Advanced Gravity Casting Magnesium Alloys for the Aircraft Industry

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1. Introduction

Selection of structural materials for aircraft applications is dictated by a number of factors including mechanical, corrosion and physical properties (particularly density) as well as availability and cost. Magnesium alloys being the lightest of all of the commonly used structural metals can be considered as one of very attractive candidates. Furthermore, magnesium alloys have other desirable properties such higher than for other alloys strength-to–density ratio combined with excellent machinability and damping capacity as well as good castabilty. On the other hand, magnesium alloys exhibit a number of negative features including inferior strength –ductility relationship, less than desirable fatigue strength, fracture toughness and creep resistance. Although general corrosion behaviour of high purity magnesium alloys is considered as acceptable, galvanic corrosion is regarded as very poor and special coating and fasteners are mandatory for most applications [1, 2].

Magnesium alloys have been known to aeronautical engineers for a long, long time. However, they have always suffered prejudice on the twin scores of fire hazard and corrosion. Nevertheless there are some aircraft applications where existing magnesium alloys are being currently used. Thus, magnesium alloys ZE41 and WE43 are used for a range of helicopter transmission castings [3]. In the aero engine industry, the above alloys are also being used along with EZ33 and EQ21 alloys both in civil and military aircrafts [4-7]. However, it should be recognized that such applications are very limited due to the reasons being partly technical and to great extent "emotional" [1]. On the other hand, according to Work program of the thematic priority ' Aeronautics and Space " which is the part of 6th EU Framework programme "World Aeronautics is entering a new age of aviation- the age of sustainable growth- characterized by the need of more affordable, cleaner, quieter, safer and more secure air travel." Thus, it is evident that magnesium alloys may and have to play a crucial role in achieving the above targets.

In respond to the growing demand for weight reduction, the consortium consisting of 14 partners initiated a comprehensive research project titled IDEA (Integrated Design and Product Development for the Eco-efficient Production of Low-weight Airplane Equipment). The development of new alloys is essential part of this project. The requirements to new alloys set by end-user are summarized in Table 1.

The alloys are designated for room temperature applications. A secondary structural part - motion transfer housing shown in Fig.1 was selected as one of reference castings.

Table 1. Technical requirements to properties of sand casting alloys

- TYS -220 MPa, UTS -290 MPa, Elongation- 3%
- Axial fatigue strength for 10^6 cycles:

  0.28 UTS at R=-1
  0.50 UTS at R=0.2

  Strict requirements to general and galvanic corrosion

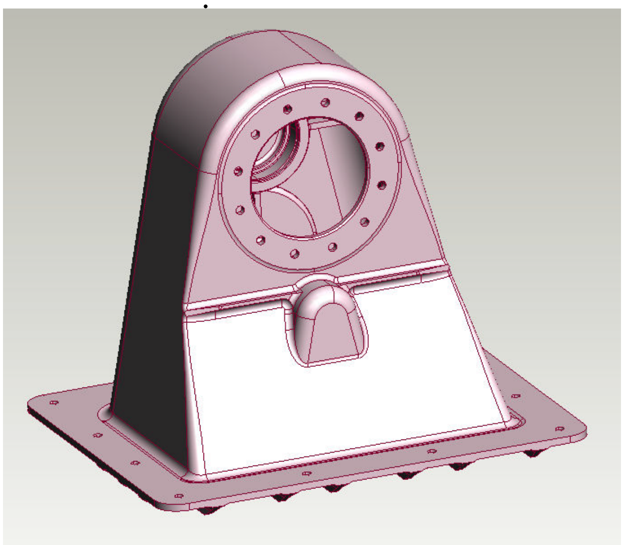

Figure1. Motion transfer housing

2. Metallurgical background to the development of gravity casting alloys

The development of new gravity casting alloys was based on implementation of major mechanisms affecting properties of those alloys. These mechanisms are precipitation hardening, solid solution strengthening and grain boundary strengthening. In general, alloying principles for the development of high strength magnesium alloys for gravity casting applications after T6 heat treatment can be reduced to the following rules [8, 9]. Grain refinement is considered as a very important tool at the development of gravity casting alloys. It is well known and documented that Zr has a grain refining effect when added to magnesium leading to the greater casting integrity and improved mechanical properties [10]. The soluble Zr fraction mostly provides the fine grain size obtained in Zr contained alloys. Mg-Zr alloys have more consistent properties through thin and thick sections and are not prone to through-wall porosity, which can cause lubricant leakage.

The main alloying elements should have a wide range of solid solubility in magnesium, which decreases sharply at room temperature. The most desirable alloying systems are those in which extensive solubility at solid solution treatment temperature can be retained with industrially adequate cooling rate in supersaturated solid solution at room temperature. This factor is very important to provide a marked response to aging.

Solutes should also have a low diffusion coefficient, to provide strong interatomic bonds and to form solid solution, which has no response to aging over service conditions. For enhanced elevated temperature properties, alloying elements should form thermally stable intermetallic compounds that have the coherency with the matrix and are effective obstacles against deformation and strengthen grain boundaries. The melting point of the precipitate is a good indication of its thermal stability.

The first precipitates to nucleate are very often metastable and coherent with the matrix providing excellent precipitation hardening. As aging progresses, metastable precipitates are transformed into stable equilibrium phases. The morphology of the precipitates including their shape and interparticle spacing affect both ambient strength and creep resistance. Based on the strict requirements listed in Table 1 and taken into consideration the availability and commercial attractiveness of the alloying elements, some of them such as Nd, Y, Gd and Ag seem to be most promising for the development of new alloys. It is believed that Nd should be considered as the main alloying element due to optimal combination of enhanced solid solubility, availability and cost. However, Nd content higher than 3% results in significant embritlement. Yttrium and particularly gadolinium have higher solubility in magnesium than neodymium On the other hand, they are relatively expensive and Gd has also a great atomic weight that requires its higher weight additions in order to obtain the same atomic percent of Gd compared to Y and Nd. Therefore, the most challenge is to find optimal combination in concentrations of the above three elements.

Zinc content should be limited in most cases to 0.3-0.8% as zinc combines with Nd, Y and Gd to form stable eutectic intermetallics thereby nullifying the contribution of the above elements to precipitation hardening. However, higher Zn content can be used in some cases when solid solution strengthening can be considered as alternative strengthening mechanism.

Heat treatment is a very important factor for obtaining a required combination of service properties. It should be selected a based on compromise between mechanical properties requirements and commercially acceptable holding time at solid solution treatment and particularly at aging. Solid solution treatment should be performed at the highest practicable temperature to dissolve coarse eutectic intermetallic phases formed during casting process. Practically the solid solution treatment is conducted at the temperatures about 20-30°C below the solidus temperature of the alloy. The most challenge is usually associated with selection of the temperature and time of aging because these variables significantly affect the final properties.

In addition to their influence on mechanical properties and creep behaviour, alloying elements should provide good castability (increased fluidity, low susceptibility to cracking, reduced porosity and greater casting integrity) combined with improved corrosion resistance and affordable cost. With regard to the last factor it is believed that it is not so critical as for the automotive industry because, for example, in the civil aircraft the value of a pound in weight saved is equal to $300 US [2].

Based on the above principles three new alloys designated MRI 204, MRI 205 and MRI 207 have been developed in the framework of the IDEA project. The alloys MRI 204 and MRI 207 are based on Mg-Zn-Zr-Nd-Y (Gd) alloying systems and are in fact also creep resistant alloys. Precipitation hardening and grain boundary strengthening are major mechanisms contributing to the strength of the above alloys. On the other hand, solid solution and grain boundary strengthening underlying unique properties of MRI 205, which is designated for room temperature applications that require high strength, combined with increased ductility. The present paper addresses mechanical properties of newly developed gravity casting alloys in comparison with commercial magnesium alloy ZE41-T5 and aluminium alloy A357-T6, which are used in some aeronautic applications. In addition the effect of casting technology is also demonstrated and discussed.

4. Experimental procedure

The study was carried out on tensile and fatigue test bars that were produced by sand, investment and gravity die casting technologies. The quality of specimens was evaluated by X-Ray radiography, using Seifert Eresco 200 MF constant potential X-Ray tube.
Tensile specimens' configuration was in accordance with BS 2970 (Form F). The room temperature tensile properties were determined in accordance with ASTM E8M. A minimum fifteen tensile specimens of each alloy were tested and the results averaged.

Fatigue specimens were machined from separately cast cylindrical bars with a 16 mm diameter. The specimens' configuration was in accordance with ASTM E466 (specimens with a continues radius between ends). The specimens had the radius of curvature 120 mm, the minimum diameter of 6.35 mm and the ends diameter of 14 mm. The reduced section was polished to 0.1 mm roughness. All specimens were tested in T6 in conditions that were preliminarily optimised for each alloy based on numerous experiments. Creep tests were performed in the temperature range 175-250°C according to ASTM E139 standard.

5. Results and discussion

The results of tensile and compression tests of new sand casting alloys are summarized in Table 2 in comparison with the benchmark commercial alloys ZE41-T5 and A357-T6.

Table 2. Mechanical properties of MRI sand casting alloys in T6 condition compared to commercial alloys

Alloy	*Casting method*	*TYS [MPa]*	*UTS [MPa]*	*E [%]*	*CYS [MPa]*
MRI 201	Sand casting	194±9	272±9	6±1	207±6
	Sand casting	206±4	306±8	4±1	245±8
MRI 204	Investment casting	210±3	302±2	3±1	234±6
	Gravity die casting	212±4	305±2	3±1	238±6
MRI 205	Sand casting	220±4	325±4	10±2	227±6
	Sand casting	220±8	304±6	4±1	259±7
MRI 207	Investment casting	215±3	285±3	3±0	249±9
	Gravity die casting	215±2	280±15	3±1	237±9
ZE41-T5*****	Sand casting	140	220	5	140
WE43-T6*****	Sand casting	180	260	6	190
A357-T6*****	Sand casting	230	290	3	250

* Metals Handbook Data

It is evident that MRI 201-T6 alloy significantly outperforms commercial magnesium alloy and has tensile and compressive properties similar to those of significantly more expensive WE43 alloy. With regard to MRI 204, MRI 205 and MRI 207 alloys, table 2 demonstrates that their tensile and compressive properties in T6 condition are comparable with those of aluminium alloy A357-T6. In addition, it should be noted that unique combination of strength and ductility was obtained on MRI 205-T6 alloy. Furthermore, table1 distinctly illustrates that casting method practically does not affect tensile and compressive properties of MRI 204 and MRI 207 alloys

One of the most important requirements to new alloys set by end user is improved fatigue behaviour. The results of axial fatigue tests (R=-1) performed on MRI alloys are given in Figure 2 in comparison with the data obtained for aluminium alloy A357-T6(shown as a lower limit and mean values lines). As can be distinctly seen MRI 205-T6 is superior to A357-T6 in axial fatigue behaviour both at high and low stresses. Other two new magnesium alloys exhibit fatigue performance similar to that A357-T6 alloy.

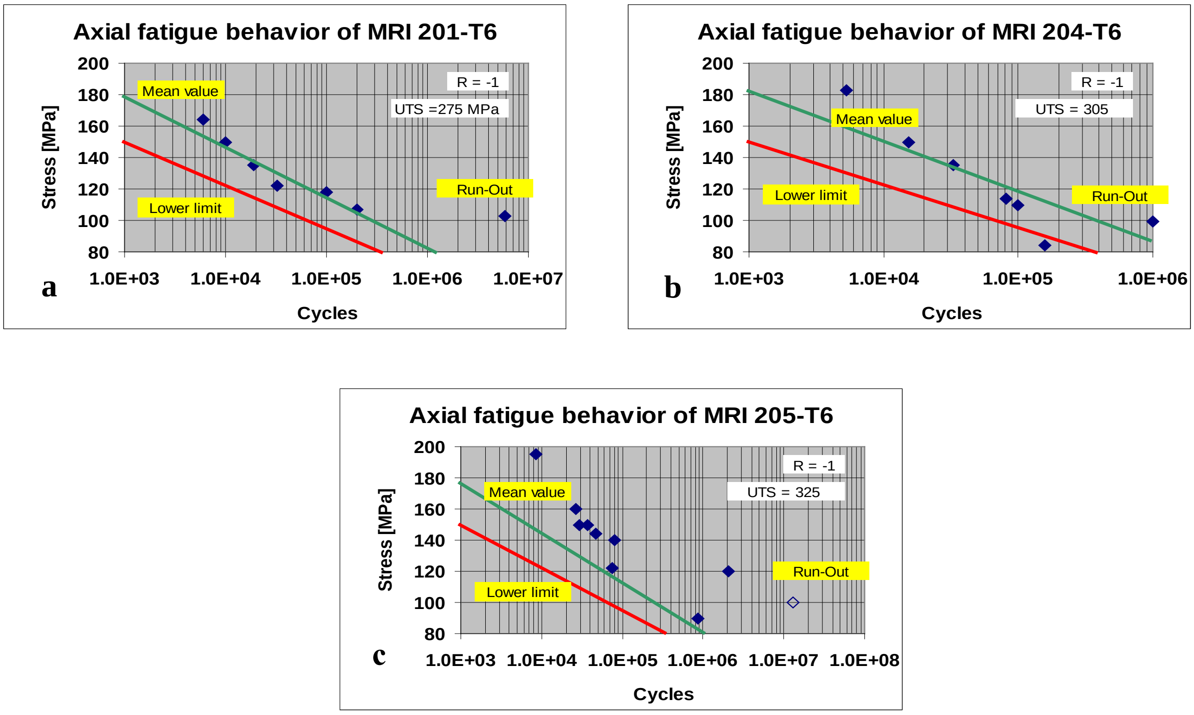

Figure 2. Axial fatigue behavior of MRI 201-T6 (a), MRI 204 -T6 (b) and MRI 205-T6 (c) in comparison with aluminum alloy A357 - T6 (represented by lower limit and mean value lines)

New alloys MRI 201, MRI 204 and MRI 207 are also designated for elevated temperature applications. For example, creep properties of MRI 201S and MRI 207 alloys are listed in Tables 2 and 3, respectively. It is evident that both MRI 201 and MRI 207 exhibit excellent creep resistance and may operate at 200-250°C under high stresses. This performance makes new alloys good candidates for high-temperature applications in automotive, aircraft, motorsport and defense industries such as engine block, cylinder head cover, helicopter gearbox housings etc.

Table 3. Creep properties of MRI201– T6 sand castings
(stress [MPa] to produce certain creep strain at different temperatures)

Time under load, h	*0.1%*	*0.2%*	*0.5%*
	At 200°C		
10	172	180	190
100	154	170	176
1000	88	102	143
	at 250 °C		
10	74	84	96
100	49	75	80
1000	34	48	55

Table 4. Creep properties of MRI207– T6 sand castings
(stress [MPa] to produce certain creep strain at different temperatures)

Time under load, h	*0.1%*	*0.2%*	*0.5%*
	At 200 °C		
10	175	183	195
100	156	173	180
1000	92	105	145
	At 250 °C		
10	70	80	92
100	45	70	80
1000	30	45	50

In conclusion, it should be noted that the results obtained so far are very promising and can serve as a background for further research. It is evident that the additional data including corrosion behaviour should be obtained prior to some practical decisions can be drawn.

6. References

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