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Recycling of Magnesium Drive Train Components

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With the development of new heat resistant magnesium alloys, the automotive industry has introduced several parts to the drive train. The rising number of large magnesium components will result in a higher quantity of automotive post consumer scrap. It was the aim of this work to find a reasonable alloy system for the recycling of these magnesium drive train components. A matrix of potential recycling alloys based on the magnesium alloy AM50 was prepared via permanent mould casting. The materials were investigated via tensile testing, creep tests and salt spray tests. Three alloys were selected for processing via high pressure die casting and the tests were repeated on the new materials. A promising system for recycling has been isolated and will be investigated more deeply for the influence of impurities.

Keywords: magnesium recycling, end-of-life vehicles, recycling alloy, post consumer scrap

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1 Introduction

Within the last ten to fifteen years several heavy magnesium parts have been assembled in passenger cars, such as gear box housings and crank cases^[1, 2]. Reasons are the lately developed new heat resistant alloys and the increasing responsibility of automotive manufacturers to reduce the vehicles weight and thereby CO₂ emissions. The latter is pushed by legislation^[3]. The rising quantity of magnesium in automobiles will result in an increasing amount of post consumer scrap.

So far magnesium recycling for magnesium alloy production is done only for clean scrap. Clean in this regard means free from impurities, contaminations and sorted according to a chemical composition or a single alloy^[4-14]. The latter is also called class 1 scrap and mainly consists of sprues and runners from magnesium die casters^[14, 15].

For automotive post consumer scrap the materials quality strongly depends on the way end-of-life vehicles are treated. Up to date automotive manufacturers have no uniform recycling system for end-of-life vehicles. By proper dismantling of old cars, the bigger magnesium components could be collected and possibly treated similar to class 1 scrap^[14]. So far the biggest part of old cars has been shredded and it is probable that this practice will be continued for reasons of economy. The magnesium fraction can be segregated from the non magnetic shredder fraction via sink float separation and eddy current separation^[16]. A further separation according to chemical composition is claimed to be feasible^[17]. Still another problem is unsolved. Due to coatings on magnesium components or aluminium alloy contaminations it is expected that magnesium post consumer scrap will be enriched with Cu, Fe and Ni during remelting.

Due to the above listed drawbacks the main use of magnesium post consumer scrap so far has been the desulphurisation of steel and the alloying of aluminium^[14]. Nevertheless there are strong arguments to investigate the possibilities of post consumer scrap recycling. The European Union launched the directive on end-of-life vehicles according to which 85 % of the vehicles weight will have to be reused and recycled with the beginning of 2015^[18]. Recycling helps to save alloying elements that would be wasted otherwise. Finally the energy consumption for recycling is much lower compared to primary production. Remelting of magnesium consumes maximum 10 % of the energy needed for electrolysis^[14].

The importance to develop secondary alloys for magnesium recycling has already been claimed some time ago^[15, 19]. Recently, patents have been lounded by GKSS and the TU-Clausthal for a recycling alloy with higher tolerance-limits for Cu and Ni, based on the AZ91^[20, 21]. This alloy allows remelting sorted scrap from a very common magnesium alloy system. A recycling alloy for processing scrap from mixed magnesium alloys would be suitable to use the upcoming material from end-of-life vehicles.

Manufacturers of vehicles use heat resistant magnesium alloys for several parts of the drive train like gear box housings and crank cases. The components usually have a high weight per component, which makes recycling

reasonable. Most heat resistant magnesium alloys contain 3–6 wt.-% aluminium and 0.3–0.6 wt.-% manganese. To attain the desired heat resistance alloying elements like silicon or calcium or strontium are added. Apart from the latter the basic system highly resembles the magnesium alloy AM50. In this work three common heat resistant magnesium alloy systems were regarded as a base material for a recycling alloy: the AS-system - silicon, the MRI-system - calcium and finally the AJ-system - strontium. To realise the scenario of the mixed post consumer scrap from the above-mentioned alloy systems, the AM50 was chosen as a base material to which decisive amounts of silicon, calcium and strontium were added. Based on these principles a matrix of potential recycling alloys was prepared and investigated in order to select the most promising alloys for further investigation.

2 Experimental

Table 1 shows the complete matrix of potential recycling alloys that has been prepared for this work. Permanent mould casting was the chosen preparation method. From the results of the investigated alloys the most promising systems have been selected for further processing via high pressure die casting.

Table 1 Prepared matrix of potential recycling alloys based on the AM50 in wt.-%

Subsystem	Sr Content in wt.-% -Alloy Codification According to [22]			
	AM50	0-AM50	0.5-AJM50	1.0-AJM51
AM50 + 0.2 Ca	0-AMX50	0.5-AJMX50	1.0-AJMX51	2.0-AJMX52
AM50 + 0.2 Si	0-AMS50	0.5-AJMS50	1.0-AJMS51	2.0-AJMS52
AM50 + 0.2 Ca + 0.2 Si	0-AMSX50	0.5-AJMSX50	1.0-AJMSX51	2.0-AJMSX52
AM50 + 1.0 Si + 0.2 Ca	0-ASM50	0.5-ASJM50	1.0-AJSM51	2.0-AJSM52

Six permanent mould cast and three HPDC alloys are discussed in this paper. The unmodified AM50 alloy was cast as a reference material in both casting techniques. For permanent mould casting, pieces of AM50 ingots were molten at 730 °C in a mild steel crucible of an induction furnace. Alloying elements were added in the pure form. The melt was stirred for 30 min, settled for 15 min, and subsequently cast into a steel mould that had been preheated to 400 °C. The mould had the geometry of a rectangle plate, with 200 mm height, 100 mm width, and 40 mm thickness. The high pressure die cast alloys were prepared in the feeding furnace of the used FRECH DAK 450-54 cold chamber machine. The procedure resembled the preparation for permanent mould casting, only that the melt temperature was set to 680 °C and the melt was stirred for one hour and settled for 30 min. The high pressure die cast test part is shown in Figure 1. For all casting operations a mixture of argon and 0.2 vol. % SF₆ was used to prevent melt oxidation. The chemical composition in wt.-% was investigated using a Spark Emission Analyser, Spectrolab M9 from SPECTRO (OES).



Figure 1 Test part that was fabricated during the HPDC trials, red ellipse marks 2 mm step from where the flat tensile specimens were cut

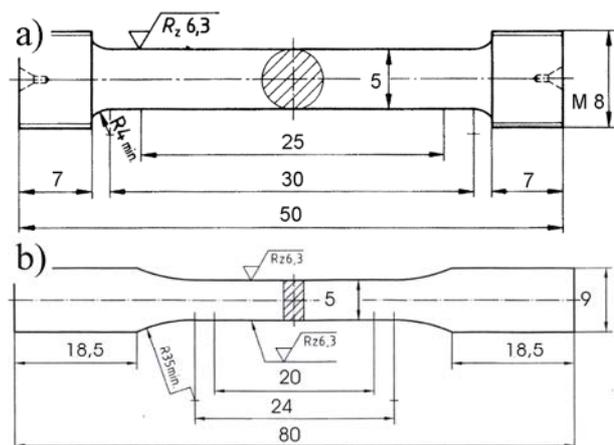


Figure 2 a) Round tensile specimen from permanent mould cast material, b) flat tensile specimen from 2 mm step of HPDC test part

To evaluate the mechanical properties, tensile tests were performed on a ZWICK Z050 tensile testing machine according to [23]. From permanent mould cast material, round tensile specimens were machined via turning according to [24]. The dimensions are shown in Figure 2 (a). From HPDC material flat tensile specimens were machined via spark erosion cutting in accordance with [24]. The dimensions are shown in Figure 2 (b). A set of

three samples was used for each average value. Tests have been performed at 20 °C and 150 °C for permanent mould cast material and at 20 °C for the HPDC material. For high temperature tests, a convection furnace was adjusted to the tensile testing machine. After mounting, the samples were held for 10 min to ensure an overall homogeneous temperature. Salt spray tests were performed according to [25]. A set of three samples was used for each average value. Corrosions properties are often important for the application of magnesium alloys. Therefore the salt spray test as common test method has been chosen. Corrosion specimens from permanent mould cast material were ground with silicon carbide paper, 1200 grit and cleaned in ethanol prior to corrosion testing. Corrosion samples from HPDC material were ground only on the cutting edges and subsequently cleaned in ethanol. Tests were performed for 48 h with a 5 % NaCl solution, pH 7. For the evaluation of the long term high temperature properties compression creep tests were done on an ATS Lever Arm Tester for 200 h at 60 MPa and 150 °C. The cylindrical samples were machined via turning and had a diameter of 6 mm and length of 15 mm.

3 Results

Table 2 lists up the chemical compositions in wt.-% for the permanent mould cast material. The content of impurities is always below the threshold of the base alloy, specified in [26] for the AM50 A. As can be seen from Figure 3, the yield strength is increasing with a growing content of alloying elements. Herein the clearest strengthening effect can be seen from the unmodified base alloy to nominal 0.9 wt.-% of additional alloying elements. In contrast to this the fracture elongation of the permanent mould cast alloys is strongly decreasing with an increasing content of additional alloying elements (see Figure 4). Compared to the tensile yield strength, the fracture elongation is strongly affected by temperature. Amongst other results these were the most important information for the choice of alloys that should be processed further in HPDC.

Table 2 Chemical composition of permanent mould cast alloys in wt.-%

Alloys	Al	Mn	Sr	Si	Ca	Zn	Cu	Fe	Ni	Be (ppm)
AM50	4.97	0.302	<0.002	0.017	0.001	0.011	0.0005	0.0023	0.0008	10
AMX50	4.93	0.309	0.004	0.016	0.122	0.011	0.0005	0.0025	0.0007	11
AMS50	4.93	0.307	0.004	0.147	0.001	0.011	0.0006	0.0023	0.0007	8
AMSX50	5.07	0.328	0.002	0.190	0.129	0.012	0.0006	0.0024	0.0007	10
AJMSX50	5.11	0.268	0.551	0.140	0.135	0.012	0.0007	0.0023	0.0007	4
AJM51	5.07	0.307	0.939	0.017	0.001	0.012	0.0006	0.0024	0.0008	6
AJM52	5.18	0.340	1.87	0.015	0.001	0.011	0.0007	0.0028	0.0006	17
AM50 A ^{b)}	4.4-5.4	0.26-0.6	-	0.1	-	0.22	0.01 ^{a)}	0.004 ^{a)}	0.002	-
AJ52 A ^{b)}	4.4-5.4	0.26-0.6	1.7-2.3	0.1	-	0.22	0.01 ^{a)}	0.004 ^{a)}	0.001	-

^{a)} max; ^{b)} [26]

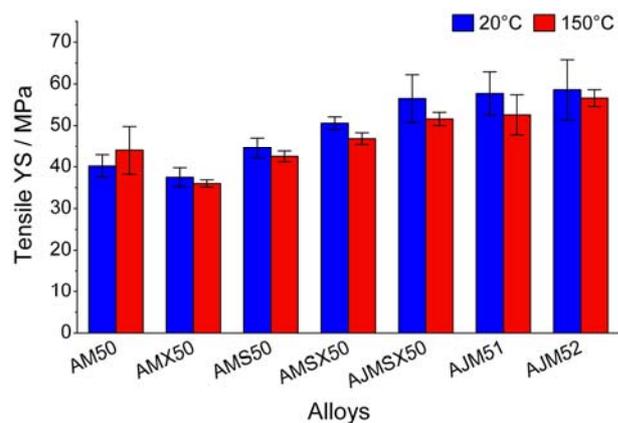


Figure 3 Tensile yield strength of the permanent mould cast alloys at 20 °C and 150 °C

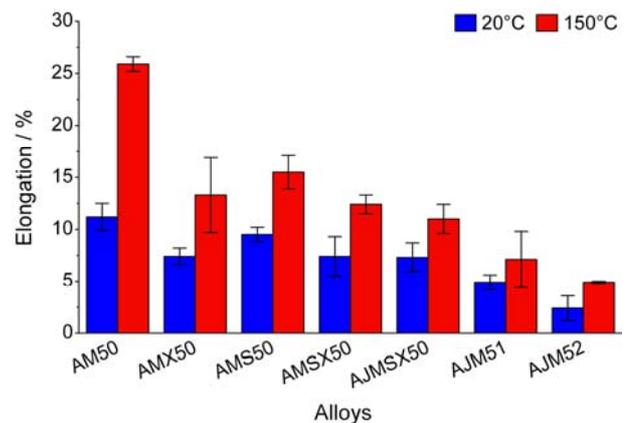


Figure 4 Elongation of the permanent mould cast alloys at 20 °C and 150 °C

Table 3 shows the chemical composition of the high pressure die cast alloys. The level of impurities is almost always below the specified threshold though for the AJMSX50 the iron content is slightly above maximum value.

Figure 5 and 6 show the most important parameters from the tensile tests. For comparison the figures also include the values of the permanent mould cast alloys and the values from HPDC AM50 A according to [26] as

well. For the tensile yield strength the norm values have been reached and in case of the AJM50 and the AJMSX50 a higher strength has been achieved. Nevertheless it is obvious that the increase in strength is not as strong as for the permanent mould cast material. The fracture elongation from the ASTM norm has not been reached. Even the unmodified base alloy lies well below the norm value.

Table 3 Chemical composition of HPDC alloys in wt.-%

Alloys	Al	Mn	Sr	Si	Ca	Zn	Cu	Fe	Ni	Be (ppm)
AM50	4.38	0.266	-	0.011	0.001	0.011	0.0008	0.0016	0.0004	6
AJM50	4.66	0.329	0.433	0.012	0.001	0.011	0.0010	0.0035	0.0002	11
AJMS50	4.79	0.325	0.431	0.162	0.001	0.012	0.0010	0.0037	0.0003	5
AJMSX50	4.62	0.336	0.416	0.149	0.140	0.011	0.0010	0.0044	0.0002	10
AM50 A ^{b)}	4.4-5.4	0.26-0.6	-	0.1	-	0.22	0.01 ^{a)}	0.004 ^{a)}	0.002	-
AJ52 A ^{b)}	4.4-5.4	0.26-0.6	1.7-2.3	0.1	-	0.22	0.01 ^{a)}	0.004 ^{a)}	0.001	-

a) max; b) [26]

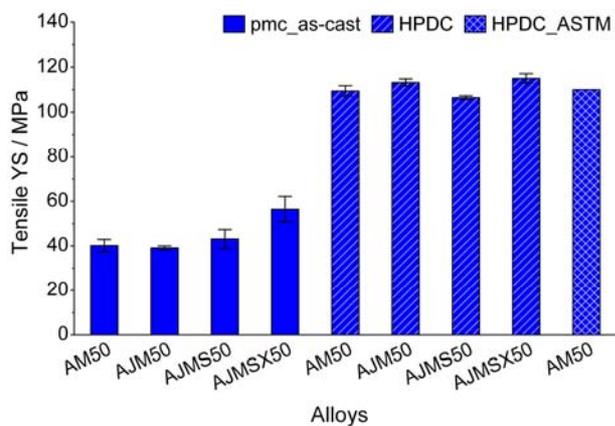


Figure 5 Tensile yield strength of the selected alloys, prepared in permanent mould and HPDC, at room temperature

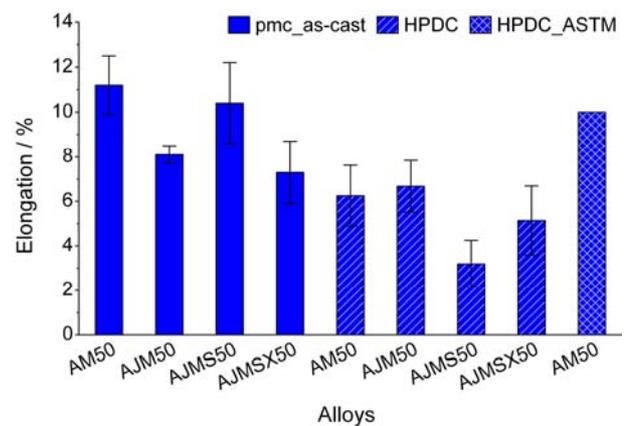


Figure 6 Fracture elongation of the selected alloys, prepared in permanent mould and HPDC, at room temperature

Figure 7 shows the corrosion rates of the selected three alloys and the base alloy respectively all in the permanent mould cast and the HPDC form. Obviously the casting techniques do not influence the corrosion behaviour too much. The creep curves of the AM50 and the AJMSX50 are shown in Figure 8 in the permanent mould as well as in the HPDC form. The minimum creep rate was measured within the last ten hours of the creep test.

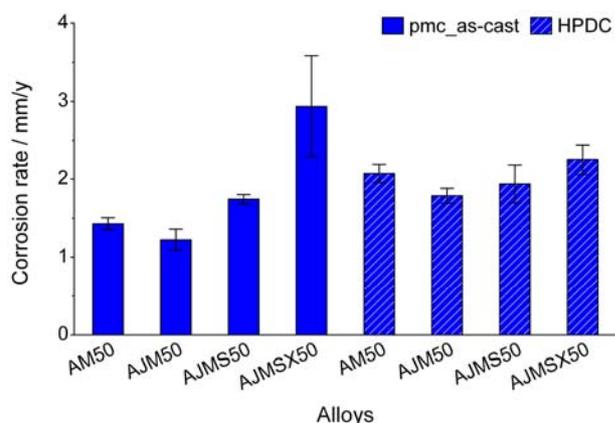


Figure 7 Corrosion rates of the selected alloys prepared in permanent mould and HPDC after 48 h of salt spray test, 5 % NaCl, pH 7

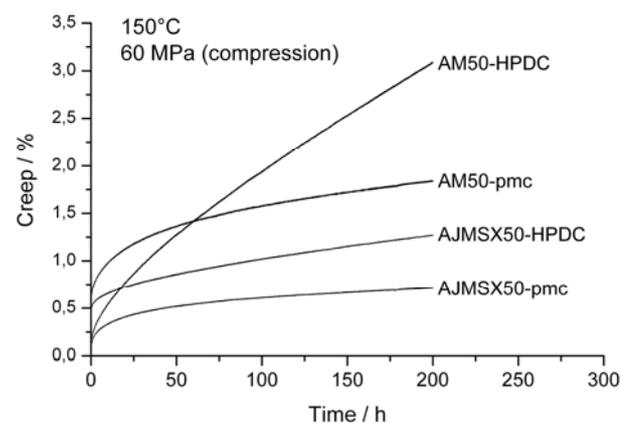


Figure 8 Compression creep curves of two selected alloys prepared in permanent mould and HPDC

From Table 4 it can be seen that the HPDC material always shows a higher minimum creep rate compared to the same alloy manufactured by permanent mould casting. For both casting techniques the AJMSX50 shows a lower creep deformation than the unmodified base alloy. In case of the HPDC material the minimum creep rate of the

AJMSX50 is reduced by a factor of five compared to the AM50. The modified alloy fabricated in HPDC has a minimum creep rate similar to the permanent mould cast base alloy.

Table 4 Minimum creep rate of two selected alloys, as presented in Figure 8, measured between 190 h and 200 h at 150 °C, 60 MPa (compression)

Alloys	Minimum Creep Rates (s ⁻¹)	
	Permanent Mould Cast	HPDC
AM50	5.60×10 ⁻⁹	3.01×10 ⁻⁰⁸
AJMSX50	2.45×10 ⁻⁹	6.12×10 ⁻⁰⁹

4 Discussion

From the permanent mould cast alloys it could be seen that the tensile yield strength was increased with an increasing content of alloying elements. Herein the strongest effect was observed for quantities of additional alloying elements up to nominal 0.9 wt.-%. At the same time the fracture elongation was steadily reduced with the increasing content of alloying elements. These observations could be made at room temperature as well as for elevated temperature. Only the addition of 0.2 % Calcium seemed to have a negative effect. The tensile yield strength of the base material was higher than at room temperature. This is most probably due to inhomogeneous material. One has to be careful with transferring the results from permanent mould casting to the HPDC process. Nevertheless the observations that have been made are supported by the ASTM norm for HPDC magnesium alloys. Table 5 shows the mechanical values of AM50 A and AJ52 A according to [26]. The latter is similar to the prepared AJM52. The fracture elongation of the AM50 A is reduced by one third compared to the heat resistant AJ52 A. At the same time the Sr addition increased the tensile yield strength of the AJ52 A.

Table 5 Selected mechanical properties of the AM50 A and AJ52 A, [26]

Alloys	Mechanical Properties	
	Tensile Yield Strength (MPa)	Fracture Elongation (%)
AM50 A	110	10
AJ52 A	141	7

Figures 9 and 10 show the microstructure of the permanent mould cast AM50 and the cross section of the 2 mm HPDC AM50 plate from the outer casting skin to the centre, respectively. The microstructure of the permanent mould cast material shows relatively coarse grains but no pores are visible. The casting skin of the HPDC alloy shows a very fine microstructure where grains are hardly visible in the optical microscope. Getting closer to the centre of the plate the microstructure gets coarser and pores are visible. These observations are typical for HPDC material.

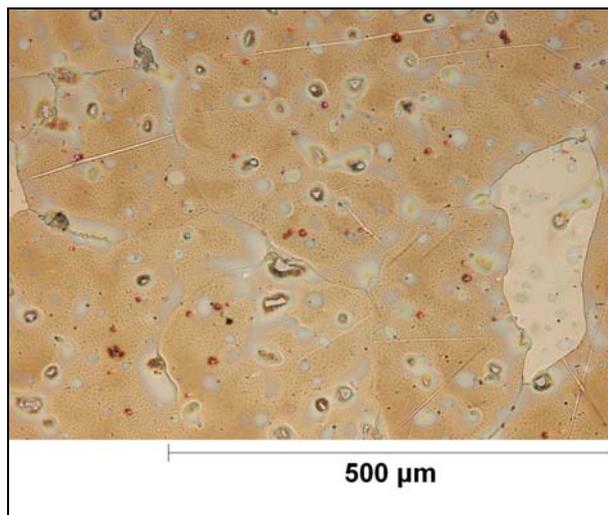


Figure 9 Microstructure of the permanent mould cast base alloy AM50

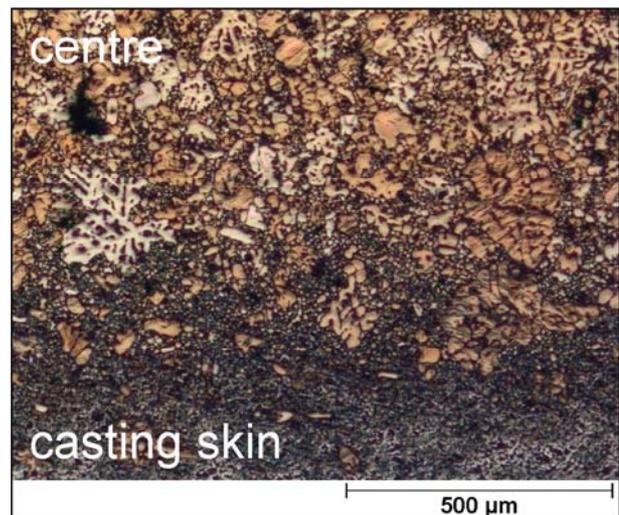


Figure 10 Cross section of the 2 mm HPDC plate from AM50, used for tensile specimens

In the flat tensile specimens that are cut from the prepared HPDC plates of course the pores lie on the surface of the cutting edge. This causes a notch effect when the sample is stressed and thereby the fracture elongation is reduced. Usually round tensile specimens with a completely intact casting skin are used for mechanical testing of

HPDC material as specified in [27]. Therefore the mechanical properties of the HPDC samples presented in this paper should not be compared to the ASTM values directly. Nevertheless it is possible to draw some conclusions. The reason for selecting the four permanent mould cast alloys for further processing in high pressure die casting was to get an alloy with a yield strength comparable or better than that of the unmodified base material and a still reasonable fracture elongation. Referring to the results from the HPDC tensile tests it can be stated that this aim has been reached. With a much higher content of alloying elements the potential recycling system would have the properties of another heat resistant magnesium alloy. This was not the intention of the authors. At the moment most automotive manufacturers favour their own alloy system. A heat resistant recycling system from post consumer scrap will probably not be accepted.

The results from the salt spray tests show that the used alloying elements have only a minor influence. The same seems to be correct for the HPDC process compared to the permanent mould casting. As the level of impurities is mostly below the specified thresholds the corrosion should not be influenced by Cu, Fe or Ni. Only for the AJMSX50 which was prepared last during the die casting trials the elevated iron content might have had a detrimental influence on the result. As the Fe level is increasing steadily from the AM50 to the last alloy a pickup of iron from the crucible seems to be probable. Of course further work has to be done on the corrosion resistance of the material, as the entry of impurities like Fe, Cu and Ni from post consumer scrap cannot be excluded in a recycling process.

As the creep resistance of metals is generally decreasing with the materials grain size, it is not surprising that the creep deformation is much higher for the die cast material always. The alloying elements Sr, Si and Ca are normally used for increasing the heat resistance of magnesium alloys. This impact can be observed for the prepared materials as well.

5 Summary

A matrix of potential recycling alloys has been set up to find a potential system for the recycling of heat resistant magnesium alloys. The matrix was first processed via permanent mould casting. Judging the mechanical and corrosion properties, three alloys apart from the base material were selected for processing on a cold chamber high pressure die casting machine. It can be stated that about 0.5—0.9 wt.-% of Sr, Si and Ca can be added to the AM50 without reducing the fracture elongation too much. At the same time the tensile yield strength and the materials creep resistance can be increased. The results from the salt spray tests do not show a negative influence from the alloying additions. Because of their mechanical properties the AJM50 and the AJMSX50 seem to be the most promising alloys for a further investigation.

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