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Materials Science and Engineering A 375–377 (2004) 651–655

MATERIALS SCIENCE & ENGINEERING A

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Non-equilibrium globular microstructure suitable for semisolid casting of light metal alloys by rapid slug cooling technology (RSCT)

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Abstract

As the semisolid processing of metals continues to gain importance and acceptance not only within research centers but also in industry, new methods and technologies are being developed to improve the quality of the semisolid cast parts and increase the productivity and reliability of the process. Within the so called thixocasting processes pre-material slugs with a globular microstructure serve as feedstock for the semisolid casting process. Studies have shown however, that for many alloys the main parameter for the production of suitable pre-material billets with a globular microstructure is the cooling rate. Therefore, the new rapid slug cooling technology (RSCT)-process has been developed, where the alloy is quenched in a specially designed cooling device. With this process, a fine and homogeneous non-equilibrium microstructure of globular α-phase dendrites was achieved. Due to micro-segregations within the globular grains melting proceed from outside towards the grain center. Thus, it is possible to produce a semisolid slurry with a well defined fraction of solid using technical Mg alloys with very low contents of eutectics like the AZ31(MgAl3Zn1), AZ61 (MgAl6Zn1) and alloys with rare earths. These alloys were processed in thixocasting to test the effectiveness of the RSCT with very promising results.

Keywords: Semisolid; Magnesium; Thixocasting; SSM; Micro-segregation

1. Introduction

The thixocasting process is a variant of the high-pressure die-casting, in which metal in the semisolid state is pressed into a die [1]. Semisolid metals behave like thixotropic fluids with visco-elastic characteristics. In the absence of shear forces, the semisolid metals are similar to a solid but on application of shear the viscosity is strongly reduced and the material starts flowing [2,3]. As a result, semisolid metals flow into the die in a laminar way with a closed front. This reduces considerably the gas porosity and the oxide inclusions in the thixocast parts. They are in comparison to conventional die cast parts weldable, heat-treatable, and pressure-tight, while maintaining very good mechanical properties.

The thixocasting process can be divided into three steps: pre-material billet production, re-heating into the semisolid state, and forming. Conventional cast alloys show a dendritic microstructure. During forming in the thixocasting process, these dendrites would hook onto each other, leading to an inhibition of flow and to segregation of the liquid and solid phases of the metal. An appropriate pre-material for thixocasting must have a globular microstructure, which enables "easy gliding" of the solid α-phase particles in the liquid phase [4]. To obtain this globular microstructure different methods have been developed. Some of them use mechanical or electro-magnetic stirring of the melt during solidification. The movement of the liquid phase breaks off the dendrite arms and branches, shaping them into a globular microstructure. A very close control of the re-heating process is needed to ensure the correct solid/liquid fraction and the homogeneous temperature distribution of the billet. After re-heating, the semisolid billet is placed in the modified pour chamber of a high-pressure die-casting machine and formed [5,6].

A pre-condition for processing metallic materials in the semisolid state is a wide enough solidification interval of the alloy. Under equilibrium conditions, the solid and liquid fractions can be obtained from the phase diagram using the lever rule. In comparison with aluminum alloys, most of the commercial magnesium alloys present a chemical composition that does not show, in equilibrium, any eutectic

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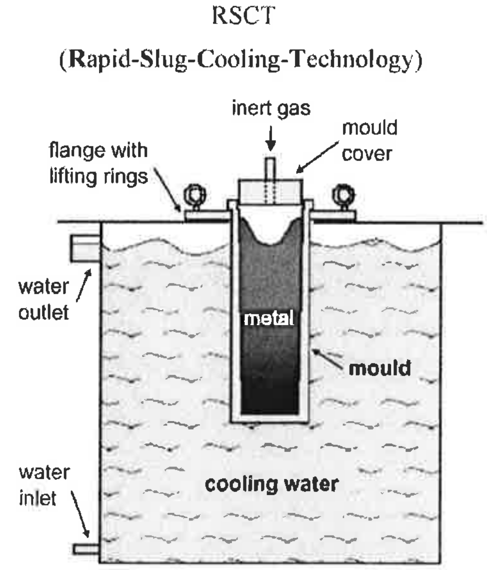
doi:10.1016/j.msea.2003.10.091

component. The maximal solubility of aluminum in magnesium is 12.7 wt.% and the technical alloys usually have an Al content of under 10 wt.% plus other alloying elements in lower quantity. In the practice, however, a certain amount of β-phase is found in almost every Mg–Al alloy between the dendrite arms and in the grain boundaries [7]. A reason for this behavior is the very low diffusion velocity of aluminum in the solid Mg-phase α-phase. At the beginning of the solidification, the first primary α-phase particles have a very low Al concentration. Because of the increase in the Al concentration in the melt, these primary particles increase their Al content until the maximal solubility of Al in Mg is achieved. Afterwards the β-phase starts to precipitate, first as β-phase intermetallic crystals and then forming an eutectic component together with the α-phase. The described solidification path can be explained using Scheil's segregation model for ternary alloy systems. The corresponding evaluation of the Scheil's equation shows that the solidus line is shifted to lower temperatures and the maximal solubility of Al in Mg is reduced [8].

During re-heating into the semisolid state the grains start to melt from outside, where the liquidus temperature is lower, towards the center. Previous studies have already shown that the solid fraction in semisolid state depends not only on the temperature but also on the deviation of global equilibrium. Furthermore, it has been observed that by applying a constant holding temperature the solid fraction depends on the holding time [9]. A very fast solidification of the Mg–Al alloys produces an eutectic component between the dendrite arms composed of α-phase and the intermetallic phase $Mg_{17}Al_{12}$ (β-phase). The morphology of this $\alpha + \beta$ eutectic is a product of the cooling and solidification rate and during the shaping of the semisolid material a function of the die filling velocity, the die temperature and the wall thickness of the cast part.

2. Experimental

During practical pre-material production studies with a single-slug-production (SSP)-device it was found that for many technical aluminum and magnesium alloys poured into a permanent mold just above the liquidus temperature, the main parameter for the generation of a fine globular microstructure is the cooling rate [10]. The SSP machine is a very versatile device that consists of an electrically heated cylindrical permanent mold built over a water-cooled copper plate. The mold temperature is measured at six different points during the process and plotted against time. After pouring the metal the mold is pneumatically lowered into a variable electro-magnetic stirrer and the melt is stirred during its solidification. For the production of magnesium billets the mold was modified with a stainless steel feeder covered with a lid after pouring. To reduce the risk of magnesium burning and to eliminate the shrinkage porosity from the billet, an inert gas mixture consisting of argon with 2% SF_6 was blown above the metal surface. Using this system parameters like mold and metal temperature, stirring intensity, solidification and cooling rate were varied. Furthermore, grain refiners were used to test their influence on the microstructure.


RSCT

(Rapid-Slug-Cooling-Technology)

Fig. 1. Rapid slug cooling technology (RSCT) quenching system for magnesium alloys.

As a result of the studies where magnesium alloys were processed in the SSP-device, the new rapid slug cooling technology (RSCT)-device for the production of thixocasting pre-material billets was developed, Fig. 1. The central part of the system is a stainless steel cylindrical permanent mold. It has an average wall thickness of 7 mm and a slightly conical inside geometry to facilitate the extraction of the produced billets. For the protection of the melt, the mold can be covered with a heavy steel cap with inert gas connection. The cooling of the mold takes place in a stainless steel water vessel with a cover lid. Water flows continuously into the vessel to maintain a constant temperature and the lid has a circular hole to insert the mold, holding it from the flange. The mold has a height of 250 mm to assure that the metal surface is lower than the water surface, enabling an homogeneous cooling over the total height of the billet. Billet diameters of 46 and 76 mm can be produced.

As a first step for production in the RSCT-device, the inner surface of the mold was covered with a boron nitride coating and warmed up to 120 °C to assure its dryness. The magnesium alloys were melted in a Ni-free stainless steel crucible provided with a cap and inert gas connection using a resistance electric furnace. After reaching the desired temperature, the melt surface was scrapped and poured into the mold. Immediately after pouring the steel cap was placed over the mold and immersed into the water vessel. Just after the metal was completely solidified the billet was immersed in water without the mold. The produced billets were about 190 mm long. After the process they were cut to 160 mm so that the upper part, where non-metallic particles and the shrinkage cavity are located, was removed, [10].

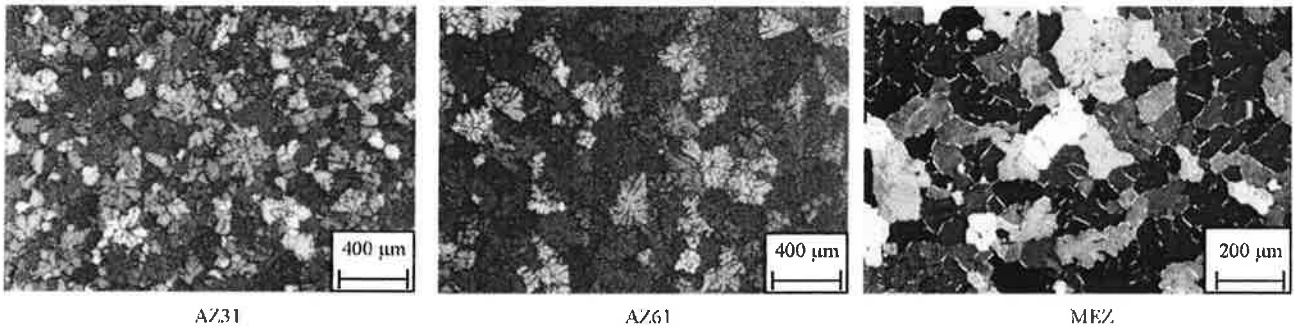
To estimate optimal process parameters experiments with mold temperatures of about 120 and 400 °C and various melt temperatures were made. We found that a melt temperature 30 K above the liquidus temperature leads to the best results. A higher temperature results in coarser grains and with a lower one cold spots were found in the billet. To be able to produce a fine grain structure a mold temperature as low as possible is advised.

3. Results and discussion

The magnesium alloys AZ91 (MgAl9Zn1), AZ61 (MgAl6Zn1), AZ31 (MgAl3Zn1), AM70 (MgAl7Mn), AM50 (MgAl5Mn) and MEZ (creep-resistant alloy with about 3 wt.% rare earths from Magnesium Elektron Ltd.) have been successfully processed using the method outlined above, Fig. 2. Because the as cast microstructure reveals very low quantities of low melting point eutectics, especially for the alloys with very low aluminum contents like the AZ31, AM50, and MEZ, concentration gradients within the grains due to micro-segregation are of vital importance for the process. During re-heating into the semisolid state, the grains start to melt from the outer boundaries towards the center until the desired solid fraction is achieved and then they are pressed into the die. Experiments show that although these alloys do not present enough eutectic and their solidification interval is quite small they can be successfully thixoformed. Fig. 3 show the development of the microstructure during the different steps of the thixocasting process for the alloy AZ31.

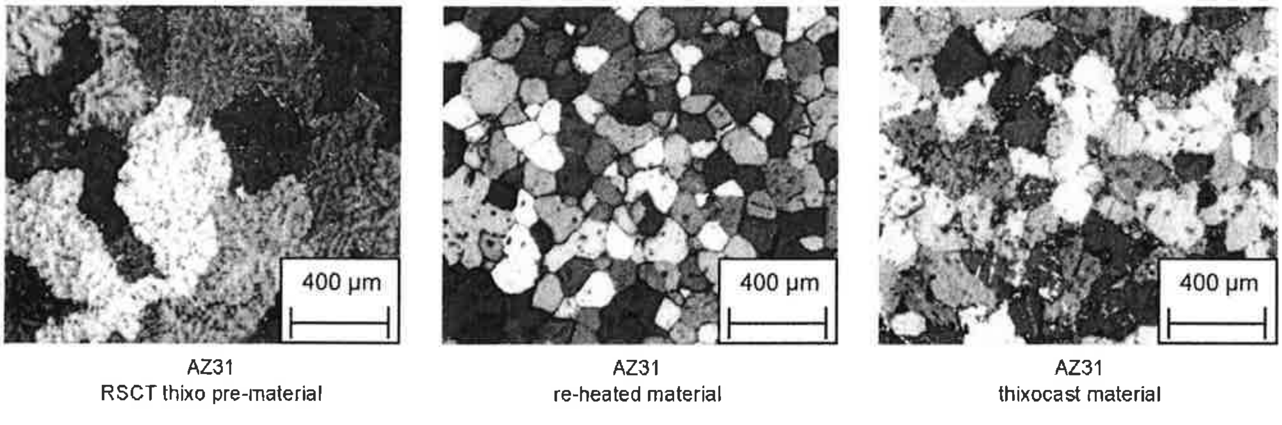
As part of the investigations samples of the pre-material produced with the RSCT process were analyzed with SEM and the chemical composition profiles within grains were determined using EDX (energy dispersive X-ray analysis). Fig. 4 shows the contents of the alloying elements as a function of the location in the grain. As expected the middle of the grain presents a lower content as the outer regions. In the case of the alloys AZ61 and AZ31, the aluminum and zinc contents decrease progressively to minima at the center of the grains, while for the alloy MEZ almost the whole content of rare earths is at the grain boundary and almost none is found within the grain.

In the re-heating experiments it has also been observed that it is relatively easy to heat the material up to a defined solid fraction. Besides the concentration gradient within the grain the latent heat of melting could play a role because if homogeneously re-heated a certain heat content means a defined solid fraction. This is still to be corroborated in future experiments.



AZ31 AZ61 MEZ

Fig. 2. Microstructure of some thixo pre-material magnesium alloys processed with the RSCT-process.



AZ31
RSCT thixo pre-material

AZ31
re-heated material

AZ31
thixocast material

Fig. 3. Microstructure development during the thixocasting process for the AZ31 Mg alloy.

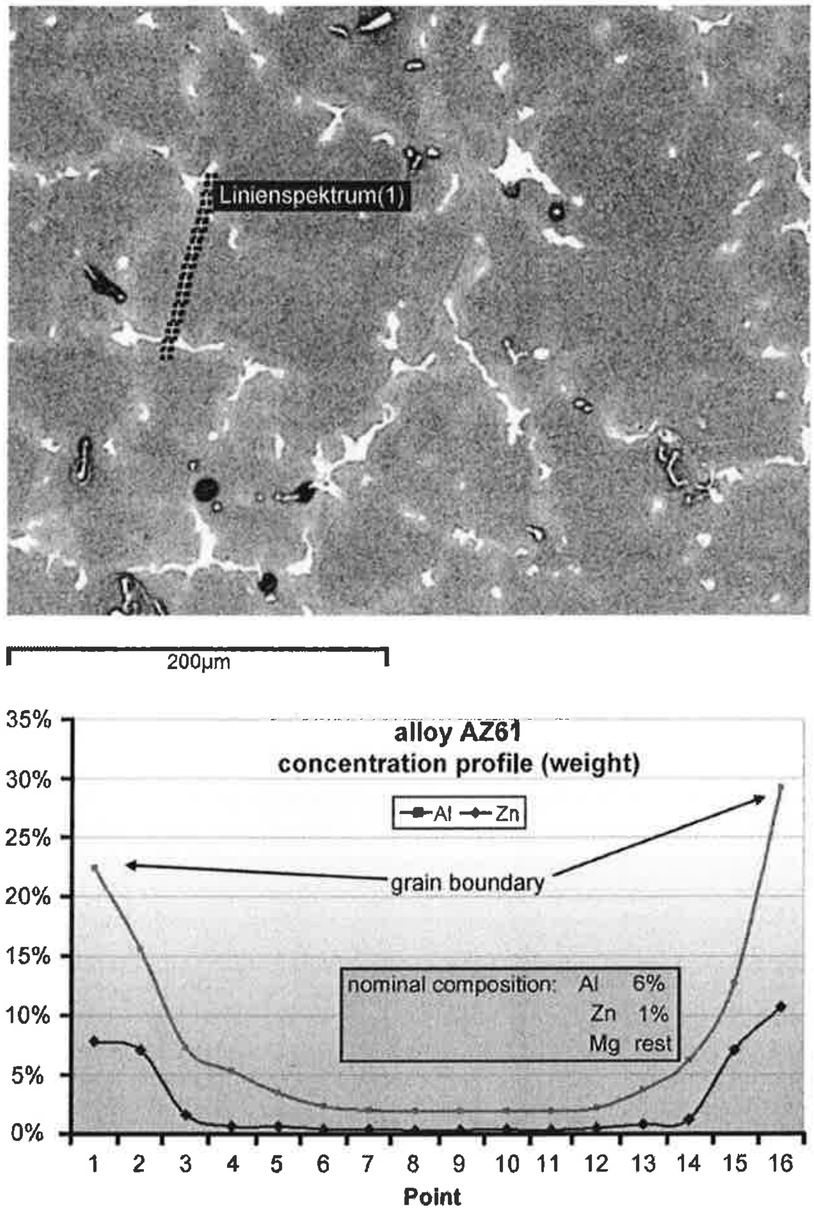


Fig. 4. Content of alloying elements as a function of the location in a grain for the alloy AZ61.

After the promising results obtained with magnesium alloys, further investigations have been performed to process aluminum alloys with good mechanical properties. The alloys M59 (AlMg5Si2Mn), AF48 (AlCu4TiMgAg), and 2618 (AlCu2MgNi + 8% TiB_2) have been already tested with the RSCT and preliminary results show a very good globular microstructure. Depending on the wall thickness in as cast condition the M59 alloy has a very high elongation value of up to 17%. With this extremely high elongation costly heat treatments can be reduced. It is also of interest because of its low die sticking tendency during forming. The AF48 shows in heat treated condition very high strength and hardness while maintaining good elongation. The alloy 2618 is a particle-reinforced material with very good hardness and wear resistance values. Processing in the semisolid state reduces the separation of the reinforcing particles.

4. Conclusions

The following conclusions can be drawn out of the present work:

- The RSCT process enables the production of billets with a microstructure suitable for thixocasting of technical Mg alloys.
- Concentration profiles within grains are achieved by rapid cooling of the melt, and thus establishing microsegregation.

- The alloys used for the thixoprocess do not need to show low melting point eutectics.
- For the RSCT-process it is advised that the alloying elements should have low diffusivity in the solid phase.
- The RSCT seems to be suitable for the pre-material production of technical high strength aluminum alloys for thixocasting.

Because of its versatility, the RSCT-process enables the production of billets from different light metal alloys without any complicate changes in the system. The use of different permanent mold materials, geometries and cooling media are already under investigation in order to optimize the process. New magnesium and aluminum alloys are to be further investigated in order to determine the full potential of the process. The process also enables the in-house recycling of the manufactured alloys.

Acknowledgements

The authors express their gratefulness to the "German Research Society" (DFG) for their financial support within the "Collaborated Research Center 289: Forming of metallic materials in semisolid state and their properties" and to "Magnesium Elektron Ltd." and "Aluminium Rheinfelden" for their material support.

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