New magnesium diecasting alloys for decorative and powertrain applications

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Abstract

Two new magnesium die casting alloys, AM-lite and AM-HP2, have been developed which address important issues for the future growth of magnesium markets. AM-lite is a new multi-purpose diecasting alloy with particular attributes for applications where high quality surface finishes are required. This alloy addresses many of the limitations of AZ91D and it competes with zinc and aluminium diecasting alloys and plastics. The other alloy, AM-HP2, has been specially developed to provide a highly diecastable creep resistant alloy that is suitable for powertrain components such as engine blocks, structural sumps, engine covers and automatic transmission housings. AM-HP2 has similar diecastability to AZ91D and has a creep resistance that is similar to aluminium alloys commonly used in powertrain components.

Introduction

Diecasting is by far the biggest market for magnesium alloys. However, at 170 000 tpa, the current size of this market is very small compared with markets for zinc and aluminium diecasting alloys and also much smaller than that for injection moulded plastics. Markets for magnesium diecasting alloys continue to grow but it is clear that the opportunities for magnesium would be considerably greater if alloys could be developed that have more attractive properties compared with competitor materials.

AMT has recently launched two diecasting alloys, AM-lite and AM-HP2, that address some of these issues and pave the way for future growth of magnesium markets.

AM-lite has been specifically developed for a wide range of diecasting applications where diecastability and decorative surface finishes are of prime importance[1]. AZ91D is the major magnesium diecasting alloy that competes against zinc, plastics, and to a lesser extent aluminium, for general diecast and moulded parts. This total market is very large and AZ91D only manages to capture a very small portion of it. The new alloy, AM-lite, complements AZ91D by addressing some of its deficiencies and is opening up new opportunities in areas where other materials are favoured.

The other new alloy, AM-HP2, was specially developed to provide improved diecastability and increased creep strength necessary for a wide range of automotive powertrain applications[2]. The ever increasing demand in the automotive industry for improved performance with reduced fuel consumption and lower exhaust emissions offers many opportunities for strong light alloys that retain their performance at high temperatures. Aluminium has continued to grow in this area at the expense of cast iron and steel but the in-roads by magnesium are small. Recent innovations by BMW with their 6 cylinder composite crank case utilising alloy AJ62 and DaimlerChrysler with their 7 speed automatic transmission housing diecast in alloy AS31, point to opportunities for magnesium. Alloys with diecastability and high temperature mechanical properties similar to aluminium alloys are required before significant in-roads can be made into these markets.

AM-lite – a new alloy for decorative applications

Addressing the limitations of AZ91D

The general purpose magnesium diecasting alloy, AZ91D, is used extensively for functional and decorative applications. In the past, few people have considered the development of alternative alloys to AZ91D to be worthwhile. This is somewhat surprising since AZ91D has some shortcomings and there is a large potential market for an alloy that alleviates these. For example, the consumer electronics industry is pushing for thinner and lighter enclosures combined with high quality surface finishes. AZ91D has been the workhorse magnesium alloy for such applications but seems to have reached its limit and is no longer able to provide the further improvements required by the industry.

Table 1 is an approximate score card of the attributes of competing materials for diecast or moulded parts that need to be surface finished. The scores are in given in the range 1-5 with 5 being best and 1 being worst.

Attribute	AZ91D	Zn	Al	Plastics
Diecastability / mouldability	3	5	2	5
As-cast surface quality	3	5	2	5
Electroplating	1	5	2	3
Painting	3	3	5	3
Melt loss	1	4	4	5
Recycling	3	5	5	1
Productivity	2	4	3	5
Mechanical properties	4	3	5	1
Conductivity (metallic feel)	4	4	5	1
Density (lightness)	5	1	4	5

Table 1. Score card showing comparitive attributes of diecast/moulded materials. A score of 5 is best, 1 is worst.

The limitations of AZ91D that are apparent in Table 1. have restricted the growth of magnesium in many important markets where good diecastability and high quality surface finishes are required. When compared with other competitor materials, the high cost of surface finishing AZ91D is a major issue. This applies particularly to electroplating.

Despite the natural advantages of magnesium's light weight, diecasters often struggle with AZ91D. The key issues are problems of castability, surface defects and surface finishing. For precision thin walled parts for the electronics industry, it is not uncommon for less than 10% of the quantity of magnesium entering the manufacturing process to end up in finished parts. Casting yields, that is the part weight divided by the total shot weight, are often 30% or less and many parts are rejected at various stages throughout the manufacturing process. Rejects after finishing are particularly troublesome due to the processing costs invested in the part and the added difficulties of recycling surface finished parts. Even for acceptable diecastings, surface filling is often necessary to cover up defects.

During development of AM-lite, particular attention was paid to addressing the shortcomings of AZ91D and development of an alloy that competes strongly on the basis of the attributes listed in Table 1.

General features of AM-lite

AM-lite has improved diecastability compared to AZ91D and the as-cast surface finish of AM-lite is of a much higher quality. Die castings made from AM-lite are very well suited for surface finishing operations. A particular advantage is that the alloy can be readily electroplated at equivalent costs to zinc alloys (Figure 1).

Figure 1. Electroplated car door handles die cast in AM-lite.

In comparison to other magnesium diecasting alloys, AM-lite is oxidation resistant at temperatures in the range of solidification and below. This results in less oxide on the surface of castings and their shelf life is considerably improved compared to castings of other magnesium alloys. One consequence of this oxidation resistance is that the material is easier to recycle than AZ91D and tests have shown that there is a strong potential for in-cell recycling of class 1 return scrap and thus save considerable costs expended on external recycling.

The design strength of AM-lite is considerably higher than AZ91D and zinc diecasting alloys. This, combined with the ability to better diecast thin sections, provides an increased flexibility for designers. Most importantly AM-lite saves costs. Compared to AZ91D these cost savings are estimated to be ~ 50% for surface finished parts and, compared to surface finished zinc diecastings, the savings are 10 – 30%.

Diecastability and as-cast surface quality of AM-lite

AM-lite exhibits considerably improved fluidity and diecastability which in many ways is similar to that of zinc diecasting alloys. The usual difficulties experienced with diecasting AZ91D, such as cracking along flow lines, cold cracks and hot cracks, are significantly reduced with AM-lite. Because of the higher alloy fluidity the dimensions of runners and volume of overflows can usually be reduced.

As might be expected, the optimum diecasting conditions for AM-lite are different from those for AZ91D. In fact AM-lite's operating window, for the production of good quality castings, is wider and therefore the alloy provides greater stability of operation in mass production situations and allows for easier automation. This is especially true as AM-lite does not adhere to, or react with, the die (soldering) as does AZ91D. Hence, the usual polishing of dies after a set number of shots is significantly reduced with AM-lite, thus reducing down-time and improving automation. Very thin sections are more easily achieved with AM-lite than for AZ91D and the alloy will reproduce very fine detail from the die. This enables the creation of special surface textures on as-cast surfaces.

Surface finishing of AM-lite castings

The much improved as-cast surface of AM-lite diecastings significantly reduces the need for polishing and buffing prior to surface finishing operations and can eliminate the need for filling of surface defects. This reduces the cost of preparation prior to coating operations and reduces rejects. In addition, because of the alloy's oxidation resistance, AM-lite castings have a long shelf life and this adds further freedom to surface finishing – particularly in hot and humid climates.

AM-lite provides a superior substrate for all surface finishing operations. Furthermore, because the alloy has an inherent creep resistance that restricts the expansion of entrapped gases during baking cycles, it is resistant to the formation of blister defects during baking of powder coated and painted articles.

AMT has worked with MacDermid, a world leading supplier of technology and chemicals to the electroplating industry, to develop an electroplating process for AM-lite. The result (Figure 2) is a process that is vastly superior to that which can be used for AZ91D and which produces electroplated finishes that are comparable in quality to electroplated zinc diecastings.

Figure 2. Automotive components diecast in AM-lite and electroplated using MacDermid's electroplating process

Mechanical properties of AM-lite diecastings

The mechanical properties of AM-lite diecastings are summarized and compared with AZ91D in Table 2. The tensile properties in this table were obtained on 2mm thick diecast plates. Both the yield strength (0.2% offset proof stress) and ultimate tensile strength of AM-lite are higher than for AZ91D. The most important difference in mechanical properties can be seen with reference to Figure 3. AM-lite maintains its linear elastic behaviour to higher stresses than AZ91D. The limit of linear elastic behaviour for AZ91D is ~ 40 MPa while for AM-lite this limit is ~100 Mpa. This means that, for stiffness critical parts, the design strength of AM-lite is considerably higher than that for AZ91D.

AM-lite also has better creep strength than AZ91D and zinc alloys. Zinc alloys creep significantly even at room temperature under relatively low loads. As shown in Figure 4, the creep strength of diecast AM-lite at temperatures around 100°C is about 65% greater than AZ91D and 500% greater than a typical zinc diecasting alloy.

Table 2. Mechanical properties of AM-lite diecastings compared to AZ91D (2mm thick plates)

Property	AM-lite	AZ91D
Yield stress (0.2% proof), MPa	160-170	120-150
Ultimate tensile strength, MPa	230-250	180-205
Young's modulus, GPa	45	44
Elastic limit, MPa	~100	~40
Tensile elongation, %	3-4	3-4

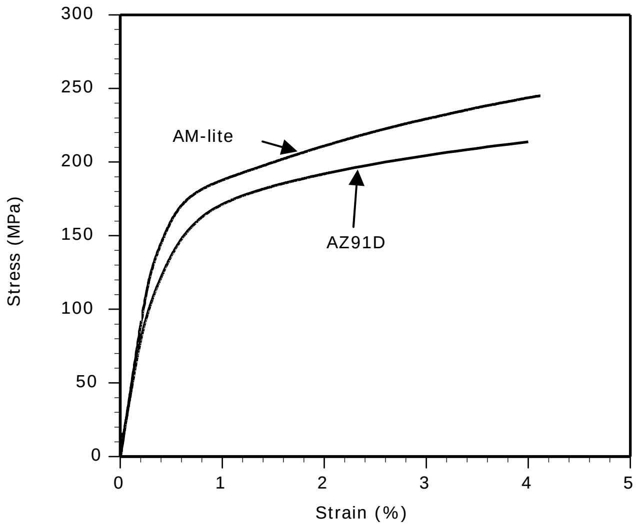

Figure 3. Tensile curves for AM-lite and AZ91D. 2mm thick die cast plates

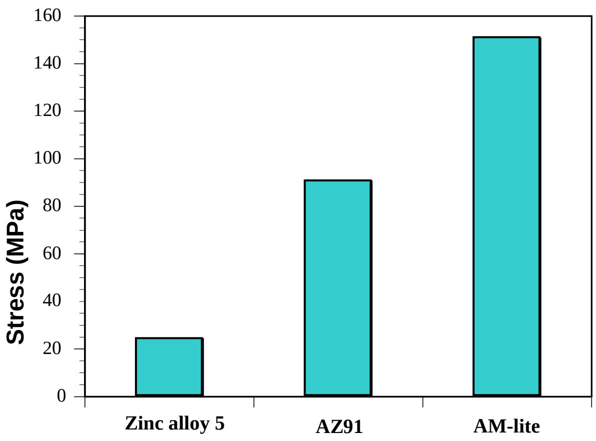

Figure 4. Comparison of creep strength of AM-lite, AZ91D and zinc Alloy 5. Stress required for 0.5% strain after 100hr. at 93°C (200°F)

Oxidation behaviour of AM-lite

As stated earlier, AM-lite has a strong resistance to oxidation during solidification. This effect is illustrated in Figure 5 which shows samples of AZ91D and AM-lite that have been allowed to solidify in air in open muffin-cup moulds. Under such circumstances AZ91D oxidizes extensively and eventually burns but AM-lite freezes with a shiny surface.

The oxidation behavior of AM-lite in the molten state and during solidification is responsible for many of the alloy's surface properties. For example, during diecasting, the surface film on a liquid metal influences its flow characteristics and in particular the ability for opposing flows to weld, or bond, metallurgically during filling of the cavity. Poor welding usually results in cracking or flow marks. The high resistance to oxidation of AM-lite enables such opposing flows to bond effectively during solidification contributing to a much lower defect density. It also allows molten metal to flow smoothly under pressure to fill small interstices created through shrinkage and, in particular, contributes to the smooth shiny as-cast surface of AM-lite die castings whose oxidation resistance persists after casting.

Figure 5. Comparison of oxidation of AZ91D (top) and AM-lite (bottom) solidified in air

The oxidation resistance of AM-lite has other important effects. While use of a cover gas is still required in melt handling, the amount of dross formed is significantly reduced. This may be helped by a furnace temperature that is typically 20°C lower than that for AZ91D. Experience from industrial trials has shown that melt losses due to dross formation are ~75% less for AM-lite than those usually experienced for AZ91D under similar circumstances. Sludge formation is negligible. Reduced melt losses are an important cost saving for diecasters. Another virtue is that there is a significant reduction of the amount of burning from magnesium adhering to tools when they are removed from the furnace, or when removing dross, leading to less fuming and a cleaner foundry environment.

AM-HP2 – A new diecasting alloy for powertrain applications

The development of AM-HP2 follows on from the highly successful sand casting alloy, AM-SC1, which provides similar creep properties to aluminium alloys used in powertrain applications. AM-SC1 was used for the block of the AVL Genios LE turbo-diesel engine that was inserted in a Volkswagen Lupo and has completed a 2 year 65 000km road test[3-5] (see Figure 6). AM-SC1 has also been selected as the preferred alloy for the block of the V6 magnesium engine that is being manufactured by the USCAR MPCC project. AM-HP2 has similar attributes to AM-SC1 but has been specially adapted for high pressure diecasting which is the favoured casting process in many automotive powertrain markets.

Figure 6. Genios LE turbo-diesel engine developed by AVL list utilizing sand cast AM-SC1 for the block

Diecastability Assessment of HP2

The diecastability of an alloy determines whether a complex component can be manufactured to specification with acceptable reject rates and costs. Because of this, particular attention was paid to obtaining a high level of diecastability during the development of AM-HP2. A special test was developed that could be used on a laboratory die casting machine and which tested all aspects of castability such as flow characteristics, hot cracking, defect levels and surface finish.

A new die was designed in order to severely test the die-casting performance of the alloy and provide a quantitative evaluation of high pressure diecastability. This die was triangular in shape and had oil heating/cooling in both the fixed and moving halves of the die set.

The die was designed to give both diverging and converging flow paths. The main features of the casting are the large rib and the central boss that are formed along one side of the part. The rib provides a very thick section parallel to the return flow direction which can show up problems of channelling, where metal flows preferentially along such thick sections. The boss is a typical feature of many structural castings and bosses are often difficult to cast with an acceptable level of defects. Sharp corners occur where the boss and the rib meet the casting, so as to maximise the effect of any hot cracking or shrinkage cracking that may occur. Finally, the die has three strips of varying surface finish parallel to the return flow direction: full polish, semi-matte and full matte (EDM finish). These strips provide an indication of the ease with which the alloy will form surfaces of these types.

Extensive trials using the experimental die have shown that high quality castings can be produced with AM-HP2 under similar diecasting conditions to those used for AZ91D with the exception that somewhat higher melt and die temperatures are used. Figures 7 and 8 show the quality of castings produced in this work. Industrial scale trials, in which parts as large as an auto 6 cylinder engine block were cast, have confirmed the good diecastability of this alloy.

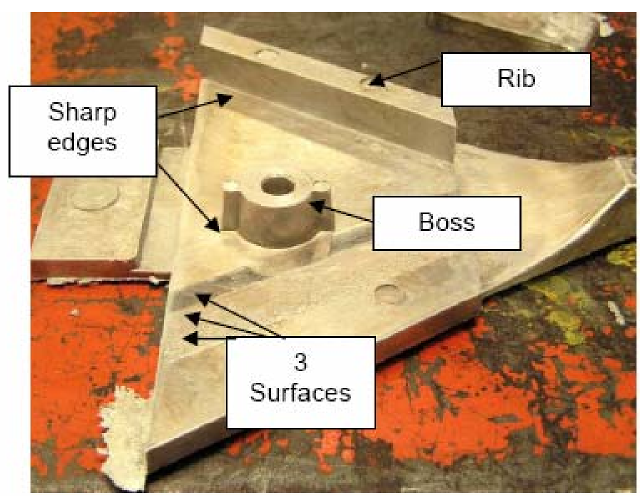

Figure 7: Photograph of casting showing large rib and boss.

Figure 8: As–cast surface of AM-HP-2 - an example of the mirror finish achievable on the casting facing the polished section of the die.

Tensile Properties

The sand-casting alloy, AM-SC1, was designed for engine block applications, with strength specifications being supplied by engine designers. The critical strength property was the tensile yield strength (TYS), both the magnitude at room temperature and the stability of TYS up to, and including, 177°C. The tensile properties of AM-HP2 have been determined at both of these temperatures (Figure 9). The yield strength of as-cast AM-HP2 is higher than that of fully T6 heat treated AM-SC1, and the thermal stability is slightly better with the decline of the yield strength at 177°C being less than 7%. The ultimate tensile strength (UTS), however, is lower in the high pressure die cast material. This is due to a lower ductility of AM-HP2 compared with fully heat treated sand-cast AM-SC1. In terms of design criteria for powertrain components, it is yield strength that is important and not ultimate strength.

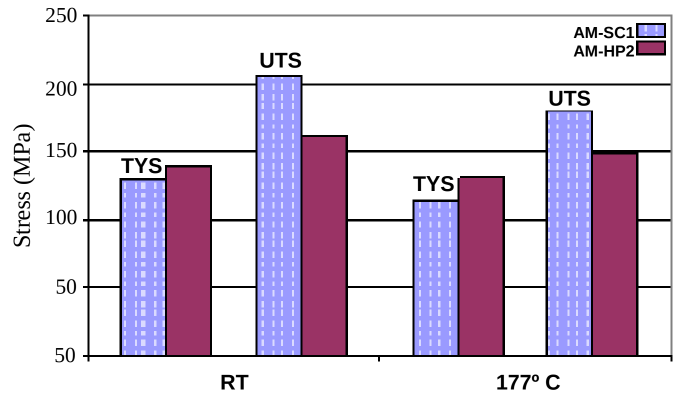

Figure 9: Tensile properties of die-cast AM-HP2 and T6 heat treated sand-cast AM-SC1

Tensile Creep Behaviour

The creep behavior of AM-HP2 has been determined over a wide range of stresses at temperatures between 150°C and 200°C. Here results are shown for a load of 90 MPa at 177°C, and a comparison made with AM-SC1. This particular test condition was chosen after consultation with engine designers. HPDC tends to produce a higher degree of structural variability than sand-casting, resulting in a banding in the mechanical property behaviour and thus it is usually necessary to show the spread of results for a particular property. The creep behaviour, which is shown in Figure 10, is no exception.

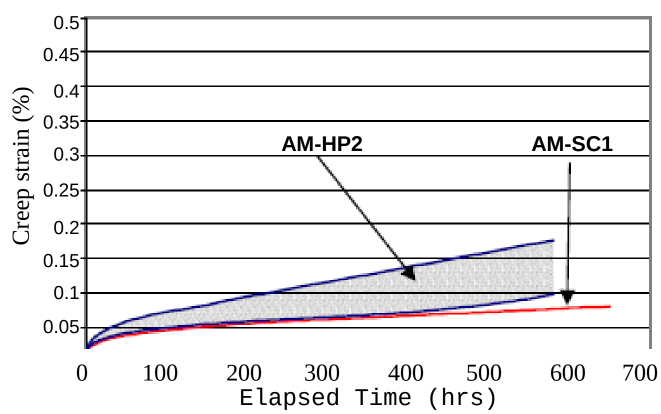

Figure 10: Creep curves for AM-HP2 and AM-SC1 at 177°C and 90 MPa.

The lower bound of the creep behaviour of AM-HP2 at 177°C and 90 MPa is very similar to that for AM-SC1, The spread of results is within acceptable limits for elevated temperature powertrain applications. The stress to produce 0.1% creep strain after 100 hours at 177°C is well in excess of 90 MPa.

It should be pointed out that the high temperature creep properties of AM-SC1 have been shown to be as good as common aluminium engine block alloys such as A380 and A319.[4,5]

Bolt Load Retention (BLR) Behaviour

It is important for powertrain applications to consider the relaxation that may occur under compressive loading – in particular at bolts. This can be simulated in a bolt load retention test. The test method involves applying an initial load (11 kN) through an assembly consisting of two identical bosses made of the test material and a high strength bolt instrumented with strain gauges. The change in load over 100 hours at an elevated temperature (177°C) is measured continuously. The significant loads, in terms of defining the BLR behavior, include the initial load at ambient temperature and the load at the completion of the test after returning to ambient conditions. The ratio of these two values gives the load retention at room temperature. Similarly, the ratio of the initial load at the test temperature, T, to the relaxed load after 100 hours at temperature gives the load retention at T. These two loads are also those used to determine the creep relaxation of the material at temperature.

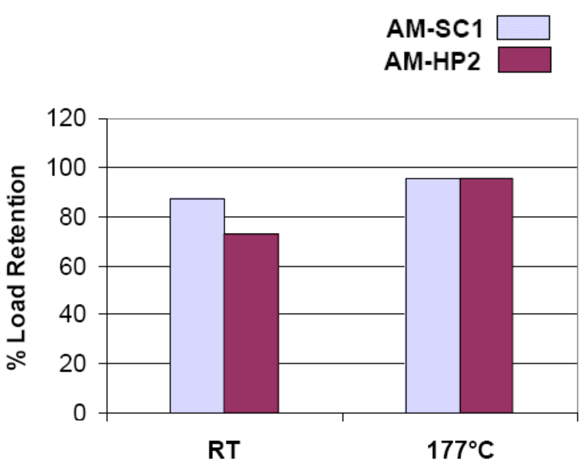

Figure 11: BLR behaviour after exposure at 177°C and a load of 11 kN. The data for 177°C is the BLR measured at the test temperature and the data for RT is the BLR measured after return to room temperature.

As shown in Figure 11, the BLR at the elevated temperature of 177°C has the same high value of 92% for both AM-SC1 and AM-HP2. The creep relaxation of the alloys is, clearly, very low under these conditions. The room temperature behaviour is somewhat better for AM-SC1 than AM-HP2.

Conclusion

AM-lite is an exciting new addition to the range of magnesium alloys available to diecasters. The alloy's attributes are such that it competes very favorably in a wide range of applications with the existing magnesium general purpose diecasting alloy (AZ91D), zinc diecasting alloys, aluminum alloys and plastics. Trials with diecasters and end-users have demonstrated that the alloy fills a much sought after need for a highly diecastable, light weight alloy capable of high quality surface finishing. As summarised in Table 3, the alloy not only achieves these technical advantages but it can also bring about considerable cost savings in comparison to its competitors.

AM-lite is particularly suited for decoratively finished products such as consumer electronics, automotive decorative trim, and domestic and commercial fittings. First commercial sales of the alloy have commenced and it is expected that in the coming year usage of the alloy will grow considerably as the alloy's benefits become more widely known through increased trialing and application to commercial products.

Table 4. Summary of key benefits of AM-lite

Attribute	AM-lite	AZ91D	Zn Alloys 3 & 5
Cost Diecastings Surface finished	60% 75%	90% 150%	100% 100%
Electroplating	Yes (readily)	Yes but with difficulty	Yes (readily)
Diecastability	Very good	Fair	Very good
As-cast surface	Very good	Poor	Very good
Surface coating	No filling Reduced buffing Minimised blisters	Filling required Extensive buffing Blister defects	Blister defects
Density	2.0 g/cm^3	1.8 g/cm^3	6.6 g/cm^3
Design strength	100 MPa	40 MPa	15 MPa
Melt loss	~1%	~4%	~1.5%
Recycling	ok	costly	ok

As powertrain applications advance it is critical to not only meet the operational performance criteria but to also be able to manufacture the part in a cost effective manner. The combined diecastability and high temperature performance of AM-HP2 can be described in relation to other creep resistant magnesium alloys with reference to a castability/creep performance space diagram suggested by Aghion et al[6] and shown in Figure 12. This diagram describes the relative positions of various alloys with respect to their ease of casting and their elevated temperature performance. Clearly, the top right hand corner is the preferred position for HPDC powertrain components. With the exception of AM-HP2 the relative positions of various alloys in this diagram are those suggested by Aghion et al. AM-HP2 has been shown to have a diecastability that is comparable to AZ91D and elevated temperature creep properties that are superior to the other alloys and which meet performance demands for one of the most demanding of powertrain applications, the engine crankcase.

1 AZ91D	**4** AJ62X	**7** ACM522
2 AS21X	**5** AE42	**8** AX52J
3 MRI 153M	**6** AJ52X	**9** MRI 230D

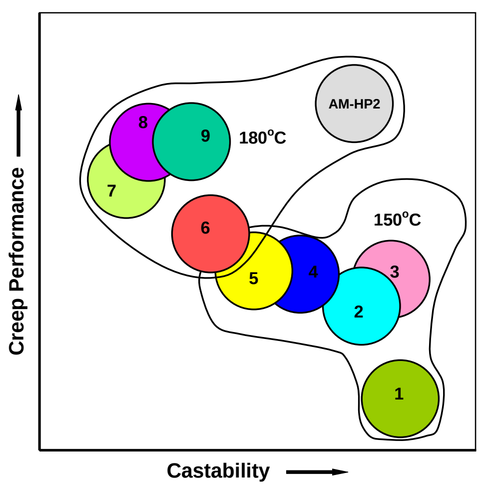

Figure 12: Schematic representation of the castability/creep performance space for current HPDC magnesium alloys (after Aghion[8]). The groupings indicate that the alloys contained within a bubble are suitable for use up to a working temperature of either 150°C or 180°C respectively.

Acknowledgments

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References

1. T Abbott, M Murray and G Dunlop, Magnesium Technology 2006, TMS
2. M Gibson, C Bettles, M Murray, G Dunlop, Magnesium Technology 2006, TMS
3. W. Schoffmann, F. Beste, M. Atzwanger, H. Sorger, F.J. Feikus and J. Kahn, 3. VDI Technical Conference Gießtechnik im Motorenbau, Magdeburg, February 1 - 2, 2005.
4. C.J.Bettles, C.T.Forwood, D.H.St.John, M.T.Frost, D.S.Jones, Ma Qian, G-L.Song,, J.R.Griffiths, J.F.Nie. Magnesium Technology 2003, ed. H.I.Kaplan, 2003 TMS Annual Meeting, San Diego March 2-6 2003, pp. 223-226.
5. C.J.Bettles, C.T.Forwood, D.H.St.John, M.T.Frost, D.S.Jones, Ma Qian, G-L.Song, J.R.Griffiths, J.F.Nie. SAE Technical Paper 2003-01-1365, SAE World Congress 2003.
6. E.Aghion, B.Bronfin, H.Friedrich and Z.Rubinovich Magnesium Technology 2004 pp. 167-172