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Tensile and creep properties of Mg-9Al based alloys containing bismuth①

YUAN Guang-yin(袁广银), SUN Yang-shan(孙扬善), ZHANG Wei-min(张为民), SUN Jian-rong(孙建荣)
(Department of Materials Science and Engineering, Southeast University, Nanjing 210096, P.R.China)

[Abstract] The microstructure and mechanical properties of Mg-9Al-0.8Zn(AZ91) alloys containing bismuth were investigated. Adding bismuth to AZ91 base alloys results in significant increase of tensile strength at both ambient temperature and 150 ℃, especially the creep rupture life at 150 ℃, while slight decrease of ductility. Microstructure observations indicate that the addition of bismuth modifies the microstructure of as-cast alloy and makes the β($Mg_{17}Al_{12}$) phase finer and more uniform in distribution. Furthermore, the discontinuous precipitation is suppressed greatly during aging process. When the bismuth addition amount exceeds 0.5%, rod-shape Mg_3Bi_2 precipitates with hexagonal $D5_2$ structure, which have high thermal stability and strengthen both the matrix and grain boundaries.

[Key words] magnesium alloys; bismuth; microstructure; mechanical properties
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1 INTRODUCTION

Magnesium alloys are being increasingly used in automobile industry in order to decrease mass thereby reducing fuel consumption and pollution[1~4]. However, the reduction of yield strength and creep resistance of Mg-Al alloy above 120 ℃ limits their applications in automobile industry[5]. Although AE42 alloy developed by Dow Chemical Co Ltd[6] has good mechanical property even at moderate temperatures. This alloy containing rare earth metals is more expensive than commonly used Mg-Al alloys[7]. Therefore, the use of low price metals instead of rare earth metals to expand magnesium alloys to high temperature applications is more desirable. Recent development have shown that the additions of the V subgroup elements in the periodic system of elements, such as Bi, Sb increase the tensile strength at both ambient and elevated temperature[5]. This paper reports some preliminary results about the effects of Bi addition on the microstructures and tensile properties as well as the creep resistance of the AZ91 alloy at 150 ℃.

2 EXPERIMENTAL

Five alloys whose compositions are listed in Table 1 were prepared in a crucible under the protection of mixed gas atmosphere of SF_6(25%, volume fraction) and CO_2(75%, volume fraction) using commercial stock. The base composition of the alloys studied was Mg-9Al-0.8Zn-0.2Mn(mass fraction, %). Different amounts of bismuth were added to the alloys in order to investigate the effects of bismuth addition and variation of bismuth concentration on the microstructures and mechanical properties of the alloys. The melt was held at 720 ℃ for 10 min then poured into permanent molds. Tensile specimens with a gauge of 15.0 mm × 3.5 mm × 2.0 mm were cut by spark erosion from the ingots. All the specimens were heated at 420 ℃ for 12 h followed by water quenching, then aged at 200 ℃ for 8 h(T_6 treatment) before testing. The microstructural observation of the as-cast and heat treated specimens were conducted using scanning electron microscopy(SEM). EPMA of precipitates were performed on specimens of different alloys using X-ray energy dispersive spectroscopy (XEDS). The phases of alloys containing bismuth were analyzed by X-ray diffractometer(XRD). The microstructure observations of specimens after creep rupture were carried out by using optical metallography (OM) and SEM.

3 RESULTS AND DISCUSSION

3.1 Microstructures

The microstructure of as-cast alloy 1 (AZ91) consisted of the matrix (α-Mg) and β precipitates ($Mg_{17}Al_{12}$) which were mainly distributed at grain boundaries, as shown in Fig.1(a). Adding bismuth to base alloy did not change the grain size of the matrix, but resulted in the modification of the morphology of β phases. Fig.1(b) shows the microstructure of as-cast alloy 2 containing 0.5% of bismuth, it can be seen that the β phase in this alloy is finer and its distribution is more uniform than that in as-cast alloy 1(Fig.1(a)). Further bismuth addition resulted in the formation of some rod-shaped precipitates which were distributed both in grains and at grain boundaries (Fig.1(c)). EPMA analysis indicated that these precipitates have an approximate composition of Mg-38Bi-4Al-1Zn. XRD pattern taken from as-cast alloy 4 is shown in Fig.2, in which some peaks can

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be indexed as arising from the phase of Mg_3Bi_2 with a hexagonal structure of DO_2. On the basis of EPMA analysis and XRD pattern these rod-shaped precipitates were identified as Mg_3Bi_2.

When the as-cast specimens of the alloys were homogenized at 420 ℃ for 12 h (T_4 treatment), most β precipitates($Mg_{17}Al_{12}$) dissolved in the matrix and the microstructures of the alloy 1 and alloy 2 consisted of only α-Mg matrix. As for the microstructures of alloys 3 ~ 5, some rod-shaped precipitates(Mg_3Bi_2) still existed in the matrix even after annealing at 420 ℃ for 12 h(Fig.3(a)) indicating the high thermal stability of Mg_3Bi_2 precipitates. Aging of these solution treated specimens at 200 ℃ resulted in the re-precipitation of β($Mg_{17}Al_{12}$) phases. Precipitation of $Mg_{17}Al_{12}$ occurred in two forms: as discontinuous precipitation at grain boundaries and continuous precipitation within the grains. For alloy 1 the lamellar precipitation(discontinuous precipitation) was dominant in the vicinity of grain boundaries(Fig.3(b)), while in alloys 2 ~ 5 containing bismuth discontinuous precipitation was suppressed greatly and some plate-shaped precipitates (continuous precipitation) distributed near the grain boundaries(Fig.3(c)).

3.2 Mechanical properties

Table 1 lists the tensile and creep-rupture data for all specimens tested. It can be seen that adding bismuth to the AZ91 alloy resulted in significant influence on tensile properties and creep resistance. At ambient temperature, the ductility decreased slightly while the yield strength increased significantly with the increase of bismuth addition amount and the maximum was obtained from alloy 4 containing 2 % bis-

Table 1 Compositions, mechanical properties of alloys investigated

Alloy No.	w/ %	RT tensile			150 ℃ tensile			Creep Rupture*	
		σ_b/ MPa	σ_s/ MPa	δ/ %	σ_b/ MPa	σ_s/ MPa	δ/ %	Life/ h	δ/ %
1	Mg-9Al-0.8Zn-0.2Mn	222	106	5.3	170	99	35	267	27
2	Mg-9Al-0.8Zn-0.2Mn-0.5Bi	232	162	4.7	180	132	24.3	360	21
3	Mg-9Al-0.8Zn-0.2Mn-1.0Bi	250	166	4.6	180	134	21.7	367	19
4	Mg-9Al-0.8Zn-0.2Mn-2.0Bi	265	184	4.4	184	138	19.6	402	14
5	Mg-9Al-0.8Zn-0.2Mn-3.0Bi	224	162	3.2	172	119	12.1	230	11

* —Creep rupture properties tested at 150 ℃, 70 MPa

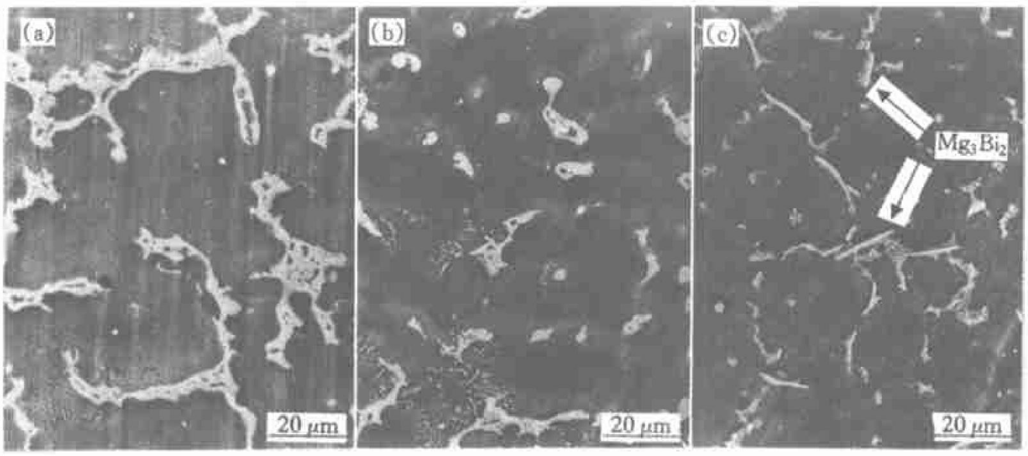

Fig.1 Microstructures of as-cast alloys
(a) —Alloy 1; (b) —Alloy 2; (c) —Alloy 4

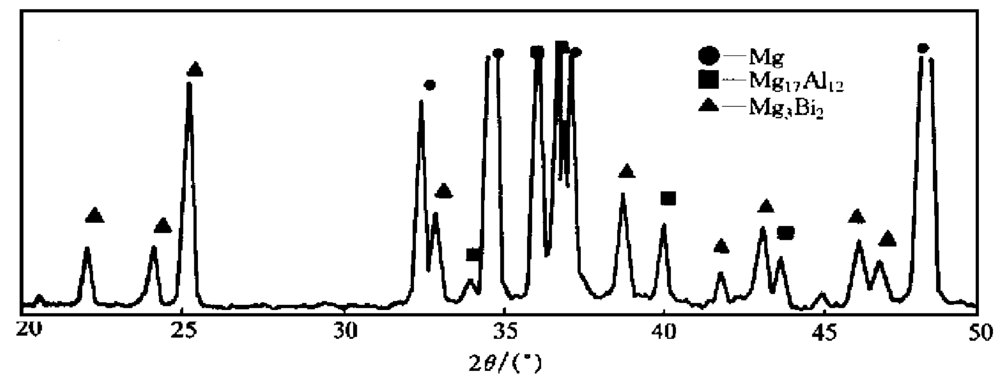

Fig.2 X-ray diffraction pattern of as-cast alloy 4

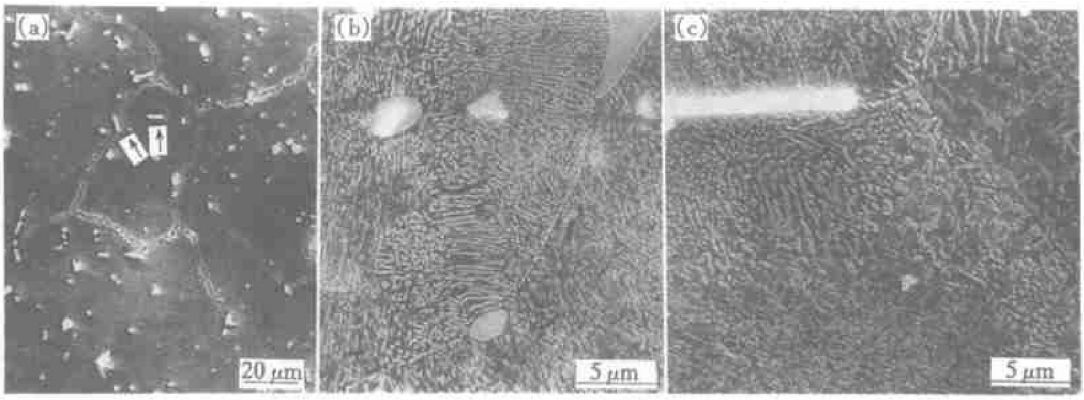

Fig.3 Microstructures of heat treated alloys
(a) —Alloy 4(T_4 treated) showing rod-shape Mg_3Bi_2 phase ;
(b) —Alloy 1(T_6 treated) showing a large amount of lamellar discontinuous precipitation near grain boundaries ;
(c) —Alloy 4(T_6 treated) showing plate-shaped continuous precipitates and rod-shape Mg_3Bi_2 particle near grain boundary

muth. Further increase of the amount of bismuth addition resulted in a slight reduction of yield strength, as shown in Fig.4. Therefore, the amount of bismuth addied to AZ91 based alloys must be limited within a certain range. The ultimate tensile strength was correlated with yield strength, and it increased with increasing yield strength. Fig. 5 shows the change of tensile properties with the increase of bismuth concentration at 150 ℃. The yield strength was also increased although the elongation decreased with the increase of bismuth addition amount.

Another important result caused by bismuth addition was in creep resistance. The creep rupture life increased rapidly with the increase of bismuth and reached 402 h(at 150 ℃, 70 MPa) compared with 267 h of alloy 1. The creep curves of the alloys studied are shown in Fig.6, from which it can be seen that the bismuth addition reduced the steady state creep rate greatly. The creep rate of alloy 4 decreased to 4.1×10^{-6} %$\cdot s^{-1}$ compared with the base alloy AZ91 which was 1.4×10^{-5} %$\cdot s^{-1}$.

Fig.7(a) ~ (d) are the optical micro-graphs and SEM micrographs showing the microstructures of alloy 1 and alloy 4 after creep tests. From Fig.7(a) it can be seen that the grains of alloy 1 were prolonged obviously and considerable cavitation developed during

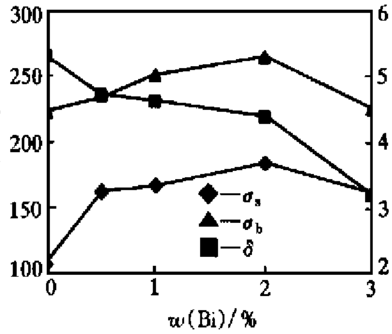

Fig.4 Variations of room temperature properties versus Bi concentration

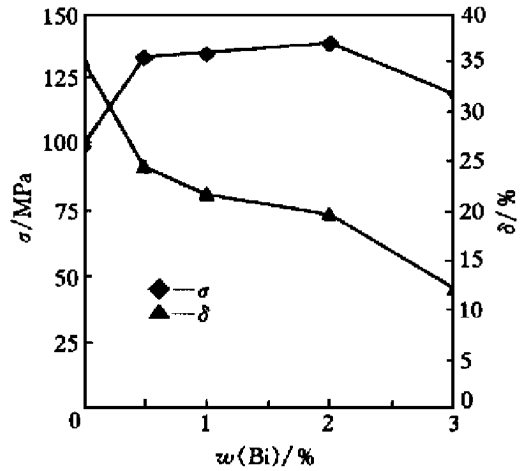

Fig.5 Variations of tensile properties versus Bi concentration at 150 ℃

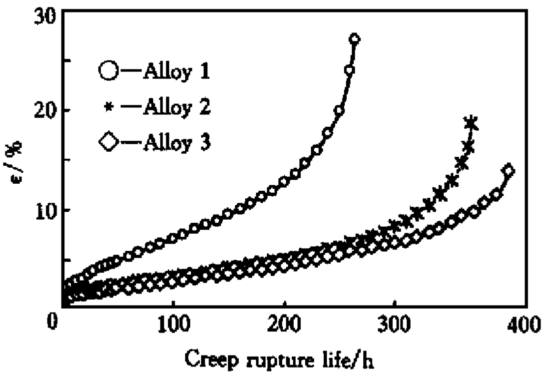

Fig.6 Creep rupture curves of alloys

creep deformation at elevated temperature. The cavities concentrated in the regions close to the interface between discontinuous precipitates β($Mg_{17}Al_{12}$) and the α-Mg grains. Furthermore, cracks along the grain boundaries can be observed (as shown in Fig.7 (b)). In comparison with alloy 1, no obviously prolonged grain can be found in creep ruptured specimens

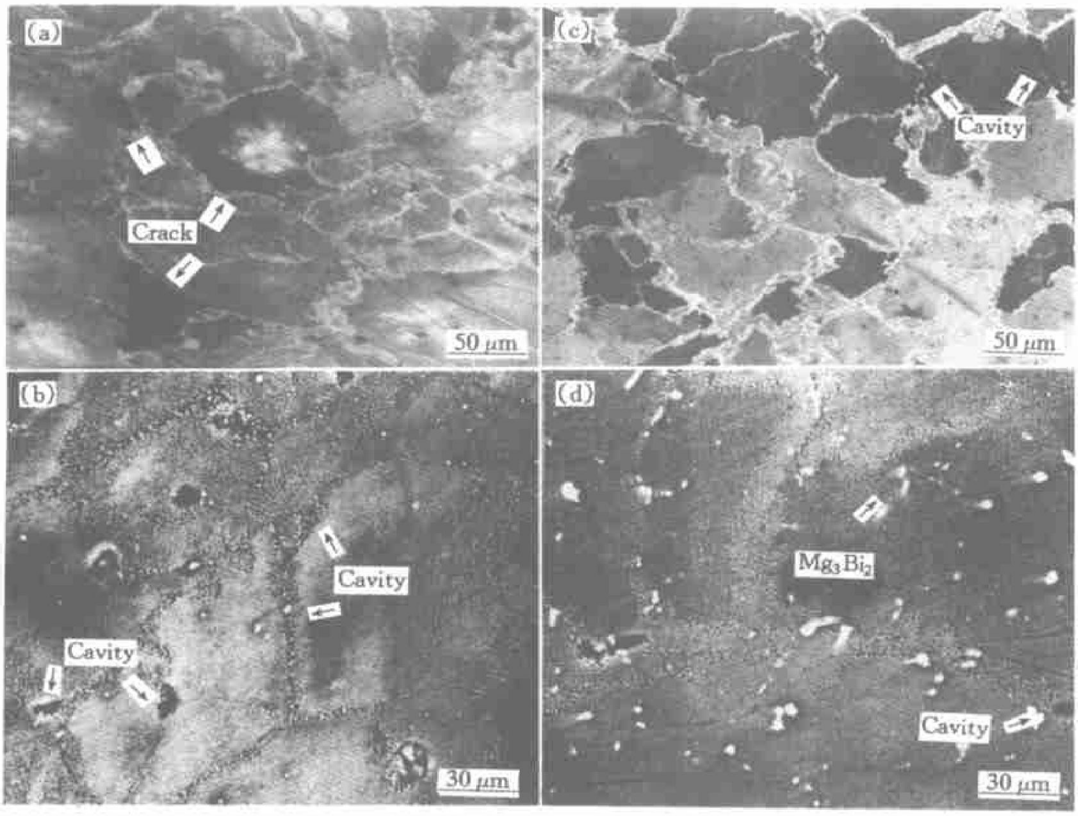

Fig. 7 Microstructures of alloy 1 and alloy 4 after creep rupture
(a) —OM and (b) —SEM of alloy 1; (c) —OM and (d) —SEM of alloy 4

of alloy 4 which contained 2 % bismuth, and only few cavities existed near the grain boundaries (Fig. 7(c) and (d)), which indicates that the matrix and grain boundaries were both strengthened by bismuth addition.

In Mg-Al alloys, discontinuous precipitation may be responsible for excessive deformation at elevated temperatures[8]. The investigations[5,9] proposed that in hexagonal materials such as Mg-Al alloys the sliding of the grain boundaries is an important deformation mechanism. The presence of many lamellae (discontinuous precipitation) in the vicinity of grain boundaries provided more surfaces on which sliding took place (Fig. 7(b)). In the present investigation, the discontinuous precipitation of $Mg_{17}Al_{12}$ in the AZ91 alloy was suppressed effectively by the bismuth addition so that the sliding of grain boundaries during the deformation of tensile and creep tests at elevated temperatures was inhibited effectively. Furthermore, bismuth addition amount exceeding 0.5 % resulted in the formation of Mg_3Bi_2 precipitates which have a higher melting point (823 ℃) than that of $Mg_{17}Al_{12}$ and the matrix, hence, they must be more steady at elevated temperatures and become effective dislocation slide or climb obstacles during the creep test. In the creep ruptured specimens these precipitates can still be observed (as shown in Fig. 7(d)), which indicates that they indeed play the role of strengthening the matrix and grain boundaries against creep.

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