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Advances in Magnesium Injection Molding (Thixomolding®)

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1 Introduction

Magnesium Injection Molding is a relatively new and environmental-friendly technique for production of high quality magnesium parts that is are near net-shape. Due to a low casting temperature near the liquidus or even in the semi-solid regime, less porosity, lower distortion and better tolerances in comparison to high pressure die casting can be achieved [1].

The present paper will introduce further advantages of the Thixomolding technology. Firstly the closed process in combination with intensive mixing in the barrel is beneficial for casting alloys containing elements that are known to be prone to oxidation, segregation or evaporation in conventional die casting.

Table 1: Overview on the most important alloying elements in magnesium alloys and their tendencies to segregation, oxidation and evaporation

Element	Al	Zn	Mn	Ca	Si	Sr	RE
Density (g/cm^3)	2,7	7,1	7,4	1,6	2,3	2,5	~6,5
Segregation	X	X	X		X		X
Oxidation	X			X		X	
Evaporation		X					

Table 1 gives an overview of the most important alloying elements in magnesium alloys. In the magnesium melting crucible a big difference in density leads to segregation of these elements on the ground. Additionally the formation of intermetallic phases with high melting points, especially Mg_2Si, Mn_5Si_3 and Al_XMn_Y, during melting is a critical factor. All these elements can form a sump in the crucible, which has to be removed from time to time. The elements Ca, Sr and Al tend to oxidation and form a slag on the melting bath surface. Magnesium itself has a relatively high vapour pressure of about 10 mbars at 700 °C. So the magnesium tends to evaporate in the air. Zink has an even higher vapour pressure of about 100 mbars at 700 °C. As a consequence there is always a steady loss of zink due to evaporation. All resulting deviations from the nominal alloy composition have to be observed and adjusted by the foundry man.

The above described procedures in the melt cause a lot of problems in the foundry practice. In magnesium injection molding, all these problems don´t occur because of a small melt volume, intensive mixing during transport in the screw and a closed processing technology. In addition the thixomolding process is characterized by a low temperature level of the melt that can reduce die sticking, hot cracking and improve die life. Beyond this the processing technology is similar to polymer injection molding, which allows the development of hot runner systems that gives thixomolding another unique selling point in comparison to die casting. Scrap can be greatly reduced, heat energy and raw material is saved and flow length during filling can be reduced dramatically.

In this study processing of a variety of commercial magnesium alloys (AZ, AJ, AS-series) using thixomolding has been investigated. For AZ91 the influence of several processing temperatures (e. g. die temperature, processing temperature and solid phase content) on the mechanical properties is discussed in detail. It is shown that excellent strength and elongation can be achieved over a wide range of solid phase contents. For all alloys tensile properties that are typical for thixomolding are presented. The trials have been performed at processing temperatures near the liquidus temperature. A comparison with data from the literature for die casting is introduced. Furthermore first results for a prototype hot runner system developed at NMF are presented.

2 Experimental

The casting trials carried out on a 220 t - thixomolding machine from Japan Steel Works (JSW) type JLM220-MG. Figure 1 shows a schematic drawing of a thixomolding machine.

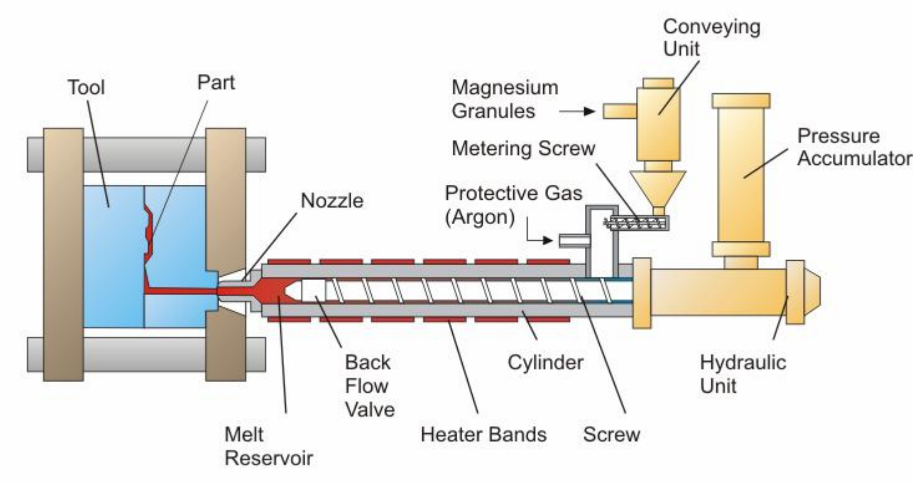

Figure 1: Schematic drawing of a thixomolding machine

The chipped raw material, delivered by ECKA granules, is dosed into the cylinder using a metering screw. In the cylinder the magnesium granules are heated up and sheared. The heating energy is supplied by electric heater bands. To prevent the magnesium from oxidation argon gas is applied. By the rotation of the screw of about 100 - 200 rpm the magnesium is transported to a melt reservoir in front of the back flow valve. After closing the mold the screw is moved forward with velocities of about 1 - 4 m/s and the molten metal is shooting into the cavity. After filling the mold a hold pressure up to 1000 bars can be achieved during solidification.

Casting trials were done using a mold for separately cast test bars according to ASTM B557 M - 02a. With one shot two tensile bars were cast. The bars had a gage length of 50,8 mm and an overall length of 228 mm. Mechanical testing was done using a Zwick/Roell

Z100 tensile testing machine. Table 2 shows the alloy compositions of the raw material measured with the glow discharge optical emission spectroscope (GDOES) GDProfiler from Horiba Jobin Yvon at NMF. Additionally the barrel temperatures used for the comparison with die casting are mentioned.

Table 2: Alloy compositions of the raw material and barrel temperatures during casting

Element	Mg	Al	Zn	Ca	Mn	Sr	Sn	Si	T_{barrel}(°C)
AZ91D	bal.	9,3	0,7		0,2				600
AZ70	bal.	6,6	0,5		0,2				610
AJ52	bal.	5,0	0,1		0,3	1,8			625
AJ62	bal.	6,5	0,1		0,2	2,1			620
AS41low	bal.	3,7	0,2		0,2			0,7	635
AS41high	bal.	4,9	0,2		0,2			0,6	630

The concentrations of the elements Fe, Ni, Cu were below the ASTM B93-2004 limits.

3 Results

3.1 Magnesium-aluminum-alloys (AZ-alloys)

An important characteristic of the thixomolding technique is the feasibility to cast the material in the semi-solid state. The solid phase content is controlled by the processing temperature. Former studies have already shown that high volume fractions of solid phase lead to lower porosity, especially in thick walled sections of the castings [9]. Figure 2 shows the mechanical properties of AZ91D as a function of casting temperature. All casting trials were done with a die temperature of 150 °C. Casting parameters like injection speed and hold pressure had been constant (full symbols). With lower casting temperatures, thus higher fraction solid, the tensile strength and the elongation seem to descend. One of the reasons for this is the reduced heat content of the melt, which results in casting defects like cold flow. This effect has already been discussed in detail [4]. By adjusting the process parameters, the mechanical properties can be significantly raised to the initial values (open symbols). All data are within the range for die casting [3]. Especially tensile strength and elongation are near or above the upper limit.

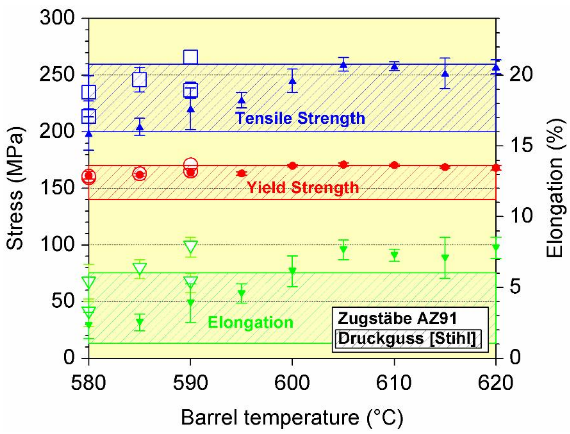

Figure 2: Mechanical properties of AZ91D as a function of casting temperature in comparison to literature data [3]

Another important issue concerning the mechanical properties of magnesium alloys is their trong dependency on the grain size [2]. In cast magnesium parts the grain size can be controlled by the solidification rate. With lower die temperatures, smaller grain sizes can be achieved.

Figure 3 shows the mechanical properties of AZ91D as a function of die temperature. The casting temperature was 590 °C, thus a volume fraction of solids of about 12 %. Yield strength rises from 145 MPa at 275 °C die temperature to 175 MPa at 50 °C. Metallographic studies showed that the grain sizes vary from about 10 µm for the lowest temperature to 20 µm at the highest die temperature. Elongation and tensile strength rise with lower die temperatures too. At 100 °C the highest values with 270 MPa and 8 % were achieved. At 50 °C there is a little decline because of some cold flow on the specimens.

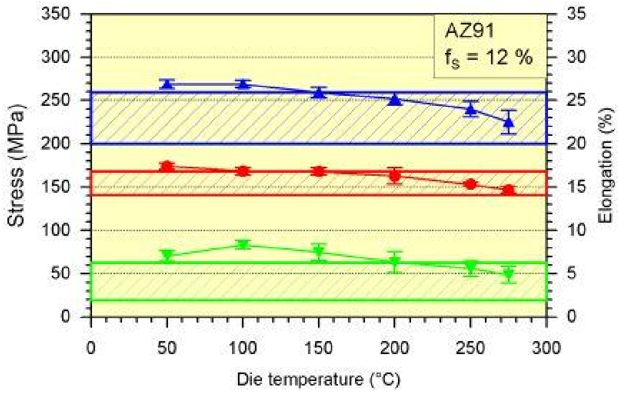

Figure 3: Mechanical properties of AZ91D with a fraction solid of about 12 % as a function of die temperature

In Figure 4 the mechanical properties of the alloys AZ70 and AZ91D, cast directly above the liquidus temperature, at room temperature and 150 °C in comparison to die cast literature data [5] are shown exemplarily.

While the properties at room temperature for AZ91 are within the same range for both processes, the thixomolded specimens are quite better at 150 °C (R_{p02}: 130 MPa, A: 19,3 %).

An interesting alternative is the alloy AZ70. At room temperature yield and tensile strength are comparable with AZ91, while elongation is significantly higher ($A_{20°C}$: 11 %, $A_{150°C}$: 25 %).

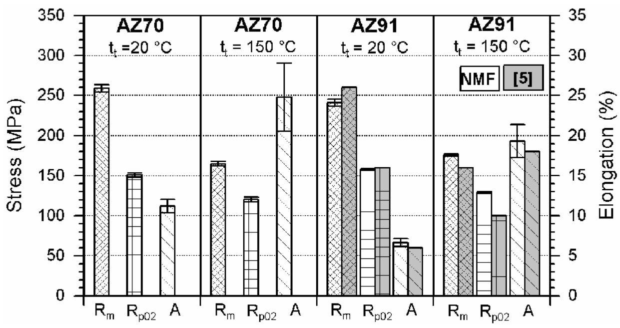

Figure 4: Mechanical properties of the alloys AZ70 and AZ91D at room temperature and 150 °C

3.2 Magnesium-aluminum-strontium-alloys (AJ-alloys)

For components that are used at higher temperatures, Mg-Al-Sr-alloys have gained importance within the last years. By adding strontium the formation of the phase $Mg_{17}Al_{12}$, which is believed to be detrimental concerning creep, is suppressed. Instead other phases like Al_4Sr are formed. Great attention was paid to the introduction of the new BMW six-cylinder-aluminum-magnesium-crankcase []. Nevertheless processing of these alloys seems to be sophisticated (high casting

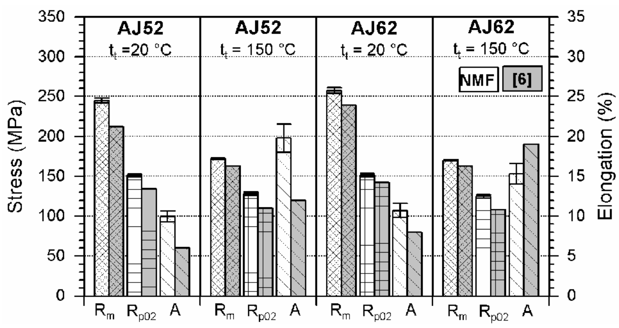

Figure 5: Mechanical properties of the alloys AJ52 and AJ62 at room temperature and 150 °C

temperatures, etc.) [5].

Thixomolding trials have been carried out smoothly for AJ52 and AJ62. Figure 5 shows the mechanical properties of these alloys at room temperature and 150 °C in comparison to conventional die cast data [6]. At room temperature and 150 °C all mechanical properties of the thixomolded specimens are significantly better than the reference. In particular thixomolded AJ52 shows higher elongations up to 20 % at 150 °C.

3.3 Magnesium-aluminum-silicon-alloys (AS-alloys)

Another way to get higher creep resistance than AZ91D is to lower the aluminum content and add some silicon. Because of the lower aluminum content less $Mg_{17}Al_{12}$ is formed. The silicon addition leads to formation of the thermal stable Mg_2Si phase, which has a melting point of about 1085 °C. Silicon-containing alloys have been used in the VW Beetle. Nowadays the Daimler Chrysler 7G-TRONIC transmission case is produced using AS31 [10].

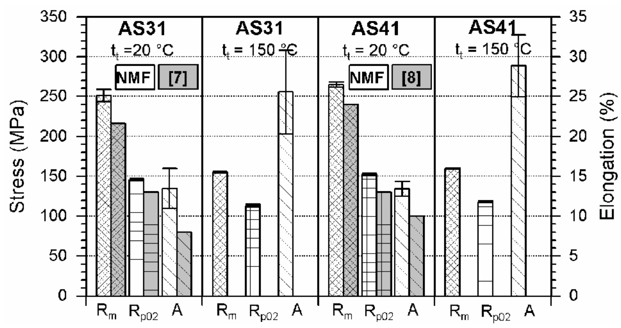

Figure 6: Mechanical properties of the alloys AS41low and AS41high at room temperature and 150 °C

In this study two AS41-derivates with different aluminum contents were thixomolded. The composition of the AS41low is within the range for AS41 and AS31. Figure 6 shows their mechanical properties. At room temperature the yield strength of AS41low is 130 MPa and elongation 13 %. AS41high has 151 MPa and 13 % elongation. For both alloys these values are much better than the reference data [7], [8]. For 150 °C no reference data were available.

3.4 Hot runner technology

Into the above mentioned die for test bars a first hot runner system was integrated. The runner system is heated up to the same temperature as the barrel. Compared to die casting the low temperatures are beneficial concerning the choice of the materials. Corrosion of the construction materials is reduced and an increased strength are the most important items. Special attention has to be paid to the thermal separation of the heated and cooled parts of the mold. Separation of the melt and the cavity is done by a cold plug, which is pushed out before every shot.

Figure 7: Different runner systems for tensile bars in thixomolding: conventional runner (left side) and hot runner (right side)

Figure 7 shows the first parts cast with this system in comparison to the conventional system. The weight of the normal part is 198 g. Thixomolded tensile bars with the hot runner system have a weight of 139 g. So there is a weight reduction of 30 % for this part. The cycle time was reduced too, because the thickest section in this part domination the solidification time, is the runner section.

Figure 8 shows the mechanical properties of test bars cast with conventional system and with hot runner system. They are both on the same level due to the fact that the conventional gating system already leads to excellent properties. Bigger advantages in the mechanical properties are expected for more complex parts with higher flow length. Melt can be transported directly to the gates with no loss of thermal energy and big solidified runner systems are saved.

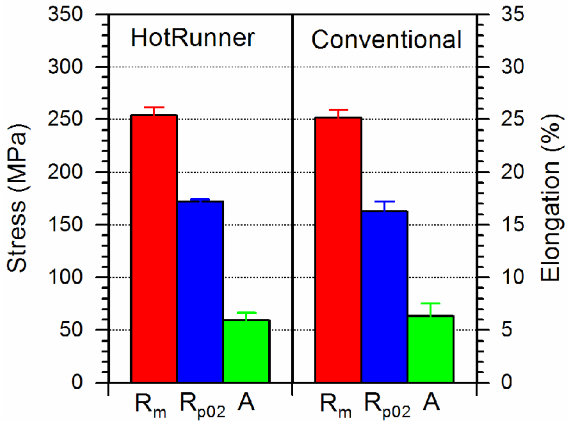

Figure 8: Mechanical properties of AZ91D cast with the conventional runner system and the hot runner system

4 Conclusions

Casting experiments with a variety of commercial magnesium alloys (AZ-, AJ-, AS-series) and testing at room temperature and 150 °C has been carried out in the present paper. Casting experiments could be realized with no problems regarding to segregation, evaporation and oxidation. Mechanical properties of AZ91D have a strong dependence of die temperature thus the cooling rate. Mechanical properties are in good agreement with literature data or even have better properties.

A first hot runner system for a test bar die was developed. Mechanical properties are on the same level than with cold runner system. 30 % weight reduction was realized and cycle time was also reduced. This leads to high quality and low cost magnesium parts. In the near future a mold with a multi point hot runner system will be developed, based on the outcomes of the one point hot runner system.

5 References

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