AM-HP2: A new magnesium alloy with improved diecastability and creep strength for powertrain applications

M.A.Gibson, C.J.Bettles*, M.T.Murray**, G.L.Dunlop**, S.P.Cashion****

** CAST Cooperative Research Centre, CSIRO Manufacturing and Infrastructure Technology, Australia*
*** Advanced Magnesium Technologies, PO Box 1364BC, Milton, QLD 4046, Australia*
**** AMT Europe GmbH Hans-Bunte-Strasse 10, 69123 Heidelberg, Germany*

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Abstract

AM-HP2 is a new creep resistant magnesium diecasting alloy that has been developed specifically for high pressure die cast powertrain applications. AM-HP2 has been developed to provide a combination of good diecastability and creep resistance at temperatures of relevance to powertrain applications. This paper describes in detail the diecastability of AM-HP2, compared to that of AZ91D, and discusses the high temperature properties using the successful sand-casting alloy AM-SC1 for comparison.

1. Introduction

Powertrain components offer a significant opportunity for reduction of weight at the front of vehicles which contributes significantly to improved performance, vehicle agility and fuel economy. Because of their large mass, engine blocks are components that provide attractive targets for the application of magnesium. This has been recognized by BMW who recently commenced mass production of a 6 cylinder petrol engine with a compound engine block comprised of an aluminium alloy insert surrounded by a die-cast outer block made from magnesium alloy AJ62.[1, 2]

AMT and its research partner CAST developed the magnesium sand-casting alloy, AM-SC1[3, 4] that was successfully used for the engine block of the Genios LE three cylinder turbo diesel engine developed by AVL List. This engine recently completed a two year 65,000 km road trial with excellent results in terms of performance and durability.[5] This demonstrated the suitability of AM-SC1 for engine block structures where stiffening inserts are kept to a minimum and cooling channels pass directly through the cast magnesium alloy. Because of its excellent properties for powertrain applications, AM-SC1 has been selected for the engine block of the V6 engine that is currently being manufactured for the USCAR MPCC magnesium intensive engine project.

The success of AM-SC1 has inspired AMT and CAST to develop a closely related alloy, AM-HP2, that is especially suitable for high pressure die casting (HPDC) and which has properties that are very similar to AM-SC1. This development is important because the cost of manufacture of engine blocks by HPDC is lower than by sand-casting and HPDC has become the casting route of choice for many light alloy engine blocks.

The diecastability of a particular alloy determines whether a complex component can be manufactured to specification by HPDC 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. This paper describes the diecastability of AM-HP2 with particular reference to the testing method, flow characteristics, defect levels and surface finish. Die-casting parameters for this particular diecastability test are presented and compared with those for the standard magnesium die casting alloy, AZ91D. Some critical elevated temperature mechanical properties for AM-HP2 are also presented and compared with the sand-casting alloy, AM-SC1.

2. Diecastability Assessment

2.1 Castability Die

Laboratory testing of the diecastability of AM-HP2 was carried out on a 250 tonne Toshiba cold chamber die-casting machine with a shot plunger diameter of 50 mm, located at CSIRO Manufacturing & Infrastructure Technology, Melbourne, Australia. A new die was designed in order to severely test the die-casting performance of the alloy being trialed and provide a quantitative evaluation of high pressure diecastability. This die, shown in Figure 1, was triangular in shape and had oil heating/cooling in both the fixed and moving halves of the die set. A thermocouple was located in the centre of the moving half.

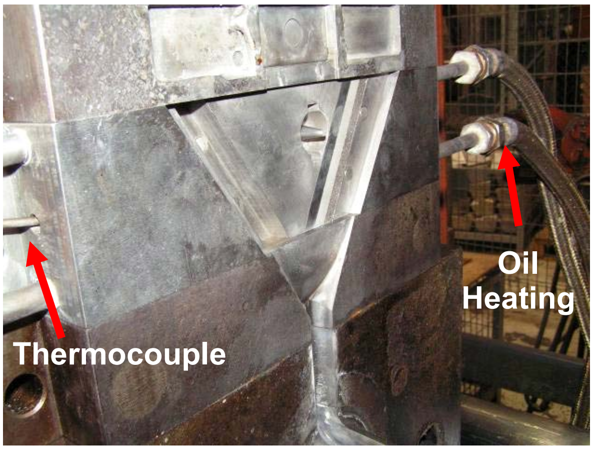

Figure 1: Moving half of the special diecastability test die

The die was designed to give both diverging and converging flow paths. This was achieved by having a fan gate, of dimensions 58 mm x 1 mm, feeding metal from the gate along the flat fixed half (diverging), across the back wall and back towards the gate (converging) (see Figure 2). This flow pattern gives an effective flow length of 130 mm, i.e. twice the height of the casting. The part produced with this die is shown schematically in Figure 3 (a), and a photograph of a cast component is shown in Figure 3 (b). 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.

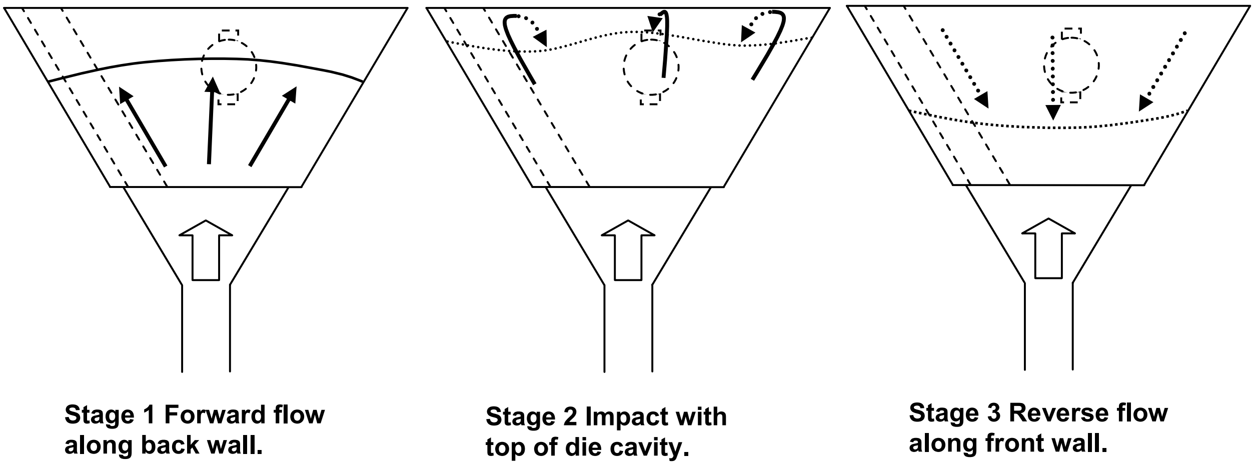

Figure 2: Diagram showing the three stages of flow during filling of the diecastability test die

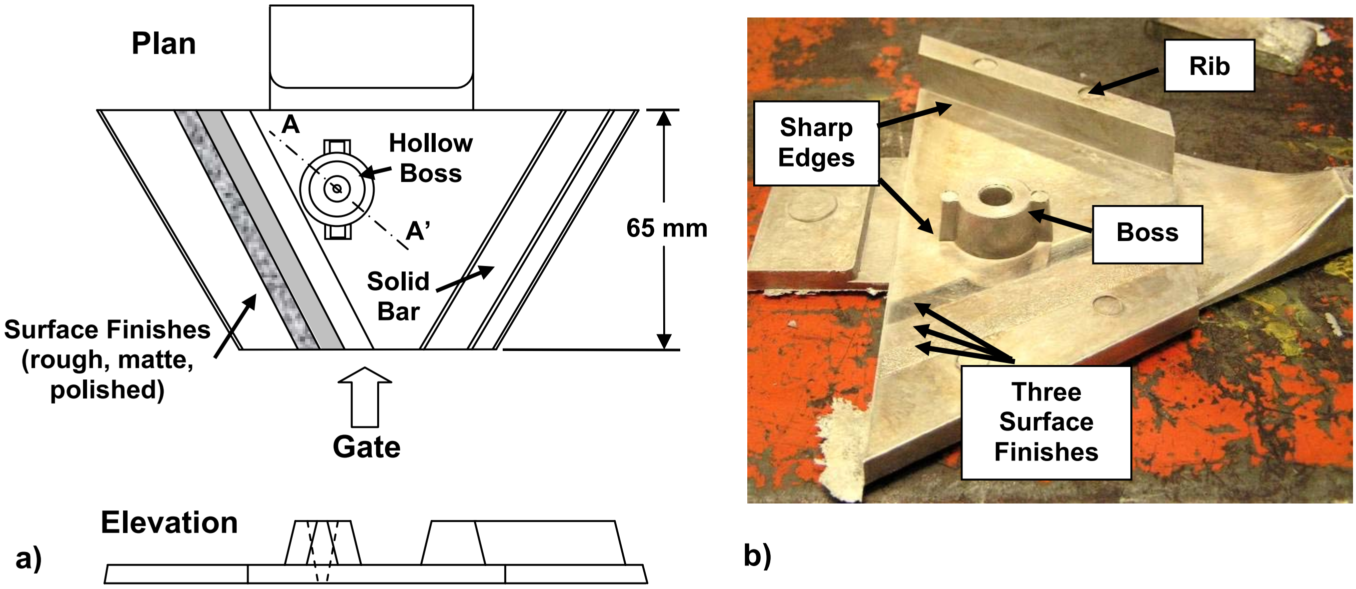

Figure 3: (a) Schematic diagram of the part that is produced with the diecastability test die (b) Photograph of casting showing large rib and boss.

2.2 Die-Casting Conditions

The die casting conditions were varied over a wide range in order to identify and characterise the best operating window for AM-HP2. The surface finish, as assessed through a simple visual inspection and shown in Figure 4, combined with any evidence of cracking at the sharp corners, were the criteria adopted for defining “good” or “bad” casting conditions. It was found that the diecastability of AM-HP2 and AZ91D was essentially the same, with the relative “widths” of the parameter windows being similar for the two alloys. However, AM-HP2 did have a more rapid change in quality at the edge of the operating window. Under the conditions of the test, 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 and, if insufficient metal was dosed into the shot sleeve leading to a reduction in the molten metal temperature entering the cavity, then surface quality diminished rapidly. In general, however, 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, although the AZ91D castings did have some surface cold shuts. For both alloys the holding time in the die was also varied so that some idea of the cracking propensity was determined. For AM-HP2 there were no signs of cracking at the sharp edges while for AZ91D there were some signs of hot tearing in one section of the large rib.

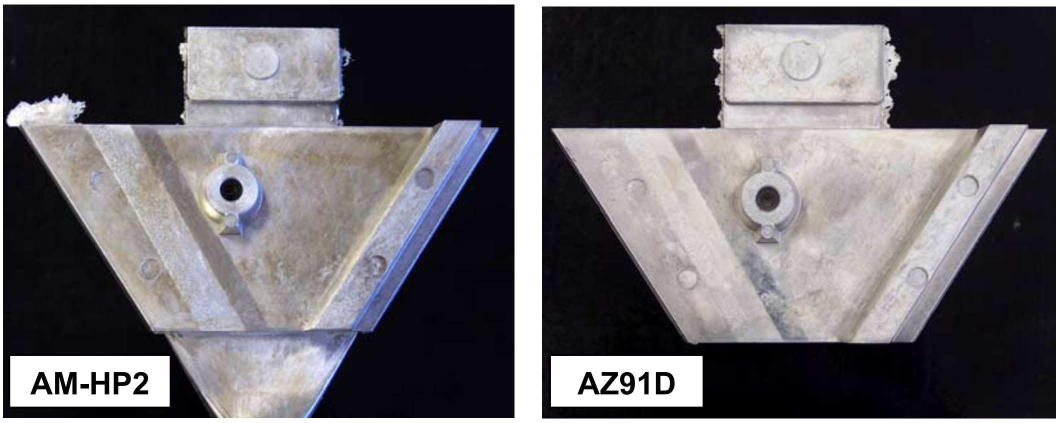

Figure 4 Comparison of surface finish of test castings from AM-HP2 and AZ91D.

On the basis of this assessment, optimum die-casting conditions for this particular die-casting cell and die setup were determined and these are presented for both alloys in Table 1.

Table 1 Best die-casting conditions for cold chamber HPDC of AM-HP2 and AZ91D.

Setting	**AM-HP2**	**AZ91D**
Melt temperature (^{o}C)	740	700
Slow Speed (m/s)	0.35	0.35
High Speed (m/s)	2.25	2.25
Gate Velocity* (m/s)	76	76
Min Oil Temp (°C)	230	180
Die Temperature (°C)	250	200
Part Cooling Time (s)	8-9	9

* Gate Velocity = $V_{plunger} \times A_{plunger} / A_{gate}$

The major differences between the two alloys are in the melt and die temperatures. In the particular configuration used in this die casting cell, the length of the transfer tube between the pump and the shot sleeve is long and the melt temperature is in part governed by heat losses occurring over this distance.

The melt and die temperatures required for successful die-casting can vary significantly depending upon the setup being used. Recently a die-casting trial of AM-HP2 was carried out in a production environment on a component with a total shot weight of 26.5 kg. The melt temperature was maintained at 700°C, and the die surfaces were heated to between 180°C and 200°C. Successful parts were produced with no obvious problems with cold flows or cracking.

2.3 Casting Quality

The casting quality was assessed through surface roughness measurements and visual inspection of the internal defect levels in the cast boss (sectioned through A-A' in Figure 3 (a)). The surface roughness comparison was carried out between the surface in contact with the polished strip on the die and the general cast surface, on a single as-cast part, selected at random, for both alloys. The surface roughness profiling was carried out over a line trace length of 5.6 mm. The results for AM-HP2 are shown in Figure 5(a) and, notwithstanding the odd "spikes" in the traces, the two alloys were found to be essentially the same. It should be noted that the comparison in each case was carried out on a single trace from one casting and as such there is no statistical significance in the results. Figure 5(b) demonstrates the quality of the as-cast mirror finish possible with AM-HP2.

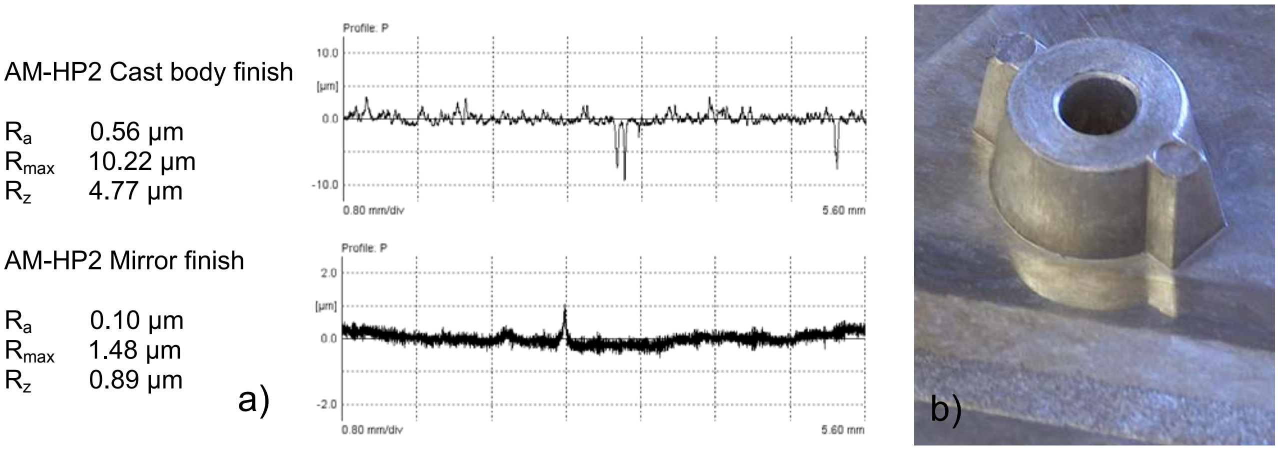

Figure 5: As –cast surface of AM-HP-2: (a) surface roughness profiles on the body of the casting and the mirror finish surface; and (b) an example of the mirror finish achievable on the casting facing the polished section of the die.

The results from a preliminary investigation of the internal structure of the castings are shown in Figure 6, which shows the hollow boss regions of parts cast in AM-HP2 and AZ91D. It can be seen that the porosity in these bosses is similar for both castings and that the overall level of defects is similar in such sections to other acceptable HPDC alloys.

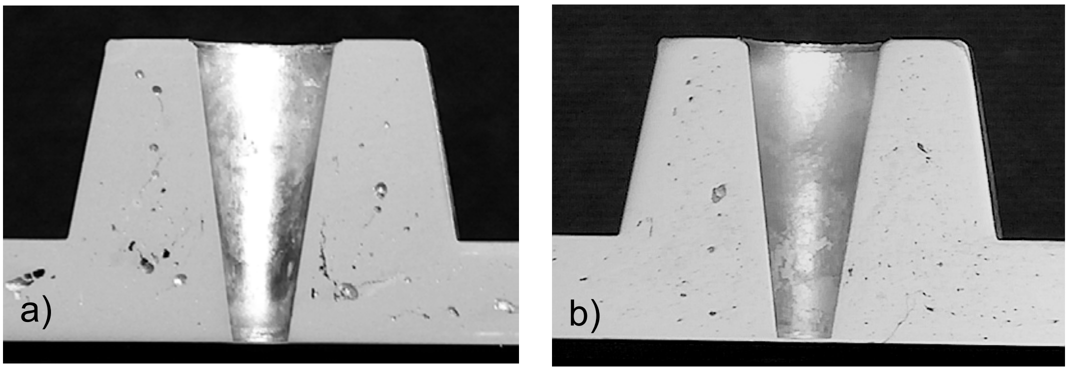

Figure 6: Macroscopic sections through the boss region of castings from (a) AM-HP2 and (b) AZ91D.

3. Elevated Temperature Performance

Having determined the optimum casting conditions for AM-HP2, further die-casting was carried out to produce “dog bone” specimens for tensile strength and tensile creep measurements and a solid boss for bolt load retention measurements. Figure 7(a) shows the dimensions of the tensile test pieces, together with an indication of the relative area of the in-gate compared to the diameter of the casting. The shape of these specimens is such that an alloy susceptible to hot tearing would show internal cracking within the gauge length. Figure 7(b) is a low magnification image of the material within the gauge length of AM-HP2 and it is clear that internal cracking was not a problem with this material.

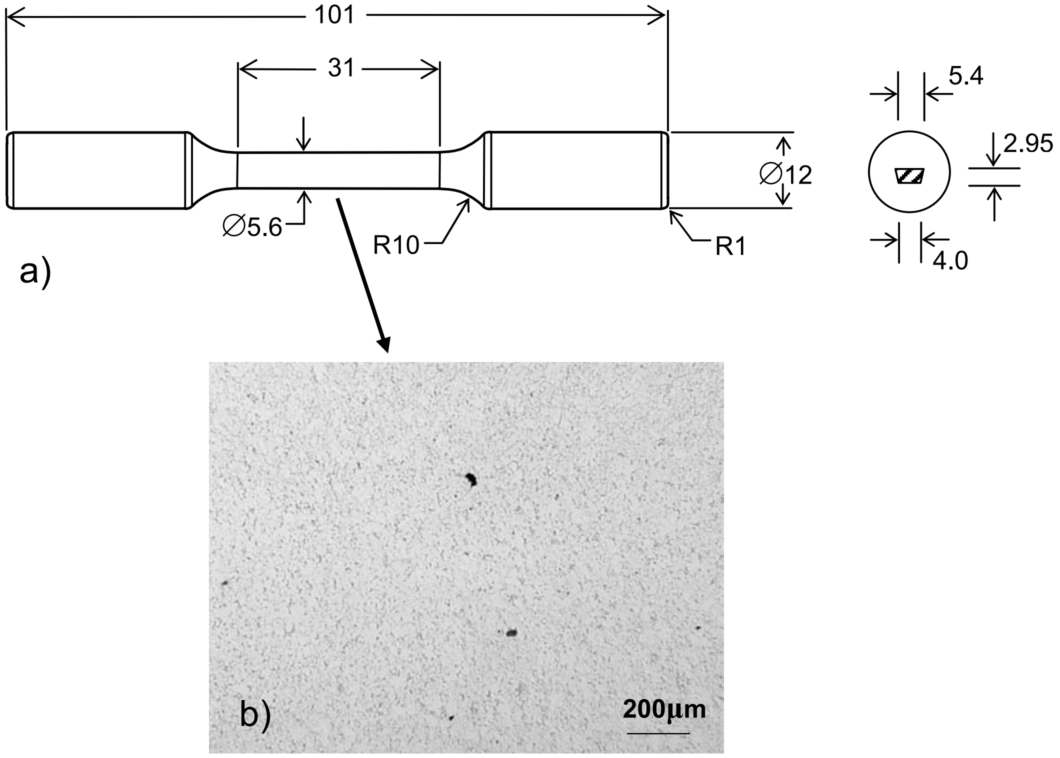

Figure 7: (a) Specimen geometry for both tensile strength and creep measurements (all dimensions in mm) and (b) low magnification image of the gauge length showing only a few small pores and no cracking.

3.1 Tensile Properties

The sand-casting alloy, AM-SC1, was designed for engine block applications, with strength specifications being supplied by engine designers.[6] 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 8). 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 that is important and not ultimate strength.

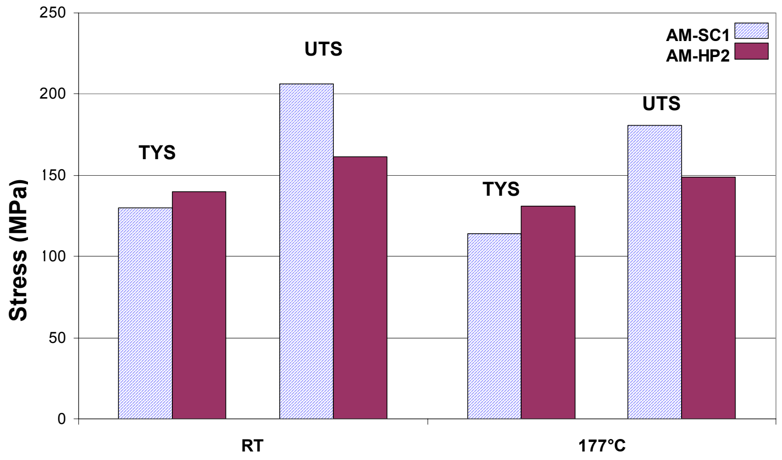

Figure 8: Tensile properties of die-cast AM-HP2and T6 heat treated sand-cast AM-SC1.

3.2 Tensile Creep Behaviour

The creep behaviour of AM-HP2 has been determined over a wide range of stresses and 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 9, is no exception.

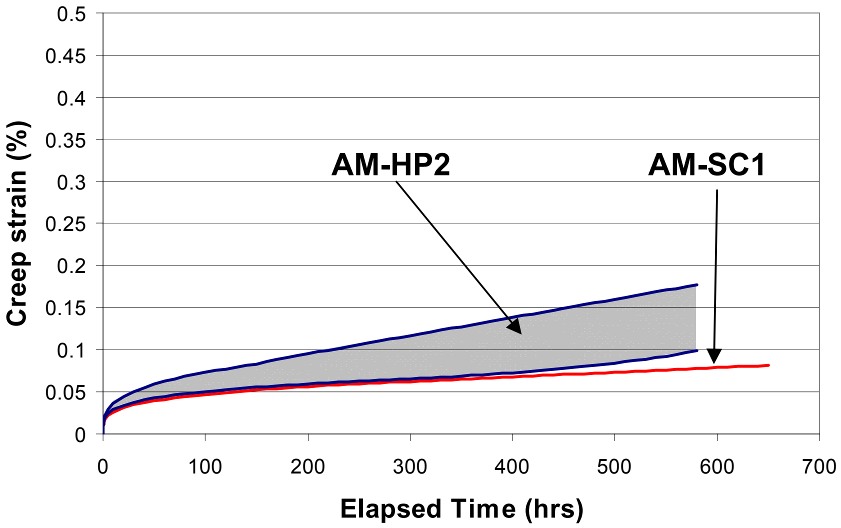

Figure 9: Creep curves for AM-HP2 and AM-SC1 at 177°C and 90 MPa.

The lower bound of the creep behaviour of AM-HP2 at 177°C and 90 MPa is very similar to that for AM-SC1, and 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.[3, 4]

3.3 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[7] 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. Figure 10(a) is a schematic of the HPDC boss, which is drilled out with an 8 mm hole and cut to 15mm in length before testing. 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 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.

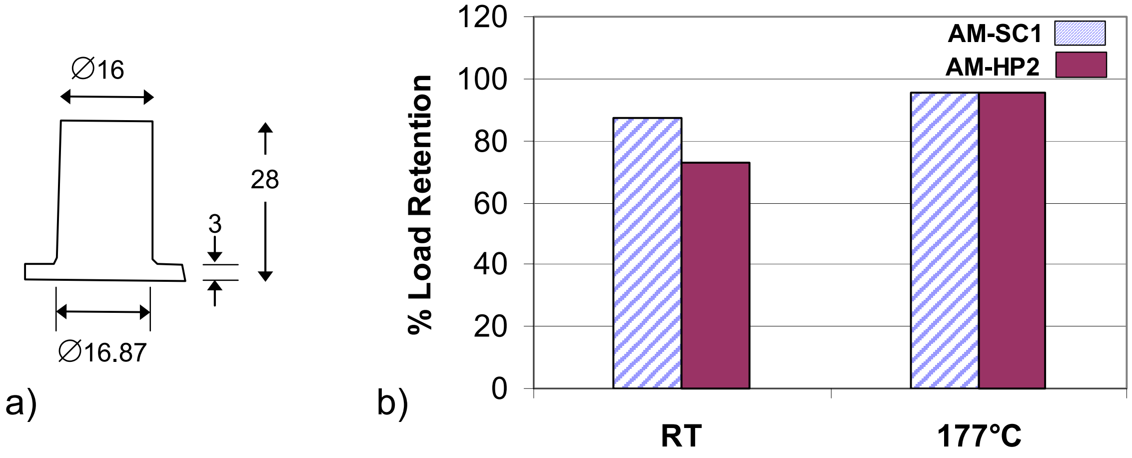

Figure 10: (a) Geometry of the cast bolt load retention sample and (b) retention behaviour after exposure at 177°C and a load of 11 kN. The data for 177°C is the BLR measured at the test temperature and the data for RT is the BLR measured after return to room temperature.

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. This is an indication of the overall bolt load retention behaviour, and the difference observed here between the two alloys can most readily be explained as being possibly due to the compressive yield strength of AM-SC1 being higher than that of AM-HP2. This has not been confirmed by direct measurement.

4. Concluding Discussion

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.[8] and shown in Figure 11. 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.

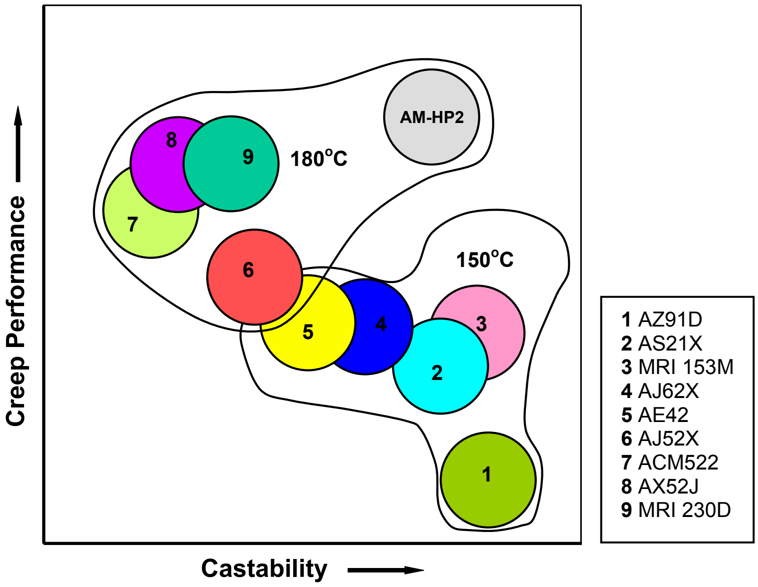

Figure 11: Schematic representation of the castability/creep performance space for current HPDC magnesium alloys (after Aghion[8]). The groupings indicate that the alloys contained within a bubble are suitable for use up to a working temperature of either 150°C or 180°C respectively.

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