Mg Casting Alloys for the Aerospace Challenge

A. Stevenson

Editor's Note: This paper is adapted from a presentation made at the 1987 TMS Annual Meeting in Denver. The full text appears in the TMS volume *Light Metals 87*.

Reviewing the magnesium alloys currently available to the aerospace industry, this paper examines their technical advantages and disadvantages. Alloys with improved ambient and elevated temperature capability to meet specific user requirements are described. High strength alloys with useful properties up to 570°F (299°C) are available. The adoption of resin bonded sands and the simultaneous development of techniques for producing longer and narrower cored passageways has enabled foundries to meet the requirements of the aerospace industries for larger, more complex castings. Further development of these techniques, along with improved melting and casting techniques, should enable thinner walled, closer tolerance castings which also feature weight saving advantages.

INTRODUCTION

While magnesium was isolated in 1808, the metal remained a laboratory curiosity until the early 1920's when practical melting and refining techniques made possible the development of casting alloys and associated foundry techniques. Since then, some 30 different casting alloys have been commercially developed and employed.

Magnesium alloys for modern aerospace applications are produced from one of two major series of alloys. The first major series of casting alloys were based on the Mg/Al/Zn system, and a number of compositions with aluminum content in the range 6-10% Al and 0.5-3.0% Zn have been developed. The higher Al-containing alloys—AZ81, AZ91 and AZ92—emerged as the main casting alloys. They continue to be used today, particularly in commercial aerospace applications where cost is a major factor.

Maximum strength is developed in the fully heat treated (T6) condition. The yield strength increases and the ductility decreases with the Al content. The specification minima are summarized in Table I.

Castings with these alloys can be readily produced via sand, investment, permanent mold, low and high pressure die casting techniques. In order to achieve optimum properties, grain refining is essential. This is normally carried out with carbon innoculation using readily decomposable organic compounds such as hexachlorethane.

With the development of foundry techniques for chilling and directional solidification, properties achievable in castings have been steadily improving, demonstrated by the specification minima for premium quality castings (Table II).

These alloys are prone to microshrinkage, and considerable skill and experience is required to achieve consistent quality. Since the porosity is oriented at right angles to the casting wall, the castings are not pressure tight. While impregnation techniques have been developed, they generally do little more than seal off the surface porosity and often require multiple sealing steps to ensure pressure tightness. Mechanical properties fall off rapidly above approximately 250°F (120°C). In the T6 condition, the alloys show susceptibility to stress corrosion cracking at stress levels above about 50% of the alloys' yield strength.

The second major series of magnesium alloys are based on the unique grain refining effect of zirconium. Even though the effect of zirconium on magnesium was known in the late 1930's, it was not until some 10 years later that an effective, reproducible method of introducing zirconium into the alloys was developed.

The discovery that the addition of rare earths (misch metal) and thorium to Mg/Zn/Zr alloys eliminated hot cracking and conferred weldability led to the development of a new range of alloys with specific combination of properties (Table III).

These alloys can be subdivided into two groups: ZE41 and ZH62 are structural alloys which retain their properties up to 300°F (150°C), while EZ33A and HZ32, which possess lower room temperature tensile properties, are designed for applications requiring creep strength at temperatures up to 480°F (250°C) and 660°F (350°C), respectively.

Table I. Mechanical Properties of Sand Cast Mg-Al-Zn Alloys

Alloy Designation	Typical Composition (%)			Heat Treatment	Tensile Properties (Nmm^{-2})			Fatigue Endurance Nmm^{-2} 5×10^7cy
	Al	Zn	Mn		YS	UTS	E%	
AZ81A	8.0	0.5	0.3	T4	78	234	7	75–90
AZ91C	9.0	0.5	0.3	T4	78	234	7	77–92
				T6	110	234	3	70–77
AZ92A	9.5	2.0	0.3	T4	76	234	6	90
				T6	124	234	1	83

Table II. Tensile Properties in Designated Areas of AZ91, AZ92 Castings to MIL-M-46062B

Alloy Designation	Designated Area Class	Minimum Properties YS KSI	YS Nmm^{-2}	UTS KSI	UTS Nmm^{-2}	Elong %
AZ91C-T6	1	18	124	35	241	4
	2	16	110	29	200	3
	3	14	97	27	186	2
	Undesignated	12	83	17	117	0.75
AZ92A-T6	1	25	172	40	276	3
	2	20	138	34	234	1
	3	18	124	20	207	0.75
	Undesignated	13	90	17	117	0.5

Table III. Mechanical Properties of Sand Cast Magnesium-Zirconium Alloys

Alloy Designation	Typical Composition (%) Zn	RE	Th	Zr	Heat Treatment	Tensile Properties (Nmm^{-2}) YS	UTS	E%	Fatigue Endurance Nmm^{-2} 5×10^7cy
EZ33A (ZRE1)	2.5	3.0	-	0.6	T5	95	140	3	65-75
ZE41A (RZ5)	4.2	1.3	-	0.7	T5	135	200	3	90-105
HZ32A (ZT1)	2.2	-	3.0	0.7	T5	90	185	4	65-75
ZH62A (TZ6)	5.5	-	1.8	0.7	T5	155	255	5	75-80

With all of these alloys, castings are produced using sand, permanent mold or investment techniques. The properties of this alloy group are developed by a low temperature aging process (T5). Properties obtained in castings are more uniform and less influenced by section thickness. Chilling has little effect on properties and the use of chills with these alloys is solely to assist in achieving directional solidification. These alloys are considerably less prone to microporosity. Where microporosity does occur, it is isolated or oriented parallel to the cast surface. Consequently, the castings are pressure tight, the alloys are free from stress corrosion cracking and have better stability at elevated temperatures.

The discovery that alloys containing silver and neodymium-rich rare earths, grain refined with zirconium, responded to a T6 heat treatment led to the development of a new range of high strength alloys.[1] Early work demonstrated that the development of the optimum temperature properties required a silver content of at least 2% and a neodymium-rich rare earth content in the range of 1.5-3%. Castability improvements corresponded to increasing neodymium content. From this work, the alloy QE22A was developed. This alloy retains its properties up to 390°F (200°C), has good castability, is fully weldable, and can be cast into relatively thin sections. Castings are produced using sand, permanent mold and investment techniques.

Subsequently, it was discovered that part of the neodymium could be replaced by thorium, resulting in improved room temperature properties. This led to the development of the alloy QH21.[2] The creep properties at 390°F (200°C) and 480°F (250°C) show a significant improvement over the previous alloy, increasing the operating envelope by 85-100°F (30-40°C). Castability and weldability of QH21 are good, and "difficult" castings are being made.

To minimize the effect of silver price fluctuations, previous research[3] indicated that copper could substitute for part of the silver, stabilizing the preferred precipitate in the Mg/Ag/Nd/Zr alloys at a lower silver content than in QE22. On this basis, a new alloy, EQ21,[4] was introduced which contained 1.5% silver with a nominal copper content of 0.08%.

While no sacrifice in room temperature properties resulted from the substitution, the alloy has the unexpected benefit of better temperature stability at elevated temperatures than QE22A (Figure 1). The high temperature properties of EQ21 rival those of QH21 at temperatures between 390 and 480°F (200-250°C).

The silver-containing alloys represented a major step forward in that room temperature properties approached those of the high strength aluminum alloys A356 and A357, making it possible for magnesium to compete on a volume for volume basis.

In parallel with the development of the silver-containing alloys, further research work was carried out on the Mg/Zn/Zr and Mg/Zn/RE/Zr alloy systems. It was discovered that solution treatment of the Mg/Zn/RE/Zr alloys in an atmosphere of hydrogen resulted in the precipitation of the rare earths in the eutectic phase as RE hydride, permitting the zinc to diffuse into the matrix where it can eventually be precipitated by a low temperature aging treatment. This led to the development of the alloy ZE63[5] which has excellent castability by virtue of its high rare earth content. In the "hydrided" condition, it has very good tensile properties and fatigue strength (Tables IV and V). Prior to hydriding, the alloy is fully weldable.

While ZE63A has been used for many years for thrust reversers on the RB211 engine, its wider use has been limited by the relatively long hydriding treatment (48 hours at 895°F (480°C) for a linch section). The development of techniques for hydriding under pressure has reduced the time required by about 50% and should result in the increased application of this alloy.[6]

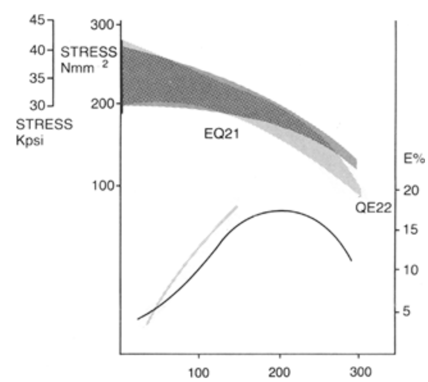

Figure 1. Effect of temperature on tensile properties of EQ21 vs. QE22.

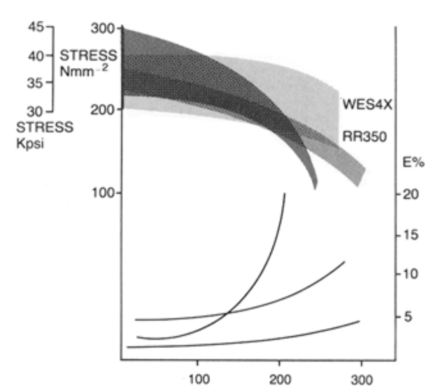

Figure 2. Effect of temperature on tensile properties of WE54 vs. the high temperature Al alloys RR350 and A356.

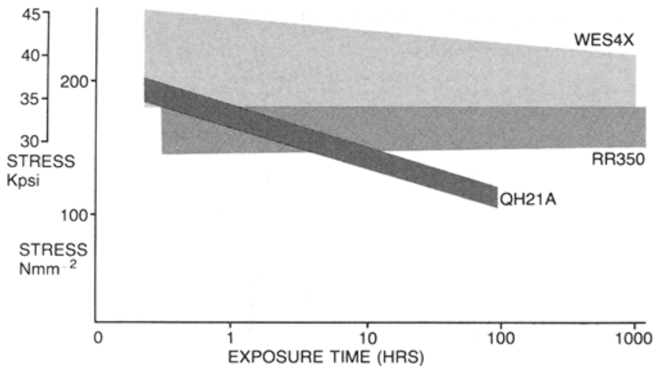

Figure 3. Effect of exposure time on tensile properties of 482°F (250°C) for WE54X compared with QH21A and Al casting alloy RR350.

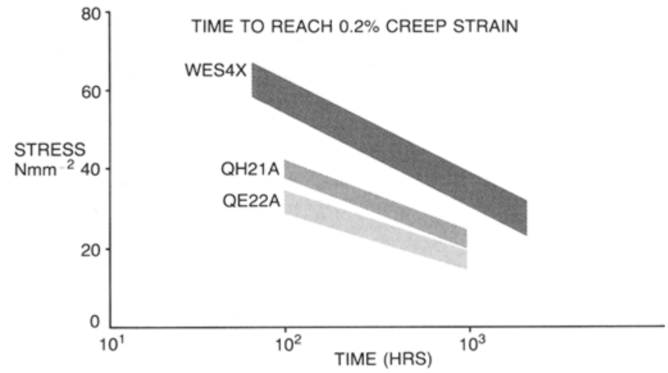

Figure 4. Stress/strain relationship for WE54 vs. QH21A and QE22A at 482°F (250°C).

Table IV. Tensile Properties of ZE63A-T5, ZE41A-T5 at Ambient Temperature

Alloy Designation	Nominal Analysis (%)			Heat Treatment	Tensile Properties-Nmm $^{-2}$ (KSI)		
	Zn	RE	Zr		YS	UTS	E%
ZE63A-T5	5.8	2.5	0.7	A	150 (21.8)	190 (27.6)	2½
				B	162 (23.5)	200 (29.0)	2½
ZE41A-T5	4.2	1.3	0.7	A	145 (21.0)	208 (30.2)	4

Heat treatment: A = two hours at 626°F (330°C) and 16 hours at 356°F (180°C); B = 24 hours at 482°F (250°C).

Table V. Mechanical Properties of ZE63A-T6 (Hydrided) vs. ZE41-T5 at Ambient Temperatures

Property	Units	ZE63A-T6	ZE41A-T5
Tensile: Yield Stress	Nmm $^{-2}$ (KSI)	173 (25.1)	154 (22.3)
UTS	Nmm $^{-2}$ (KSI)	289 (41.9)	229 (33.2)
Elong	%	10	5
Fatigue Limit (5×10^7 cycles)			
Un-notched	Nmm $^{-2}$ (KSI)	117 (17.0)	95 (13.8)
U-notched (SCF = 2)	Nmm $^{-2}$ (KSI)	71 (10.3)	80 (11.6)
Fracture Toughness-K_{ic}	MNm $^{-3/2}$ (KSI in $^{1/2}$)	21 (19.1)	15.5 (14.1)

Table VI. Fatigue Properties of Magnesium Alloys WE54, QE22A

Stress Reversals		10^6	5×10^6	10^7	5×10^7
Endurance Limit-KSI (Nmm $^{-2}$)	WE54	14.8 (102)	14.5 (100) 14.4 (99)	14.1 (97)	
Rotating Bend Test at 20°C Unnotched.	QE22A	14.1 (97)	13.8 (95)	13.6 (94)	13.5 (93)

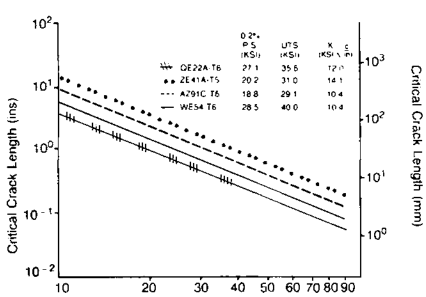

Figure 5. Critical crack lengths as a function of percentage design stress for various magnesium alloys.

CONTINUING DEVELOPMENTS

Recent work at Magnesium Elektron Ltd. has lead to the development of a new alloy, WE54.[7] The letter W is the ASTM designation for the element yttrium. The alloy's design criteria were directed towards maximizing ambient temperature properties while improving elevated temperature properties.

The alloy is a Mg/Y/Nd/Zr system in which the yttrium is added as a mixture with other heavy rare earth metals. It is comprised of 75% yttrium and 25% heavy rare earths (mainly dysprosium, erbrium, ytterbrium and gadolinium). The nominal composition of the alloy[8] is: 5.25% Y, 3.5% RE, and 0.4-0.5% Zr.

Properties are developed in this alloy by a full heat treatment (e.g., solution heat treat for eight hours at 977°F (525°C); hot water, or polymer, quench and subsequente aging for 16 hours at 480°F (250°C)).

The room temperature tensile properties obtained approach those of the aluminum alloy A356, but the short term elevated tensile properties are considerably better, comparing favorably with those of RR350 for temperatures up to 572°F (300°C) (Figure 2).

However, the effect of long term temperature exposure is even more dramatic. For example, at exposure times up to 1000 hours at 480°F (250°C), the alloy is far superior to any currently employed magnesium alloy and compares favorably with that of RR350 (Figure 3). In Figure 3, the upper edge of the shaded area on the graph represents tensile strength while the lower edge represents yield strength.

Creep testing at 480°F (250°C) shows the alloy to be superior to currently used magnesium alloys (Figure 4). Stress to rupture in 1000 seconds at 480°F is 30 ksi, almost double that for QE22A.

The fatigue endurance limit (Table VI) on rotating/bending tests for 5×10^7 is 14.0 ksi—similar to that of the silver-containing alloys. The fatigue endurance value at 480°F and 5×10^7 cycles is 11.2 ksi.

Plane strain fracture toughness of 10.4 (ksi$\sqrt{\text{in}}$) is similar to that of AZ91 and somewhat lower than values obtained on other zirconium-containing alloys (Figure 5). This value corresponds, however, to a critical crack length of 0.039 ins. (1 mm) at 100% design stress.

Special melting techniques[9] have been developed for this alloy since it cannot be melted using conventional fluxes without incurring unacceptable yttrium losses. A practical technique using argon-containing 0.5% sulfur hexafluoride as a protecting gas in conjunction with modified melting crucibles has been developed. A number of practical foundry trials have been carried out, both in this country and in Europe, producing a range of castings which have involved sand, permanent mold and investment techniques.

The alloy has good castability, is fully weldable and can be cast into relatively thin sections without difficulty. The properties demonstrated by specimens cut from castings show good consistency—there was little variation in section thickness ranging from 0.2 to 1.5 ins.

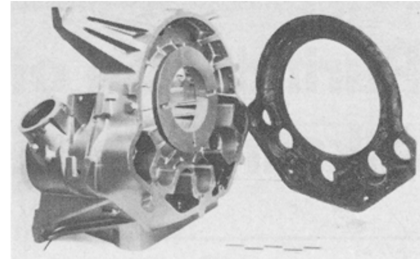

Figure 6. This casting, produced in ZE41, weighs 620 lbs. and is the main gearbox for the Westland WG34 helicopter.

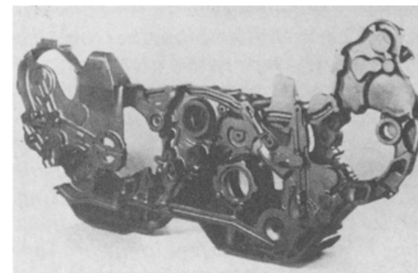

Figure 7. Shown is a sectioned gearbox casting, revealing cored passageways.

CASTING DEVELOPMENT

The magnesium foundry industry has recently undertaken two major changes in molding and melting processes.

"Dry sand processes" offer advantages with magnesium because of the metals' chemical reactivity, particularly to moisture. The adoption of the CO_2-silicate process in the 1960's, initially for core making but subsequently extended to general molding, permitted a marked increase in the complexity of castings that could be produced. More recently, cold-set and air-set systems using resin-bonded sands are replacing the CO_2-silicate system for both molds and cores. This change has been a significant factor in enabling magnesium foundries to meet the aerospace industry's requirements for more complex and larger castings (Figure 6).

The cold-set or self-set process uses synthetic organic resin binders which polymerize at room temperature through the addition of acid catalysts. Binders used include mixtures of urea or phenol formaldehyde with furfuyl alcohol, and the catalyst is a reactive aromatic sulfonic acid, such as para toluene sulfonic acid or phosphoric acid. Another system utilizes the formation of polyurethanes by reaction of phenolic novolac resins with methylene-diisocyanate using a tertiary amine such as dimethyl ethyl amine as accelerator.[10] An alternative cold box technique, the SOFAST process, utilizes phenolic or furan resins and peroxides gassed with sulfur dioxide.[11,12]

The adoption of these new molding techniques has resulted in better surface finishes in the as-cast condition and better dimensional accuracy; castings can now be produced to tolerances which would not have been considered possible a decade or so ago. The production of castings with thinner sections is also possible with consequent benefits in weight savings.

The adoption of the new core materials and core-making techniques has proven particularly beneficial for the production of cored passageways. A number of proprietary techniques have been developed, enabling longer and narrower passages down to 0.08-0.12 ins. in diameter (Figure 7).

The second significant innovation in magnesium foundry technology is that of "fluxless melting" which has been developed from work done by J.W. Freuhling.[13] The process uses semi-sealed crucibles and a protective atmosphere comprising a small percentage of sulfur hexafluoride instead of fluxes for melting and alloying. The melts are subsequently cast under a shroud of protective gas. Concentrations of 0.5-2% SF_6 are usually sufficient to completely inhibit the oxidation of magnesium at temperatures up to about 1470°F (800°C). Various carrier gases can be used (e.g., air, argon, carbon dioxide, or air/carbon dioxide mixtures).[14]

The advantages offered by the process include lower melting losses and improved material efficiencies, better environmental conditions since SF_6 is nontoxic and the virtual elimination of the risk of flux inclusions in the final casting.

While the work has been applied to the die casting of magnesium alloys, the introduction of the process into the sand casting of magnesium is relatively recent.[15] Many of the foundries casting magnesium are using the process quite successfully.

References

1. R.J.M. Payne and N. Bailey, *J. Inst. Metals*, Vol. 88, Pt. 10, 1959/60, pp. 417-427.
2. British Patent 1,463,610.
3. K.G. Gradwell, "Precipitation in a High Strength Magnesium Casting Alloy," Ph.D. Thesis, University of Manchester, 1972.
4. British patent 1,463,608.
5. P.A. Fisher, P.C. Meredith and P.E. Thomas, *Foundry*, August 1967, pp. 68-72.
6. British Patent 1,465,687.
7. U.S. Patent 4,401,621.
8. W. Unsworth and J.F. King, Proceedings of the AFS/CMI Conference "Recent Advances in Magnesium Technology," June 1985, pp. 43-57.
9. Ibid.
10. R.L. Naro and J.F. Hart, *Trans. AFS 1980*, Vol. 55, pp. 57-66.
11. W. Ellinghaus, *Giesserei 68*, Nr. 6 (1981), 16th March, pp. 135-143.
12. I. Strachan and H.J. Proffitt, *Modern Casting*, December 1981, pp. 42-43.
13. J.W. Freuhling and J.D. Hanawalt, *Trans. AFS 1969*, Vol. 77, p. 59.
14. S.L. Couling et al., Proc. International Magnesium Association, Oslo, 1979.
15. H.J. Proffitt, Proc. International Magnesium Association, Houston 1981, pp. 53-58.

ABOUT THE AUTHOR

A. Stevenson is currently with Magnesium Elektron, Inc.