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Study on a Semi-Solid Rheo-Diecasting Process With AZ91D Alloy Slurry

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In this paper, a rheo-diecasting process of AZ91D alloy semi-solid slurry produced with a twin-screw stirring mixer was investigated. The results show that the tensile strength and elongation of the sample made by rheo-diecasting were 37% and 44% higher, respectively, than those produced by conventional liquid diecasting. The castings fabricated by rheo-diecasting possessed good density with low shrinkage and could be heat treated. It is a "near-net shape" production process.

Keywords magnesium alloy, rheo-diecasting, semi-solid slurry

1. Introduction

Magnesium (Mg) alloys are considered to be among the advanced materials for the 21st century. They are some of the lightest metals used as structural materials and have the benefits of high specific strength and stiffness, high damping characteristics, good thermal and electrical conductivity, good machinability, excellent castability, and recycling ability.[1,2] Mg alloys with such characteristics have widespread applications in automotive, video, computer, and communication equipment. In the last ten years, a rapid rise in the use of Mg alloy parts has occurred, and it is predicted that this growth will continue in the first decade of the 21st century.[3]

At present, Mg components are mainly fabricated by diecasting. Although it is the most economical production method, diecasting is incapable of providing high integrity components. One of the promising technologies capable of fabricating high integrity components is semi-solid processing.[4,5] In brief, two major categories of the processes exist for forming metal parts with the semi-solid slurry: rheoforming and thixoforming. Rheoforming is a one-step operation in which the slurries produced from the liquid state are used directly in shaping operations and possesses advantages over thixoforming in terms of low energy consumption, a short production loop and simplified equipment. Currently, thixoforming is the main process used to produce industrial quality parts, especially for aluminum (Al) alloys. However, the rheoforming process is the focus of recent research.[6,7] For this paper, an investigation of rheoforming by cold chamber diecasting process was conducted on an AZ91D alloy semi-solid slurry.

2. Experimental Procedures

The process of making a semi-solid slurry using a twin-screw mixer proceeds in the following way. The liquid metal is fed into the feeding section through the liquid metal feeder at one end of the twin-screw mixer, and there rapidly cooled to the semi-solid processing temperature through the leading section. Within the stirring, extruding, twisting, shearing section, the liquid metal is converted into the semi-solid slurry. The "maturing" section is designed to provide a uniform temperature to the slurry, leading to more consistent microstructures. The outlet valve situated in the departing section at another end of the twin-screw mixer is used to control the slurry exit.

Mg alloy AZ91D is used mainly for diecasting and has a wide temperature range between the liquidus (868 K) and solidus (743 K) temperatures.[8] Its chemical composition is listed in Table 1.

The raw materials were melted in an electrical resistance crucible furnace to between 893 and 923 K under a protective gas of nitrogen and SF_6. The AZ91D alloy melt was transferred intermittently in predetermined doses to the liquid metal feeder of the twin-screw stirring mixer for production of the semi-solid slurry using a pump driven by compressed argon gas.

The twin-screw mixer processing parameters for the semi-solid slurry preparation can be summarized as follows: barrel preheat temperature, 848-863 K; pouring temperature of the melt, 883-893K; and shear rate, 6840-4100 s^{-1}. The solid volume fraction was controlled to between 10% and 50%. The mean size of non-dendritic grains was between 30 and 50 μm.

The slurry was then transported from outlet valve to the shot sleeve and die cast using a 280 metric ton Model DCC280 cold chamber die-casting machine under argon gas protection (L.K. Group Shanghai Atech Machinery Co., Ltd., Shanghai, P.R. China). The temperature of the dies was controlled by heating and cooling oils circulating through elevated temperature pipes and oil channels in the die.

Standard 6.4 mm diameter tensile bars were made by breaking the round bar about 50 mm diameter by 150 mm height from central axis of the die cast parts. The casting is a circular plate, 110 mm in diameter by 1.1 mm in thickness. Material for the die cavity insert was selected to be H-13 die steel, and the

Table 1 AZ91D Magnesium Alloy Composition (wt.%)

Al	Zn	Mn	Be	Si	Cu	Fe	Ni	Mg
9.03	0.73	0.205	0.0010	0.00183	0.0010	0.0012	0.0003	Balance

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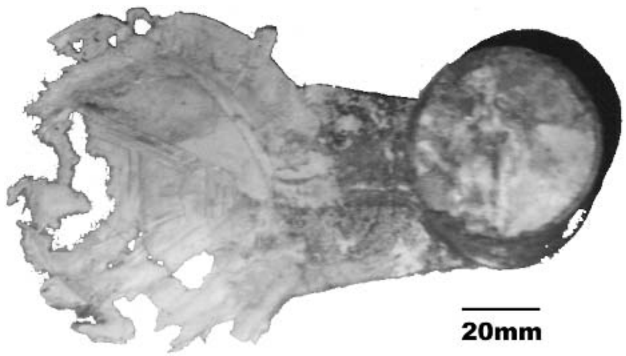

Fig. 1 Casting with incomplete filling in a gate speed of 5 m/s

Table 2 Effect of Gate Speed on Rheoforming

Gate Speed, m/s	Rheoforming Characteristic
5	Cold shuts; incomplete filling
12	No defects
30	Entrapped oxides; porosity

Note: pouring temperature of Mg melt, 883K; barrel temperature, 853K; shear rate, 5700^{-1}; injection pressure, 50 MPa

gate was 70.8 mm width and 0.8 mm height. The preheat temperature of the die was 473-523 K. The temperature of the molten Mg alloy and the mixer barrel were measured with NiCr-NiSi thermocouples. A MeF3 optical microscope was used to examine the microstructure using specimens obtained from the gate. Self-developed software was used for determination of the solid volume fractions.

3. Results and Discussion

Although the viscosity of the semi-solid slurry of Mg at certain solid volume fractions is significantly higher than that of the Mg alloy in liquid state, the slurry has obvious thixotropic characteristics, namely, its apparent viscosity value decreases with increasing shear rate. The high-pressure diecasting machine can provide pressures high enough and filling speeds fast enough to completely fill a mold cavity, therefore many benefits occur in the rheo-diecasting of semi-solid Mg alloys.

Table 2 shows the effect of gate speed on the efficiency of rheo-diecasting of the semi-solid slurry of AZ91D. Filling the die cavity with a gate speed of 5 m/s, the slurry flowed slowly and resulted in cold shuts and incomplete filling defects in the casting. Figure 1 shows a casting. Due to the low gate speed, the shearing effect on the slurry was not sufficient, and the apparent viscosity of the slurry did not decrease enough to fill the mold. Meanwhile, the filling time was prolonged and the slurry cooled more than it would in the rheoforming process. This led to a decrease in the flow of the slurry and thus resulted in the incomplete filling of the mold. At the other extreme, filling the die cavity using a gate speed of up to 30 m/s, the slurry flowed turbulently, leading to defects such as entrapped oxides and porosity. Therefore, in both high and low gate speed cases, the castings were not sound or of good quality. The results showed that filling the die cavity with a gate speed of approximately 12 m/s led to the highest quality castings.

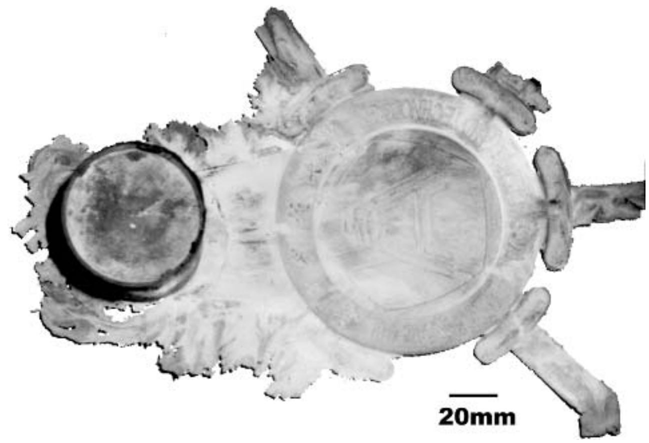

Fig. 2 Casting with excessive tucks in a 72 MPa injection pressure

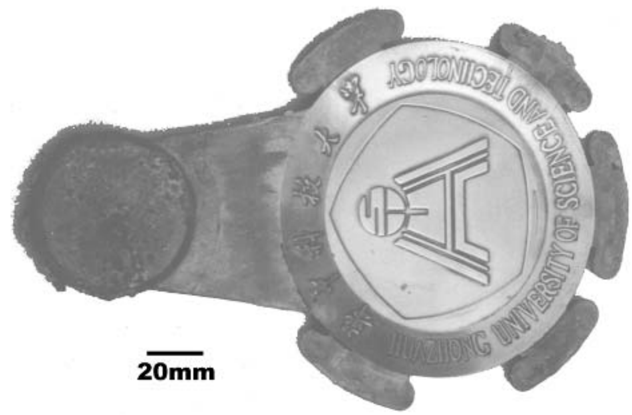

Fig. 3 The casting with appendages

Table 3 Effect of Injection Pressure on Rheoforming

Injection Pressure, MPa	Rheoforming Characteristic
20	Porosity, crack
40	No defects
72	Excessive flashing

The effect of injection pressure on the rheoforming process is summarized in Table 3. In the case of a 72 MPa injection pressure, there was excessive flashing on the casting, demonstrating that the injection pressure was too high. Figure 2 shows an example of a casting with excessive flashing. In the case of the 20 MPa injection pressure, porosity and cracking appeared in the area near the gate of the casting. This implied that the injection pressure was too low so that the capability of feeding shrinkage in the gate area was poor. In the case of the 40 MPa injection pressure, the semi-solid slurry possessed favorable rheoforming characteristics and the quality of the casting was good.

These experiments demonstrated that the rheo-diecasting is closely related to the solid volume fraction and the temperature

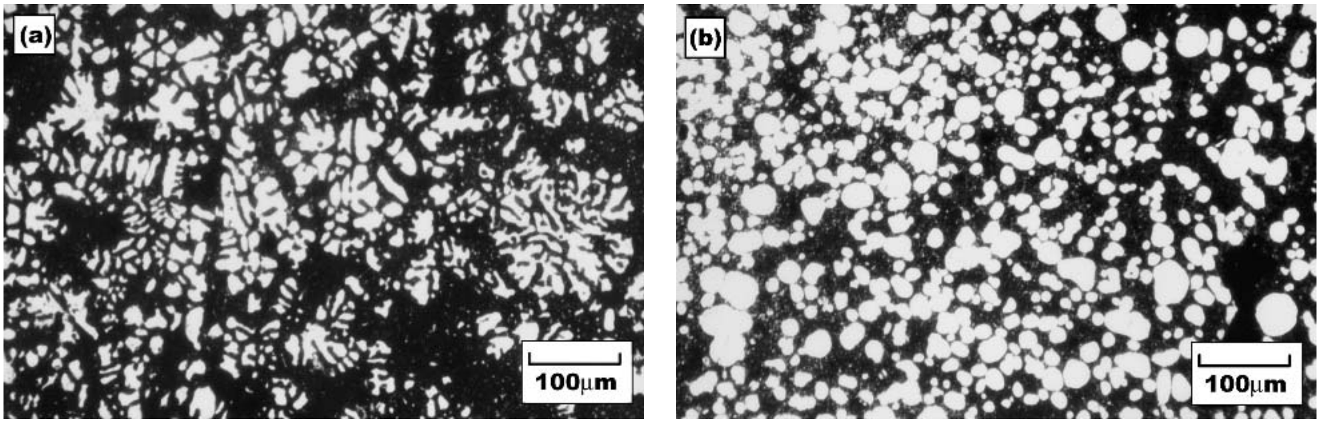

Fig. 4 Microstructures of the casting produced by liquid diecasting and rheo-diecasting: **(a)** liquid process and **(b)** semi-solid process. The bright one represents α-Mg primary phase; the dark phase is α-Mg + $Mg_{17}Al_{12}$ eutectic.

of the slurry. With an increase of the solid volume fraction or a decrease in the process temperature, the rheoforming characteristics worsen, so the gate speed and the injection pressure should be adjusted accordingly. The results of the research showed that a round thin-walled casting could be fabricated using the rheo-diecasting technique when an injection pressure between 40 and 50 MPa, a gate speed between 10 and 15 m/s, and a solid volume fraction between 10% and 50% is used.

Figure 3 shows a typical casting with appendages manufactured by rheo-diecasting. The casting was well manufactured with a clear contour and good soundness. Microstructures of castings produced by liquid diecasting and rheo-diecasting are shown in Fig. 4. The microstructure of the conventional liquid diecasting shows a dendritic character with the bright areas representing the α-Mg primary phase while the dark is the α-Mg + $Mg_{17}Al_{12}$ eutectic phase. The microstructure of the rheo-diecasting is mainly non-dendritic, being composed of globular primary grains (bright) and eutectic (dark). Measurements of density and shrinkage of the castings were made and the results summarized in Table 4. The density of the casting made by rheo-diecasting is higher than that of the conventional diecasting. The shrinkage of the casting produced by the rheoforming process was also less than the one made by conventional diecasting. Therefore, the rheo-diecasting approach realizes high integrity castings with "near-net shape."

The tensile strength, elongation and hardness were determined from standard circular tensile bars. The results are tabulated in Table 5 in three conditions: conventional diecasting, rheo-diecasting, and rheo-diecasting with a subsequent T6 heat treatment. The tensile strength and the elongation of the rheodiecast sample exceeded that of the conventional diecasting by 37% and 44%, respectively. The hardness values of the samples in the different processes were much the same. The mechanical properties of the rheo-diecasting can be improved significantly with a post-casting heat treatment. This is shown in Table 5.

Improvements in mechanical properties can be attributed to the twin-screw mixer. The semi-solid slurry rotates in a "synchronous" manner; i.e., the slurry is agitated, sheared, squeezed, ground and transported, etc.[9] As a result, the partial dendritic arms are broken and detached, eliminating the usual dendritic morphology. The temperature and composition fields at the solid-liquid interface tend to distribute the globular clusters uniformly, which decrease the temperature of undercooling and the solute concentration. This represses the growth of crystals in the usual dendritic morphology.[10] Because rheo-diecasting places strong shearing forces on the slurry, the feed rate of the casting improves, leading to quick fill speeds at high pressure so as to preserve the non-dendritic characteristics of the semi-solid slurry, ensuring sound castings with improved mechanical properties. The low temperatures and high apparent viscosity of the semi-solid slurry also leads to less shrinkage in rheo-diecast parts with less entrapped gas.

Table 4 Density and Shrinkage of the Casting Under Different Conditions

Casting Type	Density, g/cm^3	Shrinkage, %
Liquid die casting	1.78	0.775
Rheoforming die casting	1.81	0.725

Table 5 Mechanical Properties of AZ91D Alloy Under Different Conditions

Casting Type	Tensile Strength (MPa)	Elongation (%)	Hardness (HB)
Liquid die casting	135	3.2	62
Rheoforming die casting	185	4.6	63
Rheoforming die casting +T6 temper	245	7.6	65

4. Conclusions

Rheo-diecasting can improve the mechanical properties of AZ91D relative to a conventionally die cast castings. The decrease in shrinkage and entrapped gas makes castings with "near net-shape" feasible. Due to the low forming temperature, the die's service life can be increased and oxidation of AZ91D melt can be decreased. The twin-screw mixer used in this study provides sufficient mechanical stirring to produce the AZ91D semi-solid slurry with a fine, globular, non-dendritic morphology. The mixer can be combined with other processing techniques to produce slurries discretely and continuously, leading to an integrated rheoforming system.

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