Effect of casting methods on microstructure and mechanical properties of ZM5 space flight magnesium alloy

*Xu-liang Zhang¹, Guo-kang Yu¹, Wen-bing Zou¹, Yan-shuo Ji¹, Ying-zhuo Liu¹, Jia-lin Cheng²

1. Shanghai Spaceflight Precision Machinery Institute, Shanghai 201600, China

2. School of Materials Engineering, Nanjing Institute of Technology, Nanjing 211167, China

Abstract: The counter-gravity casting methods have been developed to remove the casting defects of Mg based alloys. However, the effects of different counter-gravity casting methods on the microstructure and mechanical properties have not been studied in detail. ZM5 alloys were prepared by gravity casting, low-pressure casting and counter-pressure casting, respectively. The mechanical properties, microstructure and fracture morphologies were examined and compared by means of optical microscopy, scanning electron microscopy methods and tensile testing. Results show that casting defects such as gas pore, shrinkage porosity and cavity can be eliminated by counter-pressure casting. The grain size of α -Mg is decreased significantly by counter-pressure casting. Moreover, the precipitated particles are more uniform and finer in the counter-pressure casting sample. As a result, the mechanical properties of the alloys are greatly improved. The tensile strength and elongation of the samples by counter-pressure casting are 285 MPa and 13.9%, respectively, which are much higher than those of the low pressure casting and gravity casting.

Key words: counter-pressure casting; ZM5 alloy; microstructure; mechanical properties

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Mg based alloys have attracted much attention because of their high specific strength. They are expected to have prospectively wide application in the field of structural components in armor, portable electronic devices, biomedical devices, vehicle productions and aerospace components [1-7]. More research interests are devoted to enhancing the mechanical properties (especially the strength) of Mg alloys to further expand their industrial applications, such as grain refinement strengthening and precipitation strengthening [8]. However, the qualified rate of products using the traditional gravity casting method is very low, especially for the thin-wall complex castings. The casting defects, such as oxide inclusion, misrun, cold shut and shrinkage porosity, are inevitable [5, 9]. These casting defects severely decrease the mechanical properties and the widespread applications of Mg alloys. Therefore, it is necessary to develop some new casting methods to

alleviate the casting defects.

To achieve this goal, counter-gravity casting methods, such as vacuum suction casting, low-pressure casting and counter-pressure casting, were developed in past decades [10-13]. The counter-gravity casting has been successfully applied in the production of aerospace magnesium alloy castings. However, the effects of different counter-gravity casting methods on the microstructure and mechanical properties have not been studied in detail. In this study, ZM5 alloy was selected for investigation due to its wide application as aerospace magnesium alloy. The ZM5 alloy samples were prepared by traditional gravity casting, low pressure casting and counter-pressure casting, respectively. The effects of the casting methods on the microstructure and mechanical properties of the alloys were systemically investigated, so as to provide reference for the production of magnesium alloys.

*Xu-liang Zhang

Male, Ph. D, his research interests mainly focus on the development of new materials and new technologies for non-ferrous alloy casting. Up to now, he has published more than 20 technical papers in international journals. At the same time, he has been granted more than 10 patents of China.

E-mail: mrzhang8@163.com

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1 Experimental procedure

Pure Mg and Al-Mn master alloy were preheated at 180–220 °C for 6 h. Then, the pure Mg was put into the furnace and heated to 730 °C under MgCl₂ and KCl fluxes protection. Then, the pure Al was added into

the molten Mg melt. When the melt temperature reached 700–730 °C again, Zn and Al-Mn master alloy were added into the melt. After refining treatment at 750 °C, the melt was cast using the gravity casting, low pressure casting and counter-pressure casting methods, respectively. The related process parameters of counter-pressure casting were as follows: the pouring temperature was 700–720 °C; the clay bonded sand mould was used, while the size of the mould cavity was $\Phi 340$ mm $\times$ 500 mm; the synchronous pressure was 500 kPa; the filling velocity was 0.5–0.7 kPa $\cdot$ s⁻¹, the liquid elevation rate was 1.0–1.2 kPa $\cdot$ s⁻¹; the crusting rate was 0.6–0.8 kPa $\cdot$ s⁻¹; the crusting time was 10–15 s; the crusting supercharging pressure was 5.0–8.0 kPa; the crystallization supercharging pressure was 30–50 kPa; the crystallization time was 240–300 s. The low pressure casting had a synchronous pressure of 100 kPa, and the other parameters were the same as counter-pressure casting. The ZM5 alloy castings were then strengthened by T4 heat treatment with a heating temperature of 415 $\pm$ 5 °C, a holding time of 16 h, and then air cooled.

The specimens were cut from the castings for composition, properties tests and microstructure observation. Chemical composition was checked by an ICP Optima-2000DV plasma atomic emission spectrometer. The microstructures of the alloys were examined by means of optical microscopy (OM). The tensile specimens with 10 mm gauge section diameters were prepared according to the ASTM E8M standard. Tensile tests

were conducted on a WDW-100 PC-control universal tester at room temperature using an initial engineering strain rate of 7 $\times$ 10⁻⁴ s⁻¹; a strain gauge was used to measure the engineering strain. The fracture surfaces of the specimens were examined using a JSM7600F scanning electron microscope (SEM) operated at 15 kV.

2 Results and discussion

2.1 Microstructure

The chemical composition of the alloys is shown in Table 1. Figure 1 shows the as-cast and the corresponding heat treated microstructures of the alloys obtained by different casting methods. It can be seen that a few holes exist in the gravity casting specimen, while no holes can be observed in the low pressure casting and the counter-pressure casting specimens. This is because the liquid melt filled smoothly under a constant mold-filling pressure during the low pressure and counter-pressure casting process, and the air could not be inhaled into the melt. Furthermore, the gas solubility in the melt can

Table 1: Chemical composition of ZM5 samples (wt.%)

Al	Zn	Mn	Si	Cu	Fe	Mg
8.2	0.5	0.4	0.1	0.12	0.02	Bal.

Fig. 1: Microstructures of different casting samples: (a) as-cast gravity casting; (b) heat treated gravity casting; (c) as-cast low pressure casting; (d) heat treated low pressure casting; (e) as-cast counter-pressure casting; (f) heat treated counter-pressure casting

be simply expressed as: $C_n = KP$ (K is constant, P is external pressure)^[14]. According to this expression, the gas solubility in the melt significantly increases with the increasing pressure. The solidifying velocity also increases under the high mold-filling pressure. Therefore, the gas is dissolved into the solid metal, rather than forming bubbles during the low-pressure casting and counter-pressure casting processes.

Besides the gas pores, other casting defects, such as shrinkage porosities and cavities, can also be eliminated by the counter-pressure casting method. Based on hydrodynamics, the liquid metal flowing into the inter-dendritic can be expressed by Darcy's law^[14]:

$$v = kp / \eta f_1 \quad (1)$$

where v is liquid flow velocity in the inter-dendritic; k is constant; p is pressure; η is liquid viscosity; f_1 is the volume fraction of liquid. Due to the highest differential pressure, the liquid flow velocity in the counter-pressure casting is much higher than that of the gravity casting and the low pressure casting. It is beneficial to breaking the solid phase dendritic and maintaining the feeding channels. The feeding distance and time increase significantly for the counter-pressure casting sample. Therefore, the shrinkage porosity and cavity defects are eliminated effectively using the counter-pressure casting method.

It also can be seen in Fig. 1 that the grain size of the sample prepared by counter-pressure casting is the smallest. It is known that the final average grain size is dependent on both the number and the growth velocity of the nucleus. The critical nucleus radius in undercooled melt can be calculated as^[15]:

$$r_k = \frac{2\sigma T_m}{L_m \Delta T} \quad (2)$$

where r_k is the critical nucleus radius, σ is surface free energy of per unit area, T_m is theoretical crystallization temperature, L_m is latent heat of fusion, and ΔT is melt undercooling temperature. Since the kinetic undercooling is closely related to the casting pressure, ΔT increases significantly as the casting pressure increases, resulting in the r_k decreasing drastically. Moreover, with the increase in ΔT , the growth velocity of the nucleus also decreases significantly. Due to the greatest filling pressure, the counter-pressure casting sample has the maximum number of nuclei and the minimum growth velocity, resulting in the smallest grain size.

Moreover, as shown in Fig. 1, the as-cast samples have obvious segregation at the grain boundary, which can be identified as $\beta\text{-Mg}_{17}\text{Al}_{12}$ phase according to the Mg-Al binary phase diagram and Ref.^[17]. When the samples are heated to $415 \pm 5^\circ\text{C}$ for 16 h, these $\beta\text{-Mg}_{17}\text{Al}_{12}$ particles are dissolved into $\alpha\text{-Mg}$ solid solution, due to the solubility of Al in $\alpha\text{-Mg}$ being more than 10wt.% at $(415 \pm 5)^\circ\text{C}$ according to the Al-Mg binary phase diagram. The segregation at the grain boundary disappears for the heat treated samples. However, some black particles are embedded in the interior of the $\alpha\text{-Mg}$ grains. These black particles are also $\beta\text{-Mg}_{17}\text{Al}_{12}$ phases, which are precipitated during air cooling^[17]. It is interesting to find that the

precipitated $\beta\text{-Mg}_{17}\text{Al}_{12}$ particles are more uniform and smaller in the counter-pressure casting sample, which is beneficial to improving tensile strength and plasticity.

3.2 Mechanical properties

Figure 2 shows the tensile stress-strain curves of the heat treated samples. As shown in Fig. 2, the counter-pressure casting sample exhibits the optimal tensile properties. The tensile strength and the elongation are about 285 MPa and 13.9%, respectively, which are much higher than that of the other two samples. The significant improvement of tensile properties should be attributed to its optimum microstructure with the least numbers of casting defects, the smallest grain size and the most homogeneous and fine precipitates.

Fig. 2: Tensile stress-strain curves of heat treated samples

In order to clarify the fracture mechanisms, the fracture morphologies of the samples are further investigated, as shown in Fig. 3. Because of its hexagonal close-packed (HCP) structure, Mg alloy has a very few slip systems, which would lead to the unique fracture behavior under tension loads. The fracture morphology of the gravity casting sample exhibits some obvious quasi-cleavage steps, which are the characteristic of cleavage fracture, as shown in Fig. 3(a). Therefore, it shows a corresponding small elongation. Besides some quasi-cleavage steps, a number of dimples and tearing ridges are also observed in the low-pressure casting sample, as shown in Fig. 3(b). This indicates a mix fracture mode of cleavage fracture and local ductile fracture. However, the counter-pressure casting sample shows a typical ductile fracture, as shown in Fig. 3(c). Lots of dimples and tearing ridges are observed. Moreover, there is an obvious necking phenomenon. The results also show that the sample prepared by the counter-pressure casting has the best ductility, which agrees well with the tensile experimental data.

3 Conclusion

The ZM5 alloy samples were prepared by gravity casting, low pressure casting and counter-pressure casting methods, respectively. Under the same experimental conditions, compared with the other two casting methods, counter-pressure casting is more effective to eliminate the casting defects of ZM5 alloy, such as gas pores, shrinkage porosity and cavity. The grain size

Fig. 3: Fracture morphology of heat treated samples: (a) gravity casting; (b) low pressure casting; (c) counter-pressure casting

of α -Mg also significantly decreases. Moreover, the precipitated particles are more uniform and smaller in the counter-pressure casting sample. As a result, the mechanical properties of the alloys are greatly improved. The tensile strength and elongation of the sample prepared by counter-pressure casting are 285 MPa and 13.9%, respectively, which is much higher than those at low pressure casting and gravity casting.

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