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Injection Molding of Magnesium Alloys

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1 Introduction

Within the last years several new production techniques for metals have been developed, that work in the semi-solid state. One of the most promising for Magnesium is an injection molding process, also known as Thixomolding®. A schematic drawing is shown in Figure 1.

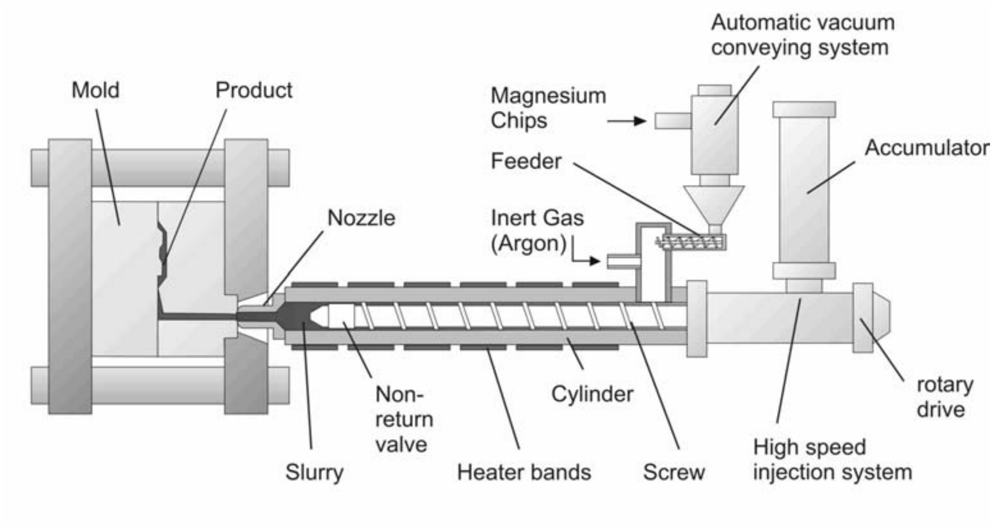

Figure 1: Schematic drawing of a Thixomolding®-machine.

Similar to injection molding machines for plastics, magnesium granules are metered from a feeding hopper into the screw of the Thixomolder®. Within the screw the magnesium material is heated up to the semi-solid state while it is transported to the nozzle. Due to shearing the solid phase is transformed from a dendritic to a globulitic shape.

Up to now more than 230 machines with clamp forces between 75 t and 1600 t have been installed. Over 95 % of them have been built by Japan Steel Works (JSW). The rest have been contructed by HPM (five machines until 1997) and Husky (since 1998). Most of the machines have been installed in

Figure 2: 220t-Thixomolding®-machine from Japan Steel Works at Neue Materialien Fürth GmbH (NMF).

Japan, Asia or Northamerica. The first JSW-machine in Europe has been set up at Neue Materialien Fürth GmbH (NMF) in March 2002 (Figure 2).

At present there are a couple of serial production parts. Some examples are shown in Figure 3. Most of them are thin-walled parts for consumer electronic products like notebooks, video cameras, cell phones, power hand tools, televisions or video projectors. Anyhow several structural parts like seat frames or shift cams for automotive applications are produced.

Figure 3: Thixomolded® magnesium parts from various vendors.

2 Experimental procedure

Casting trials have been carried out using a 220 t-Thixomolding®-machine JLM-220MG manufactured by Japan Steel Works. For fully automatic production auxiliary equipment like a take-out robot and a spray-robot has been added. Several demonstration parts have been cast (see Figure 4). Parts 1 & 2 are thin-walled castings with a wall-thickness of 1.5 mm. In part 3 wall-thicknesses of 1.5 mm, 3 mm and 6 mm are realized in one component. Parts 4 & 5 show typical functional elements like ribs or cavities. For part 1 Magnesium chips (AZ91D) manufactured by Rossborough were used. All other experiments were done using AZ91D-chips produced by Ecka Granules.

Test specimens for mechanical testing have been machined from the cast parts according to DIN EN 10002, part 1, appendix A. An Instron-4505 testing machine has been used for tensile tests at room temperature.

For determination of the overall porosity in the cast part Archimedes-principle was applied, i.e. the porosity was calculated from weighing each part in air and isopropyl alcohol. The calculation is based on a theoretical density of 1.81 g/cm^3 for AZ91.

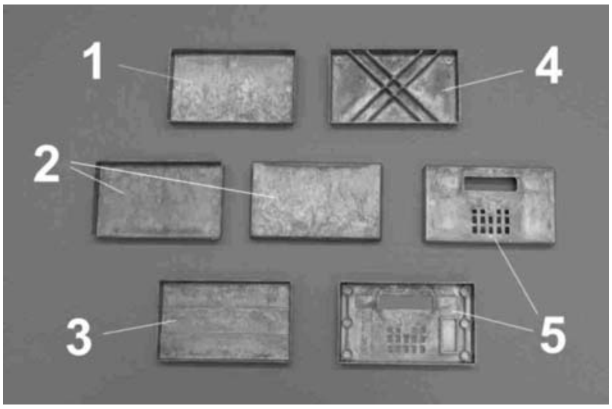

Figure 4: Demonstration parts that have been produced at NMF using Thixomolding® on a 220t-JSW-machine.

In addition to casting experiments fundamental investigations have been carried out. For examination of the solidification range of the magnesium alloys a differential scanning calorimeter (DSC, Netzsch STA 409C) has been used. Rates for heating and cooling were 5 K/min.

In order to investigate the rheological behaviour of metal melts a Searle-type high temperature rotational viscometer was used. The original viscometer set up was built by LabPlus/RheoWis. In order to achieve high accuracy several adaptations have been developed at NMF.

For simulation of the mold filling the finite element program ProCast 4.0 and the mesh-generator MeshCast 3.0 (ESI GmbH) has been applied.

3 Results

3.1 Rheological Behaviour of Semi-solid Metal Melts

If metal melts are cooled down conventionally into the semi-solid state the primary phase solidifies with a dendritic structure. When the melt is sheared during cooling a globular structure is generated. The rheological behaviour of such materials is quite complex. On the one hand the semi-solid melt shows thixotropy, i.e. the viscosity decreases during shearing. On the other hand these melts are shear-thinning [1]. In addition viscosity depends on several parameters, e.g. shape and size of the solid phase or solid fraction [2].

In this study two different materials have been investigated, Sn-15Pb for verification of the experimental set up and the magnesium casting alloy AZ91D. The tin-lead alloy has already been investigated in several studies [2, 3] due to its low liquidus temperature. In the left graph of Figure 5 the apparent viscosity for a solid fraction of 45 % (temperature T ~ 198°C) as a function of shear rate is plotted. The data points have been derived from experiments where the shear rate has been increased stepwise to 1 s^{-1}, 10 s^{-1} and 750 s^{-1} during a time period of 20 minutes. The results are in good agreement with experiments that have been conducted by Modigell et al. using a couette rheometer [2].

For low shear rates a deviation between our data and literature data attained by Laxmanan et al. [3] is observed. One reason might be that in ref. [3] a different type of apparatus with

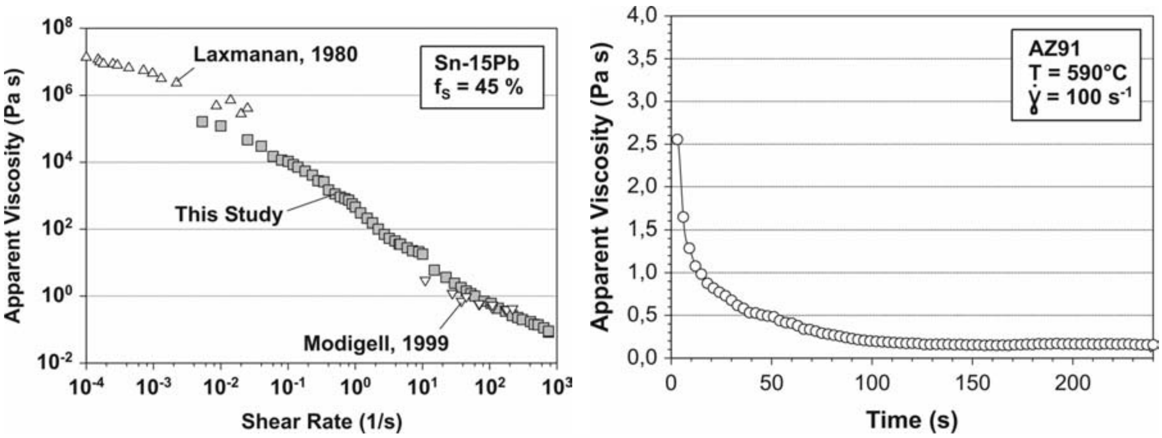

Figure 5: Rheological behaviour of metal melts in the semi-solid state. The Sn-15Pb-alloy with a solid fraction of 45 % shows typical shear-thinning behaviour (left). The apparent viscosity changes over a wide range of several orders of magnitude. An example for thixotropy is depicted for AZ91 at a temperature of 590°C and a solid fraction of ~ 12 % for a shear rate of 100 s^{-1} (right).

two compression plates was used.

An example for the thixotropic behaviour of the magnesium alloy AZ91 is shown in Figure 5 on the right. The alloy has been heated up to the totally liquid state and then cooled down to 590°C. After that a shear rate of 100 s^{-1} has been applied. The apparent viscosity drops more than one order of magnitude during a time period of 2 minutes and reaches a steady state.

3.2 Casting experiments

As already stated in the last paragraph, the flow behaviour of semi-solid magnesium melts is connected with amount, shape and size of the primary solid phase. Therefore the casting temperature is a key parameter in Thixomolding®.

Figure 6 shows the influence of the temperature in the barrel on the solid phase content for part 1 and part 2. For temperatures above 595 °C the fraction solid is close to zero. Reducing the temperature to 580 °C results in an increase of the solid phase content up to ~ 25-30 %. Size and shape of the primary particles do not change significantly. The results are in good agreement with data from literature obtained by Saito et al. from experiments on a 450 t-JSW-machine [4].

Tensile properties have been tested on flat specimens that were directly cut from parts 1 & 2 (see Figure 7). For small solid contents the tensile strength (full symbols) ranges between 200 and 250 N/mm^2 and elongation varies between 4 and 6 % which is in good agreement with results from the literature for thixomolded® tensile bars [5]. For high solid contents the properties seem to be somewhat degraded. For die casting typical values are 230 MPa and 3 % [6]. Comparing the results it must be taken into

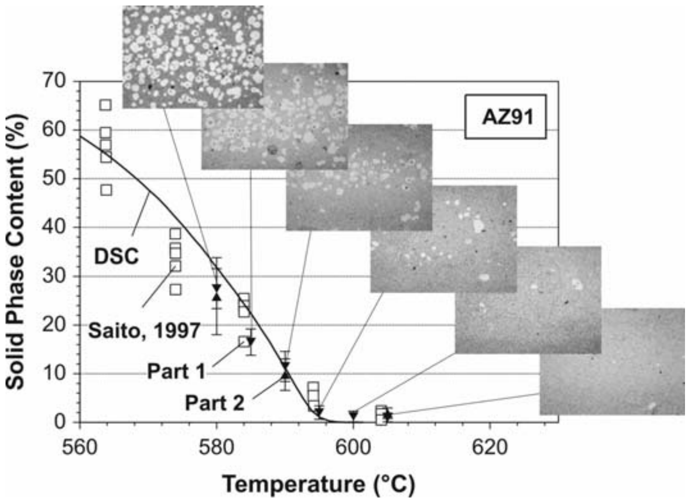

Figure 6: Primary solid phase content for parts1 & 2 as a function of the barrel temperature of the Thixomolding®-machine. Data from literature (Saito [4]) and DSC-curve for comparison.

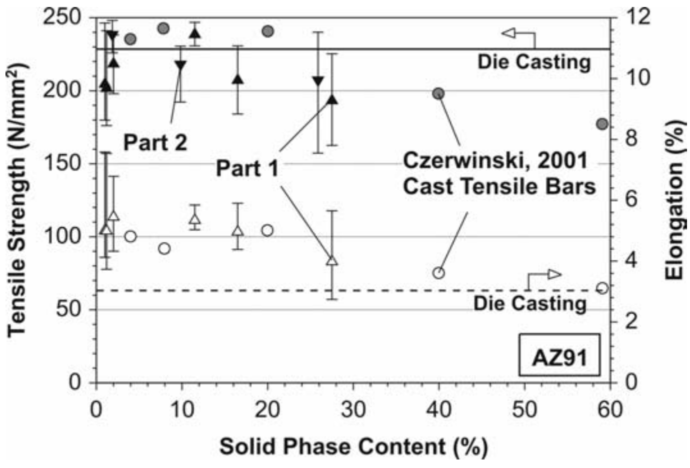

Figure 7: Tensile Strength (full symbols) and Elongation of flat specimens cut from Thixomolded® parts. The values are in good agreement with data for Thixomolded® tensile bars from the literature (Czerwinski [5]). For low fractions of solid the typical values for standard die casting are reached easily, for high solid contents the properties seem to be slightly degraded.

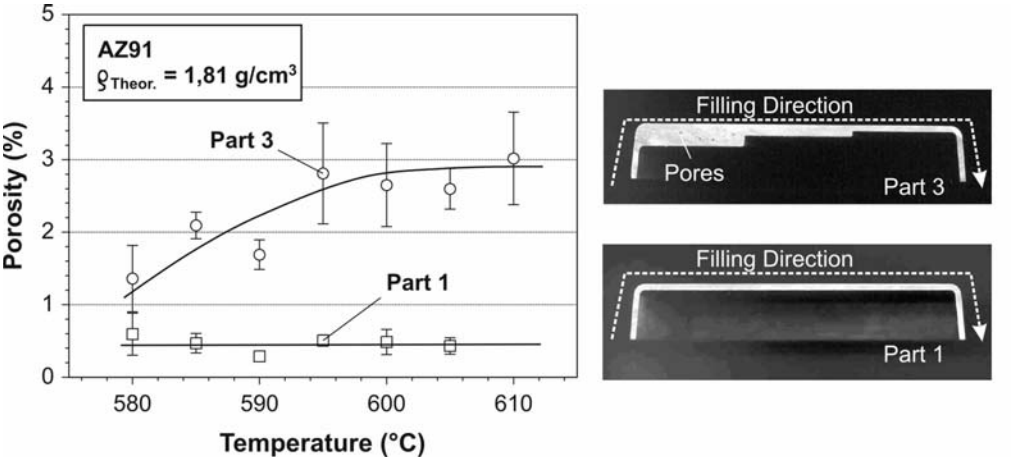

Figure 8: Porosity of parts 1 & 3 as a function of temperature (and solid fraction). For the thin-walled part 1 no influence is apparent as there is almost no porosity. Within the thick-walled section of part 3 formation of pores is observed. For low barrel temperatures (and therefore high solid contents of the melt) porosity is reduced.

account that the flat specimens used in this investigation have a unfavourable geometry compared to cast tensile bars (ratio of cross-section and surface area, stress concentration on the edges). Moreover, roughly machined surfaces were applied that have a negative effect. Therefore better results for cast cylindrical tensile bars can be expected which will be investigated in the future.

Another important issue is the porosity of cast magnesium parts. Processing in the semi-solid state is expected to reduce porosity due to decreased solidification shrinkage and a continuous flow front. In order to investigate this, the overall pore volume has been looked at for various temperatures (see Figure 8). For the thin-walled part 1 no significant change with the processing temperature is apparent. Porosity is more or less non existent. In part 3 formation of pores in the thickest cross-section (wall thickness 6 mm) is observed. Decreasing the processing temperature of the alloy leads to a noticeable reduction of porosity. This might be explained by a reduced solidification shrinkage due to a solid phase content up to 25-30 % at 580°C and a less turbulent flow front.

3.3 Simulation

In order to demonstrate the importance of the viscosity a mold filling study for part 1 has been carried out. The calculations were done using viscosity values ranging from 0.001 Pa s to 10 Pa s. In each individual run, viscosity is assumed to be constant.

Figure 9 shows the filling of the cavity at two different times ($t_2 > t_1$). For low viscosities that represent the behaviour of totally liquid

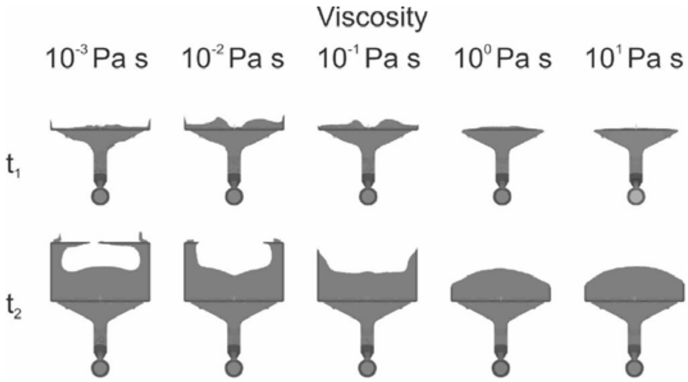

Figure 9: Dependence of the filling of the cavity on the viscosity of the slurry. For low viscosities the flow front on the edges advances faster, for high viscosities an almost laminar behaviour is apparent.

metals, an irregular flow front indicating turbulence is observed. The flow front advances faster on the left and right edges of the die cavity. High viscosities lead to a more regular flow front similar to potential flow. This implies a continuous flow front and an almost laminar filling of the cavity. Experiments for die filling with fully liquid and semi-solid slurries have been carried out by Young [7] which can be compared with the present simulations. They are in good agreement with the findings above.

4 Conclusions

A study of rheological behaviour of semi-solid melts, casting experiments with a 220 t-Thixomolding®-machine and numerical simulations of mould filling have been carried out in the present paper.

For AZ91 with a solid phase content of ~ 12 % it was shown that due to thixotropic behaviour viscosity changes during continuous shearing by one order of magnitude. In a tin-lead model alloy (45 % solid phase), shear-thinning effects cause a change of viscosity over several orders of magnitude. A computer simulation study was carried out that revealed the strong influence of viscosity on mold filling.

Casting experiments on a Thixomolding®-machine showed that for AZ91D between 580°C and 605°C the solid phase content drops from ~ 30 % to almost zero. Tensile properties for flat specimens machined out of demonstration parts are comparable to standard values for die casting. It was clearly demonstrated that a high solid content is able to decrease the porosity in thick-walled parts.

5 References

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