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Magnesium Permanent Mold Castings Optimization

F. R. Elsayed[1,a], N. Hort[2,b] , M.A. Salgado-Ordorica[2,c] and K. Kainer[2,d]

[1]National Institute for Materials Science NIMS 1-2-1 Sengen, Tsukuba-city Ibaraki 305-0047, Japan

[2]Helmholtz-Zentrum Geesthacht, Max-Planck-Strasse 1, 21502 Geesthacht, Germany.

[a]elsayed.fadyrefaat@nims.go.jp, [b]norbert.hort@hzg.de,

[c]mario.salgado@hzg.de, [d]karl.kainer@hzg.de

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Abstract Permanent mold casting is a well-established route for casting large magnesium alloys components. Casting parameters like superheat, mold temperature, and holding time can often result in inhomogeneous properties, porosity, and segregation problems in the cast part. In order to optimize the casting process, control of the casting parameters including mold temperatures and holding times is essential to promote directional solidification, and ensure defect free homogenous structure. Binary Mg-9wt.%Al and Mg-10wt.%Gd alloys were used to investigate the effect of casting parameters such as melt temperature and holding time on the part macro and microstructure.

Introduction

Magnesium alloys as structural materials have been the focus of huge research efforts for automotive and aerospace applications, in particular because of the great weight reductions, in between 30 to 75 %, that can be achieved when replacing Al or steel components with Mg-alloys [1, 2]. Permanent mould casting is normally the manufacturing route for creep resistant Mg-alloys, and semi-continuous casting of Mg-alloys is extensively used to provide feedstock for further mechanical processing at low and high temperatures (e.g., extrusion, rolling, forging, etc). At a more fundamental level, within the field of research and development of new Mg-alloys, there has been some concern on producing small quantities of Mg-alloys with the appropriate macro- and microstructure, free of defects and with homogeneous composition. The aim of the present work is to develop and optimize a direct chill permanent mould casting process at a laboratory scale. Moreover, this investigation provides with information to better understand the effect of critical casting parameters such as over heating temperature, holding time, and solidification speed on the chemical homogeneity, the macro- and the microstructure of binary Mg-alloys.

Experiments and Methods

The binary Mg-9wt.%Al and Mg-10wt.%Gd alloys used in this study were prepared from liquid mixtures of their individual elements (99.95wt.% purity) in a resistances furnace able to heat up a stainless steel crucible of 8 kg capacity. Mg ingots of about 750 g were first molten in the furnace at 720°C, and then the corresponding alloying element was added in small quantities not bigger than a few hundreds of grams. After a waiting time of 5 minutes, a six-blade boron nitride coated stainless steel propeller, turning at 150 rpm during 30 min, was used to stir the melt and ensure complete mixing. A constant flux of an Ar-SF_6 mixture (in a ratio 5:1) was introduced to the furnace during the whole melting and stirring times, in order to reduce oxidation and burning of the melt. After stirring, oxides remaining on the upper surface of the melt were cleaned out with a boron nitride coated stainless steel paddle. The temperature before pouring into the permanent mould was of 720°C and 730°C for the Mg-9wt.%Al and Mg-10wt.%Gd alloys, respectively.

A schematic representation of the experimental set-up used to solidify the specimens produced in this work can be observed on the left of Fig. 1[1]. A three-zone resistances furnace having a tubular shape is bounded in the upper and bottom parts by well-insulated opening hatches. The permanent mould, fabricated with stainless steel and coated in its inner surface with a thin layer of boron nitride, was preheated into the tubular furnace at different temperatures, depending on the specified condition. After pre-heating, the mould was extracted from the tubular furnace through the upper hatch and fixed to a support where the melting furnace could directly fill it. A smooth flux of Ar was passed through the melting furnace nozzle in order to avoid oxidation and burning of the molten metal during this stage. After pouring, the mould was introduced again into the tubular furnace through the upper hatch and it was covered with a thin steel deck. A secondary flux of an Ar-SF_6 mixture was flowing through the deck in order to keep the atmosphere above the molten metal free of oxygen. Additionally, a 1 mm diameter thermocouple was introduced into a boron nitride coated stainless steel capillary tube (3 mm diameter), that was in direct contact with the melt, at about 50 mm from the bottom of the mould.

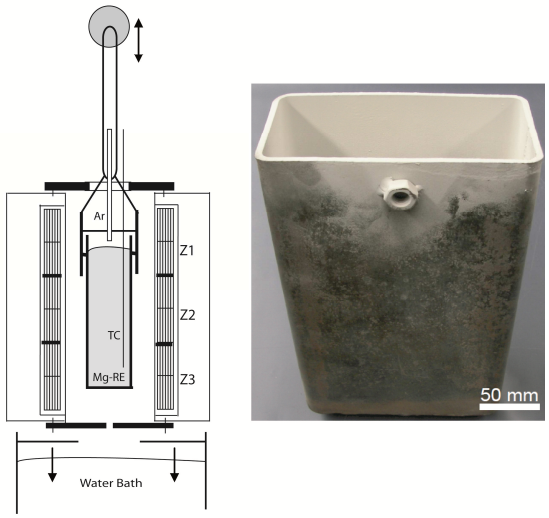

Figure 1: Schematic representation of the three-zone tubular furnace used to produce Mg-alloy ingots (left), and rectangular permanent mould (right).

The mould and molten alloy were hold during a specific time ranging between 15 and 60 minutes at temperatures ranging in between 650°C and 750°C. After this holding time, the thermocouple was extracted from the melt and the bottom hatch was opened. A *y*-axis movement inductor was specially designed in order to achieve different pulling velocities of the mould into a water bath located at about 5 cm below the tubular furnace. The pulling velocity v_p ranged in between 8 to 20 cm/min (which corresponds to a range from $1.33*10^{-3}$ to $3.33*10^{-3}$ m/s). The mould geometry used in this study can be observed on the right of Fig. 1. After solidification, the ingots were extracted from the moulds and 1.5 cm of the upper and bottom parts were directly sectioned away. In order to evaluate the composition homogeneity in the whole volume, chemical analysis was performed by means of an X-ray fluorescence analyzer XRF (Bruker S4explorer) for the Mg-Gd specimens and through spark emission spectrum analysis in a Spectrolab2003 (Sprectro Analytical Instruments GmbH and Co.) for the Mg-Al ingots at different heights of the specimens.

In order to perform macrostructure analysis, a 1 cm thick slice parallel to the main axis of each ingot was extracted. For the microstructure analysis, small specimens 20*20*20 mm^3 in volume were extracted from the center and edge regions of the bottom, middle and upper parts of the ingot. The specimens for macro- and microstructure analysis were then grinded and polished to mirror quality. No etching was necessary to reveal the grain structure in the Mg-10wt.%Gd alloy, but an etch 20 s long with a standard solution (as reported in Kree et al. [4]) was used reveal the microstructure of the Mg-9wt.%Al specimens.

[1]taken from [3]

Results and discussion

The bulk chemical composition, quantified by using optical emission spectroscopy, of the samples extracted from different positions of the Mg-9wt.%Al and Mg-10wt.%Gd rectangular billets is given as an example in Table 1. Upper, middle and lower parts correspond to small volumes extracted from different heights of the specimen, at the center and at the edge, near the longest lateral wall of the mould. The small variations on composition in between the different regions of the specimen clearly show that there are no macrosegregation effects during solidification of such a part. The chemical analysis of the Mg-10wt.%Gd specimen showed that there is a systematic lost of ≈ 1wt.%Gd during the melting and stirring operation, but then the same type of composition distribution, i.e., a very homogeneous distribution of Gd in the bulk, was observed, as can be seen in Table 1.

Table 1 - Chemical analysis in Mg-9wt.%Al and Mg-10wt.%Gd specimens

Condition	T_{hold}, °C	t_{hold}, min		wt.%Al	wt.%Al	wt.%Gd	wt.%Gd
				Edge	Centre	Edge	Centre
A	670	15	upper	9.22	9.14	9.24	9.34
			middle	9.25	8.96	9.14	9.19
			lower	9.07	9.04	9.09	9.07
B	670	30	upper	9.59	9.50	9.24	9.21
			middle	9.51	9.44	9.24	9.17
			lower	9.49	9.40	9.35	9.46
C	670	45	upper	9.18	9.13	9.33	9.28
			middle	9.14	9.06	9.25	9.21
			lower	9.11	9.01	9.42	9.40
D	690	30	upper	9.15	8.99	9.25	9.23
			middle	9.13	8.95	9.35	9.23
			lower	9.05	8.96	9.41	9.28
E	690	45	upper	9.01	8.96	9.50	9.32
			middle	9.10	8.97	9.43	9.35
			lower	9.18	9.06	9.31	9.33
F	735	30	upper	8.95	8.81	9.10	8.93
			middle	8.98	8.77	9.10	9.07
			lower	8.88	8.81	9.04	9.06
G	735	40	upper	9.00	8.98	9.22	9.26
			middle	9.12	9.07	9.07	9.04
			lower	9.09	9.03	9.04	9.18

A detailed comparison of the microstructure of the binary alloy specimens solidified with a pulling velocity of 12 cm/min, under extreme different holding times and temperatures can be observed in Fig. 2 for the Mg-9wt.%Al and the Mg-10wt.%Gd alloys. The micrographs were taken from sections perpendicular to the pulling direction. It can be clearly seen that the secondary phases size and distribution (small light particles of the intermetallics $Mg_{17}Al_{12}$ and Mg_5Gd, respectively) is quite homogenous, independently from the solidification conditions. Further characterization of the grain distribution in these type of ingots can be in [3].

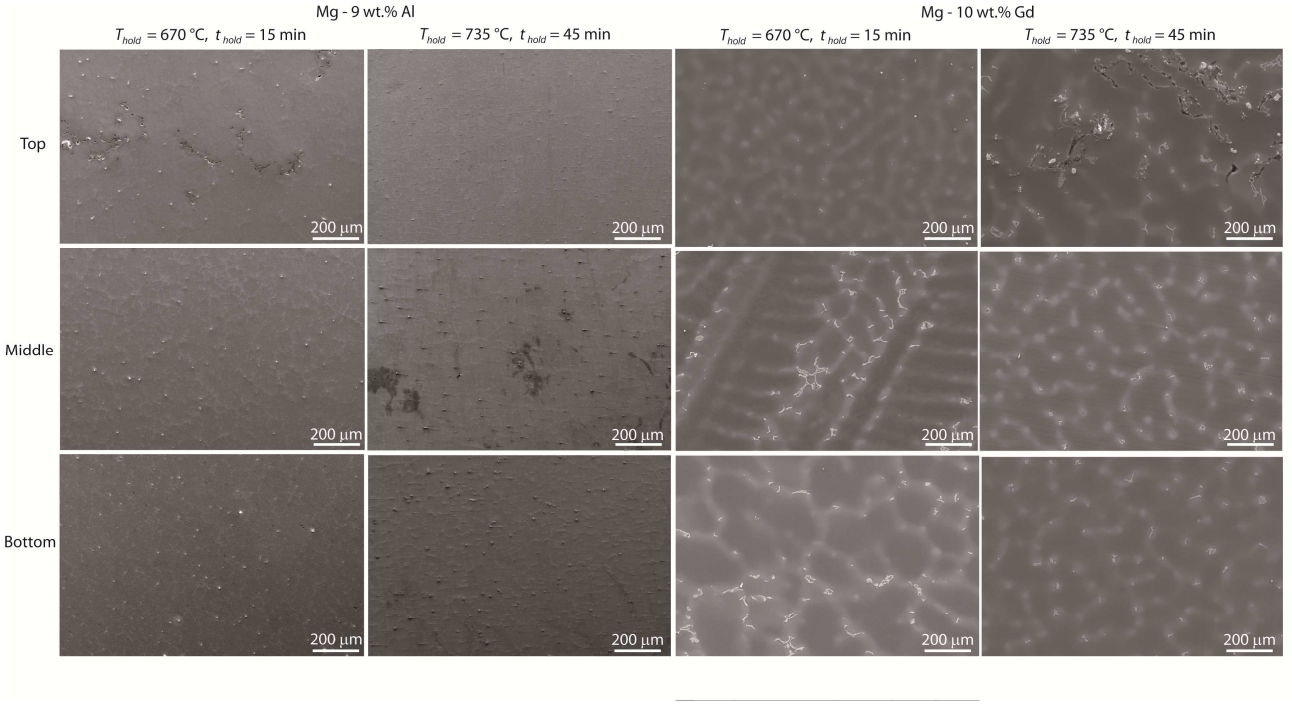

Figure 2: Comparison of microstructures obtained under different holding time and temperatures for both binary alloys.

Summary

An experimental technique has been developed in order to produce ingots at a laboratory scale through a direct chill casting process in a permanent mould. The ingots obtained under different solidification conditions showed a very homogeneous composition distribution, no macrosegregation patterns and were obtained free of porosity, cracks and inclusions. A set of solidification parameters were imposed in order to better control both the macro- and microstructure of the different specimens. It was observed that a fully columnar structure can be obtained when v_p<12 cm/min and that the occurrence of the CET can be retarded by stopping the pulling and leaving the specimen to cool down inside the furnace. At higher pulling velocities into the water bath, an equiaxed structure tends to develop, with decreasing grain size as the pulling velocity is increased.

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