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Procedia Engineering 55 (2013) 109 – 113

Procedia Engineering

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6th International Conference on Creep, Fatigue and Creep-Fatigue Interaction [CF-6]

Creep Behavior of AZ91 Magnesium Alloy

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Abstract

Effects of intermetallic phases on the creep behavior of AZ91 magnesium alloy have been studied. Thermally stable intermetallic phases such as Mg_2Si and Mg_3Sb_2 are introduced deliberately in AZ91 alloy by the adding Si and Sb (0.5% Si, 0.5% Sb and 0.5% Si+0.2% Sb, all are in wt %). Creep tests were carried out at 150 and 200°C with an initial stress of 50 MPa on the as cast samples. It is found that the β-$Mg_{17}Al_{12}$ intermetallic phase in the AZ91 alloy suffers sever cracking and facilities cavity formation due to its low melting point and incoherency with Mg matrix, which results in poor creep resistance. On the other hand, the creep behavior of AZ91 alloy is greatly improved with the presence of Mg_2Si and Mg_3Sb_2 intermetallic phases because of their better thermal stabilities. These intermetallic phases strengthen the grain boundary against sliding and hence, reduce the possibility of void formations during creep. Furthermore, they also promote more number of continuous $Mg_{17}Al_{12}$ precipitates near the grain boundaries during creep, which in turn restricts the creep deformation.

Selection and peer-review under responsibility of the Indira Gandhi Centre for Atomic Research.

Keywords: AZ91 Mg alloy; creep; intermetallic phases; continuous precipitates

1. Introduction

AZ91 magnesium alloy (Mg-9% Al-1% Zn-0.2% Mn) is wieldy used in automobile, aerospace and electronic industries due to its high castability, wide range of room temperature mechanical properties and high corrosion resistance. However, the applications of this alloy are still limited due to its poor creep resistance. The reason for this has been attributed to the presence of low melting point β-$Mg_{17}Al_{12}$ intermetallic phase, which easily coarsens at high temperatures [1]. It is also reported that the occurrence of dynamic discontinuous grain boundary precipitate of $Mg_{17}Al_{12}$, and its subsequent migration into the neighboring grains during its growth, facilitates grain boundary sliding [2]. Hence, the general strategy adopted to improve the creep resistance of Mg alloys is to have thermally stable intermetallic phases at grain boundaries [3]. Hence in the present study, the role of stable intermetallic phases such as Mg_3Sb_2 and Mg_2Si, formed due to the addition of Si and Sb, and their morphologies on the creep behavior of AZ91 alloy has been investigated.

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doi:10.1016/j.proeng.2013.03.228

2. Experimental

Alloys required for the present study were prepared by melting commercial purity Mg, Al and Zn and Al-10% Mn master alloy together with the required amount of silicon and antimony in the form of Al-20% Si and Al-10% Sb master alloys respectively. Melting was carried out in a steel crucible under proper flux cover and poured at 720°C into a preheated (250°C) cast iron mould. Four alloy, AZ91, AZ91+0.5% Si, AZ91+0.5% Sb and AZ91+0.5% Si+0.2% Sb, castings were produced. Microstructures of the polished and etched samples were studied on a Leitz-Metalloplan optical microscope. Standard creep test specimens machined out from the castings (as cast condition) in accordance with ASTM 138 standard, were subjected to a constant load creep test at 150°C and 200°C at an engineering stress of 50 MPa on a 3-ton Mayes creep testing machine with a lever ratio of 15:1. Post creep test examinations were carried out on a JEOL, JSE 35C Scanning Electron Microscope (SEM) attached with an Energy Dispersive Spectroscope (EDS).

3. Results

3.1. As cast microstructure

Figure 1 presents the as cast microstructures of castings. The base alloy microstructure consists of α-Mg matrix surrounded by the eutectic consisting of (α+β) lamellar precipitates and massive β-$Mg_{17}Al_{12}$ intermetallic phases (Fig. 1a). The (α+β) lamellar precipitation occur from the eutectic Al supersaturated α-Mg through a solid state reaction known as discontinuous precipitation. Addition of Sb to AZ91 alloy has introduced block needle shape phases at grain boundaries (Fig. 1b). With addition of Si to AZ91 alloy massive Chinese script phases are seen at grain boundaries in addition to $Mg_{17}Al_{12}$ intermetallic phases (Fig. 1c). Change in the morphology of Mg_2Si intermetallic phase can be observed with the combined addition of Si and Sb (Fig. 1d), where the massive Chinese script morphology of Mg_2Si (Fig. 1c) has been changed into a fine polygon shape. Such a morphological change in Mg_2Si intermetallic phase due to small amount of Sb addition and its mechanism has been previously reported in literature [4].

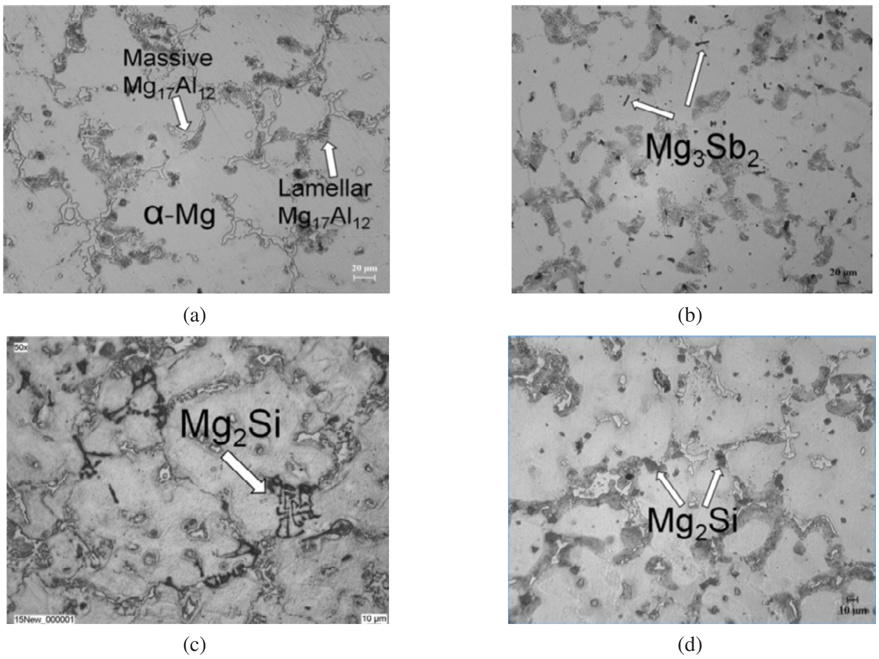


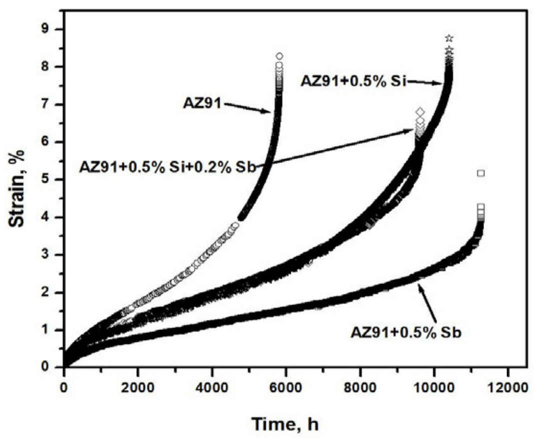
Fig. 1. Microstructures of as cast alloys (a) AZ91 (b) AZ91+0.5% Sb (c) AZ91+0.5% Si.

3.2. Creep properties

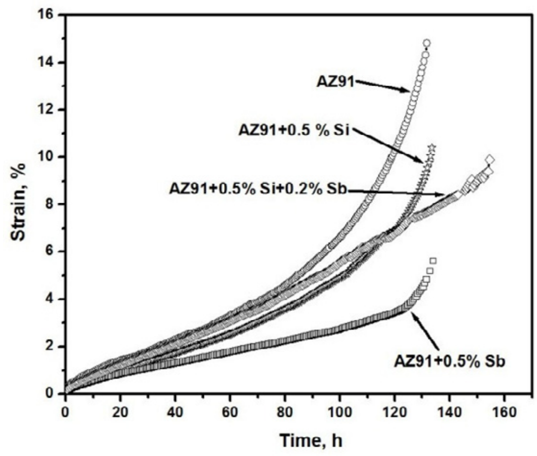
The tensile creep curves obtained for samples tested at 150°C and 200°C in the as cast condition are depicted in Fig. 2. All the curves show a typical creep behavior; short primary region followed by a secondary region of almost constant creep rate and by a tertiary stage. Creep properties such as minimum creep rate, creep strain and creep rupture life obtained from the creep results are given in Table 1. The results also clearly show that the Si and Sb added AZ91 alloys exhibit relatively superior creep resistance than that of the base alloy at 150°C but not at 200°C. Even though not much change in the minimum creep rate, significant improvement in the creep life of AZ91 alloy is noticed with the presence of Mg_2Si intermetallic phase at 150°C. The results of the present study also show a similarity between the creep behavior of AZ91+0.5% Si and AZ91+0.5% Si+0.2% Sb alloys, which indicate that the morphological change of Mg_2Si (from Chinese script to polygonal shape) intermetallic phase has not effectively altered the creep behavior at 150°C. Further, it can be also seen from Fig. 2 that the creep resistance of AZ91 alloy is drastically reduced at 200°C. Due to the higher creep rates, all alloys have exhibited a poor creep rupture lives at 200°C; thus it can be inferred from these results that the presence of Mg_2Si and Mg_3Sb_2 intermetallic phases do not significantly improve the creep performance of AZ91 at 200°C.

Table. 1. Creep properties of alloys at 150 and 200°C with an initial stress of 50 MPa.

Alloys	Minimum Creep rate, s^{-1}		Creep strain %		Creep life, h	
	150°C	200°C	150°C	200°C	150°C	200°C
AZ91	2.13×10^{-9}	1.56×10^{-7}	8.290	14.30	5817	131
AZ91+0.5% Sb	6.71×10^{-10}	7.48×10^{-8}	5.169	5.61	11264	134
AZ91+0.5% Si	1.27×10^{-9}	1.17×10^{-7}	8.461	10.38	10400	133
AZ91+0.5% Si +0.2% Sb	1.19×10^{-9}	1.56×10^{-7}	6.811	12.25	9612	153



(a)

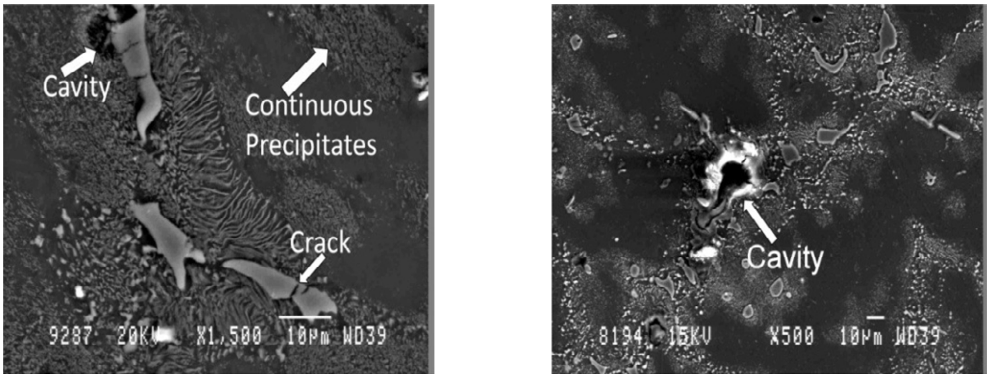


(b)

Fig. 2. Creep behavior of tested alloys at 50 MPa and (a) 150°C, (b) 200°C.

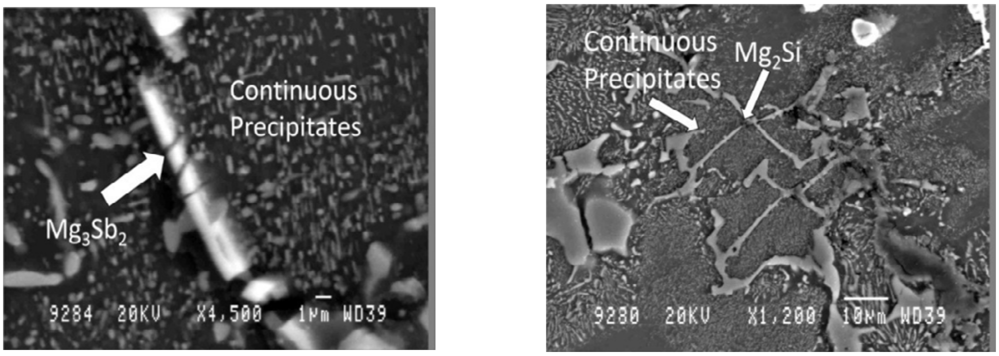
3.3. Microstructure after creep testing

Microstructure stability during high temperature exposure is very essential for creep resistance. The detailed post creep test microstructural analyses suggest that the microstructure of AZ91 alloy is not stable during creep. Fig. 3 presents the microstructures of longitudinal cross section near the fracture surface of AZ91 alloy creep ruptured at 150°C. It can be seen from the micrographs that most of the $Mg_{17}Al_{12}$ intermetallic particles have multiple cracking (Fig. 3a). Cavity formation at the matrix–particles interface (Fig. 3a) and at the grain boundary triple point is also noticed in AZ91 alloy (Fig. 3b). These cavities lead to matrix cracking and also spread easily along the grain boundary since the grain boundary contain a greater volume of discontinuous precipitates. Apart from the cracking and cavities, the important microstructural change observed after creep testing is the presence of the coarse continuous precipitates of $Mg_{17}Al_{12}$ (Fig. 3a). These continuous precipitates might have formed in sub micron in size during the initial stage of creep and coarsened to a few microns in size at the final stage of creep. Similar dynamic continuous precipitates are also observed in all tested alloys (Fig. 4). In general, greater volume of continuous precipitates is appeared near the intermetallic phases. However, cavities and microcrackings are also seen at the interfaces between the matrix and intermetallic phases such as Mg_3Sb_2 and Mg_2Si (Fig. 4).



(a) (b)

Fig. 3. SEM micrographs of longitudinal cross section near the fracture surface of AZ91alloy sample creep tested at 150°C and 50 MPa.



(a) (b)

Fig. 4. SEM photographs of longitudinal cross section near the fracture surface of alloyscreep tested at 150°C and 50 MPa (a) AZ91+0.5% Sb (b) AZ91+0.5% Si.

4. Discussion

The microstructure of as cast AZ91 alloy is found to be unstable due to the presence of eutectic α-Mg solid solution at the grain boundary area, which is supersaturated with aluminum [1, 2, 5, 6]. According to Regev et al. [1], aluminum in the solid solution provides solid solution strengthening against moving dislocations in the initial stage of creep and then Al precipitates out from the solid solution of magnesium matrix and blocks the dislocation motion leading to strain hardening. At the later stage of creep, theses precipitates coarsen and lose their ability to pin both dislocations and boundaries thus leading to faster creep. The dislocation density decides the volume of dynamic precipitates during creep. Normally, dense dislocation density is expected around a hard particle embedded in a matrix during solidification due to the difference in co-efficient of thermal expansion between them. In the present study also, differences between CTE values of the intermetallic phases ($Mg_{17}Al_{12}$, Mg_2Si and Mg_3Sb_2) and the magnesium matrix are significant and hence greater density of continuous precipitates around the hard intermetallic phases is observed.

Cavity formation is a generally observed precursor to creep fracture. Most of these cavities form as a consequence of stress concentration at locations such as a grain boundary triple point junctions and interface between a soft matrix and hard intermetallic particles [5]. Unfortunately, the melting point of $Mg_{17}Al_{12}$ intermetallic phase is low (437°C) and diffusivity of aluminum in magnesium matrix and magnesium self diffusion are high at elevated temperatures. Since diffusion is a temperature depended phenomenon, coarsening of this intermetallic phase occurs at a faster rate during creep at high temperatures. Moreover, $Mg_{17}Al_{12}$ is incoherent with α-Mg matrix (the magnesium matrix has an hcp lattice, whereas the β-$Mg_{17}Al_{12}$ intermetallic phase has a cubic lattice) [1, 2]. Due to these facts, $Mg_{17}Al_{12}$ intermetallic phase leads to easy cavity formation at the grain boundaries. On the other hand, the improvement in creep properties observed with Si and Sb added alloys at 150°C are due to the presence of Mg_2Si and Mg_3Sb_2 intermetallic phases respectively at grain boundaries, which are more stable than $Mg_{17}Al_{12}$ intermetallic phase. Additionally, these intermetallic phases promote a greater volume of continuous precipitates at the grain boundary, which reduce the activity of atom diffusion along the grain boundary and hence strengthen the alloys.

Superior creep properties are observed with the alloy containing Mg_3Sb_2 intermetallic phase compared to that of the alloys containing Mg_2Si intermetallic phase at 150°C. This shows that the Mg_3Sb_2 intermetallic phase is more effective in improving the creep properties of AZ91 alloy, which can be explained in terms of its stability. In general, the thermal stabilities of intermetallic phases are directly proportional to their melting points; higher the melting point higher the thermal stability [3]. The melting point of Mg_3Sb_2 intermetallic phase is 1228°C, which is higher than that of the melting point of Mg_2Si intermetallic phase (1085°C) [6, 7]. In addition, there exists similarity between the lattices of Mg matrix and the Mg_3Sb_2 intermetallic phase; both have hcp lattice structures. On the other hand, the Mg_2Si intermetallic phase has cubic structure. In general, in spite the significant improvement in the creep properties at 150°C, Mg_2Si and Mg_3Sb_2 the intermetallic phases have not contributed much to the creep behavior of AZ91 alloy at 200°C. This may be due to the softening effect of $Mg_{17}Al_{12}$, which is more predominant at 200°C as the mobility of aluminum and magnesium atoms increase with increasing in temperature, overcomes the strengthening effect offered by these intermetallic phases.

5. Conclusions

The following conclusions are drawn from the present study:

- The microstructure of AZ91 alloy is unstable at high temperature, which results in the formation and subsequent coarsening of low melting point continuous precipitates which leading to poor creep properties.
- The incompatibility of the massive β-$Mg_{17}Al_{12}$ intermetallic phases with the matrix facilitates the formation of cavities and severe cracking of the particles at grain boundaries thus leading early failure.
- The hard and thermally stable Mg_2Si and Mg_3Sb_2 intermetallic phases introduced into the AZ91alloy not only strengthen the grain boundary but also facilitate the formation of greater volume of continuous precipitates during creep thus improve the creep properties at 150°C, if not at 200°C.

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