

Mechanical Property Evaluation of Permanent-Mould Cast AM-SC1™ Mg-Alloy

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ABSTRACT

AM-SC1™ is a high temperature Mg alloy that was originally developed as a sand casting alloy for automotive powertrain applications. The alloy has been selected as the engine block material for both the AVL Genios LE and the USCAR lightweight magnesium engine projects. The present work assesses the potential of this alloy for permanent-mould die cast applications. Thermo-physical and mechanical properties of AM-SC1 were determined for material derived from a permanent-mould die casting process. The mechanical properties determined included: tensile, creep, bolt load retention/relaxation and both low and high cycle fatigue. To better assess the creep performance, a comparative analysis of the normalized creep properties was carried out using the Mukherjee-Dorn parameter, which confirmed the high viscoplastic performance of AM-SC1 compared with common creep resistant high pressure die cast (HPDC) Mg-alloys. These investigations revealed excellent thermo-physical and mechanical properties that are, somewhat superior to the properties of the sand cast alloy, significantly superior to other HPDC magnesium alloys and comparable to pressure die cast aluminum alloy A380.

INTRODUCTION

Weight reduction is widely accepted as an important and potentially cost-effective means of improving fuel efficiency in automobiles [1]. The attributes of magnesium alloys for light-weight structural components are well documented [2, 3]. In order to maximise the benefits available through weight savings it is important that magnesium alloys gain wider acceptance in transmission and engine applications, where the performance criteria exceed the thermal stability limits of

the current commercial AM and AZ Mg-Al alloys ($\leq 150^\circ\text{C}$).

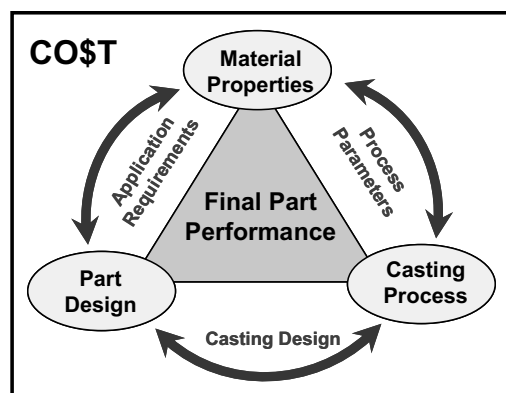


Figure 1. Interrelationship between design, material, process performance and cost (after [4]).

The optimum performance of a particular component is invariably a balance between the material properties, the part design and the casting process, Figure 1 [4]. All of these factors need to be considered, separately and in context, in a successful alloy development strategy. In addition, there is the overarching constraint of cost to be considered at each stage and the automotive industry is particularly sensitive to this driver. Good progress has been made, as demonstrated by BMW with its Mg/Al composite crankcase for an inline six cylinder engine, which uses an Al-alloy open deck insert and the Mg-alloy AJ62 for the outer shell. However, with the current trend in the automotive industry towards even better performance at higher temperatures, the use of such aluminum containing magnesium alloys will become increasingly less competitive due to their poor creep properties. Under such circumstances it may be necessary to shift the property/performance balance and

sacrifice some degree of castability to gain enhanced component performance, or to consider alternative casting technologies to HPDC, such as low pressure permanent-mould processes [1].

Magnesium alloys that utilize rare earth (RE) elements have long been recognized as those most likely to gain acceptance in applications where good elevated temperature stability is required [5]. AM-SC1 is a sand casting alloy based on the Mg-RE system that was developed for automotive powertrain applications and has been selected for the engine block of both the AVL Genios LE [6] and the USCAR lightweight magnesium engine projects [7]. The corrosion resistance of AM-SC1 has also been found to be comparable to numerous other magnesium-based alloys currently under development for automotive applications [8]. This is a lean alloy that was designed to generate satisfactory performance at minimum cost in a heat treated condition. The current work describes the material properties of AM-SC1 processed via a low pressure permanent-mould die-casting route in order to further demonstrate the suitability and versatility of the alloy for elevated temperature automotive applications. Comparisons are made with data for a number of HPDC magnesium alloys and aluminum A380 alloy.

MATERIAL

AM-SC1 was grain refined using the Zr master alloy, AM-cast, and low pressure, permanent-mould die cast into test specimens. An example of the resulting casting is shown in Figure 2. All castings underwent a T6 heat treatment, consisting of a solution treatment for 4 hours at 525°C, quenching, and subsequent annealing for 4 hours at 215°C. Both Vickers hardness HV1 (72.5 ± 2.6) and Brinell hardness HB2,5/62,5/8 (73.1 ± 1.1) were determined on a 20 mm rod and this was found to be uniform across the entire section. This level of hardness is consistent with the material being satisfactorily heat treated. Both 15 mm and 20 mm diameter rods were used to machine specimens for evaluation of mechanical properties.

The chemical composition of the castings after heat treatment was determined using a standard ICP analytical technique and this is given in Table 1, for the major alloy constituents.

Table 1. Chemical analysis of permanent-mould cast AM-SC1

Material	Nd	Ce	La	Pr	Zn	Zr
AM-SC1	1.4	0.39	0.27	0.03	0.42	0.47

MICROSTRUCTURE

The microstructure of permanent-mould cast AM-SC1 in the heat treated condition shown in Figure 3, consists of equiaxed grains (average grain size 30 ± 0.8µm) of a

magnesium-rich phase and an intermetallic phase, based on Mg₁₂RE, that is located in intergranular regions, predominantly at triple junctions.



Figure 2. Permanent-mould cast AM-SC1 test specimens, with runner system.

The presence of this intermetallic phase is an important feature, which acts to ‘lock’ the grain boundaries and provides considerable resistance to grain boundary sliding. Other important microstructural features are fine precipitate particles both within the matrix magnesium grains and on interfacial dislocations in the grain boundaries [9]. In addition, the microstructures display precipitate ‘clouds’ of a Zn-Zr intermetallic phase, located in the central regions of each grain. These are a distinctive feature of heat treated AM-SC1 [6]. The microstructures generated by either sand casting or permanent-mould casting are essentially identical, apart from a finer grain size in the case of permanent-mould casting.

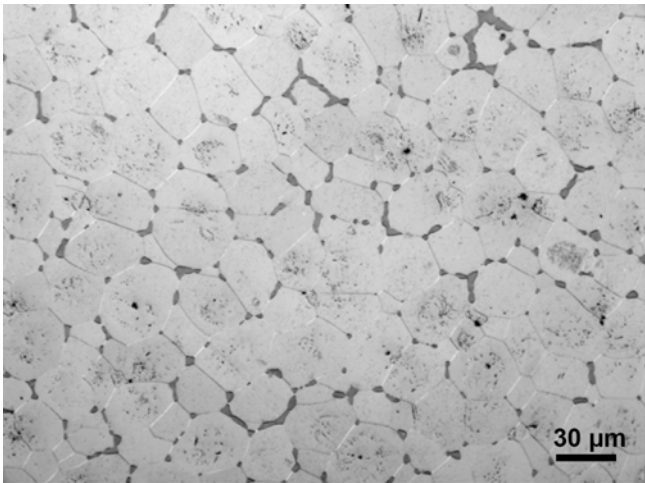


Figure 3. Optical micrograph of permanent-mould cast and heat treated AM-SC1 showing a transverse section from a 20 mm diameter rod.

EXPERIMENTAL PROCEDURES

THERMOPHYSICAL PROPERTIES

The thermophysical properties: specific heat capacity; thermal diffusivity; thermal conductivity; and thermal expansion of permanent-mould die cast specimens were determined in temperature ranges from 20°C to 500°C, 300°C, 300°C and 200°C respectively.

The specific heat capacity, c_p , was measured using Differential Thermal Analysis (DTA) according to DIN EN 821-3. A DSC 404 Pegasus instrument from Netzsch, Selb, was used for the analysis. The thermal diffusivity, α , was determined in order to calculate the thermal conductivity of the materials. The thermal diffusivity of the material was analyzed using the laser flash method in accordance with EN 821-2 using equipment from Netzsch, Selb. The laser pulse duration was 300 μ s, with a laser voltage of 410 V. The temperature increase was measured using a nitrogen cooled CdTe-detector and evaluated according to the Cape-Lehmann method. To improve the optical properties the specimens were either coated with graphite or sand blasted. The analysis was performed under argon atmosphere. The coefficient of thermal expansion was determined in accordance with DIN 51045, using a Netzsch Dilatometer.

By knowing the density ρ , the thermal diffusivity α , and the heat capacity c_p , the thermal conductivity λ was calculated using Equation 1.

$$\lambda = \rho \alpha c_p \quad (1)$$

TENSILE AND COMPRESSION TESTING

Tensile testing was conducted on standard, rectangular cross-section (6 mm wide, 3 mm thick and with a 25 mm gauge length), 'dog-bone' specimens in the temperature range from 21°C to 200°C in accordance with ASTM E8M. Compression testing was conducted on cylindrical specimens (10 mm diameter and 15 mm height) at RT and 150°C. Both tests were conducted with a crosshead speed of 5 mm/min.

FATIGUE TESTING

A comprehensive test program was undertaken covering both low cycle and high cycle fatigue range. Fatigue parameters such as stress, strain and temperature were varied within the testing program.

High Cycle Fatigue

The high cycle fatigue (HCF, 30 Hz) properties were measured at room temperature, 120°C and 150°C. For elevated temperature testing a re-circulating hot-air furnace, with insulating sleeves of a high temperature polyamide between the specimen and the collets, was used. The temperature in the gauge length was

controlled to better than $\pm 3^\circ\text{C}$ for the duration of each test. The specimen geometry is shown in Figure 4.

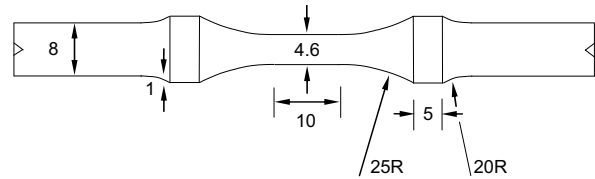


Figure 4. Geometry of HCF specimens (high-temperature version, incorporating raised collars for spot-welded thermocouples).

The work concentrated on measuring the strength at 10^7 cycles using the staircase method in accordance with British Standard BS 3518.

Low Cycle Fatigue

Low cycle axial fatigue tests (LCF) were carried out on 10 samples at room temperature, under a completely reversed cyclic strain condition ($R = -1.0$). Samples were machined and tested according to ASTM E606-92. Fatigue tests were conducted in strain control on servo-hydraulic test equipment employing a 0.5 Hz sinusoidal waveform. The total strain imposed ranged from 0.25 % to 0.7 %. The specimen geometry is shown in Figure 5.

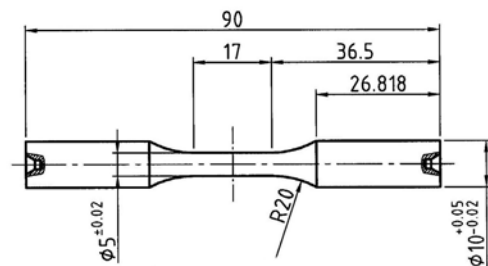


Figure 5. Geometry of specimens for LCF testing.

CREEP TESTING

The creep and stress relaxation properties of the permanent-mould die cast material were evaluated using three different test types: single level tensile creep, multilevel tensile creep, and bolt load retention.

Tensile Creep

Single level, dead weight load, tensile creep tests were performed at temperatures of 150°C, 177°C and 200°C for a duration of 600 hours, using the same specimen geometry as that used for standard tensile testing described previously.

Multilevel tensile creep tests were conducted in accordance with DIN EN 10291. To obtain the maximum possible creep information with a limited number of samples, staircase tests were performed, where several load or temperature levels were applied to a single

a single specimen. Two different test types, multi-level temperature and multilevel load tests, were performed to enable the estimation of both, stress exponent and activation energy for creep, as physical material constants. Machined test specimens as shown in Figure 6 were used for both test types. All creep tests were carried out with continuous data recording. The duration was 200 hours for each load or temperature level. The load and temperature conditions are listed in Table 2.

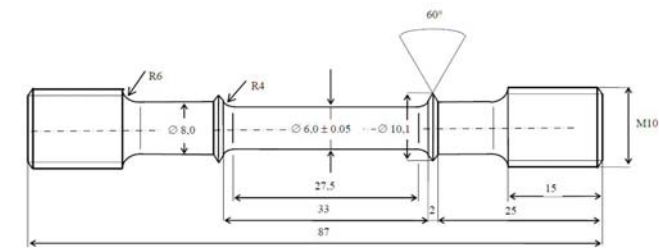


Figure 6. Geometry of specimens for the multilevel temperature and load creep tests.

Table 2. Load and temperature conditions for multilevel tensile creep testing.

Stress [MPa]	Temperature [°C]
45/60/75/90	175
60	125/150/175/200

Bolt Load Retention

Partly threaded M8 high tensile steel bolts equipped with strain gauges were used to measure the Bolt Load Retention (BLR) behavior. The test boss dimensions and a schematic diagram of the bolted assembly, which consists of a pair of identical test bosses, are illustrated in Figure 7.

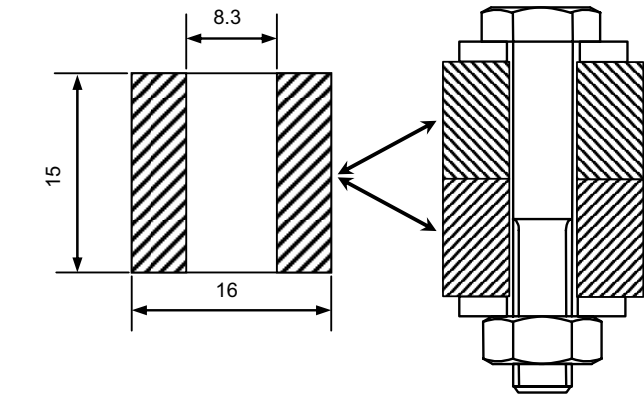


Figure 7. Specimen geometry and schematic drawing of the bolted assembly for BLR testing.

After initial loading (either 8 kN or 11 kN), the bolted assembly was held at room temperature for 2 to 6 hours until the load readings stabilized. Then, the bolted

assembly was placed in an air-circulating furnace (at 150°C or 177°C) and held at the specified test temperature, for the duration of 100 hours to observe the stress relaxation behavior. Finally, the bolted assembly was taken out of the furnace and cooled in air to ambient temperature. The bolt load signal versus time was recorded by a PC-based data acquisition program throughout the entire cycle.

A typical bolt load response curve from a standard BLR test is shown in Figure 8 where, for easy description, the four characteristic load parameters have been defined as P_I , P_K , P_R and P_F . The rise in load from P_I to P_K is a result of the net thermal expansion of the bolted assembly less the effect of yield deformation in the magnesium alloy test coupons. The progressive decrease in load from P_K to P_R is due to the stress relaxation that occurs in the magnesium alloy specimens during exposure to the test temperature. The decrease is time dependent, although, for certain alloys, after a period of exposure at temperature the load may remain nearly unchanged as the test progresses. The higher the ratio of P_R to P_K after time, t , the more durable the bolted joint would be at the test or operational temperature. The ratio of P_R/P_K is thus an important parameter for evaluating the BLR behavior of the tested material. The value of $(P_K - P_R)/t$ reflects the average rate of loss of load at temperature. The drop in load from P_R to P_F occurs when the bolted assembly is taken out of the furnace and cooled in air and this may be regarded as a reverse process of the initial expansion except that little yield deformation occurs in the test boss due to the rapid cooling rate. In a similar manner to P_R/P_K , P_F/P_I reflects the relative amount of loss of the initial ambient load after a whole BLR cycle. Therefore this ratio is widely used to assess the BLR behavior of the tested material.

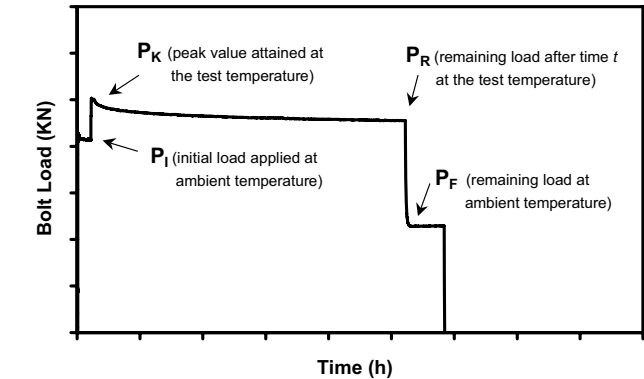


Figure 8. Schematic of the bolt load retention (BLR) curve for a given alloy at a specified test temperature.

The total loss of load for a bolted assembly after a BLR test cycle is given by $(P_I - P_F)$. This loss of load comes from two sources: the yield deformation that occurs in the experimental material when it is heated to the test temperature, and the stress relaxation that arises in the experimental material when it is held at the test