

## AM-HP2: A NEW MAGNESIUM HIGH PRESSURE DIECASTING ALLOY FOR AUTOMOTIVE POWERTRAIN APPLICATIONS

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### Abstract

AM-HP2 is a new magnesium die-casting alloy that has been specially developed to provide a combination of good diecastability and excellent creep resistance at temperatures in the range 150-200°C. This temperature range is important for many automotive powertrain applications. AM-HP2 was developed to have properties that are similar to the very successful sand-casting alloy AM-SC1 but with alloy modifications to ensure good diecastability. The alloy was developed in recognition of the significant advantages of high pressure die-casting for higher production rates and lower manufacturing costs compared to sand-casting. AM-SC1 is most suitable for production of prototypes and small production runs (as for the V6 engine block of the USCAR MPCC program) while AM-HP2 provides similar properties in the as die-cast condition (no need for a post-casting heat treatment). This paper compares the properties of AM-HP2 with other commercially available high temperature creep resistant magnesium alloys.

### Introduction

It is well recognised that magnesium alloys provide a valuable route to achieving the significant reductions in weight being sought by the automotive industry. It is equally well known that the elevated temperature properties of most commercially attractive magnesium alloys are generally inadequate for engine applications where major weight savings can be achieved.

There are two viable processing routes for engine crankcases: Low pressure/gravity casting and high pressure die casting. The low pressure/gravity route offers opportunities for more complex component design, and for a post-casting heat treatment to develop the final mechanical properties of the alloy. This secondary processing step in itself adds cost to the final product, and also generally requires a more expensive alloy to begin with – grain refinement of suitable magnesium alloys is a necessity in sand-casting alloys, for instance. In contrast, high pressure die casting is a much faster solidification process and does not require grain refinement, but it is usual that the final properties must be developed during the casting process, and therefore a slightly different approach to alloy development is required.

To date, the development of high pressure die casting magnesium alloys has concentrated on the Mg-Al alloy system, which is cost competitive and additions of aluminium contribute to improving the diecastability of magnesium-based alloys. However, the presence of aluminium is deleterious to elevated temperature creep properties and it is necessary to make further alloying

additions to overcome these problems. The most successful of these additions to date have been calcium, strontium and the rare earth elements, but even with these there are limits to the level of creep resistance that can be achieved. Moreover, these alloying additions tend to reduce the ease of die casting.

AM-HP2 is based on the Mg-rare earth (RE) alloy system and therefore avoids the elevated temperature limitations associated with the Mg-Al family of alloys.

### Experimental

#### Oxidation Trials and Castability

In order to evaluate the potential for the addition of small amounts of certain alloying elements to improve the oxidation resistance of molten AM-HP2 a number of oxidation trials were conducted. A charge of approximately 1 kg of alloy was melted in a small covered furnace using AM-cover as the cover gas for melt protection. The melt temperature was in the range 738-740°C at all times. A sample was poured into a stainless steel cup (65 mm diameter opening tapering down to 55 mm over a height of 35 mm) and allowed to solidify in a stagnant ambient atmosphere (no additional cover gas was applied). Solidification occurred generally over a period of a couple of minutes.

A detailed description of the testing procedure for the evaluation of the castability of AM-HP2 has been reported elsewhere [1]. AM-HP2 was compared to AZ91D, under processing conditions appropriate to each alloy, using a 250 tonne Toshiba cold chamber die-casting machine with a shot plunger diameter of 50 mm, and a die designed specifically for castability assessment.

#### Mechanical Properties

For the purposes of mechanical property evaluation cylindrical dog bone specimens were die cast, with a gauge length of 25 mm and diameter of 5.6 mm [1]. Tensile tests were conducted at RT, 100, 150 and 177°C and a strain rate of  $3.3 \times 10^{-3} \text{ s}^{-1}$ . Constant load tensile creep tests, using an oil bath controlled to an accuracy of  $\pm 1^\circ\text{C}$ , were conducted for a period of 600 hours, not to failure.

The bolt load retention (BLR) behaviour was determined using an assembly similar to that described by Pettersen and Fairchild [2]. The two identical alloy bosses used in the assembly were each 16 mm outside diameter, 8.3 mm inside diameter and 15 mm high. M8 high tensile bolts equipped with a load cell were used to apply the load to the assembly. The test conditions chosen for this evaluation were 150°C and 177°C, with applied loads of 8 kN and

11 kN (corresponding to compressive stresses of 54.4 MPa and 74.8 MPa respectively). These loads were applied at room temperature, prior to the assemblies being placed in an oven at the test temperature. The duration of the test was restricted to 100 hours, after which the assemblies were allowed to cool in air overnight to room temperature. The AM-HP2 samples were high pressure die cast to size, so that only the mating surfaces were machined.

**Results and Discussion**

Oxidation Trials and Castability

The composition of AM-HP2 has been modified to significantly reduce the oxidation that occurs when the alloy solidifies in air. Control samples of alloy without these modifications experience severe oxidation during solidification resulting in formation of a hard, black/brown nodular crust on the surface of the coupon. In addition, oxide stringers were observed to extend for several millimeters from the top surface into the bulk of the unmodified alloy. Figure 1(a) shows the as-solidified surface of a test coupon of AM-HP2. This sample displays little oxidation and a good surface finish. Internal oxide stringers were isolated near the top surface of the coupon (see arrow in Figure 1(b)) confirming that no problems with oxidation were encountered during the pouring of the alloy. It was also observed that the AM-HP2 composition provides significant improvements in the behaviour of the molten alloy in the furnace crucible, with far less dross formation than when unmodified alloy is melted. This oxidation resistance has a very positive influence on the castability of the alloy.

It has been shown that the diecastability of AM-HP2 is very similar to AZ91D, with the relative size of the processing windows being equivalent for the two alloys [1]. However, AM-HP2 tends to have a more rapid change in casting quality at the edge of the operating window. Under the conditions of the test and with the purpose designed die AZ91D required a die temperature of 200°C in order to obtain a good surface finish, which agrees with normal production requirements for this alloy. AM-HP2 required both hotter metal and a hotter die for optimum results. In general the castings made with both AZ91D and AM-HP2 had a high quality surface finish on both faces, which demonstrated that both alloys can flow reasonable distances in the die cavity. For AM-HP2 no propensity for cracking at the root of sharp corners was found, while for AZ91D some signs of hot tearing were observed. An example of the high quality surface finish on as-cast HPDC parts produced from AM-HP2 is shown in Figure 2.

The melt and die temperatures required for successful die-casting can vary significantly depending upon the setup being used. For example, in a successful die casting trial conducted in a production environment with a total shot weight of more than 30 kg the melt temperature was maintained at 700°C, and the die surfaces were heated to between 180°C and 200°C.

Microstructure

The internal structure of a cylindrical tensile specimen of AM-HP2 was observed to be very sound on a macroscopic scale, and free from any gross casting defects, with no cracking within the gauge length. The low magnification micrograph of Figure 3(a) shows that there is very little porosity in AM-HP2 cast under the

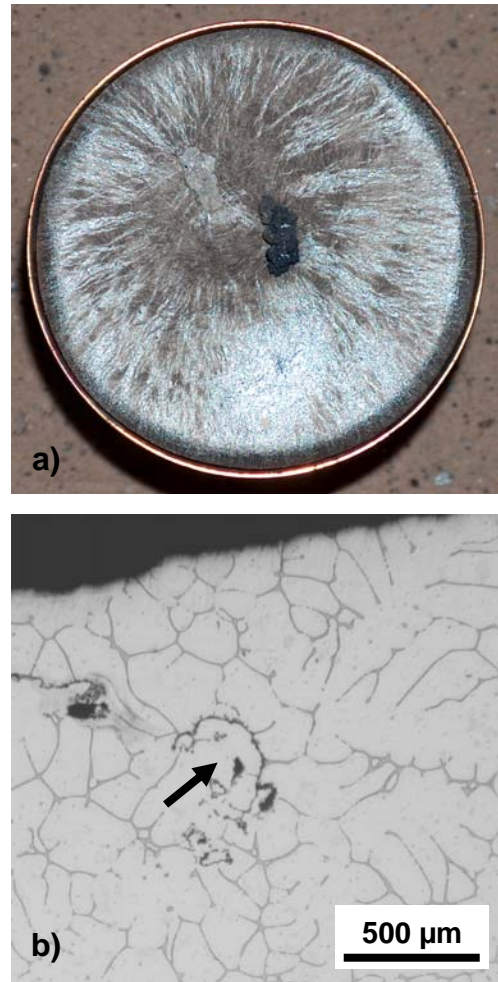


Figure 1. a) Photograph of the as-solidified top surface of a sample of AM-HP2 cast in air and b) an optical photomicrograph near the ‘free’ surface of a section through the diameter of the casting shown in (a) and showing a very limited extent of oxidation.



Figure 2. AM-HP2 part showing a high quality reflective surface finish in the as-cast condition (plate is 70 mm wide).

appropriate conditions. The higher magnification image of Figure 3(b) shows that the microstructure of AM-HP2 typically consists of a magnesium-rich matrix having a distinctly dendritic morphology and an interdendritic intermetallic phase, which is based on a Mg-RE compound similar to that observed in AM-SC1. This intermetallic phase forms an almost continuous framework throughout the structure, is thermally stable and provides mechanical rigidity to the entire microstructure. This is considered to be an essential element in a magnesium alloy with good elevated temperature creep resistance.

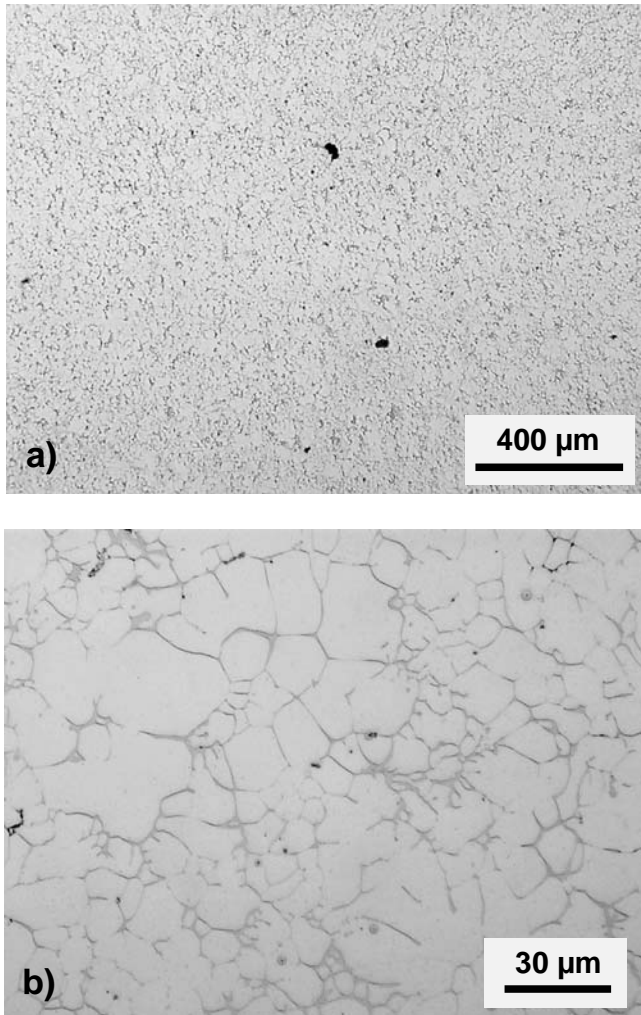


Figure 3. Optical micrographs taken from the gauge length region of the circular tensile test specimen at a) low magnification to indicate a low propensity for casting defects and b) higher magnification to reveal the as-cast microstructure typical of AM-HP2.

#### Tensile Properties

Tensile tests were conducted on as-cast specimens of AM-HP2 at various test temperatures and the results are contained in Table I. The proof stress, ultimate tensile stress (UTS) and elongation values for AM-HP2 are compared with those of AE42 and AJ62 [3], as a function of the test temperature, in Figure 4.

Table I. Tensile test data for AM-HP2.

Temp. (°C)	0.2% Proof (MPa)	UTS (MPa)	% Elong.
21	139.8 ± 3.9	161.3 ± 4.2	1.9 ± 0.4
100	140.7 ± 3.0	156.5 ± 5.9	3.4 ± 0.8
150	134.5 ± 2.2	154.9 ± 9.4	4.6 ± 1.4
177	131.2 ± 4.3	149.0 ± 7.3	4.8 ± 1.0

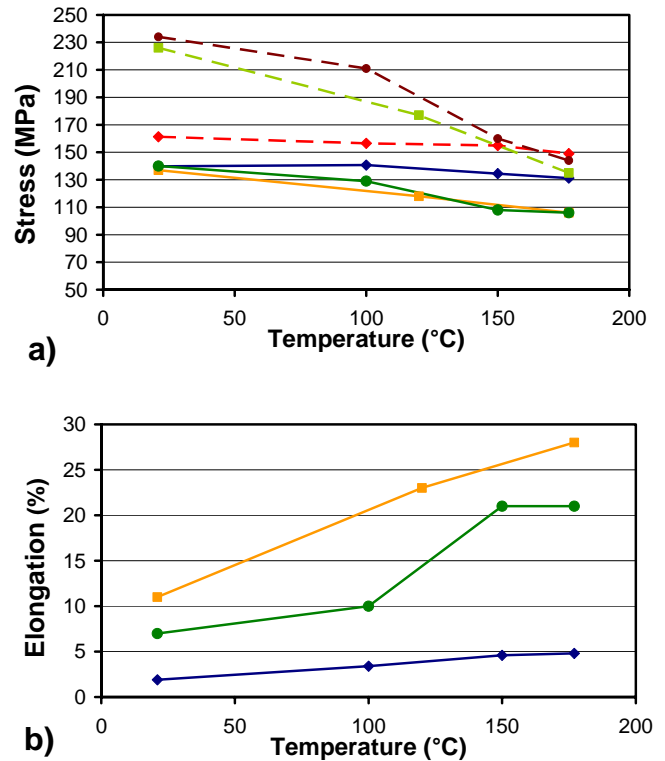


Figure 4. a) Comparison of the 0.2% proof stress (solid lines) and UTS (dotted lines) for AM-HP2 (diamond), AE42 (square) and AJ62 (circle) magnesium-based creep resistant alloys. b) Comparison of the elongation to failure for the same three alloys.

The RT properties of AM-HP2 are modest compared with those of the other two alloys. However, at test temperatures of 100°C and above, the strengths of both AE42 and AJ62 begin to decrease significantly which is in contrast to the behaviour observed for AM-HP2 (see Figure 4(a)). In fact at the temperatures of most significance to the extreme end of the powertrain (i.e. 150°C to 177°C) AM-HP2 has a distinct advantage over the other two alloys with regards to its 0.2% proof stress. It can also be seen that AM-HP2 has a lower ductility compared to AE42 and AJ62 (see Figure 4(b)) at all test temperatures, but it exhibits ample ductility for powertrain applications. Moreover, it is the fact that AE42 and AJ62 are so ductile at elevated temperatures that gives them inferior creep properties to AM-HP2.

## Creep Behaviour

The creep curve of as-cast AM-HP2 is compared with that of AM-SC1, in the T6 condition, in Figure 5 under the stringent test conditions of 177°C and 90 MPa. The creep behaviour of AM-HP2 is extremely promising, with the response being indistinguishable from that of AM-SC1 for the first 400 hours of the test, although at this time AM-HP2 displays the onset of tertiary creep. There is of course a degree of variability between die cast test specimens and this curve demonstrates the results that can be achieved for AM-HP2 under the appropriate casting conditions. It should also be noted that AM-HP2 does respond to heat treatment with a corresponding improvement in the creep performance.

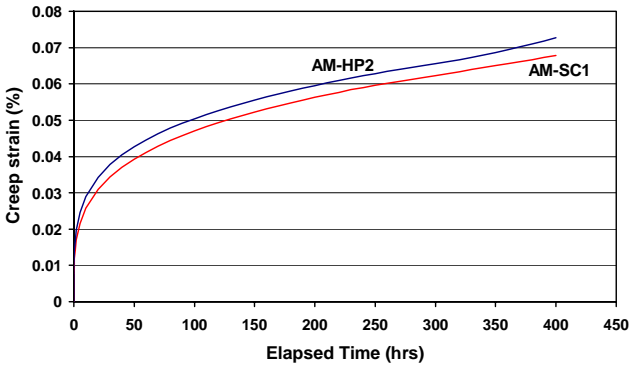


Figure 5. Comparison of the creep response of AM-HP2 and T6 heat treated AM-SC1 tested under the same conditions of 90 MPa at 177°C.

The creep properties of AM-HP2 are compared with published data for AJ62 [3], AE42 and AE44 [4] die casting alloys in Table II (note that the data for AE44 is for 100 hours only). It can be seen that AM-HP2 has better creep behaviour than any of the other alloys even though it was tested under a more severe level of stress.

Table II. Comparison of the tensile creep behaviour of AM-HP2 with that of other creep resistant die casting alloys.

Alloy	Creep Condition		Creep Strain at 200hrs (%)	Creep Rate at 200hrs ( $s^{-1}$ )
	Temp. ( $^{\circ}C$ )	Stress (MPa)		
AM-HP2	177	90	0.06	$2 \times 10^{-10}$
AJ62	175	50	0.05	$4.6 \times 10^{-10}$
AE42	177	75	0.23	$2.3 \times 10^{-9}$
AE44*	177	75	0.05	$6.9 \times 10^{-10}$
AM-SC1	177	90	0.06	$2 \times 10^{-10}$

\*(100hr data)

## Bolt Load Retention Behaviour

The overall BLR behaviour of AM-HP2 is not quite as stable as AM-SC1, with small declines at both higher loads and higher temperatures (see Figure 6(a)). AM-HP2 does not show the unusual behaviour seen with AM-SC1 at 150°C, where the overall bolt load retention is greater at the higher load. The creep behaviour, as measured by the % load retained at the test

temperature (see Figure 6(b)), is essentially the same for both alloys, within the limits of experimental error.

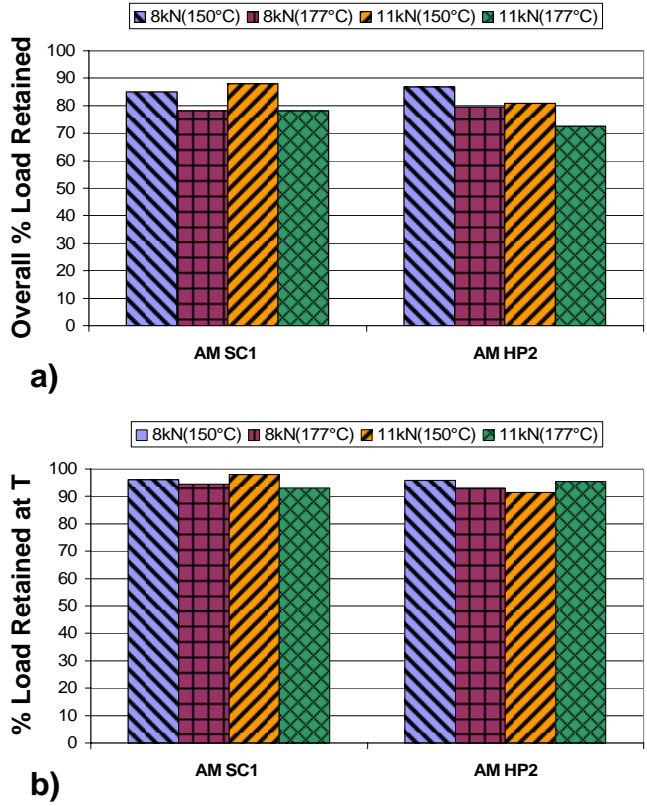


Figure 6. a) Comparison of the overall BLR behaviour for sand-cast AM-SC1 and AM-HP2. b) Comparison of the BLR behaviour at temperature for sand-cast AM-SC1 and AM-HP2.

The significant loads, in terms of defining the BLR behaviour, 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 load reached once the sample had been heated to the test temperature, T, to the relaxed load after 100 hours at temperature gives the load retention at T. These latter two loads are those used to determine the creep relaxation of the material at temperature. The BLR at the elevated temperature of 177°C, and the initial load of 11 kN, 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. This is an indication of the overall BLR behaviour, and the difference observed here between the two alloys is most likely due to the compressive yield strength of AM-SC1 being higher than that of AM-HP2. This has not as yet been confirmed by direct measurement. The BLR data from the AJ52 specification sheet provided by Noranda [5] reports that the overall behaviour (i.e. % retention at RT) for stresses in the range of 60 – 80 MPa is 45% at 150°C and 38% at 177°C (i.e. equivalent to the 11 kN test in this work). Clearly, AM-HP2 has a much better BLR response than AJ52 at temperatures most relevant to powertrain applications.

## Concluding Remarks

The combined diecastability and high temperature performance of AM-HP2 can best be described in relation to other creep resistant magnesium alloys currently under development by reference to a castability/creep performance space diagram as suggested by Aghion *et al.*[6] and shown in Figure 7. This diagram describes the relative positions of various alloys with respect to their diecastability 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 able to meet the performance demands for one of the most demanding of powertrain applications, the engine crankcase.

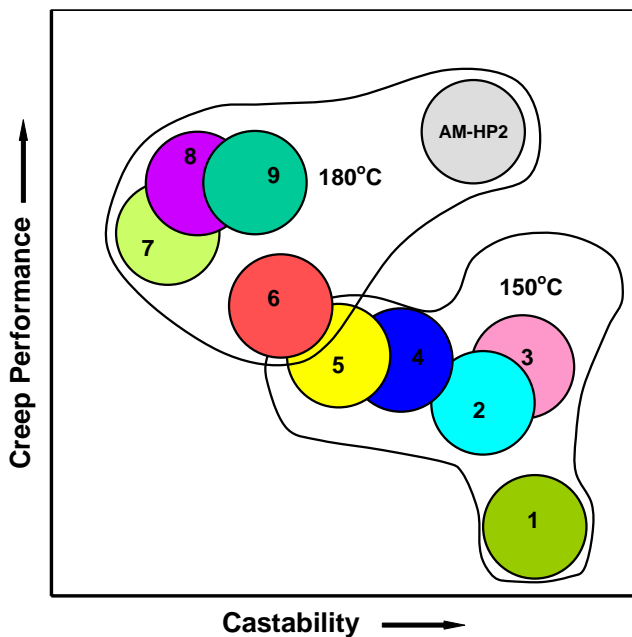


Figure 7. Schematic representation of the castability/creep performance space for current HPDC magnesium alloys (after Aghion [6]). The groupings indicate that the alloys contained within a bubble are suitable for use up to a working temperature of either 150°C or 180°C respectively. (Key: 1 AZ91D, 2 AS21X, 3 MRI 153M, 4 AJ62X, 5 AE42, 6 AJ52X, 7 ACM522, 8AX52J, 9 MRI 230D).

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