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Weibull analysis of effect of T6 heat treatment on fracture strength of AM60B magnesium alloy

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Abstract: The effect of T6 heat treatment on the fracture strength and reliability of AM60B alloy was studied. The tensile specimens were poured at three different temperatures of 670, 685 and 700 °C for different holding times of 5, 10 and 15 min. The fluidity test was also conducted to determine the fluidity length under different pouring temperatures and holding times. According to the results, the optimum pouring temperature and holding time were determined as 685 °C and 10 min, respectively. SEM fractography of the tensile specimens reveals that the entrained oxides and oxide-related porosities are the main factors responsible for the reduction of fracture strength under the non-optimal casting conditions. The Weibull statistical approach was used to quantify the scatter of fracture strength in as-cast and heat-treated conditions. For this purpose, T6 schedule was applied to the specimens prepared under the optimal casting condition. It is found that, despite minor effect on the average fracture strength, T6 heat treatment improves the reliability of castings, where the Weibull modulus is increased by 75%. According to the microstructural and fractography observations, this improvement is related to the evolution of more uniform microstructure and the elimination of coarse brittle *β*-particles in heat-treated samples.

Key words: Mg−Al alloy; AM60B alloy; die-cast; Weibull analysis; fracture strength; fluidity

1 Introduction

Due to their high specific strength, low density and good damping capacity, Mg high-pressure die-casting alloys have been widely studied and used for a wide range of applications, including aerospace and automotive industries [1−5]. Regarding to their fine-grain structure, strengthening effect exerted by second-phase particles, and supersaturation of the alloying elements, these alloys exhibit good mechanical properties and fracture toughness and, therefore, are not heat-treated conventionally [6,7]. Moreover, heat treatment may also affect the relative advantages of fine-grain structure and give rise to the surface blistering and formation of gas pore defects [6−8]. However, if done properly, it was shown that heat treatment is able to offer particular benefits for Mg−Al die-casting alloys including stress-relieving, dissolution of large and brittle particles like Mg−$Mg_{17}Al_{12}$ eutectic, and enhances their tensile properties and fracture toughness [8−10]. These alloys are conventionally subjected to T4 or T6 heat treatment process. A T4 temper involves a solution treatment at 420 °C for 16−24 h followed by water quenching. A T6 temper, however, involves an identical thermal process with an additional aging treatment at 180 °C for 8 h [9,10].

One of the most challenging aspects of Mg casting alloys is their exceptional oxidation susceptibility in molten state, which together with non-protective vulnerable nature of their surface oxide, results in very high oxide inclusion contents of 10−20 times more as compared to the Al alloys [11−15]. The entrainment of magnesium surface oxides in the bulk of a molten alloy takes place as a result of a folding action in which two dry sides of the oxides are folded over each other. This process generates un-bonded oxide−oxide interfaces in solidified casting, which act as pre-existing cracks with some entrapped air in between [13,16−19].

Regarding to their industrial importance, extensive work has been done on the effect of entrained double oxides on the tensile properties and casting reliability of Al alloys [18−23]. However, so far, few studies have dealt with Mg alloys. MIRAK et al [13] studied the characteristic of Mg double-over oxides in AZ91 Mg alloy. They showed that the morphology of bifilms is

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characterized by the amount of trapped air rather than their fold morphology. The effects of double-over oxides (bifilms) on the tensile properties and Weibull reliability of commercial purity Mg were also investigated by GRIFFITHS et al [16]. They indicated that the formation and entrainment of folded-over MgO films lead to the broader distribution of tensile properties.

Regarding to the exceptional oxidation susceptibility in a molten state, magnesium-based alloys are quite prone to the formation and entrainment of magnesium double oxides. It is believed that such oxide is one of the most important factors responsible for the scatter in fracture strength and reduction in castings reliability. Therefore, it is important to study the optimum casting parameters in order to obtain high quality castings with less entrained oxide inclusions. In this work, the effects of pouring temperature and holding time on the microstructure, distribution of casting defects and fracture strength of AM60B Mg−Al alloys were studied. Furthermore, in order to improve the reproducibility of the castings, the effects of T6 heat treatment on the fracture strength and Weibull reliability of the alloy were also studied.

2 Weibull analysis approach

The Weibull analysis approach is an effective tool for exploring the mechanical strength variability of the materials arising from their defects and structural flaws. In this approach, the weakest link theory is applied in such a way that the failure of one link, resulting from a flaw, may lead to a total failure. According to the three-parameter Weibull distribution, for an isotropic material (where the probability of the presence of a flaw in an arbitrary volume is similar throughout the material) containing N links, the probability of failure $F(x; \gamma, \alpha, \beta)$ at a loading stress of x for one link is [24−26]

$$F(x; \gamma, \alpha, \beta)=1-\exp\left[-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right] \quad (\gamma\geq 0, \alpha\geq 0, \beta\geq 0) \tag{1}$$

where γ, α and β are location, scale and shape parameters, respectively. When γ=0, the two-parameter Weibull distribution is derived as follows:

$$F(x; \alpha, \beta)=1-\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \quad (\alpha\geq 0, \beta\geq 0) \tag{2}$$

In the context of this study, $F(x; \alpha, \beta)$ represents the probability that the fracture strength is equal to or less than x. Using the equality of $F(x; \alpha, \beta)+R(x; \alpha, \beta)=1$, the probability of survival $R(x; \alpha, \beta)$, i.e., the probability that the fracture strength is at least equal to x, is defined as

$$R(x; \alpha; \beta)=\exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \quad (\alpha\geq 0, \quad \beta\geq 0) \tag{3}$$

Using linear regression method for estimating the scale and shape parameters, and taking logarithms twice, Eq. (2) is converted to a straight line form, Eq. (4), so the Weibull modulus (β) can be obtained from its slope:

$$\ln\{\ln[1/(1-F(x; \alpha, \beta))]\}=\beta\ln x-\beta\ln\alpha \tag{4}$$

It has been shown that the Weibull modulus is a better measure for material reliability than conventional statistics. Fracture strength values, which are determined from experimental work, are arranged in order as follows:

$$x_1\leq x_2\leq x_3\leq x_i\leq x_n \tag{5}$$

There are several estimates for $F(x; \alpha, \beta)$. The one that is widely used for the jth fracture, from a total of N results, is

$$F(x; \alpha, \beta)=(j-0.5)/N \tag{6}$$

3 Experimental

The chemical composition of as-received AM60B ingots is presented in Table 1. The melting operation was done in a steel crucible using an electrical resistance furnace (3×400 V/50 Hz−60 kW). Protective atmosphere system was activated as soon as the charge temperature reached 400 °C and protected the liquid surface in an adiabatic environment by a gas mixture of 99.82% N_2 and 0.18% sulphur hexafluoride (SF_6). The melt was superheated up to the desired temperature of (670, 685, 700 °C), held for 5, 10 and 15 min and stirred gently before being poured. To have tensile samples (Fig. 1), the melt was poured into a preheated (250 °C) cast-iron tensile specimen mold (ASTM B 557M−02a). The average cooling rate of the mold was around 3 °C/s.

Table 1 Chemical composition of commercial AM60B alloy used in this work (mass fraction, %)

Be	Ni	Cu	Fe	Si	Mn	Zn	Al	Mg
0.0007	−	0.003	0.002	0.031	0.304	0.155	5.830	Bal.

The obtained samples were coded according to their preparation method as XXX/XX. The first part refers to the pouring temperature of the sample, and the second part (after the slash) refers to the holding time of the melt. To investigate the effect of T6 heat treatment on the fracture strength and the strength reliability, some of tensile specimens obtained under optimized casting condition were subjected to solution treatment at 420 °C for 24 h followed by water quenching at ambient temperature. The specimens then were artificially aged at 180 °C for 8 h. The tensile tests were conducted on a Zwick/Roell-Z100 universal testing machine at a crosshead speed of 0.5 mm/min. The average of four tests was reported as the final strength. Eighteen tension