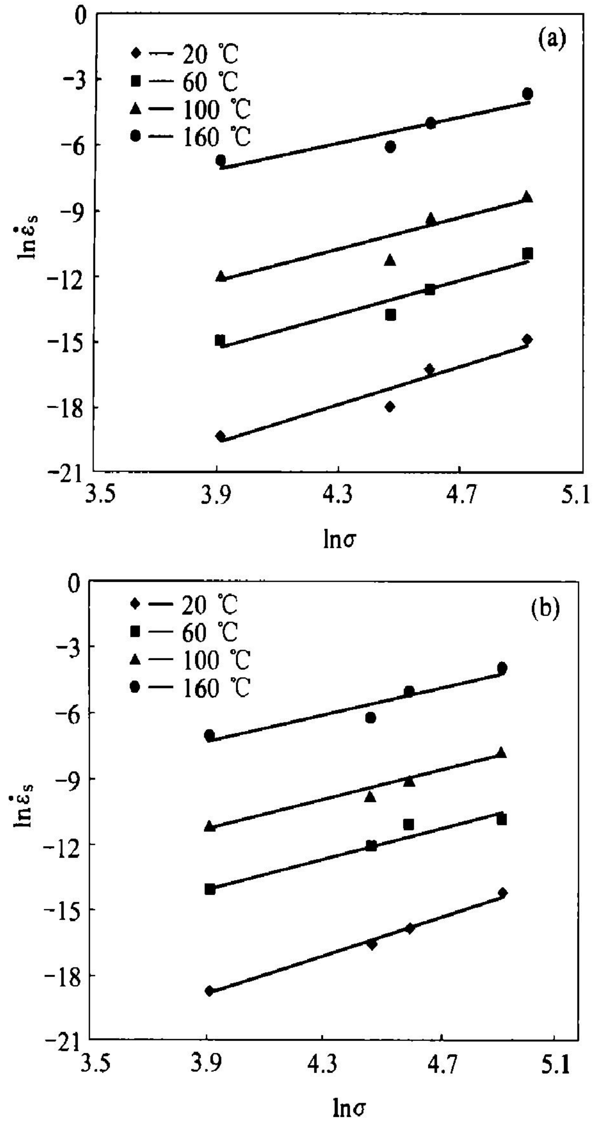

Fig. 3 $\ln\ \dot{\varepsilon}_s$ versus $\ln\ \sigma$
(a) —ZA27-Zr; (b) —ZA27

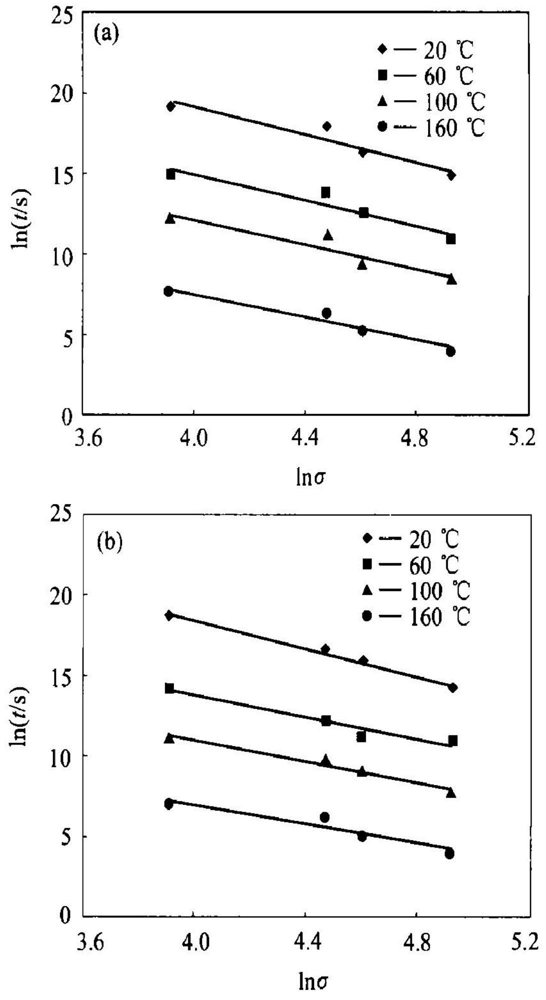

Fig. 4 Relationship between $\ln t$ and $\ln\ \sigma(\varepsilon = 1.0\%)$
(a) —ZA27-Zr; (b) —ZA27

160 ℃, and that there is a good linear relationship between $\ln\ \dot{\varepsilon}_s$ and $\ln\ \sigma$ for each alloy under all test conditions.

3.3 Total creep strain

From the creep curves the time to a total creep deformation of 0.2%, 0.6% and 1.0% was obtained for each alloy and these values were plotted as a function of $\ln\sigma$ for each temperature and $1/T$ for each $\ln\sigma$, respectively. In all cases such graphs are linear with a constant slope over all of the stress and temperature range, as shown in Fig. 4 and Fig. 5.

4 ANALYSIS AND DISCUSSION

4.1 Correlation of compressive creep data

In pressure die cast zinc-aluminum, Murphy and Durman[8] used an empirical equation of the form:

$$f(\varepsilon) = A t \sigma^n \exp(-Q/RT) \tag{1}$$

to correlate creep data, in which A is a constant which takes into account the effects of composition and structure, σ is normal stress, n is the stress exponent, t is the creep time, Q is the effective activation energy for creep, R is the gas constant, T is the absolute temperature of the test and $f(\varepsilon)$ is an undefined function of the creep strain ε; when A, σ, n, Q and T are constants, $f(\varepsilon)$ represents the shape of the creep strain versus time curve. Taking logarithms and rearranging, then

$$\ln t = \ln f(\varepsilon) - \ln A - n\ln\sigma + Q/RT \tag{2}$$

but at constant strain

$$\ln t = C - n\ln\sigma + Q/RT \tag{3}$$

where C is a new constant which incorporates A and ε. If this relationship is obeyed for the experimental alloys studied here, a plot of ln(time, to any fixed creep strain) against ln(stress) at constant temperature should be linear with a slope of $-n$, or a plot of the ln(time, to any fixed creep strain) versus $1/T$ at constant stress should be linear with a slope of Q/R over all of the temperatures and stresses used. Fig. 4 and Fig. 5 show that such plots for the two alloys with $\ln\sigma$ and $1/T$ as independent variable, are in fact all linear with the constant slopes over all of the temperatures and stresses used, respectively. The values of the stress exponent n and activation energy

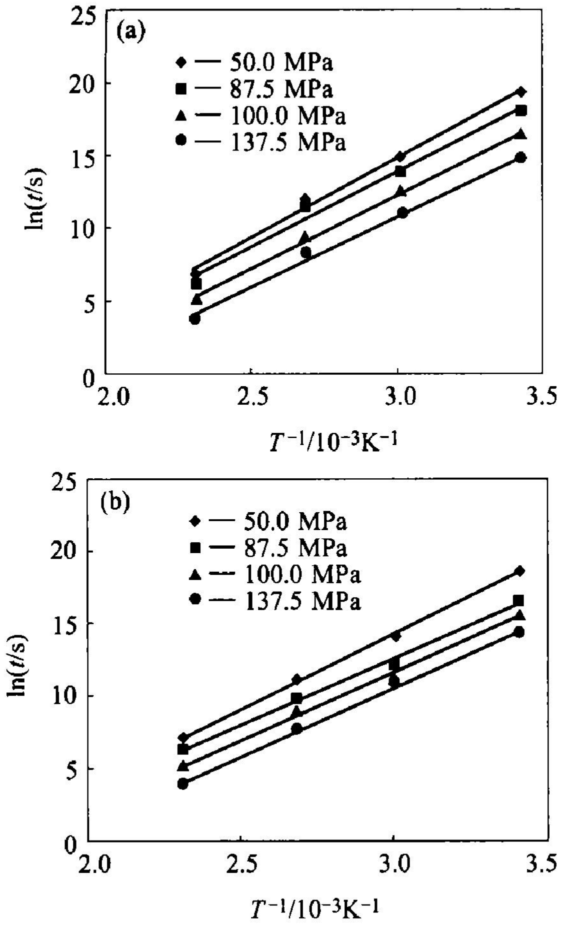

Fig. 5 Relationship between ln$t$ and $1/T$ (ε= 1.0%)
(a) —ZA27-Zr; (b) —ZA27

Q from these graphs are listed in Table 2. Table 2 shows that the values of the stress exponent n and activation energy Q of ZA27-Zr are higher than those of the ZA27 alloy, but the

Table 2 Effect of Zr on stress exponent(n) , activation energy(Q) and constant C for ZA27 alloy

Alloy	Stress exponent n				Average
	20 ℃	60 ℃	100 ℃	160 ℃	
ZA27-Zr	4.29	3.82	3.56	2.82	3.63
ZA27	4.31	3.35	3.34	2.94	3.46

Alloy	Activation energy $Q/(\text{kJ}\cdot\text{mol}^{-1})$				Average $Q/(\text{kJ}\cdot\text{mol}^{-1})$
	50 MPa	87.5 MPa	100MPa	137.5MPa	
ZA27-Zr	93.17	88.37	84.86	82.87	87.32
ZA27	88.10	77.99	79.86	78.11	81.09

Alloy	Constant C		
	ε= 0.2%	ε= 0.6%	ε= 1.0%
ZA27-Zr	- 4.91	- 3.83	- 2.86
ZA27	- 2.92	- 1.82	- 0.85

values of the stress exponent n are between 3 and 5, and the values of the activation energy Q are close to that of the lattice self-diffusion energy of zinc[9]. It can be considered that the compressive creep in the ZA27 alloy or ZA27-Zr alloy is controlled by the lattice diffusion of zinc and dislocation limb.

Thus, the compressive creep data, like tensile creep data, are well correlated by equation(3) and the creep behavior of the two alloys can be related to the testing conditions by this single relationship over all stresses and temperatures used for the test. Once the values of n and Q are known, the constant C, which is a characteristic of each combination of alloy plus chosen strain, can be obtained and data correlation shown clearly by a plot of ln(time, to a given strain) versus the parameter ($Q/RT - n\ln\sigma$), which should give linear plots of unit slope and intercept C. Fig. 6 shows such plots of ln(time, to produce creep strain of 0.2%, 0.6% and 1.0%) versus the above creep parameter ($Q/RT - n\ln\sigma$) for ZA27-Zr and ZA27, respectively. From the plots, the intercepts C were obtained, as shown in Table 2. The differences in creep behavior between the alloys are derived solely from differences in values of this constant C, and this table shows that a good correlation of the data is obtained by the parameter plot and indicates that the parameter together with the corresponding values of Q and n may be used with high confidence to estimate the compressive creep behavior of the

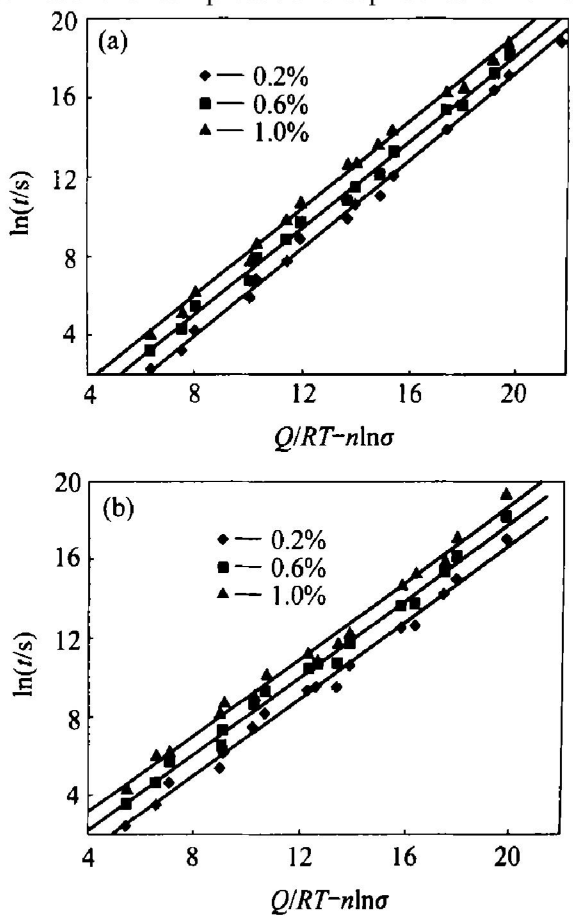

Fig. 6 Relationship between ln t and [$Q/RT - (n\ln\sigma)$]
(a) —ZA27-Zr; (b) —ZA27

two alloys.

The components made of ZA27 alloy are extensively used under compressive conditions. Using the experimentally determined values of stress exponent n, activation energy Q and creep constant C, the maximum continuous stresses which produce 0.2%, 0.6% and 1.0% creep strains in 100 000 h (about 11.4 a) at different test temperature are calculated in order to compare the relative creep performances of the two alloys. The service life is chosen on the basis of the ASME Boiler Code, according to which the creep-limited maximum allowable design stress is that produces indicated creep strain in 100 000 h. The values of the design stresses for the two alloys are listed in Table 3. It is found that the ZA27-Zr alloy has better creep performance than the ZA27 alloy below 100 ℃.

Table 3 Design compressive stresses for ZA27-Zr alloy and ZA27 alloy

Alloy	Creep strain/%	Stress to produce strain(%) in 100 000 h/MPa			
		20 ℃	60 ℃	100 ℃	160 ℃
ZA27-Zr	0.2	22.06	6.75	2.66	0.90
	0.6	29.71	9.09	3.61	1.22
	1.0	38.82	11.87	4.68	1.58
ZA27	0.2	20.19	6.10	2.57	0.92
	0.6	28.41	8.94	3.59	1.27
	1.0	36.22	11.40	4.59	1.66

4.2 Microstructure dependence of creep behavior

As mentioned above, the different compressive creep behaviors between ZA27-Zr alloy and ZA27 alloy are derived solely from differences in the values of the material structural constant C which is related to the composition and microstructure of the two alloys. Some researches[10] show that the correlation of creep rate with grain size changes with temperature, at lower temperature, creep in alloy is mainly caused by sliding in grains of alloy, thus the smaller the grain size, the higher the resistance to creep; but at higher temperatures, the grain boundary is a dislocation resource which plays an important role in creep, thus the less the grain boundary, the higher the resistance to creep. Fig. 7 shows the metallographs of the alloys. It can be found that the structure of the as cast ZA27 is composed of dendritic Al-rich α phase with the edge of β phase, and decomposed η phase in the interdendritic region, as well as a few ε($CuZn_4$) phases[11]. Zr reacts with Al, Zn, etc, to form some complex compounds, $ZrAl_3$ or $Zr(Al, Zn)_3$ which serve as nuclei in the melt[12, 13] and refines the grain of the as cast ZA27 alloy, and Zr in the form of solid solution can result in solid solute hardening in the alloy to slow down the diffusion rate of atoms, thus the creep resistance of ZA27-Zr alloy is higher than that of the ZA27 alloy below 100 ℃. However, at 160 ℃, the creep is resulted from the grain boundary sliding. These means that the refinement of grain can increase the resistance to creep for the components served at lower temperature and the coarsening of grain can improve the creep resistance of the alloy at higher temperatures.

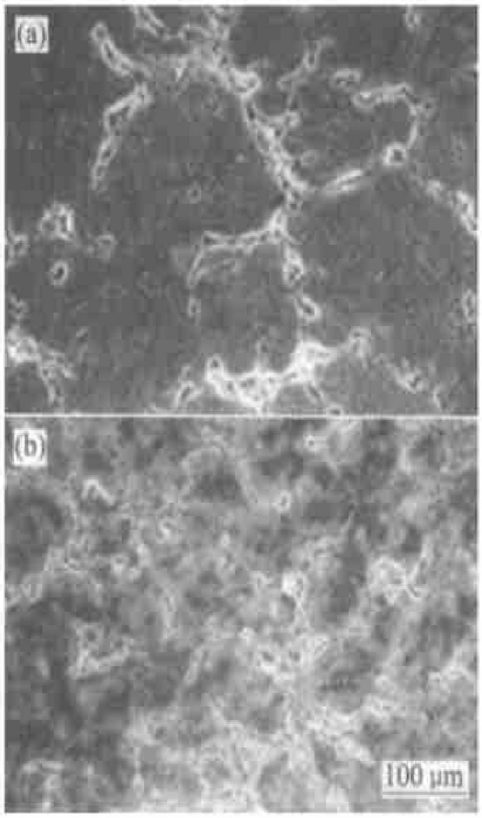

Fig. 7 Effect of Zr on microstructure of as cast ZA27 alloy(SEM)
(a) —ZA27; (b) —ZA27-Zr

5 CONCLUSIONS

1) The primary compressive creep strain and steady creep rate of ZA27-Zr alloy and ZA27 alloy increased with stress and temperature. However, the primary compressive creep strain and steady creep rate of ZA27-Zr alloy were lower than those of the ZA27 alloy below 100 ℃, and higher at 160 ℃.

2) The compressive creep behaviors of ZA27-Zr alloy and ZA27 alloy obeyed an empirical equation $\ln t = C - n\ln\sigma + Q/RT$. The different compressive creep behaviors of the two alloys were derived solely from differences in the values of the constant C, and the values of the stress exponent n, 3.63 for ZA27-Zr, 3.46 for ZA27 alloy, and the values of the activation energy Q, 87.32 kJ/mol for ZA27-Zr alloy, 81.09 kJ/mol for ZA27 alloy, respectively.

3) The creep resistance of ZA27-Zr alloy is lower

than that of ZA27 alloy below 100 ℃ and is higher at 160 ℃.

REFERENCES

[1] Savakan T, Murphhy S. Mechanical properties and lubricated wear of Zn-25Al-Based alloy [J]. Wear, 1987, 106: 211 - 214.
[2] Lopez Hirata V M, Saucedo Muñoz M, Rodriguez Herandez J C, et al. Milling characteristic of extruded Zn-Al alloy [J]. Materials Science & Engineering, 1998, A247: 8 - 14.
[3] TIAN Rong-zhang, WANG Zhi-yuan. Research on phase transformation and dimensional stability of Zn-Al alloy [J]. Zhongnan Kuangye Xueyuan Xuebao, 1992, 23 (6): 712 - 717. (in Chinese)
[4] ZHAO Pei-lian, ZHAO Xing-guo, ZHAO Hao-feng. Effect of rare earths on the high temperature properties of ZA-27 alloy [J]. Journal of The Chinese Rare Earth Society, 1988, 16(1): 41 - 44. (in Chinese)
[5] SU De-huang. Effect of Fe and Mn added on high temperature tensile properties of ZA27 alloy [J]. Materials Science & Technology, 1998, 6(3): 52 - 55. (in Chinese)
[6] PANG Shao-ping, QUAN Mei-hua, SHI Yun-bao, et al. Effects of Zr on microstructures and properties of high damping Zn-22% Al alloy [J]. The Chinese Journal of Nonferrous Metals, 1998, 8(1): 69 - 73. (in Chinese)
[7] LIU Jin-shui, ZHANG Fu-quan, SHU Zheng, et al. Influence of Ce on structures and properties of ZA43 alloy [J]. Special Casting and Nonferrous Alloy, 1998(1): 4 - 6. (in Chinese)
[8] Durman M, Murphy S. An improved parametric method for the correlation of creep data from commercial pressure-diecast zinc-based alloy [J]. Z Metallkd, 1991, 82: 129 - 134.
[9] Prasad N, Malakondaiah G, Banerjee D, et al. Low-stress creep behavior of superplastic Zn-22% Al alloy [J]. Materials Science, 1993, 28: 1585 - 1594.
[10] GUO Ting-wei(Tr). High Temperature Strength Theory and Design of Metal Materials [M]. Beijing: Science Press, 1983. (in Chinese)
[11] Zhu Y H, Torres G, Pina C. Complex microstructural changes in as-cast eutectoid Zn-Al alloy [J]. Materials Science, 1994, 29: 1549 - 1552.
[12] Mondolf L F. Aluminum alloys: Structure and Properties [M]. London: Butterworths, 1974.
[13] Ahmed A, Abdel-Hamid. Mechanism of modifying Zn-Al alloys by Ti, Ta, Ti+ Ta, V, V+ Ti, Zr or Zr+ Ti [J]. Z Metallkd, 1993, 84: 41 - 43.

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