In: Kainer, K. U. (Hrsg.): 8th International Conference on Magnesium Alloys and their Applications, Weimar, 26.-29. October 2009. 68-74

Comparison of conventional magnesium alloys with Mg-Al-Ca-Zn and Mg-Al-Sr-Zn alloys processed by injection molding

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1 Introduction

Nowadays most magnesium parts are manufactured by high pressure die casting, but beside this conventional process the use of magnesium injection molding offers various advantages. Injection molding is a technique for production of high quality, near net shape magnesium parts. Granules as precursor material are fed into the barrel and melted during shearing and transport. Finally the liquid or semi liquid melt is injected into the cavity. The lower casting temperatures compared to HPDC result in lower porosity, decreased shrinkage and distortion of the parts, longer die life and less consumption of energy [1-3]. In addition magnesium injection molding might be beneficial for processing creep resistant alloys. Most of these alloys contain elements that tend to segregation, oxidation or evaporation. In addition hot cracking or die sticking might occur. For example the elements Ca and Sr are prone to oxidation and to form dross on the melting bath surface while Si may lead to segregation of intermetallic phases. Due to the closed process under Argon gas, the intensive mixing of the melt during transport or the low processing temperatures these problems typical for HPDC might be avoided. [3-5]

In this study several commercial magnesium alloys (AZ, AM, AJ, AS and MRI series) have been processed by injection molding successfully. The mechanical properties and compressive creep resistance have been examined. In addition the potential of injection molding for developing new alloys with higher creep resistance is discussed exemplarily for alloys based on AZ91 with Ca- and Sr-additions up to 5 wt.-% illustrating the opportunity to adjust the alloy composition during processing using a patented second dosing system. The influence of the additional alloying elements on microstructure, mechanical properties and creep properties were investigated and compared with the conventional magnesium alloys.

2 Experimental

Casting trials were performed on a 220 t JSW (Japan Steel Works) magnesium injection molding machine type JLM220-MG using a mold with two separately cast bars according to ASTM B557 M 02a for tensile testing. Figure 1 shows a schematic drawing of the process. As raw material granules of the conventional alloys, delivered by ECKA Granules and Dead Sea Magnesium Ldt., are used. For Ca- and Sr-addition master alloys MgCa30 (Timminco Ltd.)

and MgSr30 (Magnesium Elektron Ltd.) were added by a patented second dosing system [6]. To prevent the magnesium from oxidation argon gas is applied during the process. The ram speed was about 2,5 m/s. After filling a holding pressure of about 300 bar was applied.

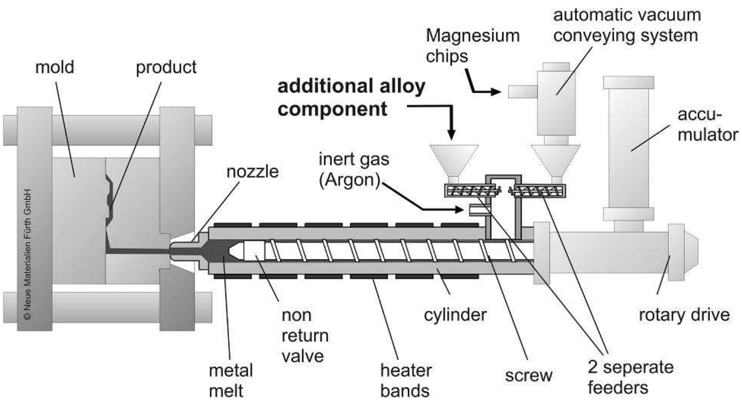

Figure 1. Schematic drawing of a magnesium injection molding machine with patented second dosing system [6].

For phase analysis an x-ray diffractometer (type D500 manufactured by Siemens) was used. Standard tensile tests were carried out on a Zwick/Roell Z100 testing machine at room temperature and 150 °C using testXpert® software. For compressive creep testing cylindrical specimens (Ø = 5 mm, h = 7 mm) were machined from the gauge length of the tensile bars. The tests were performed on ATS lever arm creep testing machines (Series 2330). The minimum secondary creep rate at 150 °C was determined for stresses varying from 40 to 200 MPa. The automatic load drive of the creep testing machines ensured a constant true creep stress during testing. Two inductive extensometers measured the plastic strain and the data were controlled and recorded during testing by WINCCS II software.

3 Results

3.1 Microstructure

Aluminium is a standard alloying element for magnesium die casting alloys. The content of Al improves significantly castability and increases strength and hardness. Due to its combination of good ductility and moderate strength AM60 is often used for applications which claim ductility [7]. The microstructure of die cast Mg-Al-alloys was characterized in literature by supersaturated α-grains surrounded by a divorced eutectic phase consisting of $Mg_{17}Al_{12}$ and α-Mg [8], which can also be expected for the alloys processed by injection molding illustrated in Figure 2. As can be observed in the micrographs of AM60, AZ70 and AZ91 the amount of strengthening eutectic phase increases with rising Al-content. For AZ91 x-ray diffraction pattern were measured which identify the intermetallic phase as $Mg_{17}Al_{12}$.

Si as alloying element is well known to improve the creep resistance [8]. The microstructure of injection molded AS31 and AS41 show the typical chinese script Mg_2Si precipitates that are formed besides the α-Mg. Si cannot form an intermetallic with Al, so $Mg_{17}Al_{12}$ as second intermetallic phase is present in Mg-Al-Si-alloys [8-9].

An important attempt to develop new Mg-alloys was done by Pekguleryuz et al. AJ52 and AJ62 represent a group of alloys whose creep properties are improved by the addition of Sr while castability is adjusted by varying the Al-content. The eutectic of these alloys shows a lamellar structure predominantly consisting of Al_4Sr and α-Mg. Decisive for the microstructure of AJ – alloys is the ratio of the weight percentage of strontium to aluminium. A ratio smaller than 0,3 indicates that there is not enough strontium to bind all aluminium, so beside Al_4Sr also $Mg_{17}Al_{12}$ is present as intermetallic phase. With increasing ratios the formation of $Mg_{17}Al_{12}$-phase is suppressed and another ternary Mg-Al-Sr-phase can be observed [9]. The appearance of this phase is not lamellar but massive. In literature two kinds of stoichiometry are mentioned. Kunst et al. identified this phase as Mg_9Al_3Sr [10] and Baril et al. as $Mg_{13}Al_3Sr$ [11]. The micrographs of AJ52 and AJ62 (Figure 2) investigated in this study show a eutectic structure that mostly consists of Al_4Sr and is more contiguous than the eutectic phase of the alloys mentioned before. The presence of the ternary phase is not obvious.

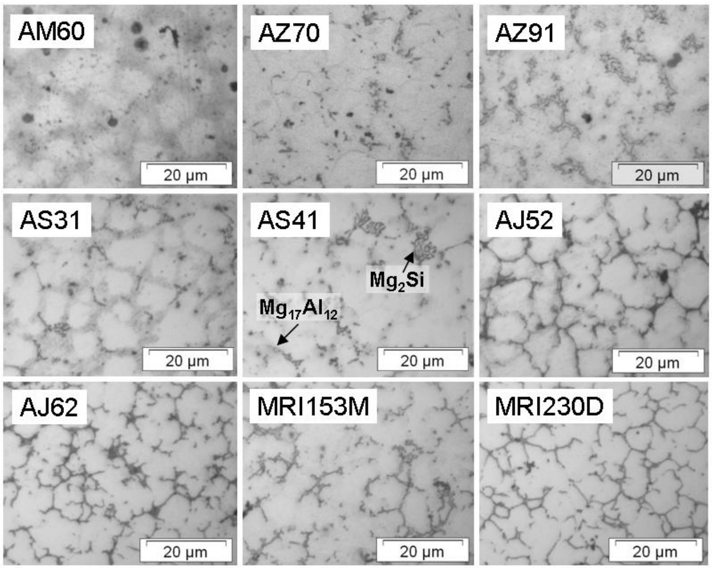

Figure 2. Microstructure of conventional alloys processed by magnesium injection molding.

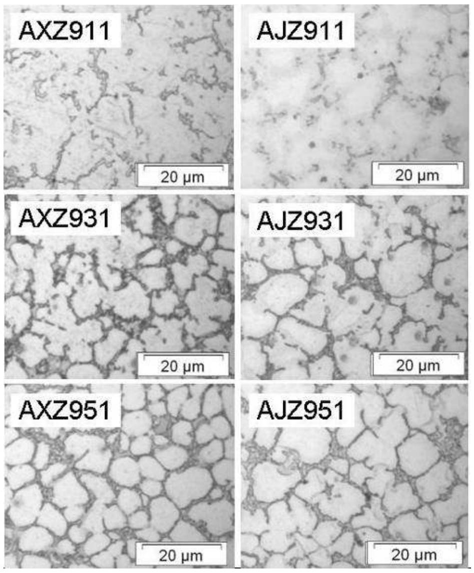

Figure 3. Microstructure of alloys based on AZ91 with Ca- / Sr-additions.

Some other magnesium alloys contain calcium to improve the creep resistance like the die casting alloys MRI153M and MRI230D developed by Dead Sea Magnesium and Volkswagen. Both alloys based on Mg-Al-Ca-RE are quite complex. They contain a number of elements with some amounts of strontium and for MRI230D also tin. They were developed for long-term applications at temperatures up to 150 °C and 190 °C, respectively [9, 12]. The micrographs of the MRI-alloys in Figure 2 show a noticeable amount of eutectic phase that is nearly continuously connected in MRI230D.

The microstructure of the modified alloys based on AZ91 is illustrated in Figure 3. The alloys are designated according to ASTM with “X” for calcium and “J” for strontium and its nominal Ca- or Sr-concentration. An addition of calcium to AZ91 leads to the formation of Al_2Ca [5]. At Ca-levels higher than 2 % the formation of the intermetallic phase $Mg_{17}Al_{12}$ is nearly completely suppressed which was detected by x-ray diffraction. The eutectic structure changes from divorced to lamellar. With increasing Ca-content a more and more contiguous eutectic network is formed. For Sr-additions the same effect can be observed. According to x-ray diffraction measurements the intermetallic phase substituting $Mg_{17}Al_{12}$ is Al_4Sr that forms a lamellar eutectic. Beside this phase the massive ternary Mg-Al-Sr- phase mentioned before was found at higher Sr-contents (AXZ941 and AXZ951).

3.2 Mechanical properties

Table 1 shows a comparison of the mechanical properties of the alloys processed by injection molding with data from the literature for die casting at room temperature and 150 °C. The alloys processed by injection molding show comparable or even exceeding values to the die casting reference.

Table 1. Typical mechanical properties at room temperature and 150 °C of the injection molded magnesium alloys for tensile specimens (ASTM B557 M-02) in comparison to data from the literature for die casting.

	T_{test}	Injection Molding			Die Casting Reference			Source
		0.2YS (MPa)	UTS (MPa)	E (%)	0.2YS (MPa)	UTS (MPa)	E (%)	
AZ91	20 °C	170	260	8	160	260	6	[13]
	150 °C	130	175	19	100	160	18	[13]
AZ70	20 °C	150	259	11				
	150 °C	120	165	25				
AM60	20 °C	150	253	11	123	247	12	[14]
	150 °C	114	157	24	<100	150	?	[14]
AS31	20 °C	145	251	13	130	216	8	[14]
	150 °C	113	155	26	87	130	?	[14]
AS41	20 °C	152	265	13	130	240	10	[14]
	150 °C	118	160	29	90	150	-	[14]
AJ52	20 °C	152	245	10	134	212	6	[9]
	150 °C	128	172	20	110	163	12	[9]
AJ62	20 °C	151	258	11	143	240	7	[9]
	150 °C	125	170	15	116	166	19	[9]
MRI153M	20 °C	158	249	7	170	250	6	[13]
	150 °C	139	187	12	135	190	17	[13]
MRI230D	20 °C	168	218	4	180	235	5	[13]
	150 °C	145	175	4	150	205	16	[13]

The properties at room temperature and at 150 °C of AZ91 cast directly above the liquidus temperature are quite better than literature data for die casting. Besides this conventional Mg-alloy AZ70 is an interesting alternative, because of its higher elongation and similar tensile strength compared to AZ91. Also the data for AM60 processed by injection molding show a good behaviour compared to literature data for die casting. For the AS-series and the AJ-alloys the mechanical properties at room temperature and 150 °C are predominantly better for the injection molded specimens compared to the reference. First results show that MRI153M exhibits comparable strength but less elongation than the reference denoted in literature. For MRI230D in particular the tensile strength and elongation is lower than the reference.

The mechanical properties of alloys based on AZ91 with Ca- and Sr-additions compared to commercial alloys processed by injection molding are illustrated in Figure 4. The alloys with low alloying content show similar mechanical properties at room temperature with tendency to slightly higher strength values. With higher Ca- or Sr-addition the material becomes brittle which is indicated by the decreasing elongation at failure, but the values, especially for additions up to 4 %, remain on the level mentioned for AZ91 DC in literature. At 150 °C testing temperature an improvement of yield strength and ultimate tensile strength can be observed with increasing alloying level in particular for Ca-additions. The AXZ- and AJZ-alloys exhibit similar or even better strength levels compared to the conventional AZ91 and also to the alkaline earth containing alloys AJ62 and MRI153M.

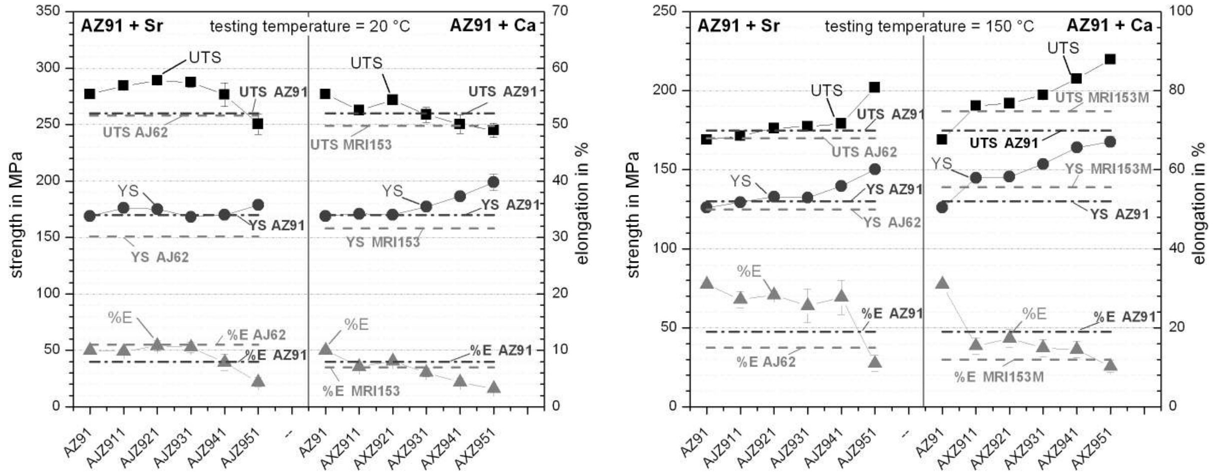

Figure 4. Mechanical properties at room temperature and 150 °C of AZ91 with Ca- and Sr-additions compared to conventional AZ91 and alkaline earth containing alloys AJ62 and MRI153M processed by injection molding.

3.3 Creep behaviour

The minimum creep rates at 150 °C of the commercial alloys processed by injection molding are given in Figure 5.

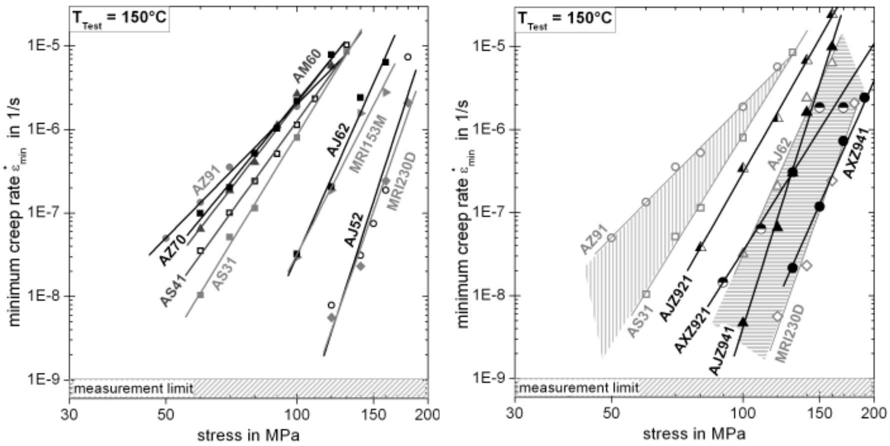

Figure 5. Minimum creep rates at a testing temperature of 150 °C versus stress for Mg- alloys processed by magnesium injection molding (left) and for comparison creep rates of AZ91 with Ca- / Sr-addition

The AZ-, AM- and AS-alloys show similar creep rates for stresses around 100 MPa. At lower stresses the creep resistance is successively better for alloys with lower Al-content and higher Si-content. So compared to AZ91 the alloy AS31 shows at 60 MPa a creep rate reduced more than one order of magnitude. In all these alloys the intermetallic phase $Mg_{17}Al_{12}$ is formed during solidification. This phase and its supplementary precipitation during creep are often declared as reason for the relative poor creep resistance of Mg-Al-alloys [12]. In AJ- and MRI-alloys the formation of this phase is suppressed by formation of other Al-containing intermetallic phases that are beneficial for creep behaviour. The alloys AJ62 and MRI153M show similar creep rates nearly two orders of magnitude better than the $Mg_{17}Al_{12}$ containing alloys. With AJ52 and MRI230D a further improvement of creep resistance can be observed.

For comparison the creep rates of AZ91 with Ca- / Sr-addition are displayed in Figure 5 right. The addition of Ca as well as Sr results in a significant improvement of creep resistance. At higher alloying levels (> 2 % Ca / Sr) the alloys show creep rates in the range of AJ- and MRI-series.

4 Discussion and Conclusions

The studied conventional magnesium alloys have been processed successfully by injection molding showing good mechanical properties compared to die casting references. Especially for AS- and AJ-series a significant improvement was found indicating better processibility. According to literature in die casting most of the creep resistant alloys have a tendency to die sticking or hot cracking [15]. For MRI- and AJ- series the castability is significantly reduced compared to AZ91. Especially for AJ52 the castability is quite poor, which is reflected in the need of special casting conditions for die casting [13]. Therefore further injection molding casting trials with more complex parts will be carried out in the future.

Moreover magnesium injection molding offers the possibility for alloy development by adjusting the composition during process. It was shown that alloys with unusual high amounts of Ca or Sr can be processed. Thus it seems to be facilitated to find optimized alloy compositions that exhibit both, improved creep resistance and good castability. The studied AJZ- and AXZ-alloys seem to be promising in this regard.

References

[1] A. Lohmüller, M. Scharrer, R. Jenning, M. Hilbinger, M. Hartmann, R.F. Singer in Magnesium Alloys and Their Applications (ED: K.U. Kainer), Wiley-VCH, Wolfsburg, Germany, 2003, 738-743.

[2] A. Lohmüller et al., 15th Mg-Automotive and User Seminar, Aalen, Germany, 2007.

[3] M. Scharrer, A. Lohmüller, R. M. Hilbinger, H. Eibisch, R. Jenning, M. Hartmann, R. F. Singer in Magnesium Alloys and Their Applications (ED: K.U. Kainer), Wiley-VCH, Dresden, Germany, 2006, 249-255.

[4] H. Eibisch, A. Lohmüller, M. Scharrer, R. F. Singer in Magnesium Alloys and Their Applications (ED: K.U. Kainer), Wiley-VCH, Dresden, Germany, 2006, 106-112.

[5] H. Eibisch, A. Lohmüller, N. Kömpel, R. F. Singer, Int. J. Mat. Res. 99, 2008, p. 56-66

[6] German patent DE 10303363 A1, 2003.

[7] C. Kammer in Mg-Taschenbuch, Aluminium Verlag, Düsseldorf, 2008, Chapter 8

[8] M. S. Dargusch, G. L. Dunlop, K. Pettersen in: Magnesium Alloys and their Applications. (Eds: B. L. Mordike, K. U. Kainer), Werkstoff-Informationsgesellschaft, Frankfurt, Germany 1998, 277-282.

[9] M.O. Pekgüleryüz, A.A: Kaya, Adv. Eng. Mat., 2003, 5, 12, 866-878.

[10] M. Kunst, A. Fischersworring-Bunk, C. Liebscher, U. Glatzel, G. L'Esperance, P. Plamondon, E. Baril, P. Labelle in Magnesium Alloys and Their Applications (ED: K.U. Kainer), Wiley-VCH, Dresden, Germany, 2006, , 498-505.

[11] E. Baril, P. Labelle, M. O. Pekguleryuz, JOM, 2003, 55, 34-40.

[12] A. A. Luo, International Materials Reviews, 2004, 49, 1, 13-30.

[13] E. Aghion, B. Bronfin, D. Eliezer, F. von Buch, S. Schuhmann, H. Friedrich, Materials Science Forum, 2003, 419-422, 407-418.

[14] Hydro Magnesium, Datasheet Mg diecasting alloys, 2001.

[15] D. Argo, M. Pekgüleryüz, P. Vermette, M. Lefebvre, Druckguss-Praxis, 2003, 2, 89-93.