Study on Compressive Creep Behavior of AE42 and AE41-xCa Alloys

Daofen Xu

Guilin University of Aerospace Technology, Guilin, 541004, China

***Abstract*—The compressive creep behavior of AE42 and AE41-xCa alloys were investigated at temperatures in the range of 125~175℃ and compressive stresses in the range of 88~112MPa with a special apparatus. The results show that the creep resistance of alloys is improved with increasing of calcium concentration, and the compressive creep strain and steady state compressive creep rate increases obviously with increasing of temperature and compressive stress. There is a good linear logarithmic relationship between $\ln\dot{\varepsilon}_s$ versus $\ln\sigma$ or 1/T under different temperatures or stresses, respectively. The steady creep rate obeys an empirical equation. The stress exponent *n*, the apparent activation energy Q_a of AE42 alloy is 5.39 and 90.41KJ/mol respectively, and the stress exponent *n*, the apparent activation energy Q_a of AE41-1.2Ca alloy is 6.24 and 37.51KJ/mol respectively, which indicates that the compressive creep mechanism is changed with the addition of Ca.**

Keywords-AE42 alloy; AE41-xCa alloys; compressive creep behavior; creep mechanism

I. INTRODUCTION

Magnesium and magnesium alloys are attractive for using as structure function material in automotive and aerospace industries to improve fuel efficiency by reducing the vehicle weight[1,2]. However, the service temperatures of these Mg-Al alloys are limited to 150℃[3]. The poor elevated temperature properties is linked to the existence of the low-melting point $Mg_{17}Al_{12}$ phase, which is comparatively soft and allows shear along the grain boundaries during operation at elevated temperatures. The most common way of improving the elevated temperature properties is through the formation of thermally stable precipitates or dispersoids along the grain boundaries to reduce the amount of $Mg_{17}Al_{12}$ phase. Rare earth elements are the most effective alloying elements for such purposes which result in significant improvement in the elevated temperature properties[4,5]. For example, AE42 alloy has been used as gearboxes by General Motors[3]. But, the high cost of these alloys compared with conventional magnesium alloys has limited their applications. Therefore, cheaper earths, such as Ca, Sr, Sm and Sb, win the good graces of the researchers[6-14]. The heat-resistant phases, such as Al_2Ca and Al_4Sr, distribute at grain boundary to minimize the intragranular deformation and hinder dislocation glide and grain boundary diffusion, which are good for improving the creep resistance property. In view of this, compressive creep behavior of AE42 and AE41-xCa alloys were investigated at different temperatures and applied stress. The constitutive equation of AE42 alloy and AE41-1.2Ca alloy was established and the compressive creep mechanism was discussed in this paper.

II. EXPERIMENTAL

Pure magnesium, pure aluminum, and Mg-10%RE (75%Nd+25%Pr) master alloys were prepared with nominal compositions listed in Tab.1. Melting of the investigated alloys was conducted in an electric resistance furnace under 10%SF_6+90%CO_2 atmosphere. The melt was held at 750°C for 30min and then poured into a metal mould at 720°C. The mould temperature is 250°C. Creep tests were performed on as cast specimens with the size of Ø8mm×10mm. All the creep tests were performed in an oil bath in order to maintain temperature stability and to prevent oxidation of the specimens.

TABLE 1. CHEMICAL COMPOSITIONS OF ALLOYS(wt, %)

Numbers	Mg	Al	RE	Ca
AE42	Bal.	4.0	2.0	—
AE41	Bal.	4.0	1.0	—
AE41-0.4Ca	Bal.	4.0	1.0	0.4
AE41-0.8Ca	Bal.	4.0	1.0	0.8
AE41-1.2Ca	Bal.	4.0	1.0	1.2

The compressive creep tests were carried out with a special apparatus composed of constant-load pressurization, heating and temperature controller, collecting data and record devices, as shown in Fig.1. The temperature was maintained constant to within ±1°C. The precision of compressive creep deformation could be up to 0.001mm. Record the data after pre-creeping 10 minutes. The experimental temperature was 125, 150 and 175°C and the applied stress was 88, 100 and 112MPa. The creep datum was evaluated as the average of three specimens at least.

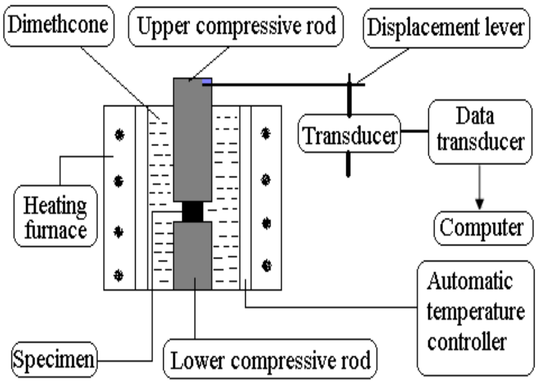


Figure 1. Schematic photograph of compressive creep apparatus

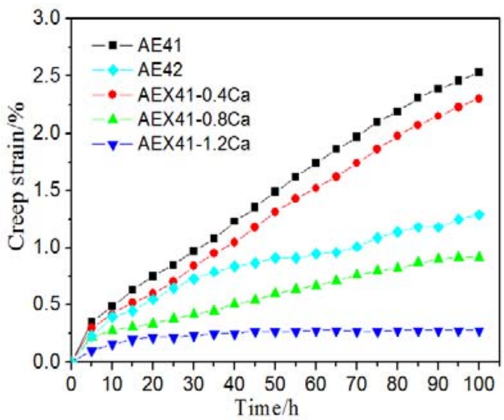


Figure 2. Compressive creep curves

III. RESULTS

The compressive creep curves of AE42 alloy and AE41-xCa alloys under the temperature 150℃and applied stress 100MPa for 100h are shown in Fig.2. It can be seen that all alloys have obvious steady-state creep stage. The creep resistance of AE41 alloy and AE42 alloy is poor and the compressive creep strain is 0.253mm and 0.129mm for 100h, respectively. The creep resistance of AE41-xCa alloys improves significantly with the increasing of Ca. The creep resistance of AE41-0.8Ca alloy and AE41-1.2Ca alloy is better than that of AE42 alloy, and the compressive creep strain is about 36% and 11% of that of AE41 alloy, respectively.

The compressive creep curves of AE42 alloy and AE41-1.2Ca alloy for various combinations of applied stress and testing temperature are shown in Fig.3 and Fig.4, respectively. It can be found that the compressive creep strain increase obviously with increasing of temperature and compressive stress. The compressive creep curve consists of decelerating creep stage, steady state creep stage and the accelerated creep stages. The steady state creep stage of AE42 alloy is shorter and results in creep rupture at 175℃. However, the steady state creep stage of AE41-1.2Ca alloy is longer under experiment condition and creep crack isn't found.

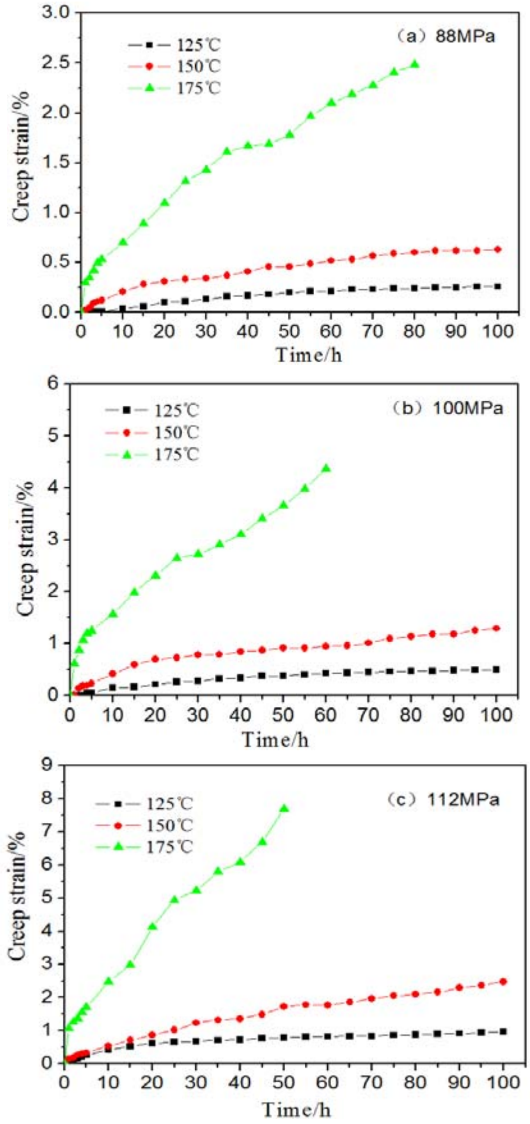
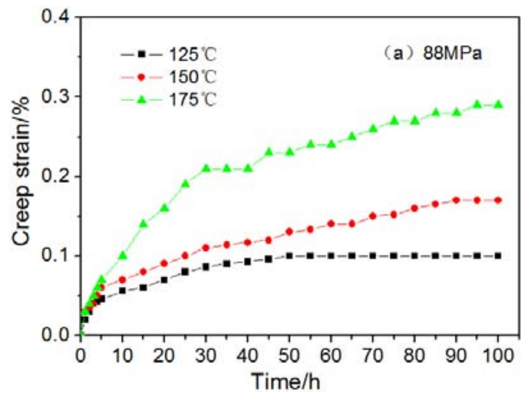


Figure 3. Compressive creep curves of AE42 alloy



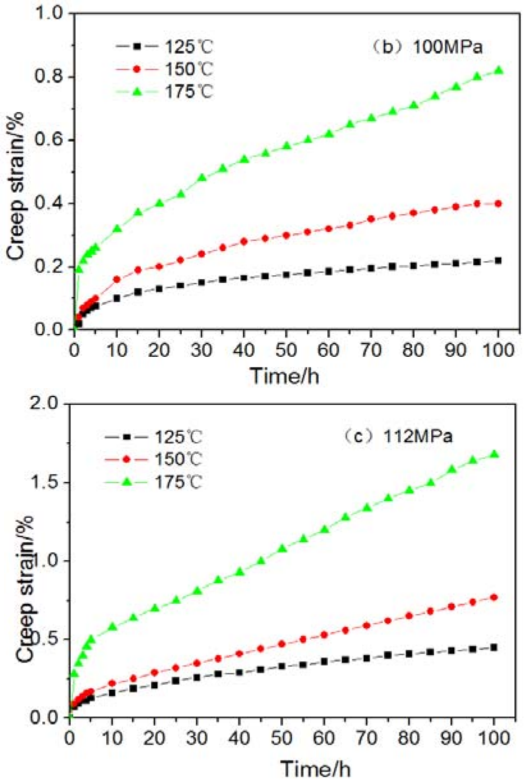


Figure 4. Compressive creep curves of AE41-1.2Ca alloy

The steady creep rate is defined as the slope of the creep strain versus time curve, as shown in Tab.2. It can be seen that the steady creep rates also increase obviously with increasing of temperature and compressive stress. Comparing the creep rates of AE42 alloy and AE41-1.2Ca alloy at tested temperature and compressive stress, it can be found that the creep rates of AE41-1.2Ca alloy are less than one order of magnitude those of AE42 alloy.

TABLE 2. STEADY COMPRESSIVE CREEP RATE OF TESTED ALLOY（$\dot{\varepsilon}_s$ /mm · s-1）

σ /MPa	T/℃	AE42	AE41-1.2Ca
88	125	8.04×10^{-8}	2.13×10^{-9}
	150	1.26×10^{-7}	3.87×10^{-9}
	175	7.31×10^{-7}	7.38×10^{-9}
100	125	7.28×10^{-8}	4.90×10^{-9}
	150	2.61×10^{-7}	9.70×10^{-9}
	175	1.54×10^{-6}	1.73×10^{-8}
112	125	1.32×10^{-7}	1.01×10^{-8}
	150	5.00×10^{-7}	1.86×10^{-8}
	175	2.80×10^{-6}	3.67×10^{-8}

The relationship between steady state compressive creep rate $\dot{\varepsilon}_s$, applied stress n and absolute creep temperature *T*, can be described by an empirical equation in a low stress level[15].

$$\dot{\varepsilon}_s = A\sigma^n \exp(-Q_a/RT) \qquad (1)$$

where *A* is a materials-related constant, σ is the normal stress, *n* is the stress exponent, Q_a is the apparent activation energy for creep, *R* is the gas constant and *T* is the absolute tested temperature.

Eq. (1) is converted to Eq.(2) by taking logarithms, then

$$\ln\dot{\varepsilon}_s = \ln A + n\ln\sigma - Q_a/(RT) \qquad (2)$$

According to Eq.(2), stress exponent *n* and activation energy Q_a can be determined from the experimental data using the following equations:

$$\ln\dot{\varepsilon}_s = K + n\ln\sigma \qquad (3)$$

$$\ln\dot{\varepsilon}_s = K' - Q_a/(RT) \qquad (4)$$

Where $K = \ln A - Q_a/(RT)$, $K' = \ln A + n\ln\sigma'$.

Fig.5 and Fig.6 shows the relationship between $\ln\dot{\varepsilon}_s$ and $\ln\sigma$ at different temperature and the relationship between $\ln\dot{\varepsilon}_s$ and 1/T under different stress of AE42 and AE41-1.2Ca alloys, respectively. It is obvious from Fig.5 and Fig.6 that there is a good linear logarithmic relationship between steady state compressive creep rate and all the temperature and stress used, respectively. The stress exponent *n* can be calculated from the slope of the $\ln\dot{\varepsilon}_s$ versus $\ln\sigma$ plot at a given temperature, and a plot of $\ln\dot{\varepsilon}_s$ versus 1/T at a specific stress will yield the apparent activation energy Q_a at a specific stress level, as listed in Tab.3.

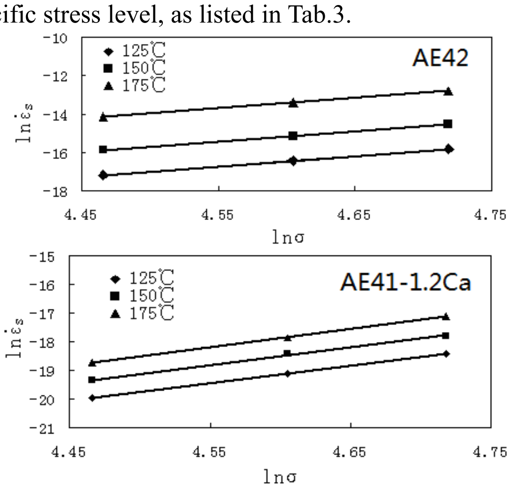


Figure 5. Relationship between $\ln\dot{\varepsilon}_s$ and $\ln\sigma$ with different temperatures

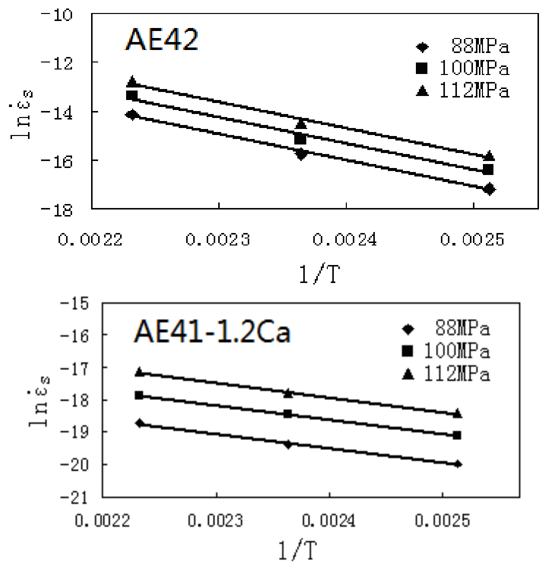


Figure 6. Relationship between $\ln \dot{\varepsilon}_s$ and 1/T with different stresses

TABLE 3. STRESS EXPONENT (n) AND ACTIVATION ENERGY (Q_a) of AE42 AND AE41-1.2Ca ALLOYS

Alloys	T/℃ 125	150	175	n (average)
AE42	5.40	5.45	5.32	5.39
AE41-1.2Ca	6.16	6.23	6.34	6.24
Alloys	σ/MPa 88	100	112	Q_a / kJ/mol (average)
AE42	90.93	90.08	90.23	90.41
AE41-1.2Ca	36.77	37.59	38.17	37.51

The values of ln$A$ at different temperatures and applied stresses are calculated by inserting all values of n and Q_a into Eq.(2), and the calculating data are plotted in Fig.7. There is also a linear relationship between $\ln \dot{\varepsilon}_s$ and $[n \ln \sigma - Q_a/(RT)]$, and ln$A$ achieved by binary linear regression. For the tested alloys, the value of A is equal to 8.19×10^{-7} and 2.88×10^{-13}, respectively. So, the compressive creep constitutive equations of AE42 alloy and AE41-1.2Ca alloy can be expressed as:

$$\dot{\varepsilon}_{s\text{-}AE42} = 8.19\times10^{-7}\sigma^{5.39}\exp[-90410/(RT)] \quad (5)$$

$$\dot{\varepsilon}_s = 2.88\times10^{-13}\sigma^{6.24}\exp[-37510/(RT)] \quad (6)$$

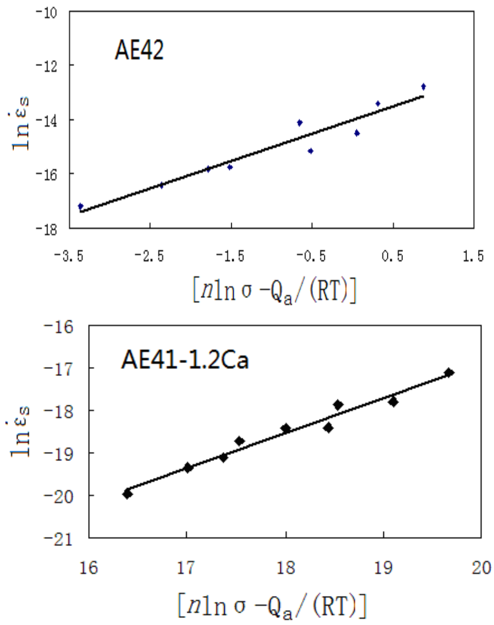


Figure 7. Relationship between $\ln \dot{\varepsilon}_s$ and $[n \ln \sigma - Q_a/(RT)]$

IV. CREEP MECHANISM

According to the Von Mises yield criterion[3], we know that there should be at least five independent slip system per grain can ensure polycrystalline material plastic deformation smoothly and maintain the integrity of the grain boundary. A typical hexagonal close packed structure was observed in magnesium alloys, which only have four independent slip systems in the (0001) matrix and $(10\bar{1}0)$ prismatic planes. The plastic deformation ability is poor, leading to brittle fracture at a low temperature. However, the atoms on the grain boundary become unstable and diffuse at elevated temperature, providing two effective slip systems to improve plastic deformation ability and magnesium alloy appears creep rupture character along grain boundaries. Recent research suggests that the creep deformation of magnesium alloy is characterized by dislocation glide and grain boundary sliding, which is a critical question to design new types of heat resistant magnesium alloys.

The stress exponent n and the apparent activation energy Q_a parameters calculated by $\dot{\varepsilon}_s = A\sigma^n \exp(-Q_a/RT)$ are used to infer the dominant creep deformation mechanisms for a material under the present test conditions[16-20]. That is, the compressive creep mechanism is determined by grain boundary diffusion where n =1. The stress exponent n=3 is for dislocation glide controlled creep. If the value of n is in the range of 4~6, the creep mechanism seems to be controlled by dislocation climb. The creep mechanism indicates the second-phase particles enhancing mechanism where n>6. The creep is respectively controlled by grain boundary sliding where Q_a≈30kJ/mol (activation energy for $Mg_{17}Al_{12}$ phase discontinuous precipitation) and grain boundary diffusion where Q_a≈80kJ/mol (the activation energy for grain boundary diffusion), and is varied to the lattice self-diffusion of magnesium where Q_a≈135kJ/mol (activation energy for self-diffusion of magnesium), and diffusion of aluminum atom in magnesium where Q_a≈143kJ/mol (activation energy for diffusion of aluminum atom in magnesium). As shown in Tab.3, the average value of the stress exponent n and activation energy Q_a of AE42 alloy was 5.39 and 90.41kJ/mol, respectively, and the stress exponent n and activation energy Q_a of AE41-1.2Ca alloy was 6.24 and 37.51kJ/mol, respectively. Thus, it can be considered that the compressive creep mechanism of AE42 alloy and AE41-1.2Ca alloy is controlled by dislocation climb, which is determined by grain boundary sliding and grain boundary diffusion, respectively.

V. CONCLUSIONS

(1) The compressive creep deformation strain and creep rate increases with the increasing of temperature and stress and the creep resistance improves with increasing of calcium concentration.

(2) There is a good linear logarithmic relationship between steady state compressive creep rate and all the temperature and stress used, respectively. The steady creep rates of AE42 alloy and AE41-1.2Ca alloy can be described as

$$\dot{\varepsilon}_{s\text{-}AE42} = 8.19\times 10^{-7}\sigma^{5.39}\exp[-90410/(RT)]$$

and

$$\dot{\varepsilon}_s = 2.88\times 10^{-13}\sigma^{6.24}\exp[-37510/(RT)].$$

(3) The stress exponent n and the apparent activation energy Q_a parameters are used to infer the dominant creep deformation mechanisms. The creep of AE42 alloy and AE41-1.2Ca alloy is predominated by dislocation climb determined by grain boundary sliding and grain boundary diffusion, respectively.

VI. ACKNOWLEDGMENTS

The financial supports by Guilin University of Aerospace Technology (Grant No.YJ1406) and Scientific Research Program of Guangxi Zhuang Autonomous (Grant No.YB2014432) are gratefully acknowledged.

REFERENCES

[1] The national development and reform commission high-tech industrial company, Chinese Materials Research Society. China's new materials industry development report(2009). Beijing: Chemical Industry Press, 2010:52-71.

[2] Poktmear I J. Recent development in light alloys.Materials Transaction, JIM, 1996, 37(1):12-31.

[3] CHEN Zhenhua.Heat resistant magnesium alloy. Beijing: Chemical Industry Press, 2007.

[4] S.M.Zhu, M.A. Gibson, J.F. Nie, et al. Microstructural analysis of the creep resistance of die-cast Mg–4Al–2RE alloy. Scripta Materialia, 2008, 58:477-480.

[5] Tomasz Rzychon, Andrzej Kielbus, Jan Cwajna, et al. Microstructural stability and creep properties of die casting Mg–4Al–4RE magnesium alloy. Materials characterization, 2009, 60: 1107-1113.

[6] ZHANG Xiao-hong, LONG Si-yuan, WU Xing-yu, et al. Effect of Ca addition on microstructure and properties of Mg-Al-RE heat-resistant alloy. Material for Mechanical Engineering, 2013, 37(5):51-53, 58.

[7] Bai Jing, Sun Yangshan, Xun Shan, at. Microstructure and tensile creep behavior of Mg–4Al based magnesium alloys with alkaline-earth elements Sr and Ca additions. Materials Science and Engineering A, 2006 (419): 181-188.

[8] ZENG Ming, XU Dao-fen, ZHANG Yao-cheng, al. Effect of Ca and Sr on Compressive Creep Behavior of AE41 Alloy. Foundry, 2008, 57(12): 1280-1283.

[9] ZHANG Yao-cheng, ZENG Ming, LIAO Chun-li, al. Effect of Ca and Si on Microstructure and Indentation Creep Property of AE41 Alloy. Material for Mechanical Engineering, 2009, 33(11): 50-53, 57.

[10] LIU Zili, PAN Qing1in, CHEN Zhaofeng, al. Influence of antimony addition on heat resistance of AE41 magnesium alloy. Chinese journal of materials research, 2006, 20(2): 186-190.

[11] WANG Shuai, WANG She-bin, LI Xiao-bin, al. Research on the substitute of RE Metals in AE42 Magnesium Alloy with Sb. Journal of TAIYUAN University of technology, 2009, 40(1): 56-59.

[12] XU Dao-fen, YE Dong, HUANG Jian. Compressive Creep Behavior of Mg-Al-RE-Ca-Sr Alloy. Foundry technology, 2009, 30(11): 1452-1455.

[13] Huang Deming, Chen Yungui, Tang Yongbai, al. Indentation creep behavior of AE42 and Ca-containing AE41 alloys. Materials Letters, 2007, 61:1015-1019.

[14] CHEN Jun, LI Quan'an, ZHANG Qing, al. Effect and Research Progress of Sm in Heat Resistant Magnesium Alloy. Materials Review, 2014, 28(4): 109-115.

[15] Humble P. Towards a cheap resistant magnesium alloy. Material Forum. 1997, 21: 45-56.

[16] Shi L, Northwood D O. Strain-harding and recovery during the creep of pure polycrystalline Magnesium. Acta Metallurgica et Materialla, 1994, 42(3):871-877.

[17] Yaocheng Zhang, Li Yang, Jun Dai, at. Effect of Ca and Sr on the compressive creep behavior of Mg–4Al–RE based magnesium alloys. Materials and Design, 2014(63): 439-445.

[18] Regev M, Aghion E, Rosen A. Creep Studies of AZ91D Pressure Die Casting. Materials Science and Engineering A, 1997, 234-236:123-126.

[19] YUAN Guaugyin, LU Yizhen, ZENG Xiaoqi, al. Influence of Sb microaddition on creep resistance and microstructure of Mg-9Al-0.8Zn alloy. Acta Metallurgica Sinica, 2001, 37(1): 23-28.

[20] Agnew S R, Liu K C, Kenik E A, et al. Tensile and Compressive Creep Behavior of Die Cast Materials Alloy AM60M. TMS Annual Meeting, 2000:285-290.