Creep resistant magnesium alloys and their properties

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Abstract
Several families of magnesium alloys have been developed to operate at the elevated temperatures experienced in automotive drive train applications. These alloys are based on additions of certain elements, in particular silicon, calcium, rare earths and strontium. This paper surveys the different types of high temperature alloys comparing elevated temperature properties, castability and factors influencing cost. While high temperature properties have attracted the most attention, the ability to produce sound castings is equally important. Castability testing was conducted on several alloys including AE44, AS31, AJ62, MRI153, AM-HP2+ and AXJ530. Factors influencing alloy cost are also very important. During 2011 a rise in rare earth prices caused a significant shift in costs. Rare earth prices have declined greatly in recent months and the outlook for these alloys is increasingly positive with Western producers commencing production. When considering creep performance, cost and castability together the alloy AE44-2 (made using only two rare earth elements: cerium and lanthanum) stands out as the best performing alloy.

Introduction
The most commonly used magnesium alloys are based on Mg-Al, for example AZ91, AM60 and AM50. These alloys have a good combination of castability and room temperature properties but are unsuited for use at elevated temperatures. At temperatures above 100-130°C they undergo excessive creep deformation even at low stress levels. The poor creep resistance of Mg-Al alloys has been considered to be associated with the formation of Mg17Al12 at elevated temperatures [1,2]. A number of special alloys have therefore been developed with improved high temperature performance [3-10]. These have additional elements that: 1) form high melting point compounds with aluminium to suppress the formation of Mg17Al12 (rare earths, calcium and strontium), 2) form high melting point compounds with magnesium (rare earth, silicon and tin) and/or 3) form strengthening precipitates (calcium and neodymium).

Several different organisations have developed and tested high temperature alloys for commercial applications. A selection of these alloys is listed in Table 1 along with the elements employed to enhance creep resistance.

An alloy’s ability to withstand high temperatures is one factor in determining its suitability for commercial application. The other two key factors are price and castability. If the price of creep resistance enhancing elements is excessive then the alloy will be uneconomic. Similarly if non-standard procedures are

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Table 1. Creep resistance enhancing elements used in selected high temperature magnesium alloys

WHEN CONSIDERING CREEP PERFORMANCE, COST AND CASTABILITY TOGETHER THE ALLOY AE44-2 (MADE USING ONLY TWO RARE EARTH ELEMENTS: CERIUM AND LANTHANUM) STANDS OUT AS THE BEST PERFORMING ALLOY.
required for production then costs may be an issue. With regards to castability, an alloy with excellent creep resistance that is unable to form acceptable parts due to cracking or filling problems is also unsuitable for commercial application.

**Creep resistance**

Creep resistance of magnesium alloys has been studied extensively by the Australian research organisation: CAST. The creep behaviour of several alloys is shown in Figure 1. Alloys AM-HP2+, AXJ530 and AE44 have excellent creep resistance under a stress of 90 MPa at 150°C. Tests conducted at a single temperature or stress do not give a complete picture of alloy performance. A more complete overview of relative performance is shown in Figure 2 where several stress levels have been applied to each alloy. The graph shows the effect of stress on the strain after 100 hours at 150°C. The order of creep performance from best to worst is AM-HP2+ > AE44-4 > AE44-2 > (AE42, MRI153M) > (AS21, AJ62, MRI153A) > AS31 > (AM60, AZ91).

**AE44 alloys**

AE44 is an Mg-4%Al-4% rare earth alloy. It is shown in the figures as two alloys: AE44-4 and AE44-2. During 2011 rare earth prices rose dramatically then fell back (Figure 3).
Rare earths typically occur as a mixture of elements with cerium being the most abundant followed by lanthanum, neodymium and praseodymium. Traditionally the lowest cost rare earth metal has been that obtained by direct conversion of the ore to metal without separation of individual elements. However, in recent years the increased demand for neodymium has led to two elements misch metal, containing just cerium and lanthanum, becoming considerably cheaper than four elements misch metal.

In view of these developments AE44 is now provided in two versions. AE44-4 contains Ce, La, Nd and Pr while AE44-2 contains just Ce and La.

While the creep performance of AE44-2 is reduced from AE44-4 it still exceeds the performance of all other alloys apart from AXJ530 and AM-HP2+. When die castability is considered the benefits of AE44-2 over other alloys is greatly enhanced.

Die castability
In some alloys, high temperature creep resistance comes at the expense of castability. If an alloy is prone to cracking or does not easily fill the die then high temperature creep resistance is of little use.

Quantification of die castability is not as straightforward as determining creep properties. Castability refers the several different aspects including tendency for cracking, level of porosity, fluidity and ease of filling, resistance to sticking and die soldering, surface finish and melt handling (including oxidation resistance and tendency for clogging problems in the melt transfer system).

In addition to different measures of castability, differences

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also exist for a single measure and alloy when used in different casting sizes and geometries.

Despite these differences, attempts have been made to rank alloys according to castability, in particular tendency for cracking and ease of filling. Figure 4 shows a die developed by CAST to assess castability \cite{11,12}. It was designed to contain difficult to cast features such as difficult to fill thin sections, decreasing then increasing section thickness in the flow direction, thick and thin sections adjacent to each other and stressed regions to induce cracking.

Each alloy was cast under four conditions: high and low die temperature and high and low second stage velocity. Ten castings from each condition were rated for each of the alloys. Ratings were made on a scale of 0-5 (0 worst, 5 best) according to the size and number of cracks and the completeness of filling.

The castability rating results are shown in Figure 5. Of the high temperature alloys AE44, AS31 and AM-HP2+ performed well. MRI153M, AXJ530 and AJ52 performed poorly.

In Figure 6 the creep performance is plotted against castability. The alloys with calcium are highlighted. Calcium can cause a number of issues related to castability. Cracking severity is often high in these alloys and this factor is included in the castability rating. Other effects are not shown in the rating including melt handling problems due to the formation of CaO films on the melt. This can lead to clogging issues in cold chamber machines without good cover gas protection in the transfer tube.

AE44 and AM-HP2+ stand out in Figure 6 as alloys with

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both good creep properties and good castability. AS31 rates particularly well in terms of this castability test but has poor creep resistance.

**Cost**

The cost of an alloy is as important as properties, especially in automotive applications. The recent rare earth price fluctuations mentioned above were of concern during 2011 but are now trending downwards (Figure 3). Additionally, non-Chinese rare earth...
producers are also coming on-line in US, Australia, Malaysia and elsewhere which should help stabilise the price.

In Figure 7 an approximate indication of alloy cost is shown. The prices shown are the cost of alloy ingredients relative to AZ91D ingredients (March 2012 prices). This cost does not include production cost or yield losses and so should be used as a rough guide only. AM-HP2+, AE44-4 (Ce-La-Nd-Pr) and MRI230D are all considerably more expensive than AZ91D. AE44-2 (Ce-La) is much lower cost than AE44-4 and represents the best all round combination of creep properties, castability and cost. AXJ530, MRI153M, AJ62, MRI153A and AS31 all have low cost ingredients but are limited by poor castability and/or poor creep properties.

Conclusions

For a high temperature magnesium alloy to be adopted in automotive applications it needs to satisfy several criteria. Arguably the most important are creep resistance, castability and cost. The magnesium-aluminium-rare earth alloy AE44-2 (rare earths = Ce, La) uniquely meets all three criteria with good castability, creep resistance and cost.

In situations where creep resistance is of greatest importance the alloy AM-HP2+ stands against other high pressure diecast alloys. It exhibits both good castability and unmatched creep resistance but at a significantly higher price than AE44-2.

References