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Correlation of microstructure and creep behaviour of MRI230D Mg alloy developed by two different casting technologies

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ABSTRACT

The relationship between the as-cast microstructure and creep behaviour of the heat-resistant MRI230D Mg alloy produced by two different casting technologies is investigated. The alloy in both ingot-casting (IC) and high pressure die-casting (HPDC) conditions consists of α-Mg, C36 ($(Mg,Al)_2Ca$), Al–Mn and Sn–Mg–Ca rich phases. However, the HPDC alloy resulted in relatively finer grain size and higher volume fraction of finer, denser network of eutectic C36 phase in the as-cast microstructure as compared to that of the IC alloy. The superior creep resistance exhibited by the HPDC alloy at all the stress levels and temperatures employed in the present investigation was attributed to the more effective dispersion strengthening effect caused by the presence of finer and denser network of the C36 phase. The increased amount of the eutectic C36 phase was the only change observed in the microstructures of both alloys following creep tests.

1. Introduction

Recently the emphasis given by automobile manufacturers in prioritising fuel conservation and emission quality on par with performance, has led to the concept of weight reduction. Magnesium (Mg) alloys are considered to be the most suitable alternative as structural materials in automobiles owing to their high specific strength, good dimensional stability, high damping capacity, excellent machinability and appreciable casting properties [1].

Powertrain applications of automobile require Mg alloys which can sustain high temperature. The major limitation of application of Mg alloy in the automobile industry is poor creep resistance being a significant factor above 100 °C owing to the presence of thermally unstable β-$Mg_{17}Al_{12}$ phase [2]. This makes it inappropriate for powertrain applications where service temperature and stress are in the range of 150–300 °C and 50–70 MPa, respectively [3,4]. Attempts were made to improve creep resistance of the Mg–Al based alloys by introducing thermally stable intermetallics through the addition of different alloying elements like RE, Ca, Si, Sn, Sb and so on [5–7]. Among these the Ca containing Mg–Al based alloys are the most economic and exhibit promising properties [6,7]. MRI230D is a Ca containing alloy developed by Dead-Sea Magnesium and Volkswagen AG for its commercial usage to enhance the sphere of utility overcoming the limitations of popular alloy like AZ91 and it is suitable for application up to 190 °C [8].

Mg alloys are mostly used in as-cast condition and the casting condition plays a crucial role in the resulting properties. Factors such as porosity, solidification rate, grain size, volume fraction and morphology of intermetallic phases, degree of solute supersaturation as well as various strengthening mechanisms affect creep and other mechanical properties of Mg alloys. Gutman [9] investigated the influence of casting parameters on creep and strength of AZ9lD alloy and established that precipitation of β phase improved creep resistance of permanent mould cast alloy. For die-cast alloy, creep was controlled by the extent of micro- and macro-porosity. Spigarelli et al. [10] reviewed the literature on creep behaviour of AZ91 alloy produced by die-casting, ingot-casting and thixoforming and concluded that the creep behaviour of the alloy depends on grain size and intragranular precipitates interacting with dislocations. Caceres et al. [11] reported variation in tensile properties of AZ91 alloy fabricated by sand-castings with varying cooling rates. Zhu et al. [12] investigated the creep properties of Mg–Al–Ca alloy produced by die-casting, squeeze-casting and ingot-casting. The best and the worst creep resistance was exhibited by the squeeze-cast and the die-cast alloys whereas the ingot-cast alloy exhibited the intermediate creep resistance.

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Han et al. [13] observed that the nanoscale indentation creep behaviour of AC52 alloy increased with an increase in cooling rate. Srinivasan et al. [14] investigated the effect of intermetallic phases on the creep behaviour of AZ91 alloy and observed that the intermetallic phases strengthen the grain boundaries against sliding and reduce the possibility of void formation during creep. Ferri et al. [15] investigated the effect of solidification rates on mechanical properties of ZAXLa05413 alloy and observed a direct relationship between grain size and secondary dendritic arm spacing with improved mechanical properties. Zheng et al. [16] reported superior creep and other mechanical properties of the Mg–3Sm–0.5Zn–0.4Zr (wt%) alloy in die-cast condition. Kim et al. [17] too stated that the die-cast alloy with relatively higher volume fraction of Mg_2Sn and CaMgSn phases exhibited higher creep resistance as compared to the ingot-cast alloy in the Mg–4Al–2Sn alloy containing Ca. Bai et al. [18] too observed the difference in tensile and creep properties owing to the difference in casting conditions in the Mg–4Al–(1–4) La alloy.

The conclusion arising out of the afore-mentioned review points out that creep and other mechanical properties of Mg alloys vary significantly with casting technologies. Therefore, it is worth examining its effect on creep behaviour of the promising creep-resistant MRI230D Mg alloy developed for automobile powertrain applications, as there is paucity in the literature. In the present investigation an attempt has been made to apprehend the relationship between the microstructure and creep behaviour of the MRI230D alloy in different casting conditions (i.e., ingot-casting (IC) and high pressure die-casting (HPDC)) in order to substantiate the better casting technology for mass production.

2. Experimental procedure

The nominal chemical composition of the MRI230D alloy is shown in Table 1. The HPDC alloy was cast into cylindrical rod having 19 mm diameter and 179 mm length using a cold chamber high pressure die-casting machine (Model: FRECH DAK 450-54RC). The melt temperature was 690 °C and the pressure during solidification was 300 bar. For gravity casting the melting was carried out in an electrical resistance furnace using stainless steel crucible. The melt temperature was 690 °C and it was poured into a steel mould preheated to 250 °C. During melting solid flux provided by FOSECO Industries Limited was used to protect the melt from oxidation. A mixture of SF_6 (0.5 vol%) and Ar (99.5 vol%) was purged to protect the melt during pouring. The IC alloy was cast into rectangular block with dimension of 350 mm $(L) \times 125$ mm $(W) \times 60$ mm (H) using conventional gravity casting. The specimens for creep testing having 6 mm diameter and 15 mm length were machined from the respective castings by spark erosion technique. All the creep tests were carried out in compression using a lever arm (10:1) creep set-up (Model: ATS 2330) in the stress range of 60–120 MPa and at temperatures of 175 °C and 200 °C. The specimens for microstructural investigation were prepared by standard metallographic techniques. Etching of the specimens was carried out using a solution of 100 ml ethanol, 10 ml acetic acid, 6 ml picric acid and 20 ml of distilled water. Microstructural observation of the alloys was carried out using optical microscopy (OM) and field emission scanning electron microscopy (FESEM) (Model: FEI Sirion XL30) armed with an energy dispersive X-ray spectroscopy (EDS). The phases present in the alloy in both casting conditions were identified by X-ray diffraction (XRD) using CuK_α radiation ($\lambda = 1.541$ Å).

Table 1
Nominal chemical composition of the MRI230D alloy.

MRI230D alloy	Al	Ca	Zn	Mn	Sr	Sn	Mg
Element (wt%)	6.45	2.25	< 0.01	0.27	0.25	0.84	Balance

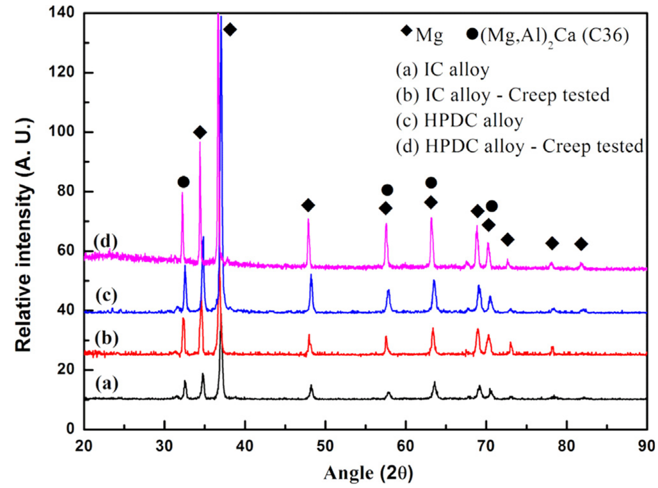

Fig. 1. XRD patterns for the MRI230D alloys in two different casting conditions.

3. Results and discussion

3.1. As-cast microstructure

Fig. 1 shows the XRD patterns obtained from the as-cast MRI230D alloy in both casting conditions. It is evident from the figure that the alloy in both casting conditions consists of primary Mg (α-Mg) peak and the peak corresponding to $(Mg,Al)_2Ca$ phase. The peak corresponding to β-$Mg_{17}Al_{12}$ phase was not present. Thus, the low melting point β-$Mg_{17}Al_{12}$ phase generally observed in Mg–Al alloys is completely suppressed with the addition of Ca in the present investigation, which is beneficial for creep resistance. Mondal et al. [19] too reported elimination of β phase in the Mg–Al alloy with addition of RE. Bai et al. [18] observed the suppression of β phase in the IC and HPDC Mg–4Al–(1–4)La alloy with increase of La as well.

Optical micrographs of the MRI230D alloy in two different casting conditions are shown in Fig. 2(a and b). The alloy in both casting conditions consists of polygonal grains. However, it is obvious that the HPDC alloy exhibited relatively finer grain size as compared to that of the IC alloy. The average grain size determined by linear intercept method was 35 ± 1 μm and 8 ± 0.5 μm for the IC and HPDC alloys, respectively.

The SEM micrographs of the MRI230D alloy in two different casting conditions are shown in Fig. 3(a and b) and the magnified view of Fig. 3(b) is shown in Fig. 3(c). EDS analysis carried out at the grain interior of the micrograph shown in Fig. 3(c) exhibited an average composition of 96.50 ± 0.67 Mg, 2.70 ± 0.64 Al, 0.30 ± 0.14 Ca, 0.19 ± 0.05 Sr, 0.17 ± 0.03 Sn and 0.20 ± 0.06 Mn (at%), which corresponds to α-Mg. Similarly, EDS analysis from the bright lamellar phase present along the grain boundaries and triple points revealed an average composition of 38.7 ± 4.2 Mg, 45.2 ± 7.3 Al and 15.8 ± 1.8 Ca (at%). EDS analysis carried out by Terada et al. [20] on the grain boundary eutectic phase exhibited an average composition of 24.7 Mg, 56.9 Al and 18.0 Ca (at%) and they have reported it as C36 ((Mg, Al)$_2$Ca) phase in the litertaure. Therefore, the grain boundary phase is probably the C36 phase as marked by the arrows in Fig. 3(c). In addition, a few globular Al–Mn rich particles (shown by arrows in Fig. 3(c)) were also observed and EDS analysis exhibited an average composition of 52.3 ± 8.6 Al, 39.6 ± 2.3 Mn and 8.1 ± 0.8 Mg (at%). EDS analysis