

FURTHER IMPROVEMENTS IN HPDC Mg ALLOYS FOR POWERTRAIN APPLICATIONS

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Abstract

Rare earth containing magnesium alloys are the most promising alloys for powertrain applications. AM-HP2 has the best creep properties of currently proposed high pressure die casting alloys for elevated temperature applications. One of the most important issues for all creep resistant Mg alloys has been to obtain excellent creep properties and good castability simultaneously. A new die for assessing multiple aspects of castability has been designed. This die allows assessment of the many aspects of castability that are required for good casting quality including die filling, susceptibility to hot tearing and defects at flow fronts. Using this die, alloys with improved die castability and which retain the already excellent creep properties of AM-HP2, have been identified.

Introduction

One of the most important considerations in the development of a diecasting alloy is the castability of the alloy. However, since this is such a difficult property to define [1,2], it is often not until industrial beta-trials take place that the actual castability can be truly tested. The concept of good castability in a high pressure die casting plant incorporates many things. Firstly, the melt needs to be well controlled to reduce burning or excessive oxidation. The metal needs to readily fill the die cavity (fluidity), and the final part must not have continuous hot tears or porosity that extend to the surface. However, there are a number of other defects that may occur, including issues related to flow from thin to thick sections, flow around notches and where metal flow fronts meet from different directions. Furthermore, thick sections, such as bosses are prone to defects resulting from insufficient filling or due to shrinkage cracking when they are poorly fed. Internally, banded defects [3] and externally solidified dendrites [4, 5] affect the casting integrity and the mechanical properties of the part. The alloy needs to be resistant to soldering to the die surface, and the part needs to be strong enough to be able to be ejected from the die without deformation and ductile enough that it does not fracture. If an alloy can do all of these things then it is deemed castable.

In the laboratory some aspects of castability, such as hot tearing [6-8] and fluidity [9-11], are easily measured. Also, the amount of porosity in castings can be characterized using conventional metallographic techniques [12] and advanced techniques including digital image analysis [13, 14] and X-ray tomography [15] are now being used to characterize porosity. Rules of thumb can be devised for improving each of these factors including an increase in the amount of eutectic to improve fluidity, elimination of low melting point phases to reduce hot tearing and reducing the freezing range of alloys to reduce the amount of shrinkage porosity [11, 16].

Many casting defects can be minimized by good design of the casting, its feeding and the inclusion of overflows, vents and the use of vacuum. However, one of the most important reasons that casting is often used to make parts is that complex shapes are able to be made, which means that hot spots, regions of high stress and long flow lengths inevitably occur, all of which exacerbate the occurrence of casting defects. Hence the production of a good casting relies on both a good casting design and an alloy with sufficient castability to be able to make that casting.

In the end, a stable process is dependant upon the operating window for casting, i.e. the range of parameters in which an alloy is able to be cast. This window needs to consider operational parameters such as melt temperature, delay time between the filling of the shot sleeve and casting, the change over position between low speed and high speed injection, gate velocity and die temperature amongst other things. Since each alloy has its own solidification characteristics, different alloys have different operating windows.

There has been a large amount of work on the development of Mg alloys with high creep resistance for powertrain applications [17, 18]. One of the factors that has limited the uptake of these alloys is the need for good creep properties to be combined with good castability [2, 19]. Many of these alloys have been evaluated for particular aspects of castability in the laboratory [20] and there are plenty of examples of new alloys that have been cast into commercial dies [20-22]. These trials have definitely helped improve the castability of the alloys [20, 22, 23]. AM-HP2 is a creep resistant alloy that has been developed jointly by CAST and AMT [24]. It has outstanding creep properties compared with other Mg alloys. However, whilst it has been observed that the alloy has good castability in the simple geometries needed to produce test samples, it was important that it be trialed in a die that tested its castability so that the composition could be

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optimized for castability. Furthermore it is important that its castability is compared with other Mg alloys, competing for similar applications.

This paper introduces a new casting design developed as a screening test for the castability of magnesium-based alloys. It is designed to test an alloy's castability by incorporating as many of the factors that the quality of a casting as possible. Whilst making parts in an experimental die will not be able to define the casting parameters for an industrial casting, it can show how different alloys prefer different casting conditions so that the operating window for casting an alloy can be found more rapidly. This paper focuses on the use of the new castability die and its role in the development of more castable and more creep resistant Mg alloys.

The Castability Die

A part made from the new castability die is shown in Figure 1. It was fed by a 3 part fanned gate, as indicated by the broad white arrows along the bottom edge of the part. It is a flat square plate with a dimension of 130mm and is mostly 3mm thick. It contains two boxes: an outer one with walls 1.5mm thick and 10mm high and an internal box with walls 1mm thick and 20mm high. The outer box has 3 notches on one side, 1, 1.5 and 2mm in diameter to initiate hot tears and flow instabilities (as indicated by the narrow white arrows on the LH edge of the part in Figure 1).



Figure 1. A part made in the new castability die in its as-cast condition. The 3 part fanned gate enters the casting from the lower part of the photograph.

Inside the centre box, the thickness of the bottom plate reduces to 2mm and then to 1mm. There are a series of ribs on the gate side of the box, which generate hot spots and stress raisers. At each corner of the inner box is a rib which goes to a boss of 10mm diameter and 20mm high, which tests an alloy's tendency to form shrinkage defects in thicker sections. One of the bosses near the gate is directly fed by metal through the gate, the other is indirectly fed. There are three 10mm rectangular sections which are 1, 2 and 4mm thick at the opposite end of the die from the gate

for testing the alloy's fluidity (as indicated by the black arrow towards the top of the part in Figure 1). On each side are two bars that are similar to the gauge length of tensile specimens as a further test of hot tearing. At the top edge of the casting, opposite the gate, were three small overflows.

The die tests an alloy's fluidity by requiring it to fill deep thin sections perpendicular to the metal flow and flow through thin sections parallel to the metal injection. The hot tearing resistance is tested by the inclusion of ribs and sections constrained by shrinkage, as well as the sections on either side of the casting which look like the gauge length of tensile specimens. To feed the back edge of the die, divergent metal flows must join. The flow of the metal is disturbed by notches in the wall of the outer box. Soldering can be observed during casting and the propensity to warping or fracture during ejection can also be monitored. Furthermore, the casting can be sectioned in different areas, such as the bosses, the thin to thick section geometries and in other places around the casting to assess the amount and type of porosity and the presence of defect bands that are common in magnesium alloys.

It should be noted that the test die was designed to be a screening die to evaluate an alloy's castability in a casting generically similar to those that may be found in industry. It is not meant for a rigorous scientific assessment of, for example, fluidity or hot tearing. There are other die configurations that are more suitable for this purpose.

Experimental Methods

The purpose of this study was to use the new castability die to evaluate the castability of highly creep resistant alloys based on the Mg-rare earth alloy, AM-HP2. Casting was undertaken on a Toshiba 250 tonne cold chamber high pressure die casting machine at CSIRO. The melt was protected using AM-Cover (HFC-134a in CO₂ carrier gas). Fourteen different alloys were evaluated in all and this paper will show results from two of these alloys. One of the alloys is close to the original AM-HP2 (Alloy A) and the other was the best of the alloys evaluated which had both excellent castability and retained the excellent creep properties that have been achieved by AM-HP2 (Alloy B).

During the casting of the first alloy, the casting parameters were altered extensively in order to establish a baseline. The trials involved increasing the speed of metal injection (1-2 m/s plunger velocity) and also increasing the die temperature (250°C to 300°C). Out of this, a matrix of casting conditions was selected which would be used to produce a series of samples (three at each set of conditions) to be evaluated for casting quality (both external and internal).

The castings were evaluated by visual observation and through metallographic observation of their internal microstructure. A quality scale (from worst (1) to best (5)) was established to grade the external appearance of a cast part with regard to two factors associated with fluidity, and the extent cracking manifest on the surface of the part (see Table 1).

Selected castings were sectioned for observation of the defects in the microstructure (Figure 2). A wide variety of regions were studied so that the defect structure within the casting could be

evaluated. The samples were ground and polished using standard metallographic techniques and observed in an optical microscope.

Table 1. Definitions for the grading system applied to castability die parts for evaluation of performance.

Grade	Quality Factor	
	Filling	Cracking
1	Major filling problems e.g. box edges not filled, thin section in base of box not filled.	Extensive cracking throughout casting.
2	Almost filled but large amounts of 'spangling'/ turbulent flow defects.	Significant cracking throughout casting.
3	Filled but a lot of roughness in edges and flow defects around notches.	Some minor localised cracking.
4	Fully filled but some roughness at edges of boxes, or minor defects behind notches or flow swirls in overflows.	Only some minor flow lines/cold shuts or very minor dimpling, hairline cracking.
5	Fully filled including overflows, no obvious defects behind notches.	No visible signs of cracking or flow defects.

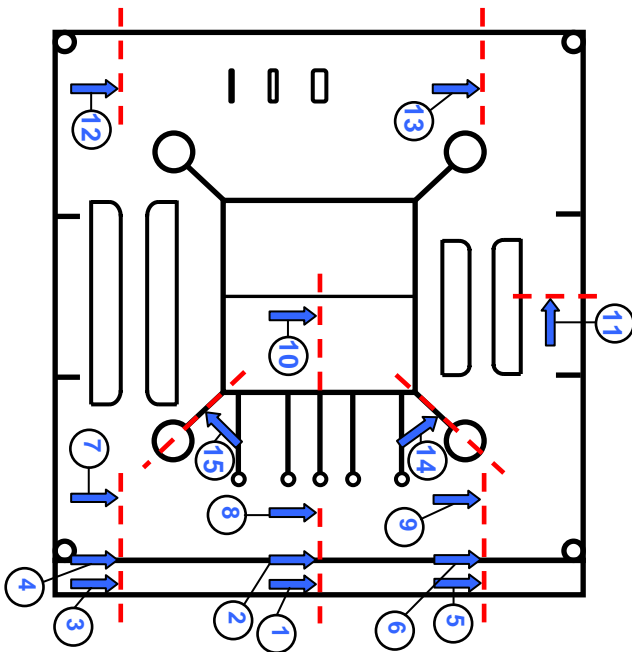


Figure 2. Positions where the castings were sectioned for metallographic observation.

Results

One of the important findings of these experiments was that obtaining the optimum casting parameters is critically important for the performance of the alloy. The difference between the

worst and best set of casting parameters showed a lot greater variation in casting quality than did the difference between alloys. As expected, the surface quality of all the alloys cast tended to improve with an increase in the injection velocity and an increase in the die temperature (Figure 3). Metallography of the internal sections showed that alloys that contained a very low rating from external observations also had a large number of internal defects. Hence the visual observation of the external appearance of the die casting was useful for obtaining an indication of the internal casting quality.

Despite the casting conditions having a large effect on the casting quality, it was apparent that once the optimum operating window had been established for each alloy there was also a large difference between the quality of the castings made from the different alloys, often with only relatively small changes in composition. The best castings obtained by Alloy A rated according to the criteria given in Table 1 were at a die temperature of 300°C and a gate velocity of 2m/s (Figure 3). However, Alloy B produced better castings at a lower die temperature than Alloy A and the castings at the highest gate velocity were rated at above 4 (Figure 3), despite the difficulty of the casting design. Importantly, it appears that the operating window of Alloy B is relatively wide which means that the production of high quality castings is not too sensitive to variations in process parameters. Hence it is probably more able to be cast effectively in industry.

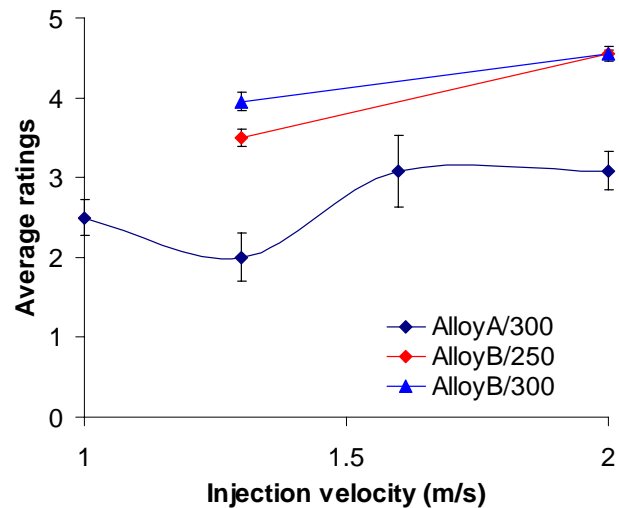


Figure 3. Variation in the ratings from visual observation injection velocity for Alloy A at a die temperature of 300°C and Alloy B for die temperatures at both 250 and 300°C. The data is an average of the filling and cracking ratings and the error bars estimate the variation of quality between the castings.

Microstructural observation of Alloy A castings (Figure 4) showed that at the gate the casting appeared to be of high quality with only some expected porosity present (Figure 4(a)). However, other sections of the casting showed some internal cracking ((Figure 4(b)), probably related to insufficient feeding and/or hot tearing particularly at distances further from the gate (Figure 4(c)&(d)). The cracking was not particularly extensive; especially when compared to castings produced at lower die temperatures and injection velocities. Furthermore the cracking

was fully contained within the casting, which means that cracking will not affect its pressure tightness. However, given the observation of the defects within the casting in this alloy, it does appear that, in castings where there are hot spots and high shrinkage stresses in constrained sections, there would be a tendency for this alloy to have some castability problems. As is typical in HPDC castings some gas porosity was observed.

The most difficult parts of the casting to fill well are the bosses which are attached to the corner of the internal box by ribs, which were observed using sections 14 and 15 in Figure 2. Because each boss is a thick section which needs to be fed through a thin section, all alloys have great difficulty in producing defect free bosses. As expected for Alloy A there was a fair amount of cracking and porosity (Figure 4(e)).

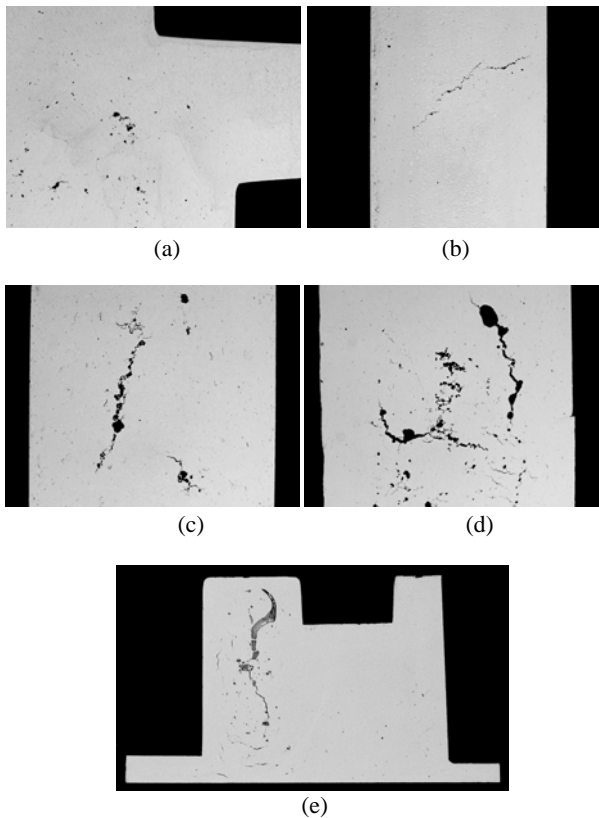


Figure 4. Optical micrographs showing the defect structure within the casting produced from Alloy A at an injection speed of 2m/s and a die temperature of 300°C. Positions are shown in Figure 2. (a) Position 2 (b) Position 10 (c) Position 11 (d) Position 13 and (e) Position 15.

Alloy B showed a very sound microstructure in all regions of the casting. Figure 5 shows the defect structure of sections from the same areas as those sampled for Alloy A (Figure 4) and it can be seen that no cracking was observed and the only defects present were low levels of dispersed porosity. Even at lower injection speeds for the die temperature of 300°C the level of defects observed was relatively low. At a die temperature of 250°C, some banded defects were observed, as are often seen in HPDC Mg alloys [3]. It is apparent that Alloy B is much more easily cast, both in terms of filling the die efficiently and in terms of reducing the amount of cracking observed in the cast part.

Some porosity and cracking was observed in the boss section, (Figure 5(e)) but it still showed a substantial improvement over Alloy A. It should be noted that all alloys including, AZ91 show defects, in sections such as this.

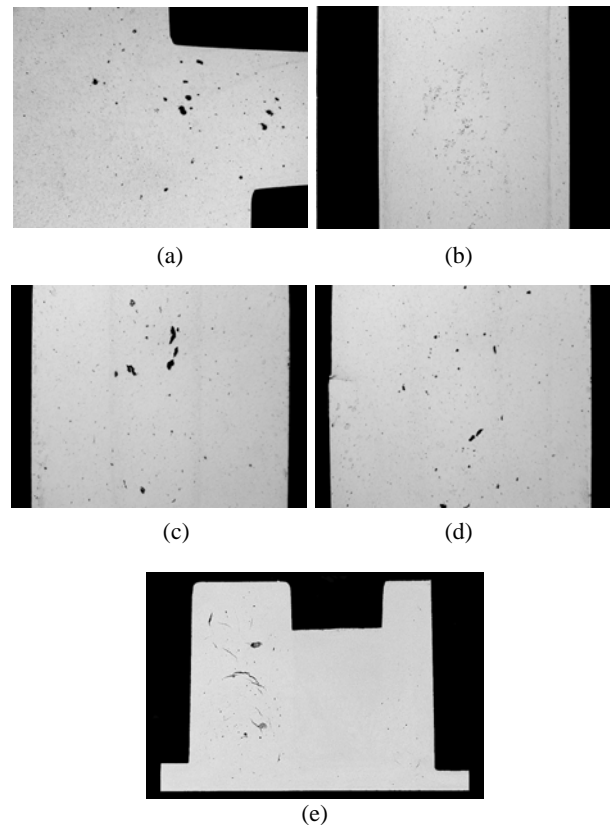


Figure 5. Optical micrographs showing the defect structure within the casting produced from Alloy B at an injection speed of 2m/s and a die temperature of 300°C. Positions are shown in Figure 2. (a) Position 2 (b) Position 10 (c) Position 11 (d) Position 13 and (e) Position 15.

Creep Properties

Creep properties of the various alloys tested were evaluated, as it is critical to be able to optimize both castability and excellent creep properties.

Benchmark creep test conditions of 177°C and 90MPa were used for initial evaluation of the suitability of the alloys for application in engine blocks. Under these conditions most Mg based alloys perform poorly. Both Alloy A and Alloy B have a creep resistance that far exceeds that obtained by rival HPDC creep resistant alloys such as AJ52 and AE44 (Figure 6). AE42, the benchmark creep resistant alloy from only a few years ago, is also plotted to show how much the creep properties of HPDC magnesium alloys have improved over a relatively short space of time.

Alloy B was found to have excellent creep properties similar to the sand casting alloy AM-SC1. In fact, the creep properties of Alloy B are better than Alloy A, which tended to go into tertiary creep after about 500 hours. Alloy B appeared to still be undergoing primary creep after this time.

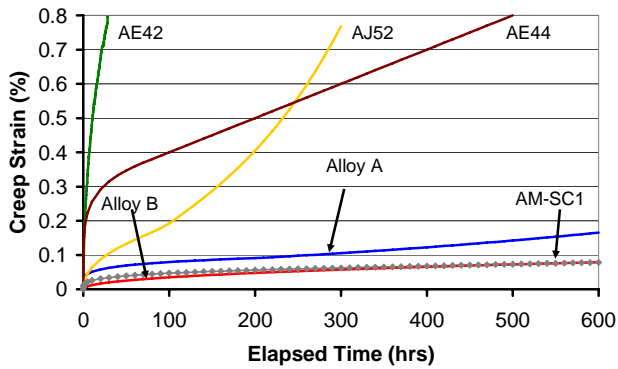


Figure 6. Comparison of the creep performance of recently proposed HPDC alloys for powertrain applications with AM-SC1(T6) and Alloys A and B. All alloys were tested under the same conditions, 177°C and 90 MPa.

Discussion

It is apparent that whilst studies into fluidity and hot tearing are very important to assist alloy development, reliance upon these tests to assess castability is not sufficient, because castability is very complex to evaluate. The die developed and presented in this paper has been very useful for evaluation of the castability of a series of alloys as it simulates conditions that are often observed in commercial HPDC parts. These include divergent and convergent melt flows, section thickness changes, hot spots, regions of high stress concentration and the feeding of deep sections perpendicular to the melt flow.

The work performed so far has shown that there are two uses of this die. The first one is to obtain an understanding of the casting parameters by which an alloy is best cast, although it is likely that the optimum casting conditions will always be both alloy and part specific. In general, for the alloys tested here, a hotter die temperature and a higher injection speed produce the best castings. However, it may be anticipated that alloys with different non-equilibrium solidus temperatures, different high temperature strengths, or susceptibility to soldering may require different casting parameters for optimum casting conditions.

The second, and more important use in the case of the current study, is to assist with the optimization of alloy composition to obtain sound castings. This study has shown that relatively minor changes in alloy composition can substantially affect the castability of an alloy. Because of the many factors that appear to affect an alloy's castability including the alloy's temperature-fraction solid profile, the amount and morphology of precipitate phases, the surface tension of the oxides, the formation of inclusions etc., it is difficult to predict an alloy's castability despite there being some guidelines to point alloy designers in the right direction. The die presented here is able to evaluate many of these factors in one casting trial for a particular alloy.

Both of these factors are important when considering the commercial prospects for a promising alloy. If an alloy is able to cast a relatively complex part on a small scale it is more likely, although not certain, that it will be able to cast a commercial part as well. More importantly though, is that optimizing casting into the experimental die gives the die casting operators an idea of the casting parameters that are likely to be required for optimum

casting of an alloy. As shown in Figure 3, not having the casting conditions optimized for a particular alloy can be as detrimental to casting quality as the alloy composition itself. Hence it is likely that if it is attempted to cast new alloys, particularly creep resistant alloys, in a manner similar to known alloys, e.g. AZ91, they will not perform very well. They may be just as castable, but the optimum casting parameters are likely to be different. It is planned to assess the casting windows for common alloys such as AZ91 and AM60 and use the die to demonstrate the differences in the optimum casting conditions for new alloys.

An important lesson for alloy designers that has been reinforced in this study is that, once a series of alloys that has reasonable castability is identified, then the creep properties of an alloy can be improved considerably if the researchers have a reasonable understanding of creep mechanisms. This has been shown already in the Mg-Al system where alloying elements have been added, which have substantially improved the creep resistance of the alloys in this system [20, 25, 26], although usually at some reduction in castability. However, the creep resistance of Mg-Al alloys is so poor to begin with that even orders of magnitude improvement in creep resistance does not lead to alloys that are particularly useful in the more demanding powertrain applications such as engine blocks. Hence a different, castable system with improved base level creep resistance is required as a base for the development of creep resistant Mg alloys. This has been the approach taken in the development of AM-HP2 alloy variants and substantial improvements to creep resistance have been achieved, whilst still achieving acceptable castability.

Conclusions

A new die has been shown to be able to show differences in castability between different variants of the AM-HP2 alloy. This has allowed for alloy compositions with optimized castability to be developed. Furthermore, an alloy composition with good castability was found to also have excellent creep properties, which are an order of magnitude better than other candidate HPDC Mg alloys.

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