Advances in Magnesium Thixomolding®

Neue Entwicklungen beim Thixospritzgießen von Magnesium

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Neue Materialien Fürth

Contents

Abstract

Within the last years a new injection molding process for magnesium, also known as Thixomolding®, has been adopted to industrial production in Asia and North America. Since 2002 Neue Materialien Fürth GmbH (NMF) is concentrating on the enhancement of this new technique.

In this paper the state-of-the-art of the Thixomolding®-technology will be presented. The advantages of Thixomolding concerning quality and economics will be discussed exemplarily for demonstration parts and prototypes that have been cast at NMF using a 220 t-Thixomolding®-machine. Special attention will be paid to processing of new materials. In addition new developments in process technology like the hot runner technology or a new production method for magnesium granules will be introduced.

An overview on new capacities for serial production in Europe will complete the presentation.

In den letzten Jahren wurde in Asien und Nordamerika ein neuer Spritzgießprozess für Magnesium, das Thixomolding®, in die Serienproduktion eingeführt. Seit 2002 wird bei der Neue Materialien Fürth GmbH (NMF) die Weiterentwicklung dieser Technik intensiv vorangetrieben.

In diesem Beitrag soll der aktuelle Stand der Technik vorgestellt werden. Die Vorteile des Thixomoldings im Hinblick auf Bauteilqualität und Wirtschaftlichkeit werden anhand von Demonstrationsbauteilen und Prototypen diskutiert, die bei NMF auf einer 220 t-Thixomolding®-Maschine hergestellt wurden. Besonderes Augenmerk soll dabei auf die Möglichkeiten zur Verarbeitung von neuen Werkstoffen gelegt werden. Darüber hinaus wird über neue Entwicklungen im Bereich der Prozesstechnik, wie z.B. die Heißkanaltechnik und ein neues Herstellungsverfahren für Magnesiumgranulat, berichtet.

Abschließend soll eingehend über neue Möglichkeiten zur Serienproduktion von Thixomolding®-Bauteilen in Europa berichtet werden.

1 Introduction

Thixomolding® (Magnesium Injection Molding) is a relatively new technique for the production of high quality magnesium parts. The technique is quite similar to polymer injection molding. Magnesium granules are fed into the cylinder using a metering screw. During transport in the cylinder the magnesium granules are heated up to a semi-solid or totally liquid state. At last the Magnesium melt is injected with ram speeds up to 6 m/s under high pressure into the mold cavity.

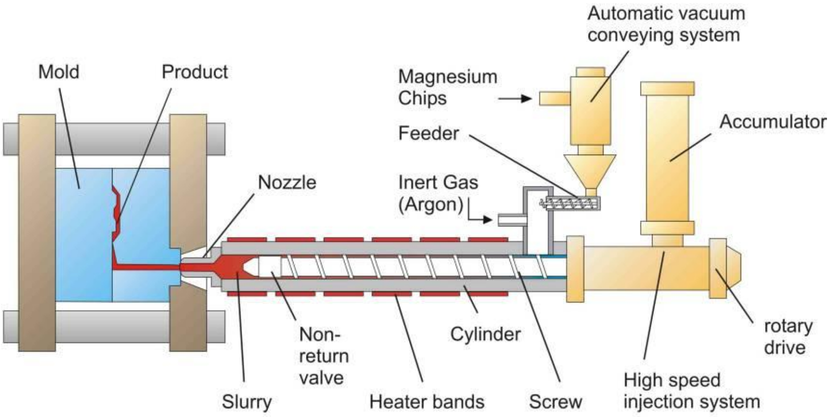


Figure 1: Schematic drawing illustrating the Thixomolding process

Worldwide more than 300 machines with clamp forces between 75t and 1600t have been installed during the last 15 years. 90 percent of the machines have been set up in Asia. In North America another 30 machines are in use. At present Japan Steel Works Ltd., Tokyo (JSW) and Husky Injection Molding Systems Ltd. provide Thixomolding machines.

In 2002 a 220t JSW-Thixomolder has been set up at Neue Materialien Fürth GmbH (NMF, see Figure 1). Since 2005 another three 650t Husky-machines have been installed in Belgium, France and Austria.

Figure 2: 220t-Thixomolding machine at Neue Materialien Fürth GmbH.

In this paper the state-of-the-art of the Thixomolding technique will be summarized and some interesting new developments such as particle reinforcements or the hot runner technology will be presented.

2 Characteristics of the Thixomolding® process

2.1 Properties of thixomolded parts

Investigations at NMF within the last years have shown that most of the commercial Magnesium die casting alloys are suitable for Thixomolding as well. In Table 1 a comparison of the mechanical properties at room temperature and 150°C for a selection of alloys is given. The Thixomolding casting trials have been carried out at NMF and have already been discussed in detail earlier [1, 2].

Table 1: Typical mechanical properties at room temperature and 150°C of several thixomolded Magnesium alloys for separately cast tensile specimens (ASTM B557 M-02). For comparison data from the literature for die casting are given [3-6].

	Test.-temp. (°C)	**Thixomolding (NMF)**			**Die Casting Reference**			
		R_m (MPa)	Rp_{02} (MPa)	E (%)	R_m (MPa)	R_{p02} (MPa)	E (%)	Source
AZ91D	RT	260	170	8	260	160	6	[3]
	150	175	130	19	160	100	18	[3]
AM60B	RT	253	150	11	247	123	12	[4]
	150	157	114	24	-	-	-	-
AZ70	RT	259	150	11	-	-	-	-
	150	165	120	25	-	-	-	-
AJ52	RT	245	151	10	212	134	6	[5]
	150	172	128	20	163	110	12	[5]
AJ62	RT	257	151	11	239	142	8	[5]
	150	170	125	15	163	108	19	[5]
AS31	RT	251	145	13	216	130	8	[4]
	150	155	113	26	-	-	-	-
AS41	RT	265	152	13	240	130	10	[6]
	150	160	118	29	150	90	-	[4]

For all alloys the mechanical properties of the thixomolded specimens attain or even exceed the values of the die casting reference. Especially for the AJ- and AS-series excellent strength and elongation was obtained.

In earlier work it has already been demonstrated that semi-solid processing has a positive effect on the porosity of thick-walled parts [7]. It was shown that the porosity of a demonstration part with wall-thicknesses up to 6 mm was reduced from ~3% to ~1,5% by increasing the solid phase content up to ~30%.

A study has now been carried out for an engine bracket. The wall thickness of the part varies from ~4 mm to ~22 mm. The part weight is ~430 g. The casting trials have been carried out on the 220t-Thixomolder at NMF using the alloys AZ91 and AJ62. A ram speed of ~ 3 m/s was used. The barrel temperature was 590 °C for AZ91 and 605 °C for AJ62, respectively. The microstructure is shown in Figure 3. For AZ91 a solid phase content f_S of ~ 10-15 % was detected. For AJ62 the primary solid phase content was ~ 8-10%.

Figure 3: Engine bracket produced at NMF using Thixomolding (left) and examples for the microstructure.

For determination of the overall porosity in the cast engine brackets 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/cm³ for AZ91 and 1.80 g/cm³ for AJ62, respectively. The results are shown in Figure 4. As a reference the porosity of die cast engine brackets was determined.

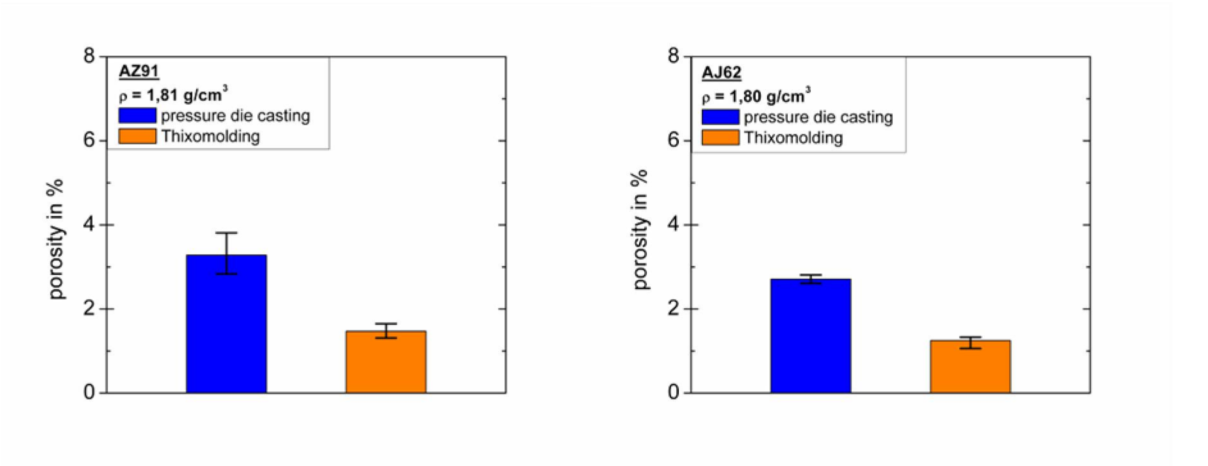


Figure 4: Comparison of the overall porosity of engine brackets produced using Thixomolding and die casting, respectively. For both alloys (AZ91 and AJ62) the porosity was reduced significantly by using Thixomolding.

While the die cast parts show an overall porosity of ~ 3 %, the use of Thixomolding reduces porosity to ~1,5 %. This might be explained by a reduced solidification shrinkage due to the solid phase content and less turbulence during mold filling.

2.2 Consumption of energy and cover gas

Besides the quality of the castings production processes have to fullfill additional economic and environmental requirements. Increasing energy price and the need to reduce emissions are important aspects in serial production.

In casting processes the needed energy for heating up the alloy to the processing temperature is a relevant factor. A rough estimate to calculate the energy ΔE needed can be obtained easily with the following equation:

$$\Delta E = \int_{RT}^{T_S} C_{P,Solid}\, dT + \Delta H + \int_{T_L}^{T_P} C_{P,liquid}\, dT$$

For AZ91 an average heat capacity $C_{P,solid}$ = 1,084 KJ/kg K in the solid was calculated from the heat capacities at room temperature T_{RT} and at the solidus temperature T_S = 420 °C given in [8]. For the latent heat ΔH = 362 KJ/kg and the heat capacity in the liquid $C_{P,liquid}$ = 1,308 KJ/kg K above the liquidus temperature T_L = 598 °C data from the same article were used.

The results are plotted in Figure 5. In comparison to die casting energy demand in Thixomolding to reach the processing temperature was found to be 12 – 24 % lower depending on the solid phase content.

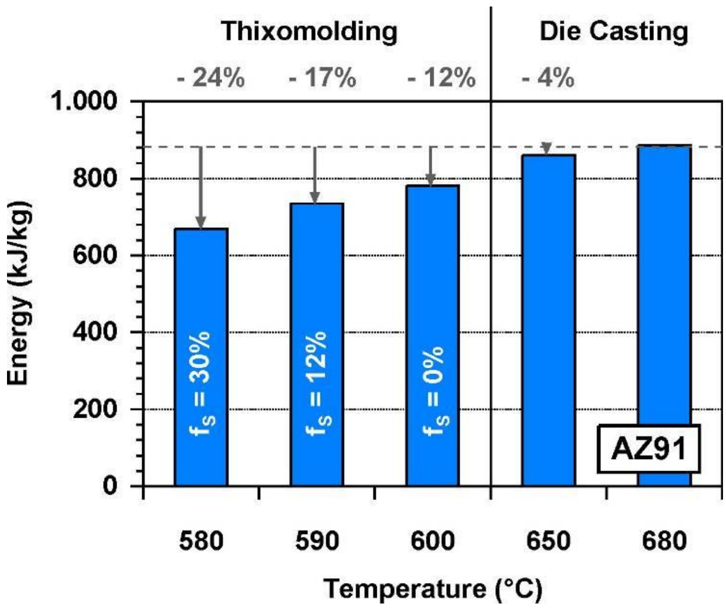


Figure 5: Energy needed in die casting and Thixomolding for heating AZ91 to the processing temperature.

Another important issue in casting Magnesium is the usage of cover gas. In die casting various protective gas systems are established. The most common are basing on SO_2, SF_6, or HFC-134a mixed with a carrier gas like dry air, N_2 or CO_2. [9, 10]. Each of these systems is associated with problems.

The toxicity of SO_2 and its smell nuisance comprise problems for the machine operator. Due to reaction with humidity formation of sulphuric acid can occur leading to corrosion at the casting machines [10]. SF_6 has the highest Global Warming Potential (GWP) of all known gases. For a time horizon of 100 years its GWP is 22200 [11]. Due to ratification of the Kyoto-Protocol the European Union has banned usage of SF_6 when more than 500 kg are emitted per year [10]. For HFC-134a a Global Warming Potential of 1300 is assumed [11]. This is seventeen times less than SF_6 but nevertheless still problematic. An additional improvement might arise due to the higher reactivity of HCF-134a leading to a reduced amount of gas emitted to atmosphere. On the other hand a thermal disintegration at high temperature has to be taken into account that results in the release of toxic hydrogen fluoride [10].

In Thixomolding the volume of liquid magnesium is very limited. The solid Magnesium chips in the cold forepart of the screw together with the machine design impede the influx of oxigen. A sufficient protection can be obtained by a small flow rate of Argon inert gas.

Figure 6 comprises a selection of typical cover gas systems. In die casting a gas consumption of 400 Nl/h was assumed which corresponds to the suggestion of Rauch Fertigungstechnik (Austria) for a Magnesium furnace MDO70E with a capacity of ~180 kg. As a carrier gas nitrogen was assumed. Characteristic compositions of the gas mixtures were taken from the literature [9, 10]. For a 220t-Thixomolding machine 25 Nl/h Argon is a useful flow rate. For N_2/SF_6 and N_2/HFC-134a the CO_2-equivalent was calculated from annual gas consumption. It can be found that the CO_2-equivalent of N_2/SF_6 is much higher than for N_2/HFC-134a. No Global Warming Potential for SO_2 and Argon has to be considered.

Another interesting point are the arising expenses related to gas consumption for the different cover gas systems. The use of Thixomolding can reduce these costs by more than 80 %.

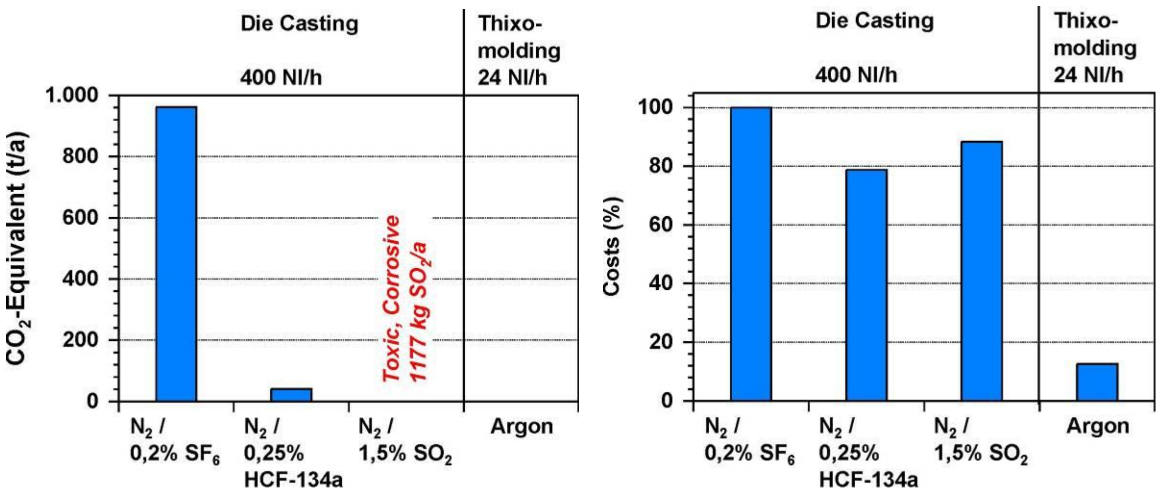


Figure 6: Global Warming Potential of several die casting cover gas systems (left) and relative costs for gas consumption (right) of these gas mixtures compared to Thixomolding.

3 New developments in Thixomolding

3.1 Alloy development

NMF has developed a Thixomolding variant that allows to modify the alloy composition directly during processing [12 – 14]. A secondary feeding system is applied to the Thixomolding machine that is used to add alloying elements to a main feedstock. During transport in the screw both components are mixed resulting in a new composition that is injected into the cavity. The composition can be adjusted very accurately by controlling the mass flow of either dosing screws.

By using this method a screening for new alloys can be done very easily. Moreover it can be used for production of alloy compositions that are difficult in handling in conventional melting production due to segregation, oxidation or evaporation. At NMF more than 70 alloys have been cast via this technique. A typical example is given in the following.

In order to enhance the properties of AZ91 at elevated temperature Ca was added. As feedstock AZ91D granules supplied by Ecka Granules and MgCa30 granules (30% Ca + 70% Mg) were used. According to ASTM the Ca-containing alloys are labelled with "X" for Ca in the following: e.g. AXZ951 stands for AZ91 with 4.5 to 5.5 % Ca. Figure 7 shows the mechanical properties at room temperature and 150 °C as a function of the Ca content. The hatched areas indicate data from the literature for die cast AZ91 [15 – 17].

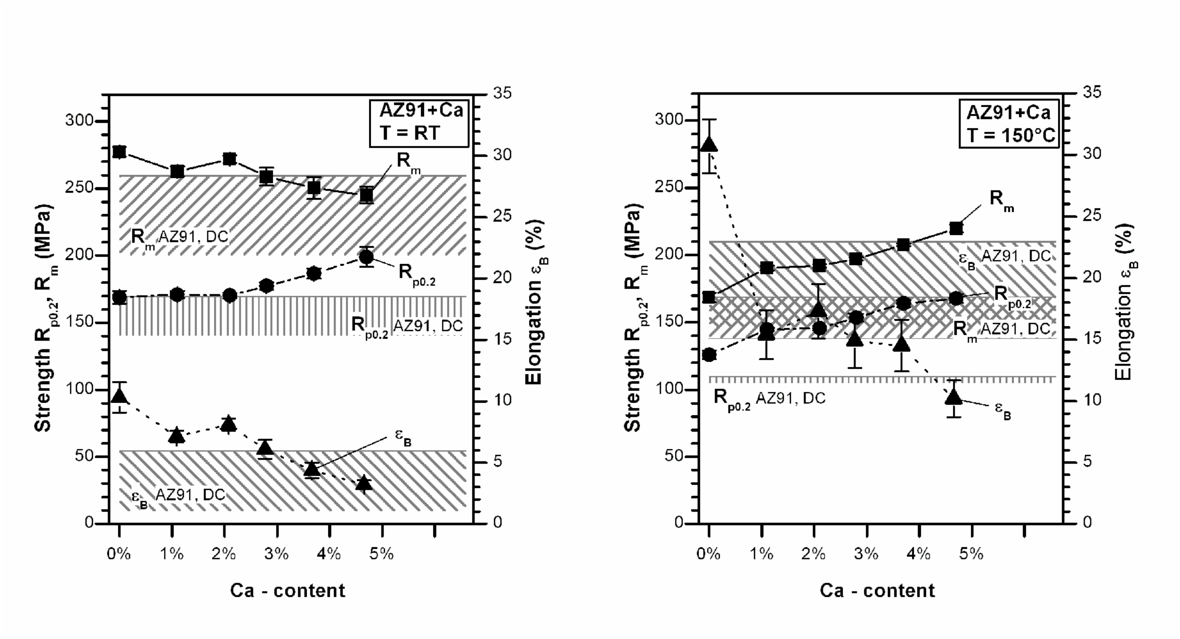


Figure 7: Tensile properties at room temperature (left) and 150 °C (right) for AZ91 containing upt ~5% Ca. Especially at elevated temperature yield strength and ultimate tensile strength are increased.

At room temperature the tensile yield strength R_{p02} raises with increasing Ca content, while the ultimate tensile R_m decreases slightly. At the same time the tensile elongation % E is reduced which is associated with an embrittlement of the alloys. Nevertheless even for high Ca content tensile strength and elongation reach the reference data for AZ91. At elevated temperature yield strength as well as ultimate tensile strength show a distinct increase with the Ca content and exceed reference data for AZ91 significantly. The embrittlement leads to a considerable decrease of elongation at failure.

In addition an influence on the creep properties at elevated temperature can be found. In Figure 8 the secondary creep rate at 150 °C is plotted versus the applied stress. Even at low stresses AZ91 shows the well-known low creep resistance. The additon of 1 % Ca reduces the creep rate by a factor of 10. At high Ca levels the creep rate can be improved by three orders of magnitude (for details see [13, 14]).

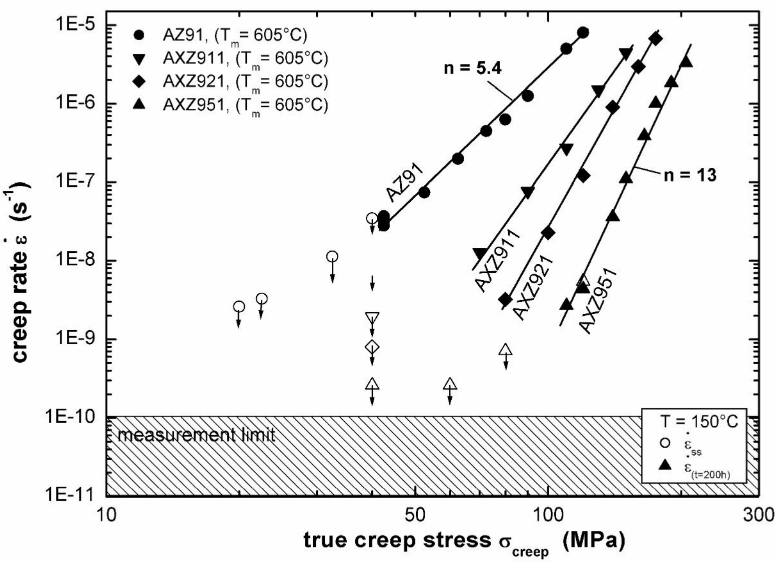


Figure 8: Steady state creep rates of AZ91 with varying Ca addition versus true creep stress. A remarkable creep rate reduction of up to 3 magnitudes for 5% Ca can be observed.

3.2 Particle Reinforced Magnesium alloys

Metal Matrix Composites (MMC) offer improved strength, stiffness and wear resistance [18]. Therefore several attempts have been made during the last decades to produce particle or short fibre reinforced light metal parts. In most cases the reinforcement was incorporated into a totally liquid melt followed by a conventional casting process like die casting [18, 19]. In order to maintain a uniform dispersion the melt had to be stirred vigorously. However, this processing route was associated with several problems [18 – 20]:

- Agglomeration of particles
- Settling of the particles in the crucible
- Formation of porosity due to entrapment of gases at high temperatures
- Reactions between the metal matrix and the reinforcement as a result of high temperatures and long dwell periods during mixing

In this regard the Thixomolding-process offers several benefits:

- Intense mixing
- Short contact times
- Low processing temperatures

An example for the potential of particle reinforced Magnesium alloys is given in Figure 9. Young's modulus was measured at samples with a diameter of 5 mm and a length of 50 mm that were machined from permanent mold cast AZ91 reinforced with SiC particles (average size ~ 9,3 µm). In the measured range the modulus increases from 40 MPa to approximately 60 MPa, which is close to the level of Aluminium alloys. Comparable effects were found for compressive yield strength and ultimate compression strength (details see [21]).

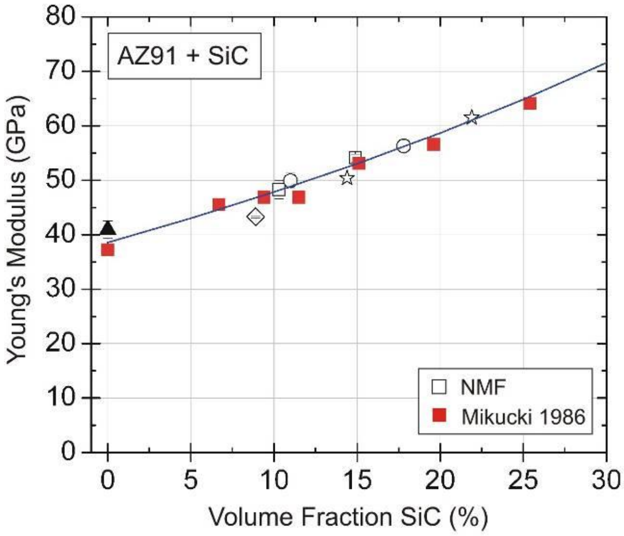


Figure 9: Youngs modulus for AZ91 reinforced with SiC particles. Addition of ~25 % SiC results in an increase of the Youngs modulus of ~ 50 %. The data derived at NMF for specimens produced by permanent mold casting are in good agreement with data from the literature for die cast specimens [18].

As a prototype geometry a power steering pump bracket was cast at NMF using Thixomolding (see Figure 10). As a reinforcement SiC particles with an average size of 9,3 µm were used. The matrix alloy was AJ62. A quite uniform distribution of the particles in the matrix is observed. Moreover no reactions between the reinforcement and the magnesium alloy became evident.

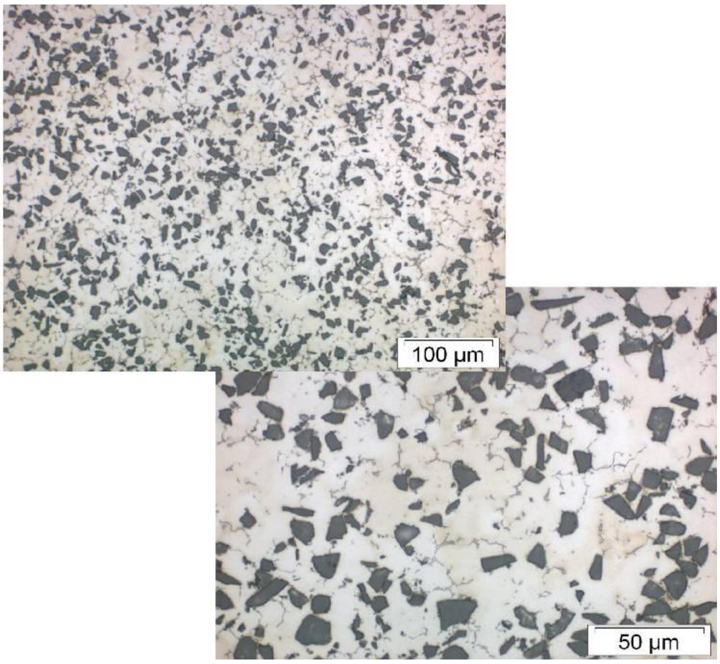
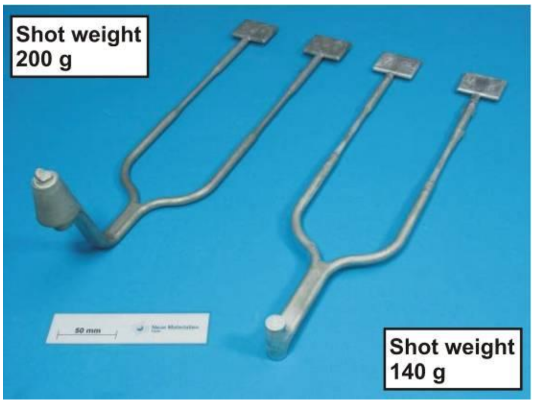


Figure 10: Power steering pump bracket (left) produced by Thixomolding using AJ62 reinforced with 15 % SiC. The micrographs show a uniform distribution of the particles. No reactions between SiC and the matrix alloy was detected.

3.3 Hot Runner Systems

In serial production of Magnesium parts the shot weights are often much higher than the part weight. Especially for thin-walled parts scrap can sum up to 50 – 80 percent. In plastics injection molding hot runner systems are commonly used. A transfer of this technique to Magnesium die casting is difficult due to corrosiveness of the metal melt and the limited strength of mold steels at high temperatures (>600°C).

The low processing temperatures in Thixomolding make it easier to adopt the hot runner technology. First attempts have been made at NMF for a simple geometry (see Figure 11). The first part of the gating system of a mold for tensile specimen was heated which resulted in a reduction of the shot weight by approximately 30 %. Concurrently the flow length was reduced by ~120 mm. It was found that the mechanical properties were improved by the use of the hot runner. This can be explained by a decrease of casting defects, i.e. cold shuts or oxides. The advantages were most obvious for a high solid phase content.



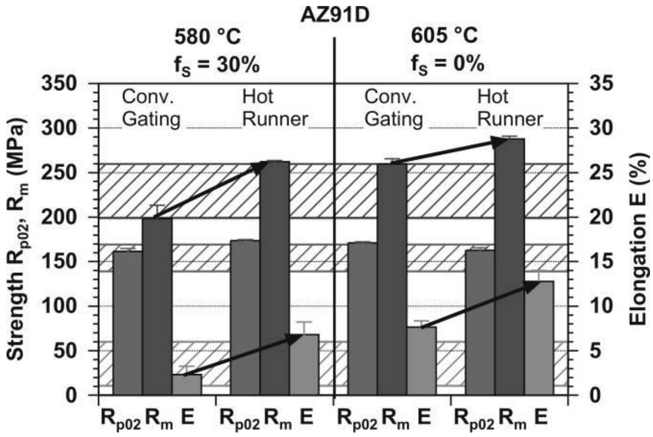


Figure 11: A simple hot runner system was adopted to a mold with tensile bars. The shot weight was reduced by 30 % and the mechanical properties were improved significantly.

Following a more complex mold with a two drop system has been designed. A thin-walled box (dimensions 64 mm x 105 mm x 32 mm, wall thickness 2 mm) was realized in a two cavity mold successfully (see Figure 12). Again the shot weight was reduced compared to the conventional gating system by ~35 percent. Due to the fact that the maximum diameter of the “cold” gating system was reduced from more than 30 mm to less than 12 mm it was possible to reduce cooling and cycle time.

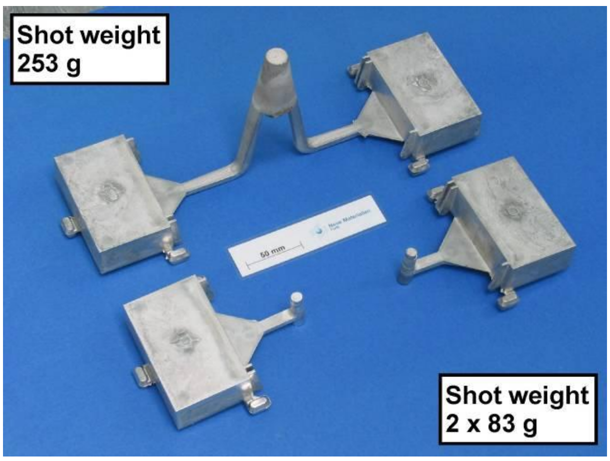


Figure 12: Two drop hot runner system realized for a thin-walled box. The shot weight was reduced ~ 33 % compared to a conventional gating system.

3.4 Melt metallurgical production of Magnesium granules

One important aspect concerning the part costs in Thixomolding is the price of the Magnesium chips. At present they are produced by machining from cast ingots. This additional operation leads to a higher price of the feedstock in comparison to die casting of approximately 20 %.

In order to reduce cost, a new production process for Magnesium granules is under development at NMF in cooperation with Ecka Granules. A prototype equipment has been set up that allows to produce the granules directly by a melt metallurgical technique (see Figure 13).

Figure 13: Equipment for the melt metallurgical production of Magnesium granules at NMF.

Some examples for granules produced with this process are shown in Figure 14.

Figure 14: Different grain sizes of granules produced by a melt metallurgical process at NMF.

4 Conclusions

Thixomolding® is a production process for high quality magnesium parts. Good mechanical properties and low porosities can be achieved. In comparison to die casting energy consumption is reduced by up to 24 %. Due to the process characteristics Argon can be used as an inert gas leading to a reduction of costs.

Furthermore Thixomolding is more suited for processing new alloys and particle reinforced magnesium than die casting. In addition the advantages of using hot runner systems have been demonstrated. At present a new production method for Magnesium granules is developed that will increase economic efficiency of Thixomolding in the near future.

5 Literature

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