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SEMI-SOLID CASTING OF AZ91D MAGNESIUM ALLOY FROM EXTRUDED BILLETS

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Abstract

Commercial magnesium castings in the AZ91D magnesium alloy are mostly pressure die cast from liquid metal at elevated temperatures, or produced using the proprietary Thixomolding process at a low percentage solid fraction. Semi-solid casting of magnesium billets from reheated feedstock is relatively unknown; unlike aluminum alloys, continuously cast bars suitable for this purpose are not readily available commercially. In this respect, the use of extruded billets is a clear alternative. This paper demonstrates the feasibility of casting AZ91D magnesium alloy from 76.2 mm (3 in) diameter extruded billets reheated to below the liquidus temperature to provide a varying amount of solid. Upon heating, the fine primary alpha phase is transformed into globular particles similar to what is commonly observed in heating continuously cast and electromagnetically stirred material with a fine non-dendritic structure. Subjected to a high shearing force during die casting, the thixotropic nature of the alloy allows complete die filling to be achieved readily. In the experiments, the feedstock material is contained in a crucible and heated using an in-house induction system specially designed to provide a variable energy source necessary to maintain an even temperature throughout the workpiece. The alloy temperature and input power are controlled by a thermocouple inserted at the center of the 152.4 mm (6 in) billet or slug. Slugs heated to different temperatures (and thus containing different percentages of solid) are cast into a number of complex box-like components. Various sections of the castings are cut and evaluated to establish variations in microstructure and mechanical properties. The influence of certain casting parameters on castability is examined, with the view to identifying those critical to die filling. Results are compared with those obtained from castings produced from liquid metal.

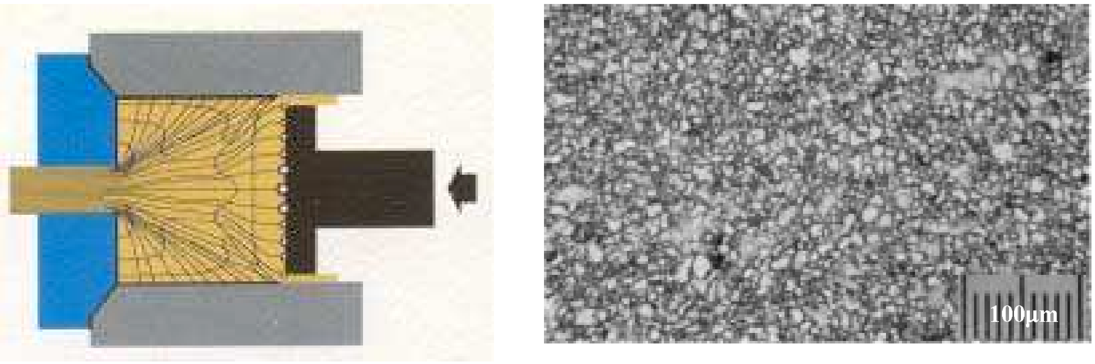
Introduction

The AZ91D magnesium alloy (9 % aluminum and 1 % zinc as principal alloying elements) is probably the most popular magnesium alloy for conventional pressure die casting. Extensively studied over the years, this alloy has excellent castability and could produce complex thin-walled components in a variety of applications, particularly in the automotive and electronic sectors – an advantage no doubt responsible for its wide usage. Driven mostly by commercial interests, research efforts over the past few decades have been concentrated in the characterization of properties and optimization of production methods with the view to further expanding its use. More recently, a lot of development work has been undertaken in the casting of components at temperatures below the liquidus - in the semi-solid state, or in a state containing a significant amount of solid [1-4]. Two known commercial processes are the Thixomolding process [1,2] which uses magnesium alloy chips as feedstock to produce a material with a low solid fraction by means of a rotating screw in a barrel and the New Rheocasting process [3,4] which produces a slurry through controlled nucleation and cooling of liquid metal just prior to casting. Thixocasting, another semi-solid production process, produces components from reheated billets with a non-dendritic structure. It is commonly applied to aluminum alloys but not to magnesium alloys, due largely to the lack of cast feedstock in commercial quantities.

In an earlier paper on thixocasting of AZ91D [5], it was demonstrated that complex box-like components could be produced from billets prepared by using a combination of super-heat reduction and electromagnetic stirring technique. In this paper, the feedstock material for casting these components was extruded from cylindrical ingots and was not subjected to any post treatment. Results of casting trials of material reheated from 565 to 650 ºC are presented. This wide casting temperature range allows the study to be carried out in components produced from material with approximately 50 % to 0 % solid [6,7].

Experimental

Extrusion of AZ91D Feedstock



(a) (b)

Figure 1. (a) Schematic of the indirect extrusion process, and (b) microstructure of the extruded material perpendicular to the extrusion direction.

The AZ91D feedstock material was prepared by indirect extrusion from 203 and 254 mm cylindrical ingots in a 1800 T capacity extrusion machine at the Materials Research Laboratory, Industrial Technology Research Institute (ITRI), Taiwan. The ingots were preheated to a temperature range of 300 to 350 ° C. In terms of parameters, an extrusion rate of 10cm~20 cm/min, a die temperature of 350 to 400 ° C and pressure 100 to120 Kg/cm2 were used. The original size of the material was reduced to the required diameter of 80 mm in one step (Figure 1a). The microstructure of the extruded material consists of very fine-grained equiaxed Mg-rich primary phase (mostly below 20 μm) and eutectic (Figure 1b).

Induction Heating and Die Casting

Billets of 80 mm diameter and 15.2 cm in length (also commonly referred to as slugs) were reheated in ceramic crucibles insulated at the top. Reheating was carried out in an induction system specifically designed for thixocasting of lightweight alloys, as shown in Figure 2 [5]. Precision control of power input into the induction coil was done by means of a thermocouple located centrally at a depth of 1.28 cm on the top surface of the slug. This control produced a temperature variation of ± 3 ° C from the side circumference to the core of the slug when heated to a temperature below the liquidus. Above the liquidus temperature, a temperature difference of ± 1 ° C in the molten metal in the crucible was achievable. A steady stream of SF_6 /CO_2 mixture applied at the top end prevented the magnesium from being oxidized.

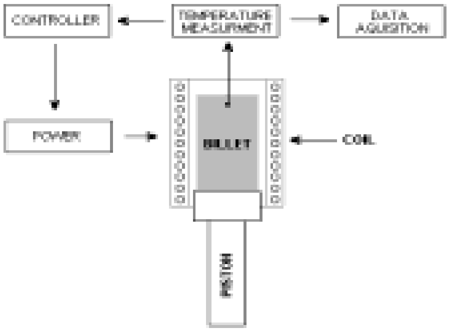


Figure 2. Schematic of set-up for reheating the billet; a thermocouple was embedded at the center of the billet to monitor the temperature and control power input.

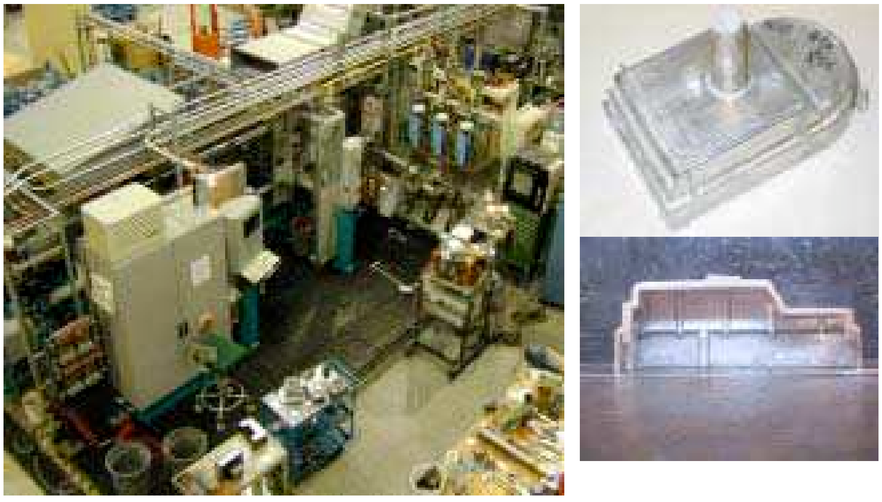


Figure 3. Die Casting Laboratory; top view and mid-sectional view of the box casting through the runner are shown.

The slugs with varying amounts of solid and liquid were cast into components at the Industrial Materials Institute using a Bühler 600 T capacity SC N/53 die casting machine (Figure 3). The lowest alloy temperature employed was 565 ° C and the highest, 650 ° C. The die was designed to allow material to flow centrally into the cavity through a cylindrical gate at the top of the box, thereby minimizing the flow distance to the edge of the box (see components in Figure 3). The casting parameters used were very similar to those described previously [5]: A ram speed of at least 1 m/s, a die temperature of 200 –250 ° C and a metal pressure in access of 1000 bars (100 MPa). The box casting has a height of 6 cm and weighs 0.95 kg. Its wall thickness varies from 9 mm near the gate to 5 mm at the bottom edge.

From each casting batch, 3-4 sub-sized ASTM strip samples with a width of 6.35 mm at the reduced section were machined from the flat rectangular area at the top of the box around the gate region for tensile testing. For comparison purposes, a few tensile trips of the same thickness were also machine from the as-extruded feedstock. The microstructure of each temperature batch was evaluated by taking samples from the flat rectangular region. These samples were mounted, polished and etched for 5 seconds in glycol (75 cc of gloycol, 24 cc of distilled water and 1 cc of concentrated nitric acid) and examined in an optical microscope.

Results and Discussions

Effect of Casting Parameters on Cavity Filling

The ability to fill the complex box casting was very much dependent on the temperature of the alloy and the die casting parameters chosen. Past experiments on AZ91D alloy prepared from electromagnetically-stirred billets have indicated that complete filling of the part having little or no cold shuts could be achieved by applying a piston velocity of at least 1 m/s and a metal pressure of at least 1000 bars (100 MPa), while keep the die temperature in excess of 200 ° C [5]. The alloy was reheated to a temperature range of 570-580 ° C, corresponding to a solid fraction of approximately 0.45 [6,7]. Experience with the extruded billets was very similar. Below this temperature range, parts could not be completely filled, the most problematic areas being found around the circular wall section (Figure 4). Increasing the metal pressure (greater than 1200 bars), piston speed (to 1.5 m/s) and die temperature (by 50 ° C or more) further provided some improvement to the surface finish, but not enough to significantly reduce cold shuts and other surface defects common to magnesium castings. Liquid alloy at a temperature of 600 – 650 ºC, on the other hand, had little difficulty filling the cavity. As with parts containing some solid, the surface finish and quality of the part improved with increased die temperature, piston velocity and metal pressure.

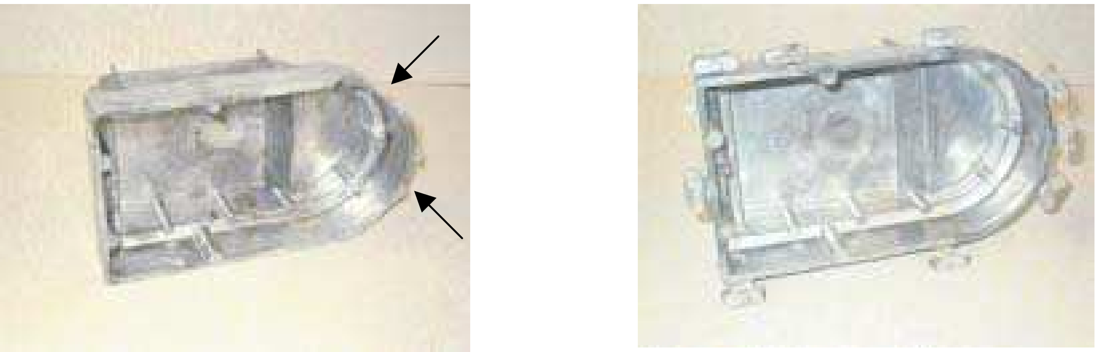


Figure 4. Arrows showing unfilled regions around the circular wall of a partially filled casting produced from a slug at 565 ° C (left) and a fully filled casting produced at 580 ° C (right). Note the absence of overflows in the partially-filled part.

Microstructures at Various Casting Temperatures

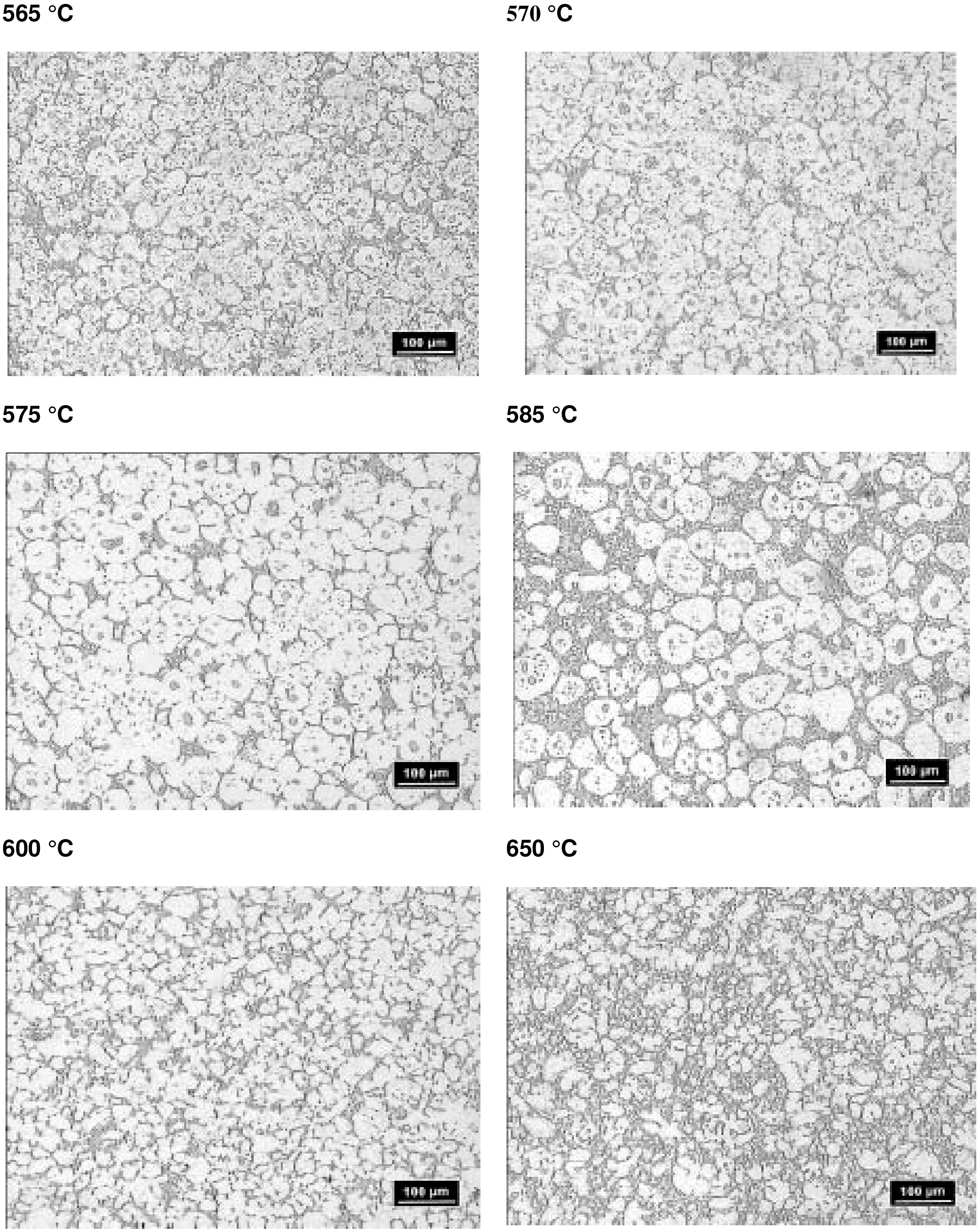
Typical microstructures of parts cast at various alloy temperatures (specimens taken from the top flat region near the gate) are shown in Figure 5. It is evident that the original structure in the extruded material exhibited a profound transformation during induction heating. The original equiaxed α phase was transformed into a globular phase typically seen in alloys in the thixotropic state during forming. As the alloy begins to melt, agglomeration of the α phase takes place. With increasing temperature, this phase becomes more rounded and better defined. The amount of eutectic phase, consisting of a mixture of the α phase and the brittle intermetallic $Mg_{17}Al_{12}$ phase, is also significantly increased. The microstructure obtained from the alloy without any solid particles at 600 ° C (being 5° C above the liquidus [8]) does not display the distinctive globular α phase observed at 585 ° C and below. Instead, a mixed structure containing fine equiaxed particles and some globular and rosette particles is observed. At 650 ° C, there is a lot finer α particles between the much larger α rosette and dendritic arms. Since both these microstructures are generated from molten AZ91, the solidification behavior is more akin to what takes place in conventional pressure die casting where a molten metal stream undergoes rapid solidification when it encounters a relatively cold die surface.

Tensile Properties of Components

Table 1 shows results of tensile tests conducted on sub-sized ASTM 9 mm strips cut from the flat region at the top of the box. Results of tests on specimens machined from the as-extruded feedstock material were included for comparison purposes. As it was not possible to truly distinguish the properties of batches produced at intervals of only a few degrees ºC, it is more meaningful to represent these results by a group that were cast at temperatures below the liquidus and a second group at temperature above the liquidus. However, it should be mentioned that within each temperature batch, there were significant variations in properties, depending on the morphology, level of defects and inclusions such as oxide particles found in the specimens. Specimens that contained some defects generally displayed values that were at the lower end of the range. Most of these defects were caused by shrinkage voids between grains of the primary phase (see Figure 6). Examination of some fractured surfaces of tensile specimens cast below the liquidus temperature revealed that fractures usually occurred through these voids and along the brittle $Mg_{17}Al_{12}$ phase. The tensile, yield and elongation values of the group produced from liquid were found to be slightly superior to those produced below the liquidus temperature. Compared to values obtained from the as-extruded bars, however, the properties obtained from cast specimens were markedly inferior. It is evident that the absence of defects commonly seen in castings and the fine microstructure associated with the extruded material were responsible for its excellent tensile properties.

Table 1 Tensile Properties of As-Extruded Billet and Cast Parts

Property	As-Extruded	Parts < Liquidus (565 – 590 º C)	Parts> Liquidus (600-650 º C)
Tensile Strength, MPa	292	170-190	180 -220
0.2% Yield Strength, MPa	209	115-140	130 - 140
% Elongation	10.3	1.5 – 2.5	2.0 – 4.0



565 °C

570 °C

575 °C

585 °C

600 °C

650 °C

Figure 5. Microstructures of parts produced at various casting temperatures. The primary phase (in white) becomes more rounded and larger as the temperature increases (top four micrographs), but distinctively non-globular when the alloy is cast in the liquid state.

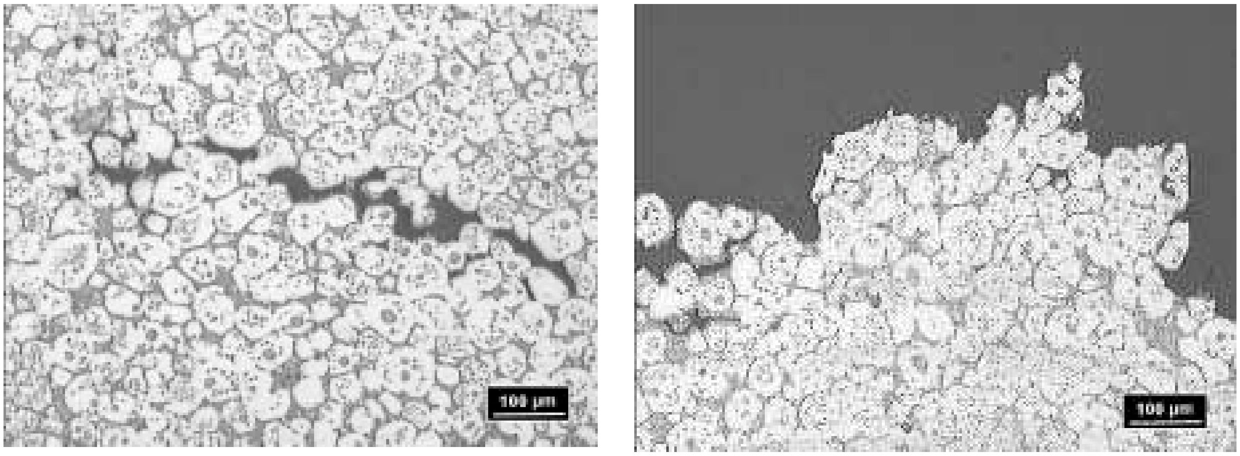


Figure 6. Micrograph of shrinkage voids in a part cast at 575 ° C (left) and a cross-section through a fracture showing preferential path along these voids and the brittle $Mg_{17}Al_{12}$ phase (right).

Conclusions

Excellent castability was observed in extruded AZ91D magnesium alloy reheated inductively to different solid fractions below the liquidus temperature. As with material prepared by electromagnetic stirring, filling of a complex cavity in the semi-solid state could be achieved by reheating the material to 570 –580 ° C and applying very similar casting parameters.

The original fine equiaxed structure in the extruded material was transformed during reheating into a globular structure. This morphology after reheating is typically seen in thixotropic semi-solid alloys prior to forming.

Significant variations in the tensile properties of castings produced at different temperatures were noted.

Acknowledgements

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