Enhancements in Magnesium Die Casting Impact Properties

Final Report

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ABSTRACT

The need to produce lighter components in transportation equipment is the main driver in the increasing demand for magnesium castings. In many automotive applications, components can be made of magnesium or aluminum. While being lighter, often times the magnesium parts have lower impact and fatigue properties than the aluminum.

The main objective of this study was to identify potential improvements in the impact resistance of magnesium alloys. The most common magnesium alloys in automotive applications are AZ91D, AM50 and AM60. Accordingly, these alloys were selected as the main candidates for the study. Experimental quantities of these alloys were melted in an electrical furnace under a protective atmosphere comprising sulfur hexafluoride, carbon dioxide and dry air. The alloys were cast both in a permanent mold and in a UBE 315 Ton squeeze caster.

Extensive evaluation of tensile, impact and fatigue properties was conducted at CWRU on permanent mold and squeeze cast test bars of AZ91, AM60 and AM50. Ultimate tensile strength values between 20ksi and 30ksi were obtained. The respective elongations varied between 2% and 11%. The Charpy V-notch impact strength varied between 1.6 ft-lb and 5 ft-lb depending on the alloy and processing conditions. Preliminary bending fatigue evaluation indicates a fatigue limit of 11-12 ksi for AM50 and AM60. This is about 0.4 of the UTS, typical for these alloys. The microstructures of the cast specimens were investigated with optical and scanning electron microscopy. Concomitantly, a study of the fracture toughness in AM60 was conducted at ORNL as part of the study. The results are in line with values published in the literature and are representative of current state of the art in casting magnesium alloys.

The experimental results confirm the strong relationship between the aluminum content of the alloys and the mechanical properties, in particular the impact strength and the elongation. As the aluminum content increases from about 5% in AM50 to over 9% in AZ91, more of the intermetallic $Mg_{17}Al_{12}$ is formed in the microstructure. For instance, for 1% increase in the aluminum content from AM50 to AM60, the volume fraction of

eutectic present in the microstructure increases by 35%! Eventually, the brittle $\text{Mg}_{17}\text{Al}_{12}$ compound forms an interconnected network that reduces ductility and impact resistance.

The lower aluminum in AM50 and AM60 are therefore a desirable feature in applications that call for higher impact resistance. Further improvement in impact resistance depends on the processing condition of the casting. Sound castings without porosity and impurities will have better mechanical properties. Since magnesium oxidizes readily, good melting and metal transfer practices are essential. The liquid metal has to be protected from oxidation at all times and entrainment of oxide films in the casting needs to be prevented. In this regard, there is evidence that use of vacuum to evacuate air from the die casting cavity can improve the quality of the castings. Fast cooling rates, leading to smaller grain size are beneficial and promote superior mechanical properties. Micro-segregation and banding are two additional defect types often encountered in magnesium alloys, in particular in AZ91D. While difficult to eliminate, segregation can be minimized by careful thermal management of the dies and the shot sleeve. A major source of segregation is the premature solidification in the shot sleeve. The primary solid dendrites are carried into the casting and form a heterogeneous structure. Furthermore, during the shot, segregation banding can occur. The remedies for this kind of defects include a hotter shot sleeve, use of insulating coatings on the shot sleeve and a short lag time between pouring into the shot sleeve and the shot.

1. INTRODUCTION

Magnesium alloys are the lightest of all common structural materials. On a relative weight scale, with steel rated at 100, magnesium alloys is 23(!) followed by aluminum alloys with 35 and titanium at 58. These relative weight ratings are depicted in Figure 1.1. Zinc is the only other base metal slightly lighter than steel. The need to produce lighter components in transportation equipment is the main driver in the increased demand for magnesium castings. The PNGV program has focused much of the recent attention on automotive applications of magnesium. The large volume and market share of this industry are well known. So is the need to produce parts at very competitive prices. The light weight is even more important in aerospace applications where savings in weight are a premium. Light weight is a major consideration in selection of materials for portable equipment: computers, luggage and power tools. Reducing inertia is desirable in reciprocating and moving machinery where magnesium alloys are finding increased demand.

Another outstanding characteristic of magnesium is its exceptional dimensional stability. This property is due to the intrinsically stable microstructure and relatively high creep resistance. As a result, magnesium components require no stress relieving or annealing treatments.

When vibration is a concern, magnesium alloys is often the material of choice. It has excellent ability to absorb energy anelastically. In many power tool housing applications this is a critical consideration, leading to a quieter operation of the equipment.

Other important advantages of magnesium alloys include a good combination of dent resistance and a high stiffness to weight ratio. Magnesium alloys have a low tendency to gall, therefore can be utilized as bearing surfaces with journal hardnesses above 400 Brinell and loads up to 2,000 psi as long as forced lubrication is provided (Dow).

Magnesium alloys have a distinct fatigue limit, and can operate almost indefinitely at cyclic loads that are below the fatigue limit. Their high thermal conductivity permits rapid heat dissipation, minimizing thermal stresses and distortion. They are non magnetic and non-toxic.

For an identical weight of metal, magnesium has a much larger volume, and will yield more parts. Based on the relative weight rating, for every part made in zinc it is possible to get two identical parts in aluminum or $3 \frac{2}{3}$ parts in magnesium. This fact did not go unnoticed and helped magnesium gain a significant market share despite its higher price. The magnesium segment of the die casting industry continued to grow at higher rates than any other segment. Magnesium shipments in the US in 1996 were 70,7000,000 lb, an increase of 17% relative to the 1995 shipments of 58,300,0000. Predictions are that shipments will increase by 10,000,000/year (FMT).

The automotive industry use of die cast magnesium components has increased from 11% to more than 20% per year. Shown in Figure 1.2 is the current and projected use of magnesium die casting in North American-produced automobiles in metric tons(Luo).

Figures 1.3, 1.4, 1.5 show present and potential automotive uses of die cast magnesium components (in pounds). Based on these estimates, the amount of magnesium could eventually reach 150lb per vehicle. In many automotive applications, components can be made of magnesium or aluminum. While being lighter, often times the magnesium parts have lower impact and fatigue properties than the aluminum.

This investigation was undertaken to identify potential improvements in the impact resistance of magnesium alloys, in particular AZ91D, AM50 and AM60.

2. EQUIPMENT

2.1 Melting Equipment

Melting magnesium alloys requires a protective atmosphere to prevent oxidation and burning of the metal. The most common protective atmosphere for melting of magnesium alloys is a mixture of sulfur hexa-fluoride with carbon dioxide and dry air. At the beginning of the project a 2000ppm sulfur hexafluoride in carbon dioxide mixture was received from Praxair. Subsequently, a Tri-Mix unit for in-situ mixing of the protective gas was provided by Strico-Dynarad.

Magnesium does not dissolve iron as aggressively as aluminum but can react rather violently with oxides due to its high affinity for oxygen. Accordingly, steel crucibles can be used for melting and containing molten magnesium. Ferritic stainless steel crucibles are preferred since they suffer less oxidation. Austenitic stainless steels are not acceptable due to the tendency of magnesium to dissolve nickel. The crucibles utilized in the present study were made of carbon steel.

A Lindberg electrical melting furnace was used for melting up to fifty pounds of magnesium alloys. This furnace is shown in Figure 2.1.1. The dome on top of the furnace was custom made. It provides a larger enclosure for the protective gas. The molten metal is accessible through the hinged door, normally kept closed and sealed with a high temperature refractory sleeve ribbon.

A larger 35KW melting furnace was provided by Strico-Dynarad. This furnace is capable of melting up to 500 pounds of magnesium. The dome is equipped with a hinged door for feeding of magnesium ingots and a sliding pneumatic door for ladling of the metal. This furnace is shown in Figure 2.1.2.

Hand ladles were used to cast the alloys. These special hand ladles were fabricated to Garfield Alloys specifications shown in Figure 2.1.3.

2.2 Permanent Mold

Tensile test bars were cast in a steel permanent mold shown in Figure 2.2.1. This vertical mold has two standard ASTM bars and is fed from a central runner connected to each bar by two gates. The cavity of the mold was coated with a thin Boron Nitride mold release coating. An embedded thermocouple provides temperature readings of the mold.

2.3 Squeeze Casting Equipment

The 315 UBE VHSC squeeze caster at CWRU shown in Figure 2.1.1 is a clamping force of 350 metric tons and a vertical shot sleeve that can apply up to 60 tons force. The other characteristics of the unit are shown in Figure 2.3.2. The sub-systems and operating sequence of the squeeze caster are shown in Figures 2.3.3 and 2.3.4 and are briefly described below:

Step 1: The robotic ladle scoops molten metal from the melting furnace and carries it to the shot sleeve as shown in Figure 2.3.5. The shot sleeve is in the “Furnace Side” position (tilted). The ladle pours metal into the shot sleeve as shown in Figure 2.3.6 -1. -

Step 2: While the ladle transfers molten metal to the shot sleeve, the dies shown in Figure 2.3.8 are closed.

Step 3: The shot sleeve moves to the “Machine Side” position (upright, as shown in Figure 2.3.6-2 and 2.3.7) and docks with the die as illustrated in Figure 2/3.6-3. The plunger pushes molten metal into the cavity, as illustrated in Figure 2/3.6-4. The motion of the plunger is controlled by a programmable controller. A high velocity is employed to bring the metal fast to the gate, before it cools much. A slower, controlled velocity is used for smooth, turbulence free filling. The position of the plunger, the velocity and the pressure can be monitored on the Visi-Track monitoring unit as shown in Figure 2.3.9.

Step 4: The dies open. The extractor unit shown in Figure 2.3.10 moves in between the dies. With the receiver underneath the casting, the ejector pins push the casting out of the ejector die, onto the receiver plate. While the extractor retracts, die lubricant is applied on the dies. A separate plunger lubrication robot also shown in Figure 2.3.10 applies lubricant on the plunger. For short experimental runs, a manual spraying unit shown in Figure 2.3.11 has been used.

Additional auxiliary equipment includes a Sterling Oil Die Heater shown in Figure 2.3.12, capable of heating oil to 550°F, corresponding to a die temperature of 500°F.

A schematic of the insert used to squeeze cast test bars is shown in Figure 2.3.13.

3. EXPERIMENTAL

3.1 Alloy Compositions

The composition of the investigated magnesium alloys is shown in Table 3.1. The thermochemical properties are shown in Table 3.2.

Table 3.1: Composition of Mg Alloys

Alloy	Al	Mn	Zn	Si	Cu	Ni	Fe
AZ91D	8.3-9.7	0.15	0.35-1.0	0.1	0.03	0.002	0.005
AM50	4.2-5.4	0.27	0.15	0.2	0.01	0.002	0.004
AM60	5.5-6.5	0.25	0.22	0.1	0.01	0.002	0.005

These alloys are predominantly processed by die casting. AZ91 has excellent castability and good strength. AM50 has excellent ductility and energy-absorbing properties.

AM60 is similar but has slightly higher strength. The alloying elements in these alloys include:

Aluminum

Aluminum and magnesium are mutually soluble in the liquid phase. The binary aluminum magnesium phase diagram is shown in Figure 3.3. The solubility limit of aluminum in magnesium in the solid state at the eutectic temperature is 12.7 weight percent. On the magnesium-rich side it shows an eutectic at 69% magnesium and 437°C. This eutectic is a mixture of magnesium solid solution and a brittle $\text{Mg}_{17}\text{Al}_{12}$ intermetallic compound. As the aluminum content of the alloy increases, there is a progressive increase in the amount of the eutectic. Figure 3.4 (Aune et.al.) illustrates the increase in the fraction of the eutectic in the structure as a function of the aluminum content. Increasing the aluminum content thus increases the amount of the eutectic and lowers the ductility of magnesium - aluminum alloys. Above 7% aluminum the eutectic forms a continuous network along the grain boundaries and the alloy loses most of its ductility.

Aluminum improves strength and hardness of magnesium aluminum alloys. From a processing standpoint the aluminum addition makes magnesium alloys easier to cast due to the formation of the low melting eutectic. When aluminum is present in excess of 6% the alloy responds better to heat treatment. An aluminum content of 6% is considered to possess an optimum combination of strength and ductility.

Zinc

Next to aluminum, zinc is the most effective alloying element in magnesium. In AZ91 it is used in combination with aluminum to produce good room-temperature strength; however, when added to magnesium alloys containing 7-10% aluminum in more than 1%, it has a tendency to cause hot tearing. Zinc helps in suppressing the corrosive effect of iron and nickel impurities. The binary eutectic magnesium zinc phase diagram is shown in Figure 3.5.

Manganese

Manganese increases slightly the yield point of magnesium without affecting considerably the tensile strength. Its main function is to increase the saltwater resistance of Mg-Al and Mg-Al-Zn alloys. It forms Al-Mn-Fe intermetallic compound particles with the harmful iron and other heavy-metal elements that subsequently precipitate from the melt. It only has limited solubility in magnesium as depicted in the peritectic phase diagram shown in Figure 3.6. In the presence of aluminum the solubility of manganese in magnesium is limited to 0.3%.

3.2 Solidification Behavior

The fast cooling rate in die casting does not allow the solidification to proceed according to the equilibrium phase diagrams. Instead, a non-equilibrium structure evolves as described below (Sakkinen):

Process	AZ91D	AM50/AM60
Solidification of primary Mg (Solid Solution) from the molten metal.	1,103°F	1,139°F AM50 1,144°F AM60
Growth of Mg(ss) from the liquid. The liquid becomes enriched in aluminum.	1,103°F-818°	1,139°F- 818°F
Mg(ss) growth ends. The liquid reaches eutectic temperature.	818°F	818°F
The eutectic solidifies as two phases: eutectic Mg(ss) and Mg ₁₇ Al ₁₂ intermetallic.	818°F	818°F

Slow diffusion rates of Al and Mg in solid solution allows eutectic Mg(ss) to remain present as a supersaturated solid solution at room temperature.

818°F to RT

818°F to RT

3.2 Permanent Mold Casting Experiments

The three magnesium alloys, AZ91D, AM50 and AM60 were cast in the test bar permanent mold described in section 2.2. One round of casting experiments were conducted at CWRU. A second round of experiments were conducted with AZ91D at Garfield Alloys in Cleveland, Ohio. A third round of casting experiments were conducted with AM50 and AM60 at MagReTech in Bellevue, Ohio.

All casting experiments were conducted with a temperature data acquisition system attached to the mold. The mold was initially pre-heated to 400°F. After casting about twenty specimens, the temperature of the mold increased to about 600 °F.

The as-cast tensile properties of the bars were tested in a Baldwin 60,000 pound tensile machine. The ultimate tensile strength and elongation of each cast test bar were measured. Charpy V-notch samples and bending fatigue specimens were machined from the same bars. The rotating bending fatigue strength was measured on a RR Moore fatigue machine.

3.3 Squeeze Casting Experiments

Tensile test bars of the investigated alloys were squeeze cast in the 315 Ton UBE VHSC described in section 2.3. Figure 3.3.1 shows the design of the test bar insert and the dimensions of the test bars. The molten metal was delivered to the shot sleeve

manually. While this is common practice in die casting of magnesium alloys, it was noticed that some oxidation takes place during the transfer and is trapped in the casting. Two problems encountered in squeeze casting of magnesium alloys were cold shuts and hot tearing. These problems were not encountered during squeeze casting of identical test bars of aluminum 356. The cold shuts occur mostly in the overflow region, which is the coldest area of the insert. Magnesium alloys have lower heat capacity than aluminum and therefore lose their heat faster to the die. The hot tearing is caused by the wider solidification range of magnesium alloys.

4. RESULTS

4.1 Tensile Properties

The results of the tensile testing of the AZ91D test bars cast at CWRU in the permanent mold are shown in Figures 4.1.1a,b. Ten castings were made, each with two test bars. The average ultimate strength was 18.8 ksi $\pm$ 0.92ksi and the elongation was 2.2 $\pm$ 0.35%. These relatively low values are attributed to oxidation of the alloy during the hand ladling of the metal from the melting furnace to the permanent mold. The scatter in the elongation measurements is also a result of the large amount of oxides present in the metal. Another round of AZ91D test bars was cast at Garfield Alloys in the permanent mold. The results are shown in Figures 4.1.2a,b. Five castings were made, each with two test bars. The average ultimate strength was 20.6 ksi $\pm$ 1.92ksi and the elongation was 2.8 $\pm$ 0.57%. While better, the ultimate tensile strength is still relatively low. Note these bars were tested in the as-cast condition. The tensile properties could be improved by an aging treatment.

Results of the tensile testing of the AM50 test bars cast at CWRU in the permanent mold are shown in Figures 4.1.3a,b. Ten castings were made, each with two test bars. The average ultimate strength was 21.7 ksi $\pm$ 3.35ksi and the elongation was 7.6 $\pm$ 2.22%. The scatter in the elongation measurements is also a result of oxides trapped in the metal during hand ladling of the metal from the melting furnace to the permanent mold. Another round of AM50 test bars was cast at Garfield Alloys in the permanent mold. The results are shown in Figures 4.1.4a,b. Eight castings were made, each with two test bars. The average ultimate strength was 27.7 ksi $\pm$ 2 ksi and the elongation was 10.8 $\pm$ 1.81%.

AM60 test bars cast at CWRU in the permanent mold are shown in Figures 4.1.5a,b. Sixteen castings were made, each with two test bars. The average ultimate strength was 24.1 ksi $\pm$ 2.74 ksi and the elongation was 8.5 $\pm$ 1.78%. The scatter in the elongation measurements is also a result of oxides trapped in the metal during hand

ladling of the metal from the melting furnace to the permanent mold. Another round of AM60 test bars was cast at Magretech in the permanent mold. The results are shown in Figures 4.1.6a,b. Ten castings were made, each with two test bars. The average ultimate strength was 29.7 ksi +/- 1.6 ksi and the elongation was 11.2 +/- 0.66%. A summary of the tensile testing results is shown in Table 4.1.7.

Table 4.1.7: Summary of tensile properties in PM cast alloys

Alloy	Cast at	UTS (ksi)	Std.Dev(ksi)	Elong. (%)	Std.Dev. (%)
AZ91D	CWRU	18.8	0.92	2.2	0.35
AZ91D	Garfield	20.6	1.92	2.8	0.57
AM50	CWRU	21.7	3.35	7.6	2.22
AM50	Garfield	27.7	2.0	10.8	1.81
AM60	CWRU	24.1	2.74	8.5	1.78
AM60	Magretech	29.7	1.6	11.2	0.66

4.2 Impact Properties

The impact specimens cast in the permanent mold were machined from the bottom side, grip section of the tensile test bars. This procedure allows for a direct comparison between impact and tensile properties for the same casting. The squeeze cast impact specimens were machined from the runners of the casting. The testing at CWRU was performed with an instrumented machine.

Results of the Charpy V-notch impact testing of the AZ91D test bars, squeeze cast at CWRU are shown in Figure 4.2.1. Seventeen castings were evaluated, each with two test bars. The average impact strength was 1.71 ft-lb +/- 0.56ft-lb. This is a relatively low value, and is attributed to oxidation of the alloy during the hand ladling of the metal from the melting furnace to the shot sleeve of the squeeze casting machine.

Results of the Charpy V-notch impact testing of AM50 permanent mold test bars cast at CWRU are shown in Figure 4.2.2. Ten castings were evaluated, each with two test bars. The average impact strength was 2.1 ft-lb +/- 0.35ft-lb.

Results of the Charpy V-notch impact testing of the AM50 test bars, squeeze cast at CWRU are shown in Figure 4.2.3. Three castings were evaluated, each with two test bars. The average impact strength was 1.70 ft-lb +/- 0.49ft-lb. This is a relatively low value, and is attributed to oxidation of the alloy during the hand ladling of the metal from the melting furnace to the shot sleeve of the squeeze casting machine.

The impact strength of die cast AM50 steering wheels was also evaluated. The thin section of the wheel makes it difficult to obtain a large enough piece for fabricating standard Charpy V-notch samples, with the exception of the hub area. The location of the sampling is shown in Figure 4.4.9. Eight wheels were evaluated in all. The results are shown in Figure 4.2.4. The average impact strength was 1.6 ft-lb +/- 0.18ft-lb.

Results of the Charpy V-notch impact testing of AM60 permanent mold test bars cast at CWRU are shown in Figure 4.2.5. Fourteen castings were evaluated, each with two test bars. The average impact strength was 2.0 ft-lb +/- 0.24ft-lb.

Results of the Charpy V-notch impact testing of the AM60 test bars, squeeze cast at CWRU are shown in Figure 4.2.6. Eleven castings were evaluated, each with two test bars. The average impact strength was 2.1 ft-lb +/- 0.65ft-lb. This is a relatively low value, and is attributed to oxidation of the alloy during the hand ladling of the metal from the melting furnace to the shot sleeve of the squeeze casting machine.

Results of the Charpy V-notch impact testing of AM60 permanent mold test bars cast at Magretech are shown in Figure 4.2.7. Four castings were evaluated, each with two test bars. The average impact strength was 5.0 ft-lb +/- 0.65ft-lb. It should be noted

this test was conducted at Tensile Testing, an accredited independent testing facility in Cleveland. The test results and the calibration certificates are enclosed in the Appendix. A 230 ft-lb Charpy Impact Machine was used there.

Results of the Charpy V-notch impact testing of AM50 permanent mold test bars cast at Garfield Alloys are shown in Figure 4.2.8. Three castings were evaluated, each with two test bars. The average impact strength was 4.5 ft-lb +/- 0.5ft-lb. It should be noted this test was also conducted at Tensile Testing.

The results of the impact testing are summarized in Figure 4.2.9.

Table 4.2.9: Summary of impact properties.

Alloy	Cast at	Type	Impact Strength (ft-lb)	Std. Dev (ft-lb)
AZ91D	CWRU	Squeeze Cast	1.71	0.56
AM50	CWRU	Permanent Mold	2.1	0.35
AM50	CWRU	Squeeze cast	1.7	0.49
AM50	Die Cast	Die Cast	1.6	0.18
AM50	Garfield Alloys	Permanent Mold	4.5	0.50
AM60	CWRU	Permanent Mold	2.0	0.24
AM60	CWRU	Squeeze cast	2.1	0.65
AM60	Magretech	Permanent Mold	5.0	0.5

4.3 Fatigue Properties

A limited number of RR Moore bending fatigue experiments were carried out with permanent mold AM50 cast at Garfield Alloys and permanent mold AM60 cast at Magretech. The results are tabulated in Table 4.3.1 and shown in Figures 4.3.2 and 4.3.3.

Table 4.3.1: Fatigue Properties of AM50 and AM60

AM50

Stress(ksi)	Cycles
15	29000
12.6	69000
12.6	229000
11.7	1580000
11.7	6627000
10.4	15597000

AM60

Stress(ksi)	Cycles
11.7	32000
11.7	44000
10.4	74000
7.45	143000
7.45	216000
7.45	466000

The fatigue limit measured for AM50 compares favorably with values published in the literature. The fatigue limit for AM60 is lower than expected. Further testing was undertaken to determine the source of the lower than expected results. The data was not available at the time of this writing.

4.4 Microstructures

Some of the squeeze and permanent mold cast specimens were cut and polished for metallographic examination. The objective was to compare the microstructures obtained with these casting methods and their relationship to the respective mechanical properties.

Figure 4.4.1 illustrates the typical microstructure of permanent mold cast AZ91. In Figure 4.4.2 (a)(b) the microstructures of permanent and squeeze cast AZ91 are shown side by side. Both show primary dendrites of magnesium solid solution and a network of the eutectic β -Mg₁₇Al₁₂ magnesium solid solution. The squeeze cast specimen was taken from the biscuit. The cooling rates of the permanent mold casting and the heavy section biscuit are similar, thus the similarity between the coarseness of the two microstructures. In effect, the microstructure of the squeeze cast parts can vary considerably, depending on the local cooling rate: near the surface the cooling rates are higher resulting in fine microstructures; in the center the structure is much coarser, corresponding to the slower cooling rates. These structures are illustrated in Figure 4.4.3. Note the bi-modal distribution of the primary magnesium solid solution dendrites. The large dendrites originate from premature solidification in the shot sleeve, injected into the casting.

Figures 4.4.4 and 4.4.5 shown side by side squeeze cast and permanent mold cast AM50. In this case the squeeze cast microstructure is slightly finer than the permanent mold cast structure.

Figures 4.4.6 and 4.4.7 and 4.4.8 shown side by side squeeze cast and permanent mold cast AM60. The squeeze cast microstructure is again slightly finer than the permanent mold cast structure.

The finest structure of a die cast steering wheel is shown in Figure 4.4.9. The micrograph was taken from the center portion of the wheel.

5. DISCUSSION

5.1 Tensile Strength and Elongation

The tensile properties listed by ASTM for die cast AZ91D in the as-cast condition are UTS of 34ksi, YS of 23ksi and elongation of 3%. Additional properties listed by the ASTM are shown in Figure 5.1.1. The ASTM standard discourages use of separately die-cast bars for evaluation of mechanical properties. It recommends mechanical property control based on proof testing of the whole die casting. A similar approach is taken by the SAE standard.

Aune and Westengen investigated the effect of aluminum content on mechanical properties of magnesium aluminum alloys. The compositions included in the study are tabulated in Table 5.1.2. Specimens were die cast in a 400-ton cold chamber die casting machine. The UTS and yield strength values obtained for these alloys are shown in table 5.1.3 and plotted as a function of aluminum content in Figure 5.1.4. The total fracture elongation is shown in figure 5.1.5. The total fracture elongation decreases with increasing aluminum concentration. This decrease is caused by the increasing amount of the brittle $Mg_{17}Al_{12}$ intermetallic phase in the structure.

Tensile properties of AZ91D and AM60 were reported by Fantetti for die cast and plaster cast with and without a chill. The results are shown in Figure 5.1.6. A clear relationship between the tensile properties and the grain sizes shown in Figure 5.1.7 was noted. The finer grain size facilitated by the fast cooling rates of the die casting process yielded higher tensile properties.

Similar dependency of the tensile properties on the grain size were reported by Sasaki et.al. as shown in Figure 5.1.8. These authors also measured the dendrite arm spacing (DAS) and related it to the grain size as shown in Figure 5.1.9. The effect of the dendrite arm spacing on the tensile properties is illustrated in Figures 5.1.10 and 5.1.11.

It is interesting to notice that for small DAS the UTS and elongation are not DAS dependant in the T6 condition. The short diffusion path makes the solutioning treatment very effective, virtually eliminating the brittle $Mg_{17}Al_{12}$ brittle intermetallic compound from the grain boundaries. For the larger DAS structures generated by gravity casting, the UTS and elongation are DAS dependant in both the as-cast and T6 condition, since the diffusion distances are longer and the $Mg_{17}Al_{12}$ brittle intermetallic compound is not entirely removed from the grain boundaries.

The typical range of the tensile properties reported by Sasaki et.al. for squeeze cast AZ91 in the T6 condition are shown in Figure 5.1.12. The relatively low elongation values are attributed to segregation and microporosity. Better properties were obtained by semi-solid casting of AZ91 in the T4 condition as shown in Figure 5.1.13. No segregation or microshrinkage were detected in this case.

A study comparing properties of virgin and recycled AM60B was conducted by Guy et.al. The tensile properties for these alloys were similar, as shown in Table 5.1.14 and Figures 5.1.15 to 5.1.16.

Another comparative study of virgin and recycled magnesium alloys was conducted by Grebetz. The study covered properties of ingots as well as die cast specimens. The mechanical properties measured for AZ91D, AM60B and AM50A are summarized in Tables 5.1.17, 5.1.18 and 5.1.19. respectively. The tensile properties of cut-out specimens from V-10 valve covers are shown in Table 5.1.20.

Significant improvements in mechanical properties were reported by Ito et.al. for the Pore Free Die Casting Process (PFD). In this process the die cavity is flooded with oxygen which reacts with the molten metal to generate a vacuum during filling. Improvements of 20% in strength and 250% in elongation are reported for AM60 as shown in Table 5.1.21.

5.2 Impact Properties

Originally, automotive applications of magnesium alloys were predominantly non-structural. Recent trends of making vehicles lighter calls for increasing utilization of magnesium in load bearing components such as steering control structures and wheels. Consideration needs to be given to structural deformation during collision. Passenger safety requires alloys that deform and absorb energy in a ductile manner rather than in a brittle mode. As a result, there is much interest in improved ductility, tougher magnesium alloys for automotive structural applications.

The most common measurement of the impact toughness is the energy absorbed during fracture testing of a standard size specimen namely the Charpy bar shown in Figure 5.2.1. In the impact test, the specimen is placed between two anvils and a pendulum strikes it in the middle. In the instrumented version of the test, an electronic sensor is attached to the striking edge of the pendulum to measure the force and velocity of the pendulum during impact. The characteristics of a ductile and a brittle impact curve are shown in Figure 5.2.2. The most important feature in the test is the total energy absorbed by the specimen during fracture.

Grebetz conducted extensive impact testing of AZ91D and AM60B. The results are shown in Figures 5.2.3 and 5.2.4 respectively both for un-notched Charpy bars. AZ91D exhibits relatively low values, between 2.3 and 5.5 ft-lb. AM60B on the other hand shows significantly higher values between 4.5 and 13 ft-lb. The wide spread in the results originates from casting defects. The low impact strength specimens were shown to have more porosity, shrinkage and hot tears than the high impact strength specimens.

Aune and Westengen investigated the effect of aluminum content on mechanical properties of magnesium aluminum alloys. The compositions included in the study are tabulated in Table 5.1.2. Specimens were die cast in a 400-ton cold chamber die casting machine. The impact strength values obtained for these alloys are shown in Table 5.2.5

and plotted as a function of aluminum content in Figure 5.2.6. A decrease in impact strength with increasing aluminum concentration is evident. The drop is most dramatic above 7% aluminum. This drop is caused by the increasing amount of the brittle $Mg_{17}Al_{12}$ intermetallic phase in the structure. Above 7% aluminum the brittle $Mg_{17}Al_{12}$ phase forms a continuous network along the grain boundaries, thus facilitating trans-granular crack propagation.

Aune and Westengen also found a good correlation between impact strength and fracture elongation, as shown in Figure 5.2.7 and suggested using impact testing as a quality control factor for die cast products that require high ductility.

The effect of DAS on fracture toughness of gravity cast AZ91 in the T6 was reported by Sasaki et.al. and is shown in Figure 5.2.8.

The study comparing properties of virgin and recycled AM60B conducted by Guy et.al. also covered impact properties. The Izod and Charpy impact for these alloys were similar, as shown in Tables 5.2.9 and 5.2.10.

Elimination of porosity by application of vacuum can improve significantly the impact resistance of magnesium-aluminum alloys as demonstrated in Figure 5.2.11(Albright).

Fantetti reports higher impact resistance for AZ91 and AM60 when casting the alloys in plaster than by die casting as shown in Table 5.2.12. He attributes the lower properties of the die cast parts to their higher porosity. He measured a density of 1.79g/cm^3 for the plaster cast AZ91 alloy and 1.71 g/cm^3 for the die cast alloy.

The good correlation between elongation and impact is also apparent in the properties reported by Sakkinen for AZ91D, AM60 and AM50 as shown in Figure 5.2.13.

5.3 Fatigue

Improved fatigue properties are reported by Ito et.al for a Pore Free Die Casting Process designated Magtek as shown in Figure 5.3.1. The fatigue limit (10^7) is about 9.5 kg/mm², equivalent to the fatigue limit of a DX-30 aluminum alloy (Al-9%Si-0.3%Mg). These improved properties are attributed to the soundness of the pore free casting.

Fatigue properties of AZ91D and AM60 were reported by Fantetti for die cast and plaster cast with and without a chill. The results are shown in Figure 5.3.2 and 5.3.3. As with tensile properties, the finer grain size facilitated by the fast cooling rates of the die casting process yielded higher fatigue properties. Fatigue strength for die cast specimens is in the range of 83 to 90MPa while for the plaster cast T6 chilled specimens it is in the range of 54 to 61 MPa. These values are approximately 1/3 of the UTS and are in agreement with the fatigue strength being between 0.2 -0.43 of UTS for cast magnesium alloys (Ogaveric V.V. and Stephens R.I.).

A study comparing properties of virgin and recycled AM60B conducted by Guy et.al. also covered fatigue properties. Preliminary results are shown in Table 5.3.4.

A cooperative program at Hydro-Magnesium generated low and high fatigue data for AM60 shown in Figure 5.3.5. The specimens for this program were provided by Spartan Light Metal Products (Albright)

5.4 Microstructures

5.4.1 Common Phases

After the magnesium solid solution, the most common phase encountered in magnesium-aluminum alloys is the β -Mg₁₇Al₁₂ intermetallic. During solidification, primary dendrites of magnesium solid solution form first. The remaining liquid becomes

gradually richer in aluminum. Upon cooling to the eutectic temperature, $\beta\text{-Mg}_{17}\text{Al}_{12}$ forms side by side with magnesium solid solution. In die casting, a finer microstructure with $\alpha\text{-Mg}$ grains about $0.5\mu\text{m}$ is formed near the surface, due to the faster cooling rates. The microstructure near the surface and at the center of a 1mm thick AZ91D die casting is depicted in Figure 5.4.1. (Dunlop et al.). The $\alpha\text{-Mg}$ grains are about $4.0\mu\text{m}$ in the center of this section. A small fraction of larger $\alpha\text{-Mg}$ grains, about $20.0\mu\text{m}$ in diameter, are also present. These originate from partial solidification of the alloy (approximately 20%) in the shot sleeve. This solid fraction is carried into the cavity during the shot and continues to grow there. Etching of this alloy reveals a highly supersaturated $\alpha\text{-Mg}$ phase surrounding the $\beta\text{-Mg}_{17}\text{Al}_{12}$ intermetallic as depicted in Figure 5.4.2. The Al content in these regions is 10-12 wt% compared to 4-5 wt% in the center of the primary grains.

Carlson measured the nominal grain diameter across the diameter of a 6 mm AM60 die cast test bar and found a variation from $12\mu\text{m}$ in the skin region to $25\mu\text{m}$ in the center of the bar as illustrated in Figure 5.4.3.

The $\beta\text{-Mg}_{17}\text{Al}_{12}$ intermetallic compound can take one of two forms depending on whether the alloy contains zinc. In an alloy without zinc, the eutectic forms as a massive compound which contains islands of magnesium solid solution; in an alloy that contains zinc, it takes a divorced form - particles of the compound dispersed in the Mg solid solution.

The solubility of aluminum in magnesium decreases with temperature. During aging of a solutioned alloy, the excess of aluminum precipitates as continuous or discontinuous $\text{Mg}_{17}\text{Al}_{12}$ intermetallic. At aging temperatures above 400°F the precipitates form a continuous Widmanstatten pattern. Discontinuous precipitation, which starts at the grain boundaries and has a lamellar form, is favored by lower aging temperatures and aluminum content of above 8%. At approximately 550°F the lamellar precipitate begins to coalesce, and at approximately 700°F it re-dissolves in the matrix.

The $\beta\text{-Mg}_{17}\text{Al}_{12}$ intermetallic is brittle and unless finely dispersed in the matrix it will reduce the ductility of the alloy. Heat treatment such as T6 can be utilized to refine the $\beta\text{-Mg}_{17}\text{Al}_{12}$ distribution of gravity and sand cast alloys. However, die cast parts can not usually be heat treated due to blistering. Hence, the AZ91 alloy that has a high Al content and therefore large amounts of $\beta\text{-Mg}_{17}\text{Al}_{12}$ intermetallic phase in the microstructure, suffers from low ductility. The AM50 and AM60 alloys have lower amounts of the $\beta\text{-Mg}_{17}\text{Al}_{12}$ brittle phase due to their lower Al content and exhibit higher ductilities than AZ91.

5.4.2 Porosity

Porosity is detrimental to mechanical properties, affecting in particular fatigue and impact properties. Gas porosity is hard to avoid in die casting but can be minimized by optimizing the processing conditions. Alloys with long freezing range such as AZ91 suffer from additional microporosity due to microshrinkage. This microshrinkage is less pronounced in shorter freezing range alloys such as AM50 and AM60 which partially accounts for the higher ductility encountered in these alloys.

Microshrinkage induced porosity in AZ91 ingots was studied by Bakke et. al. They report porous regions depleted in Al and Zn in the center-top of the ingot that is last to solidify. This can be explained by inverse segregation as the last melt, enriched in alloying elements is drawn back to the colder regions. The shrinkage in the colder regions creates an interdendritic flow from the top-center that leaves behind an interdendritic porous network depleted in Al and Zn.

Rodrigo et.al. conducted a systematic study of porosity distribution in AM60B and AZ91D die castings. The theoretical density they used for AM60B is 1.79g/cm^3 and for AZ912B it is 1.81 g/cm^3 . They found an increase in total porosity with increase in sample thickness as illustrated in Figure 5.4.4. Most of this porosity appeared in the

forms of bands. The depth and width of the porosity bands depend on the distance from the gate as illustrated in Figure 5.4.5. The porosity distribution found across a 10 mm AM60B die cast bar is shown in Figure 5.4.6. These features are related to the “banding” effect described in more detail in section 5.4.4.

A Canadian study has reported minor additions of Strontium to reduce to some extent microshrinkage porosity in sand cast AZ91, by affecting the porosity distribution.

5.4.3 Propensity for Segregation and Hot Tearing

The sensitivity of magnesium aluminum alloys to hot tearing is related to the aluminum content as shown in Figure 5.4.7. When die cast in small cross-sections at high shot velocities, AZ91 is relatively insensitive to hot tearing. Segregation banding is however encountered in larger section aluminum magnesium castings in die casting, squeeze and semi-solid castings. This type of segregation is occurring when pressure is applied to a partially solidified metal. Liquid metal of eutectic composition is “extruded” and pushed selectively into some areas of the casting. The segregated structure is more prone to hot tearing. Examples of segregated areas in a squeeze cast AZ91 are shown in Figure 5.4.8 (Sasaki et.al.)

5.4.4 Banding

Banding is a special type of segregation encountered in pressure assisted casting processes, especially those with thin sections and sharp changes in cross-sectional area. It is observed parallel to the surface of die castings. Dunlop et. al. proposed the following mechanism to explain banding defects: Some of the alloy solidifies prematurely in the shot sleeve. When this partially solidified metal is pushed into the cavity casting, it forms upon contact with the die a skin of solid metal. The partially solidified metal entering the cavity encounters resistance to flow by this solid skin. The shear between

the solid skin and the mushy metal entering the cavity causes segregation of liquid along the edge of the solid skin as illustrated in Figures 5.4.9 a,b,c. This liquid shears easily and allows the mushy alloy to flow into the cavity. However, it eventually cools and solidifies. Another band may form further away from the die wall to accommodate flow of the mushy metal. These liquid segregated (solute-rich) bands of the shear plane have a low solid fraction and are weaker than the rest of the alloy. If the mushy metal is still moving but there is not enough interdendritic liquid to fill the band, porosity or tearing may form.

Dahle and StJohn conducted a detailed investigation of banding. They concluded that the location of the bands is related to the thickness of the layer solidified on the die walls and is therefore a function of the heat content of the molten metal, the cooling capacity of the die and the amount of flow. Dahle et.al. interpret the banding phenomena in terms of fundamental solidification processes. The growth of dendrites in the solidifying alloy leads to an increase in the viscosity of the liquid metal. Eventually, the arms of the dendrites start impinging on each other. This is called the “Dendrite Coherency Point”. Beyond this point a certain threshold stress must be exceeded in order for the mushy alloy to behave as a liquid. Upon further solidification the dendrites grow and coarsen until a point is reached when they start interlocking. This is called the “Maximum Packing Solid Fraction”. The two points are illustrated in Figure 5.4.10. In magnesium alloys the solidification range is relatively wide, often in excess of 100°C, in contrast to most aluminum die casting alloys where this range is only 20-30°C. As a result, the mushy zone occupies more volume in the casting, and increases the likelihood of banding defects. The mechanism of the band formation is depicted schematically in Figure 5.4.11. The strength distribution shows a minimum in the banding zone, at the minimum of the “W” shaped curve. It is zero below as long as the solid fraction is below the coherency point. Note that the fraction solid is below the dendritic coherency point. The central region will flow in a plug-like fashion, “lubricated” by the liquid that has the least resistance to deformation. This liquid is enriched in solute and therefore the last to solidify. When the fraction solid is above the maximum packing point as illustrated in Figure 5.4.12, the band may develop a high level of porosity. This is because the supply

of interdendritic liquid is not sufficient to feed the shrinkage and the voids created by the “plug-like” motion of the center region.

5.5 Effect of Alloy Chemistry and Processing on the Properties

The mechanical properties alloys reported in the literature vary widely among different magnesium alloys and even within the same alloy type. Much of this variation can be explained by the variation in the processing parameters used to cast the specimens. Some of the most significant factors that affect mechanical properties include:

a. Aluminum and Zinc Content

The effect of aluminum and zinc on the tensile properties of binary magnesium alloys are illustrated in Figure 5.1.5. A 3% Al alloy is the most ductile. The 9% Al alloy provides the maximum strength. The effect of Al and Zn on magnesium is not limited to mechanical properties but also affects the castability as illustrated in Figure 5.5.2.

The effect of aluminum content on the mechanical properties of AM type alloys is reported by Albright as shown in Figures 5.5.3 and 5.5.4. It is clear that an increase in the Al content leads to higher strength but lowers the ductility. These trends originate from the microstructure of the alloys, specifically the amount of the brittle $Mg_{17}Al_{12}$ phase.

The same trend was reported by Grebetz as shown in Figure 5.5.5.

b. Cooling Rate and Section Size

The strong effect of section size on ultimate tensile strength for AZ91D is shown in Figure 5.5.6. (Dunlop et. al.). The yield strength for a 1mm section is 185MPa as compared to 130 MPa for a 6mm section. This difference is largely due to the much higher volume fraction of the “skin” or fine hard surface layer in the thin die cast sample than in the thicker specimens. This “skin effect” is well documented and is attributed to the very high cooling rate experienced by the surface of the cast part in contact with the steel die. As a result of this high cooling rate, a fine microstructure of very small α -Mg grains (smaller than 0.5 μ m) and a higher volume of the intergranular β -Mg₁₇Al₁₂ phase are formed in the skin region.

Finer inter-dendritic spacing near the surface of the casting has also been reported for AZ91 cast in a permanent mold. These results, shown in Figure 5.5.7, lead to higher mechanical properties near the surface.

c. Vacuum

One processing option reported to contribute to enhanced ductility is the application of vacuum to the die cavity in order to remove gas at the time of the metal injection. Stress-strain curves for AM50 die cast with and without vacuum are shown in Figure 5.5.8 (Albright).

Elimination of porosity by application of vacuum can also improve significantly the impact resistance of magnesium-aluminum alloys as demonstrated in Figure 5.5.9.

Even more dramatic improvement in tensile properties of AM60 by using vacuum and optimized die design are reported by Dierks et. al. from Spartan. These results are shown in Table 5.5.10 and Figure 5.5.11. Significant improvements are reported for un-notched Charpy impact resistance of AM60 shown in Figure 5.5.12.. Similar

improvements are reported for elongation of AM50 shown in Figure 5.5.13. The fatigue limit reported by Dierks for AM60 with this improved processing is about 15ksi as shown in Figure 5.5.14.

5.6 Effect of Heat Treating on the Properties

Aluminum magnesium alloys respond to solutioning and aging heat treatment with a moderate increase in strength and a slight decrease in elongation. The purpose of the heat treating is to dissolve the massive $Mg_{17}Al_{12}$ intermetallic by solutioning it in the matrix and then re-distribute it as a finer precipitate. Typical temperatures and times for the heat treating process are shown in Table 5.6.1 as provided in ASTM B661-87. Aging curves for sand cast AZ91 are illustrated in Figure 5.6.2 (Ito et.al.). Attainable strength is somewhat higher at lower aging temperatures. Aging at higher temperatures reduces the time required to attain maximum strength. Solutioning times between 10 to 16 hours were employed depending on the grain size. Finer structures resulting from fast cooling rates require shorter solutioning times due to the shorter diffusion path. As in aluminum, die cast products may develop blistering during heat treating due to entrained gas porosity and may not be heat treatable.

6. Fracture Toughness of AM60B (S.K. Iskander, R.K.Nanstad, S. Viswanathan, R.L. Swain)

Introduction

The purpose of this report is to document results of tests performed by the Fracture Mechanics Group (**FMG**) of the Metals and Ceramics Division at ORNL to characterize the initiation fracture toughness of 5-mm thick samples of magnesium alloy AM60B. Fracture toughness is strongly influenced by material thickness due to three-dimensional constraint effects. The tests performed were standardized fracture mechanics tests on compact tension specimens and Charpy V-notch impact energy tests on subsize specimens. There were several considerations in the choice of tests that were performed. It is noted that some materials exhibit anisotropic initiation fracture toughness, (besides possible temperature dependence), due to their microstructure. Thus, characterization of the fracture toughness behavior included tests in different orientations and temperatures. The Charpy testing was performed to further explore the effect of orientation on toughness in directions that could not be explored because of the limitations of material dimensions. An additional benefit is to determine if there is a correlation between fracture toughness and Charpy impact energy in magnesium alloys, in which case the Charpy test could provide a more economical test that could be used to screen materials.

The usefulness of the results of the fracture mechanics tests would be enhanced in conjunction with user experience in the use of the material and or service performance. Other examinations were performed to support observations during fracture toughness test including:

1. Scanning Electron Micrographs (**SEM**) of fracture surfaces.
2. Metallography of surfaces normal to the "longitudinal" and "transverse" directions.
3. Photography of fracture surfaces.

Material Used

The specimens used in this study were machined from the stock supplied as

tensile specimens by United States Advanced Material Partnership*. The tensile specimens were machined from a dashboard panel with an average thickness of 5-mm thick. The nominal chemical composition for magnesium alloy AM60B is shown in Table 1.

Table 1. Chemical composition (wt%) of AM60B tested, balance is Mg.

Al	Mn	Si	Zn	Fe	Cu	Ni	Others (total)
	(0.25 min)	Maximum					
5.5 - 6.5	0.3	0.1	0.22	0.005	0.01	0.002	0.003

For the fracture toughness, the tensile properties and Young's Modulus E are required. Young's Modulus was estimated from values given in Ref. [1] and were 5×10^3 ksi at -40°C and 4×10^3 ksi $+120^\circ\text{C}$. Available room temperature tensile test results supplied by Partnership*, were used and were 117 and 207 MPa (30 and 17 ksi) for ultimate strength and yield stress, respectively.

In order to track specimen orientation**, the longitudinal axis of tensile specimens was arbitrarily designated as the L-orientation, and the normal to that orientation in the plane of the specimen designated as the transverse or T-orientation. The thickness direction is the S-orientation, and thus is normal to both L and T directions. ASTM standard E-399 specimen proportionality was used in dimensioning of compact specimen. In specimens designated to be in the L-T orientation, the first letter L gives the direction normal to crack propagation, and the second is that of crack propagation. The layout of the compact tension specimens with respect to the tensile specimens end-tabs from which they were machined is shown in Fig 1. A drawing of a 0.19-in thick compact tension [0.19T C(T)] specimen is given in Fig 2. Actual specimen thickness was dependent upon the dimension of the material available, and was measured individually for each specimen.

*United States Advanced Material Partnership, United States Consortium for Automotive Research, Cooperative Research and Development Program on Design and Product Optimization for Cast Light Metals.

**The designation of the orientations is defined in ASTM E-399.

The toughness characterization test matrix includes Charpy impact testing. The Charpy test is very simple to perform, and, if it can be related to performance in service, (and or fracture mechanics tests), it can be used as a guide in material selection or screening from the same class and thickness of materials. A summary of the tests performed is shown in Table 2.

One of the compact tension specimens was tested without precracking in order to determine the effect of notch acuity. The notches were all electro-discharge machined (EDMed) and subsequently fatigue pre-cracked. A closeup photo of the specimen that is EDMed out of the end tabs is shown in **Fig 3**. The width of the notch root was 0.1-mm (0.004") which was then fatigue pre-cracked as prescribed in ASTM E - 399. A closeup of the specimen root notch area before fatigue precracking is shown in **Fig 4**. Specimens are fatigue pre-cracked to a relative crack depth of 55% of nominal specimen width "W".

After testing, initial and final crack lengths were measured and compared to those inferred by computer program via unloading compliance measurements. Both results were in reasonable agreement. One specimen was tested with only an electro-discharge notch made with an 0.004" dia. wire to determine whether the costs of fatigue pre-cracking could be avoided. The specimens were machined with notches on the top and bottom to enable "outboard" clip gages to be mounted on the load line, see **Fig 2**. The specimen and clip gage were then mounted in a Tinius Olsen testing machine, see **Appendix A**. The applicable load range of the testing machine was verified in accordance with ASTM E-4.

The high-rate 16-bit electronic board used to control testing and perform data acquisition was developed by the FMG. The FMG also developed the computer code used to control the testing, store the data, and analyze the results, see **Appendix B** for a sample output from the computer code used in the analysis of one of the compact tension specimens tested.

Fig 1 Typical layout of L-T orientation compact tension specimens in end tabs of tensile specimens

Table 2. Matrix of tests performed on compact tension specimens of AM60B magnesium alloy.

Specimen Type	Number of Specimens	Test Temperature	Orientation
Compact 0.190T	2	RT	TL
	2	65°F	
	2	120°F	
	1	RT (no pre-cracking)	
Compact 0.190T	2	RT	LT
	2	65°F	
	2	120°F	
Subsize Charpy 4.7 × 4.7 × 25 mm	2	RT	TL
	2		TS
	2		LT
	2		LS

Fig 2 Schematic drawing of the 0.19T C(T) Compact Tension specimen used

Fig 3 Closeup of a 12.6 x 12.2 (L x T), 4.8-mm thick compact tension specimen as electro-discharge machined from end tabs of tensile specimen stock.

Results of fracture toughness testing.

The results of fracture toughness testing at room temperature did not reveal a significant effect of orientation, see Table 3. None of the compact specimens exhibited unstable fracture. The tearing modulus is a measure of the specific energy to propagate the crack, and in this case, increases with crack length. It may be noted that the fracture toughness of the specimen without any fatigue pre-cracking is larger than that

Fig 4 Closeup of compact tension specimen notch root area as electro-discharge machined and before pre-cracking

with fatigue pre-cracking, as expected. This indicates that fatigue pre-cracking is important in order that accurate fracture toughness values are obtained. It is important to note that the fracture toughness values reported are dependent on the material thickness, which in this case is approximately 5 mm. This thickness dependence is due

Table 3. Results of fracture toughness testing.

Specimen ID	Test Temperature (°C)	Tearing Modulus*	Initiation Fracture Toughness, J_Q ** (kJ·m ⁻²)
Specimen Orientation L-T			
9LT5	-40	13	10
8LT4	-40	9	11
9A	RT	14	12
9A1	RT	20	11
1LT1	120	17	26
1LT2	120	13	23
Specimen Orientation T-L			
8TL3	-40	8	10
8TL4	-40	6	12
1	RT	16	11
1A1	RT	17	12
9TL5	120	13	21
9TL6	120	13	12
Specimen Orientation T-L (No fatigue pre-crack)			
1A	RT	10	

* Defined as the non-dimensional parameter $T = \frac{E}{\sigma_f^2} \frac{dJ}{da}$, where σ_f is the flow stress, which is defined as the average of the ultimate strength and yield stress.

** J_Q is defined in ASTM E-813, para. 9.2.6

to the constraint provided by the material thickness in a plane normal to the crack edge. The very high stresses normal to the crack plane causes a lateral contraction in the thickness. For example, a 1-mm thick sheet material would give higher toughness values than a 10-mm thick plate.

For purposes of comparison with test results in which cleavage or unstable fracture occurs, in which the stress intensity factor, K , is applicable, a conversion of the

value of J to K_J is used. Definitions of K and J are given in ASTM E-399 and E-813, respectively. Strictly speaking, K is defined only for predominantly elastic stress fields and plain strain situations. Nonetheless, this conversion is used, but the resulting values of K_J should be used with caution in comparison to values of K obtained in which unstable fracture occurs. The conversion uses either of the two expressions $K_J = \sqrt{EJ}$ or $K_J = \sqrt{\frac{EJ}{1-\nu^2}}$ for plane stress and plane strain conditions, respectively, where E = Young's Modulus and ν = Poisson's ratio. In situations in which the values of J are not valid in terms of the applicable standard, it is common to use the symbol J_Q , as defined in ASTM 813, para. 9.2.6.

Photographs of fracture surfaces of five representative compact specimens is given in **Appendix C**. Note the lamination-like voids on some of the fracture surfaces. These voids did not affect the fracture toughness values since the crack propagated normal to them. This may not have been the case if the crack was running parallel to the lamination and the lamination size was of the same size as the flaw. In the latter case, the lamination would have "arrested" the flaw propagation, and the flaw would have had to re-initiate on the surface beyond the lamination, absorbing more energy than in the case of no lamination.

Scanning electron microscopy (**SEM**) on one of the fracture surfaces was performed and is shown in the **Appendix D**. The SEMs also confirm the observation of stable tearing, with no evidence of cleavage.

Results of Charpy Impact Testing.

Charpy V-notch (CVN) impact testing at room temperature, (in both orientations L-T and T-L orientations that were tested using compact tension), also did not reveal a significant effect of orientation, confirming the results of fracture toughness testing, see **Table 4**.

All Charpy testing performed by the FMG uses instrumented strikers that generate a voltage output that can be captured and displayed as a voltage vs time during impact graph, or "trace". From this trace, a force vs time trace can also be deduced. It is useful to examine the force vs time trace to confirm the lack of unstable tearing during impact testing, a typical one is shown in **Fig. 5**. Note the lack of a sudden drop in load after maximum load is reached. The relatively small load drops are typical of tearing behavior. All the instrumented traces exhibited stable tearing behavior under impact loading conditions.

Fig 5 Force vs displacement trace from instrumented striker

The CVN specimen thickness was limited by that of the material available, and a drawing of the specimens used is shown in **Fig 6**. Fracture toughness testing could only be performed in the L-T and T-L orientations. The confirmation of no orientation effects of both Charpy and fracture toughness testing encourages the assumption that the lack of

Fig 6 Dimensions of Charpy specimen used.

orientation effects exhibited in the T-S and L-S orientations (that could not be tested using compact tension specimens because of the available material dimensions), is also an indication of the isotropic fracture toughness behavior.

Table 4. Results of Charpy Impact Testing.

Specimen ID	Specimen Orientation	Dial Energy (J)
1	T-L	0.87
2		0.66
1	T-S	0.66
2		0.73
1	L-T	0.80
2		0.66
1	L-S	0.99
2		0.60

Metallography and Scanning Electron Microscopy Results

Metallography performed on three faces of a sample of AM60B failed to reveal any significant differences in microstructure between them, supporting the results of the fracture mechanics and Charpy testing, Fig. 7. Some porosity, besides the voids previously mentioned, was observed on the surfaces metallographically examined.

Observations And Conclusions

Fracture testing of magnesium AM60B alloy at room temperature did not reveal unstable fast fracture in the four orientations tested, L-T, T-L, T-S, and L-S*. The

*The only two orientations that could not be sampled for fracture toughness testing because of material stock dimension limitations were the S-T and S-L.

fracture toughness behavior appears to be isotropic with respect to orientation of the propagation of the flaw. For all the compact tension specimens tested, the operator discontinued the test when clip gage ran out of measuring range after approximately 2-mm stable crack extension. This is significant since more energy per unit crack surface created is needed to propagate the flaw during stable tearing, which is measured by the Tearing Modulus*. The positive tearing moduli measured for AM60B magnesium alloy is a measure of the amount of energy that would be required to propagate the flaw in a stable tearing mode. Some materials exhibit negative values of the tearing modulus, which is an indication that once a crack initiates, relatively very little energy is needed to continue flaw propagation. The latter behavior is undesirable in situations where some fore-warning about incipient failure of the structure is important. In contrast to stable tearing, is unstable cleavage fracture during which no or relatively very little energy absorbed during fracture, earning such cases the designation of "catastrophic failure". During stable tearing with positive tearing modulus, the energy input needed to propagate crack extension provides some warning of structural failure. The fatigue pre-cracking required prior to testing of compact tension specimens was easily performed (difficult in brittle materials). Compared to a structural aluminum alloy (a reference will be supplied in the final draft), the tearing modulus of 5-mm thick AM60B is superior, 15 vs 1. Another important measure of the fracture toughness of materials is the value of J_Q , which measure the energy necessary to initiate a flaw. That of AM60B is about the same as the structural aluminum alloy previously mentioned, 12 vs 14 kJ/m² (a reference will be supplied in the final draft). Again for purposes of comparison, the J_Q of stainless steel 316L can be greater than 100 kJ/m², indicating that 316L is much more resistant to initiation of a flaw than either AM60B or the structural aluminum.

As mentioned above, the initiation fracture toughness is isotropic in the L-T, T-L, T-S and L-S orientations tested. Charpy impact testing of subsize specimens (largest that could be machined from the material) did not reveal any significant difference in impact energy between the different orientations, confirming the results of compact

* **Defined in the footnotes of Table 3.

tension testing. The trace from the instrumented Charpy V-notch impact testing also confirmed stable tearing behavior under impact loading conditions.

The specimen tested without fatigue pre-cracking exhibited a higher toughness as expected. Scanning-electron microscopy and Metallography confirmed stable tearing behavior.

Fig 7 Unetched metallographic images of two perpendicular surfaces of magnesium alloy AM60B

RECOMMENDATIONS FOR FUTURE WORK

The scatter in results of fracture toughness values, both from compact tension and Charpy, is relatively significant as can be seen from the previous results. Thus, several other batches of approximately the same thickness of this material should be tested to explore batch-to-batch variations. This will enable a base-line for the fracture toughness of this material to be established. If service experience and or model structural tests of this material indicate inadequate fracture toughness, possible alternatives to be explored are: heat-treatments and or variations on alloy composition.

References

1. Table 6, Chapter 8, "Magnesium", in *Metals Handbook*, Desk Edition, Howard E. Boyer and Timothy L. Gall, Editors, American Society for Metals, Metals Park, Ohio, 1985.

Appendix A. Details of Load-Line Clip Gage Mounting

**Crack-mouth opening displacements are measured
on load-line with ORNL developed clip gages**

Fig. A1 Load-line crack-mouth opening displacement clip gage mounted "over-the-top" on 4.8 mm thick compact tension specimen of magnesium alloy AM60B

Fig. A2. Compact specimen mounted with clip gage in testig machine.

**Appendix B. Typical Output from the Computer Code Written by the Fracture
Mechanics Group to Analyze Fracture Mechanics Tests.**

SPECIMEN

IDENTIFICATION: MG9A

MATERIAL

CODE: MAGNESIUM

YOUNG'S MODULUS: 41.37 (GPA), 6000 (KSI)

POISSON'S RATIO: 0.300

STRENGTHS

YIELD: 117.211 (MPA), 17.00 (KSI)

ULTIMATE: 206.843 (MPA), 30.00 (KSI)

GEOMETRY: C(T)

ORIENTATION: L-T

WIDTH: 10.165 (MM), 0.4002 (IN)

THICKNESS: 4.788 (MM), 0.1885 (IN)

SIDE GROOVE RATIO: 0.0 (PERCENT)

EXTENSOMETER LOCATION: 0.000 (MM), 0.0000 (IN)

FRONT SURFACE-TO-LOAD LINE DISTANCE: 2.507 (MM), 0.0987 (IN)

FRONT SURFACE-TO-INITIAL-CRACK FRONT DISTANCES

DISTANCE 1: 7.328 (MM), 0.2885 (IN)

DISTANCE 2: 7.427 (MM), 0.2924 (IN)

DISTANCE 3: 7.513 (MM), 0.2958 (IN)

DISTANCE 4: 7.625 (MM), 0.3002 (IN)

DISTANCE 5: 7.849 (MM), 0.3090 (IN)

DISTANCE 6: 7.635 (MM), 0.3006 (IN)

DISTANCE 7: 7.600 (MM), 0.2992 (IN)

DISTANCE 8: 7.465 (MM), 0.2939 (IN)

DISTANCE 9: 7.374 (MM), 0.2903 (IN)

FRONT SURFACE-TO-FINAL-CRACK FRONT DISTANCES

DISTANCE 1: 8.849 (MM), 0.3484 (IN)

DISTANCE 2: 9.070 (MM), 0.3571 (IN)

DISTANCE 3: 9.398 (MM), 0.3700 (IN)

DISTANCE 4: 9.492 (MM), 0.3737 (IN)

DISTANCE 5: 9.467 (MM), 0.3727 (IN)

DISTANCE 6: 9.525 (MM), 0.3750 (IN)

DISTANCE 7: 9.220 (MM), 0.3630 (IN)

DISTANCE 8: 9.314 (MM), 0.3667 (IN)

DISTANCE 9: 9.200 (MM), 0.3622 (IN)

TEST

ROUTINE REVISION: 1.02/07-JUL-88

TYPE: UC

MACHINE

MANUFACTURER: MTS

CAPACITY: 22 (KIP), 97.9 (KN)

IDENTIFICATION NUMBER: HYD-02

ENGINEER: SKI

TECHNICIAN: RLS

TEMPERATURE: 21.1 (DEG C), 70.0 (DEG F)

DATE: 11-FEB-99

NOTE: NONE

TERMINATION CONDITIONS: TEST STOPPED ON TECHNICIAN DEMAND

ANALYSIS

ROUTINE REVISION: 1.14/28-JUN-95

PROCEDURE: FMG

UC RESULTS

CALCULATED EFFECTIVE MODULUS

CMO EXTENSOMETER

CALCULATION TEST CYCLE: 2

MODULUS: 28.90 (GPA), 4192 (KSI)

ADJUSTMENT $[(EM-YM)/YM]$: -30.14 (PERCENT)
INITIAL CRACK LENGTH
MEASURED: 5.051 (MM), 0.1989 (IN)
CMO CALCULATED: 4.972 (MM), 0.1958 (IN)
ERROR $[(CICL-MICL)/MICL]$: -1.56 (PERCENT)
FINAL CRACK EXTENSION
MEASURED: 1.756 (MM), 0.0691 (IN)
CMO CALCULATED: 1.662 (MM), 0.0654 (IN) (1)
ERROR $[(CFCE-MFCE)/MFCE]$: -5.35 (PERCENT)
CMO PQ: 0.360 (KN), 81 (LB)
CMO KQ: 7.14 (MPA*SQRT(M)), 6.49 (KSI*SQRT(IN))
CMO KIC: NOT CALCULATED (2)
PMX: 0.653 (KN), 147 (LB)
ASTM J-INTEGRAL RESULTS
CMO/CMO [J-INTEGRAL/CRACK EXTENSION]
JF: 24.64 (KJ/M²), 140.7 (IN*LB/IN²)
POWER-LAW MODEL $[J_I=A_1*CE^{A_2}]$
A1: 20.33 [SI], 374 [ENGLISH]
A2: 0.36199 [SI], 0.36199 [ENGLISH]
RESULTS EXCLUDED FROM MODEL: CYCLES 1, 2, 3, 4, 5, 6, 7, 8, 19, 20 AND 21
JQ: 12.09 (KJ/M²), 69.0 (IN*LB/IN²)
KJQ: 22.36 (MPA*SQRT(M)), 20.35 (KSI*SQRT(IN))
TEARING MODULUS: 14
JIC: NOT CALCULATED (3)
KJIC: NOT CALCULATED (3)

- NOTES:
1. ESTIMATED LAST-CYCLE CRACK EXTENSION
 2. VALIDITY CHECKS FAILED: HIGH PMX/PQ RATIO [E399 9.1.2], LOW SPECIMEN THICKNESS/MEASURED INITIAL CRACK LENGTH RATIO [E399 9.1.3]
 3. ASTM PROCEDURE NOT FOLLOWED

SPECIMEN

IDENTIFICATION: MG9A
 MATERIAL CODE: MAGNESIUM
 ORIENTATION: L-T
 GEOMETRY: 0.19T C(T) NO SIDE GROOVE
 INITIAL CRACK LENGTH: 5.051 (MM)

TEST

ATMOSPHERE: AIR
 TEMPERATURE: 21.1 (DEG C)

ANALYSIS

CRACK EXTENSION METHOD: UC
 J-INTEGRAL METHOD: ASTM
 EXTENSOMETERS: CMO/CMO [J-INTEGRAL/CRACK EXTENSION]

CYCLE	EXTEND-END LOAD	EXTEND-END DISPLACMT	CRACK EXTENSION	J-INTEGRAL	KJ
	KN	MM	MM	KJ/M ²	MPA*SQRT (M)
1	0.395	0.1019	-0.030	1.61	8.15
2	0.460	0.1300	0.000	2.55	10.27
3	0.518	0.1606	0.012	3.92	12.74
4	0.546	0.1815	0.033	4.75	14.02
5	0.583	0.2104	0.052	6.12	15.91
6	0.605	0.2321	0.090	7.14	17.19
7	0.630	0.2625	0.111	8.82	19.10
8	0.635	0.2843	0.171	9.88	20.21
9	0.644	0.3107	0.222	11.24	21.57
10	0.646	0.3490	0.345	12.91	23.11
11	0.648	0.3872	0.408	14.68	24.64
12	0.632	0.4257	0.540	16.50	26.13
13	0.615	0.4674	0.679	18.15	27.40
14	0.592	0.5021	0.775	19.65	28.51
15	0.570	0.5410	0.898	20.73	29.28
16	0.513	0.5822	1.220	20.95	29.44
17	0.472	0.6183	1.288	22.22	30.32
18	0.440	0.6564	1.462	22.68	30.63
19	0.413	0.6943	1.586	23.51	31.19
20	0.390	0.7309	1.654	24.65	31.94
21	0.377	0.7398	1.662	24.64	31.92 (4)

NOTES: 4. ESTIMATED LAST-CYCLE EXTENSION

SPECIMEN

IDENTIFICATION: MG9A
 MATERIAL CODE: MAGNESIUM
 ORIENTATION: L-T
 GEOMETRY: 0.19T C(T) NO SIDE GROOVE
 INITIAL CRACK LENGTH: 0.1989 (IN)

TEST

ATMOSPHERE: AIR
 TEMPERATURE: 70.0 (DEG F)

ANALYSIS

CRACK EXTENSION METHOD: UC
 J-INTEGRAL METHOD: ASTM
 EXTENSOMETERS: CMO/CMO [J-INTEGRAL/CRACK EXTENSION]

CYCLE	EXTEND-END LOAD	EXTEND-END DISPLACMT	CRACK EXTENSION	J-INTEGRAL	KJ
	LB	IN	IN	IN*LB/IN ²	KSI*SQRT (IN)
1	89	0.0040	-0.0012	9.2	7.42
2	103	0.0051	0.0000	14.6	9.35
3	116	0.0063	0.0005	22.4	11.59
4	123	0.0071	0.0013	27.1	12.76
5	131	0.0083	0.0021	34.9	14.48
6	136	0.0091	0.0035	40.8	15.64
7	142	0.0103	0.0044	50.4	17.39
8	143	0.0112	0.0067	56.4	18.39
9	145	0.0122	0.0087	64.2	19.63
10	145	0.0137	0.0136	73.7	21.03
11	146	0.0152	0.0161	83.8	22.43
12	142	0.0168	0.0212	94.2	23.78
13	138	0.0184	0.0267	103.6	24.94
14	133	0.0198	0.0305	112.2	25.95
15	128	0.0213	0.0354	118.4	26.65
16	115	0.0229	0.0480	119.6	26.79
17	106	0.0243	0.0507	126.9	27.59
18	99	0.0258	0.0576	129.5	27.88
19	93	0.0273	0.0625	134.3	28.38
20	88	0.0288	0.0651	140.8	29.06
21	85	0.0291	0.0654	140.7	29.05 (4)

Appendix C. Photos of five fracture surfaces of representative compact specimens

Fig. C1. Fracture surface of magnesium alloy AM60B of one half of the 4.8-mm thick compact tension specimen 9A.

Fig. C2 Fracture surface of magnesium alloy AM60B of one half of the 4.8-mm thick compact tension specimen 9A1.

Fig. C4 Fracture surface of magnesium alloy AM60B of one half of the 4.8-mm thick compact tension specimen MG1.

Fig. C3 Fracture surface of magnesium alloy AM60B of one half of the 4.8-mm thick compact tension specimen A1.

Fig. C5 Fracture surface of magnesium alloy AM60B of one half of the 4.8-mm thick compact tension compact specimen 1A, which was not fatigue pre-cracked.

**Appendix D. Scanning Electron Microscopy of Fracture Surface of Magnesium
Alloy AM60B 4.8 mm Thick Compact Tension Specimen.**

The location of the scanning electron figures with respect to the fracture surface shown later in this Appendix are as shown schematically in Fig. D1, and are along the path of fracture propagation. Note that the fracture in region shown in Fig. D5 is of interest to reveal the type of fracture surface due to the specimen being manually broken apart, since testing was discontinued after about 2 mm of ductile crack growth. The surfaces have the same features as those produced by stable tearing during fracture toughness testing.

Fig. D1 Schematic of location of the scans performed and shown on the following pages. The numbers refer to the last one or two digit(s) of the SEM photo.

Fig. D3. This is a continuation of the view to the right of that shown above in Fig. D1, where the fatigue pre-cracking continues.

Fig. D2. Inside edge and fatigue pre-cracked area adjacent to electro-discharged notch.

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FIGURES

Figure 1.1: Relative weight ratings of common structural alloys (IMA)

Figure 1.2: Estimated magnesium consumption for the big three(Luo)

Figure 1.3: Average Al and Mg contents in 1999 vehicles of Big Three (Luo)

System	Product	Technical Challenges
Interior	airbag housing Window regulator housing glove box	improved casting process rapid prototyping design for magnesium
Body	Door frame/inner A & B pillar hatchback frame spare tire jack	thin-wall design thin-wall casting joining and welding
Chassis	Wheel spare tire rim control arm rack and pinion housing brackets for rail frames	high-strength alloy development new casting processes (squeeze and semi-solid metal casting) low-cost coatings
Powertrain	automatic transmission case engine block crankcase oil pan starter housing oil/water pump housing intake manifold engine mount	creep-resistant alloy development design for magnesium fastening strategy engine coolant compatibility

Figure 1.4: Potential Mg applications and technical challenges (Luo)

System	Product	GM	Ford	Chrysler	Europe	Asia
Interior	instrument panel	yes		yes	yes	
	knee bolster retainer	yes				
	seat frame	yes		yes	yes	yes
	seat riser	yes	yes	yes		
	seat pan		yes	yes		
	console bracket		yes			
	airbag housing			yes		
	steering wheel	yes	yes	yes	yes	yes
	keylock housing	yes	yes	yes		
	steering column parts	yes	yes	yes	yes	yes
	radio housing		yes			
	glove box door	yes				
	window motor housing		yes		yes	
Powertrain	valve cover/cam cover	yes	yes	yes	yes	yes
	4WD transfer case	yes	yes			
	manual transmission case				yes	yes
	clutch housing & piston	yes				
	intake manifold	yes			yes	
	engine oil pan				yes	
	Alternator/AC bracket			yes		
	transmission stator	yes				
	oil filter adapter	yes				yes
	electric motor housing	yes				
Body	door frame				yes	
	tailgate				yes	
	roof frame	yes			yes	
	sunroof panel	yes	yes		yes	
	mirror bracket	yes	yes	yes	yes	
	fuel filler lid				yes	
	door handle				yes	yes
Chassis	wheel	yes				
	ABS mounting bracket	yes		yes		
	brake padel bracket	yes	yes	yes		yes
	brake/accelerator bracket	yes	yes			
	brake/clutch bracket		yes			
	brake padel arm		yes			

Figure 1.5: Global applications of Mg in automobiles

Figure 2.1.1

Equipment For Magnesium Permanent Mold Casting

Furnace

Test Bar Permanent Mold

Figure 2.1.2: StricoDynarad magnesium melting furnace

Figure 2.1.3: Hand ladle for magnesium

Figure 2.3.1 Squeeze casting machine

Figure 2.3.2

Squeeze casting machine equipment

TYPE —UBE VCS315

1. DIE CLAMPING UNIT

DIE CLAMPING FORCE	315 TON	
PLATEN DIMENSIONS	42×38 INCHES	1060×950 MM
DIE STROKE (MAX)	24 INCHES	600 MM

2. SHOT UNIT — S63

SHOT FORCE	20 ~ 63 TON	
SHOT STROKE (MAX)	25 INCHES	630 MM
SHOT SPEED (MAX)	3.2 INCHES/SEC	80 MM/SEC

3. CASTING WEIGHT (MAX)	11 LB	5KG
-------------------------	-------	-----

Steps in the squeeze casting process

Figure 2.3.3

Operation of the injection unit

Figure 2.3.4

Automatic ladling machine

Figure 2.3.5

Operating sequence of the horizontal die clamping/vertical shot system

Figure 2.3.6

<Side View>

<Top View>

<Bottom View>

Figure 2.3.7 View of shot sleeve

Ejector die

Cover die

Inserts for squeeze casting tensile test bars

Figure 2.3.8

<Typical Monitoring plot>

Visi-trak shot monitoring system

Figure 2.3.9

For dies

For shot sleeve

Automatic die lubricant spraying units

Figure 2.3.10

Manual die lubricant spray equipment

Figure 2.3.11

Oil Die Heater

(Sterlco, M2B9016-J1)

Infrared Die Heater

Die heating equipment

Figure 2.3.12

Table I Thermochemical properties of AZ91. (Data taken from Metals Handbook (4))

Liquidus temperature	595 °C
Solidus temperature	470 °C
Incipient melting temperature	421 °C
Specific heat	1.05 kJ/kgK at 20°C
Coeff. Of thermal expansion	$26 \cdot 10^{-6}/K$ at 20-100°C
Thermal conductivity	72 W/mK at 100 - 300°C
Latent heat of fusion	373 kJ/kg

Table 3.2: Thermochemical properties of AZ91D (Metals Handbook)

Figure 3.3: The binary aluminum-magnesium phase diagram (Roberts)

Figure 3.4: Fraction of eutectic as a function of aluminum content (Aune et.al.)

Figure 3.5: The binary magnesium-zinc phase diagram (Roberts)

Figure 3.6: The binary magnesium-manganese phase diagram (Roberts)

Figure 4.1.1(a)

Tensile Strength of AZ91 PM Test Bars

CWU03010-F

Figure 4.1.1(b)

Elongation of AZ91 PM Test Bars

Figure 4.1.2(a)

Tensile Strength of AZ91 PM Test Bars

Figure 4.1.2(b)

Elongation of AZ91 PM Test Bars

GA02160-F

Figure 4.1.3(a)

Tensile Strength of AM50 PM Test Bars

CWRU01250-F

Figure 4.1.3(b)

Elongation of AM50 PM Test Bars

Figure 4.1.4(a)

Tensile Strength of AM50 PM Test Bars - CWRU04110

Figure 4.1.4(b)

Elongation of AM50 PM Test Bars

GA04110-F

Figure 4.1.5(a)

Tensile Strength of AM60 PM Test Bars

Figure 4.1.5(b)

Elongation of AM60 PM Test Bars

Average Elongation = $8.5 \pm 1.78(\%)$

CWRU01310-F

Figure 4.1.6(a)

Tensile Strength of AM60 PM Test Bars

M05020-F

Figure 4.1.6(b)

Elongation of AM60 PM Test Bars

M05020-F

Figure 4.2.1

Charpy V-Notch Impact Strength of AZ91 SC

CWRU01190-T6

Figure 4.2.2

Charpy V-Notch Impact Strength of AM50 PM

Figure 4.2.3

Charpy V-Notch Impact Strength of AM50 SC

Figure 4.2.4

Figure 4.2.5

Charpy V-Notch Impact Strength of AM60 PM

Figure 4.2.6

Charpy V-Notch Impact Strength of AM60 SC

CWRU01210-F

Charpy V-Notch Impact Strength of AM60 PM

Figure 4.2.7

Figure 4.2.8

Charpy V-Notch Impact Strength of AM50 PM

Figure 4.3.2

Fatigue Curve of AM50 PM Test Bars

Figure 4.3.3

Fatigue Curve of AM60 PM Test Bars

Figure 4.4.1

Typical Microstructure of AZ91 PM

a. PM-CWRU0300(Acetic acid etched)

b. PM-GA02160(Acetic acid etched)

Figure 4.4.2 (a)

Typical Microstructure of AZ91 PM & SC

a. PM-CWRU03010-F(Acetic acid etched)

b. SC-CWRU01190(Acetic acid etched)

Figure 4.4.2 (b)

Microstructure of AZ91 PM & SC

a. PM-GA02160-F(Acetic acid etched)

b. SC-CWRU01190(Acetic acid etched)

Typical Microstructure of AZ91 SC Test Bar

Figure 4.4.3

Figure 4.4.4

Typical Microstructure of AM50 PM & SC

a. PM-GA04110-F(Acetic acid etched)

b. SC-CWRU01250-F(Acetic acid etched)

Figure 4.4.5

Typical Microstructure of AM50 PM & SC

a. PM-GF04110(Acetic acid etched)

a. PM-CWRU01250(Acetic acid etched)

c. SC-CWRU01250(Acetic acid etched)

c. SC-CWRU01250(Acetic acid etched)

Figure 4.4.6

Typical Microstructure of AM60 PM

a. AM60 PM-M05020-F(Acetic acid etched)

b. AM60 PM-CWRU01310-F(Acetic acid etched)

Figure 4.4.7

Typical Microstructure of AM60 PM & SC

a. AM60 PM-M05020(Acetic acid etched)

b. AM60SC-CWRU01210(Acetic acid etched)

Figure 4.4.8

Grain Size of AM60 PM & SC

a.PM-M05020-T6(Acetic acid etched)

b.SC-CWRU01210-T6(Acetic acid etched)

Figure 4.4.9

Location of CVN Test Bars From Steering Wheel

Typical Microstructure of AM50 Steering Wheel

Acetic acid etched

Table 3 Minimum tensile-property requirements for die-cast test bars (as-cast condition)

Alloy	Tensile strength		Yield strength		Elongation in 50.8 mm (2 in.), %
	MPa	ksi	MPa	ksi	
AM50A					
AM60A, AM60B	220	32	130	19	8
AS41A, AS41B	210	31	140	20	6
AZ91A, AZ91B, AZ91D	230	34	160	23	3
Ref 1					

Table 2 Typical mechanical properties of separately die-cast test bars (as-cast condition)

Alloy	Tensile strength		Yield strength		Elongation(a), %	Impact strength(b)	
	MPa	ksi	MPa	ksi		J	ft · lb
AE42	230	34	145	21	11	12	9
AM20	210	31	90	13	20	18	13
AM50A	230	34	125	18	15	18	13
AM60A, AM60B	240	35	130	19	13	18	13
AS21	220	34	120	17	13	12	9
AS41A, AS41B	240	34	140	20	15	16	12
AZ91A, AZ91B, AZ91D	250	36	160	23	7	9	7

(a) In 50.8 mm (2 in.). (b) Unnotched Charpy test bars

Figure 5.1.1: Typical tensile properties of magnesium alloys

TABLE 1
Magnesium Alloy Composition

<i>Trial</i>	<i>%Al</i>	<i>%Zn</i>	<i>%Mn</i>	<i>%Si</i>	<i>%Fe</i>	<i>%Cu</i>	<i>%Ni</i>	<i>Be ppm</i>
1	2.0	0.01	0.50	0.01	0.0020	0.0010	0.0005	4
2	4.8	0.01	0.29	0.01	0.0013	0.0017	0.0005	6
3	5.3	0.01	0.29	0.01	0.0018	0.0017	0.0002	5
4	5.8	0.01	0.30	0.01	0.0030	0.0017	0.0003	6
5	6.4	0.01	0.28	0.01	0.0033	0.0019	0.0005	6
6	6.9	0.01	0.29	0.01	0.0042	0.0019	0.0005	6
7	7.5	0.01	0.26	0.01	0.0056	0.0020	0.0004	4
8	8.0	0.01	0.26	0.01	0.0064	0.0020	0.0008	4

Figure 5.1.2: Compositions employed in the Aune et.al. study

TABLE 3
Mechanical Property Values of Mg-Al-Mn Alloys

	<i>% Aluminum Content</i>							
	<i>2.0</i>	<i>4.8</i>	<i>5.3</i>	<i>5.8</i>	<i>6.4</i>	<i>6.9</i>	<i>7.5</i>	<i>8.0</i>
Ultimate Tensile Strength (MPa)								
Average	217	229	249	253	250	248	258	245
Std. Dev.	3	12	6	8	12	14	14	7
Std. Dev. (%)	1	5	2	3	5	6	6	3
Tensile Yield Strength (MPa)								
Average	99	116	123	125	131	132	151	159
Std. Dev.	7	3	3	5	6	5	9	18
Std. Dev. (%)	7	2	2	4	4	4	6	11
Total Elongation at Fracture (%)								
Average	18.8	15.2	16.0	16.1	14.3	12.8	8.7	5.4
Std. Dev.	2.0	1.7	1.3	1.4	2.9	2.5	1.8	1.6
Std. Dev. (%)	10.6	11.1	8.4	9.0	20.4	19.3	20.7	29.6

Figure 5.1.3: Tensile properties of magnesium alloys obtained in the Aune et.al study

Figure 5. UTS and 0.2% Values of Cold Chamber Die Cast Mg-Al-Mn Alloys.

Figure 5.1.4: Tensile properties of magnesium alloys obtained in the Aune et.al study

Figure 7. Total Fracture Elongation of Cold Chamber Die Cast Mg-Al-Mn Alloys versus % Aluminum Content.

Figure 5.1.5: Elongation of magnesium alloys obtained in the Aune et.al study

Table IV. Average Mechanical Properties at 20 °C

Alloy-condition	No of samples	U.T.S. (MPa)	Y.S. (MPa)	E (%)
Diecast AZ91D	21	245 <i>36.2 Ksi</i>	153 <i>22.1 Ksi</i>	5.9
Plaster-cast AZ91E (with chill, T6)	16	213 <i>30.9 Ksi</i>	124 <i>17.9 Ksi</i>	3.0
Plaster-cast AZ91E (without chill, T6)	8	165 <i>23.9 Ksi</i>	118 <i>17.1 Ksi</i>	1.4
Diecast AM60B	19	238 <i>34.4 Ksi</i>	117 <i>16.9 Ksi</i>	13.2
Plaster-cast AM60B (with chill, T6)	10	212 <i>30.7 Ksi</i>	71 <i>10.2 Ksi</i>	9.1
Plaster-cast AM60B (without chill, T6)	12	163 <i>23.7 Ksi</i>	70 <i>10.1 Ksi</i>	5.9

Figure 5.1.6: Tensile properties of magnesium alloys obtained in the Fantetti et.al study

Table V. Grain Size Measurements

Casting condition	Grain size range μm
Plaster (with chilling) AZ91E	120-180
Plaster (without chilling) AZ91E	200-230
Diecast AZ91D	9-11

Figure 5.1.7: Grain size of the castings in the Aune et.al study

Figure 5.1.8: Effect of grain size on tensile strength of gravity cast AZ91 T6 alloy
(Sasaki et.al.)

Figure 5.1.9: Relationship between DAS and grain size in gravity cast AZ91 T6 alloy
(Sasaki et.al.)

Figure 5.1.10: Effect of DAS on tensile strength of gravity cast AZ91 T6 alloy
(Sasaki et.al.)

Figure 5.1.11: Effect of grain size on tensile strength of gravity cast AZ91 T6 alloy
(Sasaki et.al.)

Figure 5.1.12: Tensile strength vs. elongation of squeeze cast AZ91 T4 alloy (Sasaki et.al.)

Figure 5.1.13: Tensile strength vs. elongation of thixocast AZ91 T4 alloy (Sasaki et.al.)

	Primary	Secondary	Grebetz Electro- lytic	Grebetz Refined Recycled	ASTM B94 Typical
#samples	98	98	24	30	--
AveUTS (MPa)	238 <i>35.2 ksi</i>	234 <i>34.6</i>	232 <i>34.3</i>	232 <i>34.3</i>	220 <i>32.5</i>
Std.Dev.	14	14	10	12	--
MaxUTS (MPa)	266 <i>39.3</i>	264 <i>39.0</i>	259 <i>38.3</i>	251 <i>37.1</i>	--
MinUTS (MPa)	168 <i>24.2</i>	176 <i>26.0</i>	215 <i>31.8</i>	215 <i>31.8</i>	--
AveTYS (MPa)	125 <i>18.5</i>	128 <i>18.9</i>	127 <i>18.8</i>	131 <i>19.4</i>	130 <i>19.2</i>
Std Dev.	6	6	2	3	--
MaxTYS (MPa)	138 <i>20.4</i>	137 <i>20.2</i>	132 <i>19.5</i>	137 <i>20.2</i>	--
MinTYS (MPa)	109 <i>16.1</i>	92 <i>13.6</i>	122 <i>18.0</i>	125 <i>18.43</i>	--
Ave. % Elong.	11.7	11.0	9.2	9.1	8
Std Dev.	2.5	2.4	1.4	1.7	--
Max. % Elong.	18.2	18.5	13.8	13.5	--
Min. % Elong.	3.5	3.4	7.1	7.1	--

Table 2. Summary of Mechanical Properties of Secondary and Primary AM60B Compared to Grebetz et al¹ Published Data

Figure 5.1.14: Tensile properties of virgin and secondary AM60B (Guy)

Figure 1

Figure 2

Figure 5.1.15: Tensile properties of virgin and secondary AM60B (Guy)

Figure 2

Figure 3

Figure 5.1.16: Tensile properties of virgin and secondary AM60B (Guy)

Table VI. Mechanical Properties of AZ91D Test Bars

	TYS (MPa)	UTS (MPa)	Elong. (%)	Impact Energy (J)
MRT Heat #1	157 ± 2	246 ± 8	5.9 ± 0.8	9.8 ± 2.9
MRT Heat #2	156 ± 2	247 ± 8	6.2 ± 0.9	8.8 ± 1.1
MRT Heat #3	155 ± 2	248 ± 8	6.0 ± 0.8	9.5 ± 2.1
Dow Virgin	154 ± 2	243 ± 9	5.7 ± 1.0	11.6 ± 2.5

$\approx 22.9 \text{ KSI}$ 35.2 KSI 8.2 J

Figure 5.1.17: Tensile properties of virgin and secondary AZ91D (Greibetz)

Table VII. Mechanical Properties of AM60B Test Bars.

	TYS (MPa)	UTS (MPa)	Elong. (%)	Impact Energy (J)
MRT Heat #1	134 ± 3	257 ± 6	12.7 ± 1.0	22.8 ± 4.2
MRT Heat #2	134 ± 2	257 ± 5	13.3 ± 1.5	20.2 ± 4.4
MRT Heat #3	132 ± 2	255 ± 4	13.3 ± 0.9	20.6 ± 4.8
Dow Virgin	129 ± 3	252 ± 7	13.5 ± 1.5	23.2 ± 4.8

19.0 37.2 17.4

Figure 5.1.18: Tensile properties of virgin and secondary AM60B (Greibetz)

Table VIII. Mechanical Properties of AM50A Test Bars.

	TYS (MPa)	UTS (MPa)	Elong. (%)	Impact Energy (J)
MRT Heat #1	125 ± 2	250 ± 3	15.2 ± 1.1	25.2 ± 4.0
MRT Heat #2	124 ± 2	249 ± 3	15.5 ± 1.2	24.6 ± 2.9
MRT Heat #3	124 ± 2	251 ± 3	16.2 ± 1.2	25.7 ± 3.8
Dow Virgin	119 ± 2	242 ± 5	15.2 ± 1.6	27.8 ± 3.9

18.6 35.7 20.8

Figure 5.1.19: Tensile properties of virgin and secondary AM50A (Greibetz)

Table X. Tensile Properties of Cut-Out Specimens from V-10 Valve Covers.

	TYS (MPa)	UTS (MPa)	Elong. (%)
MRT Heat #1	142 ± 14	188 ± 21	1.5 ± 1.0
MRT Heat #2	141 ± 12	195 ± 26	2.5 ± 1.7
MRT Heat #3	138 ± 4	186 ± 16	1.5 ± 0.7
Dow Virgin	147 ± 6	197 ± 19	2.1 ± 1.1

21.8% 29.1%

Figure 5.1.20: Tensile properties of AZ91D from a V-10 valve cover casting (Greibetz)

Table 1 Mechanical properties of MAGTEK

Products		MAGTEK (Pore-Free diecastings)*1					Ordinary die castings*1			Permanent mould castings*2			
Alloy	Properties Heat treatment	Tensile strength (kg/mm ²)	Yield strength (kg/mm ²)	Elongation (%)	Impact value*3 (kg·m/mm ²)	Hardness (HRB)	Tensile strength (kg/mm ²)	Yield strength (kg/mm ²)	Elongation (%)	Tensile strength (kg/mm ²)	Yield strength (kg/mm ²)	Elongation (%)	Hardness (HRB)
AZ91D	F	24~25	15~16	4~5	0.6	34	20~24	15~17	0.5~3	18	10	2	17
	T ₄ *4	28~31	12~13	11~14	2.7	18	*6	*6	*6	28	9	12	10
	T ₆ *5	26~28	17~18	6~7	0.5	50	*6	*6	*6	28	14	6	34
AM60B	F	27~28	14~15	16~19	2.0	15	24~27	12~15	4~10				
	T ₄ *4	27~29	12~13	20~22	5.0	14	*6	*6	*6				

*1 : ASTM test pieces

*2 : JIS #4 test pieces

*3 : Sample without notch

*4 : MAGTEK : 420°C × 2 hrs → air quenching, Permanent mould diecasting : 420°C × 16 hrs → air quenching

*5 : MAGTEK : 420°C × 2 hrs → air quenching → 170°C × 16 hrs

Permanent mould diecasting : 420°C × 16 hrs → air quenching → 170°C × 16 hrs

*6 : Tests impossible due to for blistering and distortion

Figure 5.1.21: Mechanical properties of Pore Free Diecasting (Ito)

Figure 5.2.1: Configuration of un-notched Charpy impact test specimen

Figure 5.2.2: Difference between brittle and ductile behavior in Instrumented Impact

Figure 5.2.3: Charpy impact of AZ91 die cast un-notched specimens (Greibetz)

Figure 5.2.4: Charpy impact of AM60B die cast un-notched specimens (Greibetz)

	% Aluminum Content							
	2.0	4.8	5.3	5.8	6.4	6.9	7.5	8.0
Machined-In Notch								
Average	5.2	3.0	3.0	2.8	2.4	2.0	1.7	1.0
Std. Dev.	0.3	0.2	0.3	0.1	0.3	0.2	0.2	0.3
Std. Dev. (%)	6	6	9	4	12	11	12	30
Cast-In Notch								
Average	5.2	3.4	3.2	3.1	2.8	2.4	1.8	1.1
Std. Dev.	0.3	0.4	0.4	0.3	0.2	0.3	0.2	0.4
Std. Dev. (%)	6	11	10	8	7	14	11	36
Unnotched								
Average	18.0	18.3	17.7	16.7	18.1	18.0	7.2	3.8
Std. Dev.	4.8	4.0	5.2	4.3	5.0	3.9	2.4	1.7
Std. Dev. (%)	27	22	29	26	28	21	33	45

Figure 5.2.5: Impact properties of magnesium alloys obtained in the Aune et.al study

Impact Strength Characteristics of Mg-Al-Mn Alloys Relative to Impact Test Bar Geometry and Al Content.

Figure 5.2.6: Impact properties of magnesium alloys obtained in the Aune et.al study

Figure 5.2.7: Impact strength versus fracture elongation of magnesium alloys (Aune)

Figure 5.2.8: The effect of DAS on fracture toughness of gravity cast AZ91 (T6) Sasaki

	IZOD		Charpy	
	Primary	Secondary	Primary	Secondary
# samples	51	51	80	76
Average	11.8 J	11.0 J	16.3 J	13.5 J
Std Dev	2.2 J	2.2 J	2.7 J	2.9 J

Table 3. Summary of Charpy and IZOD Impact Results

Table 5.2.9: Charpy and Izod impact of primary and secondary AM60 (Guy)

Figure 9

Figure 5.2.10: Charpy impact energy distribution for primary and secondary AM60 (Guy)

Table 5.2.11: Room temperature instrumented impact curves from various die casting alloys (Albright)

Table VI Charpy Impact Tests (Unnotched)

Alloy-condition	Number of samples	Impact energy (J)
Diecast AZ91D	15	5.0 <i>3.75 A.B</i>
Plaster-cast AZ91E T6-chill	10	5.7 <i>4.27 A.B</i>
Plaster-cast AZ91E-T6	10	4.5 <i>3.34 A.B</i>
Plaster-cast AZ91E As Cast	10	3.0 <i>2.25 A.B</i>
Diecast AM60B	15	8.3 <i>6.2 A.B</i>
Plaster-cast AM60B T6-chill	12	16.6 <i>12.45 A.B</i>
Plaster-cast AM60B-T6	12	11.8 <i>8.5 A.B</i>
Plaster-cast AM60B As Cast	10	6.9 <i>5.12 A.B</i>

Table 5.2.12: Impact resistance of plaster cast and die cast AZ91 and AM60B (Fantetti)

Figure 7 Fatigue strength of MAGTEK (AZ91D/AM60B)

Figure 5.3.1: Fatigue strength of Pore Free Die Cast AZ91 and AM50(Ito)

Figure 5.3.2: Fatigue strength of die cast AZ91(Fantetti)

Figure 5.3.3: Fatigue strength of plaster-cast AZ91-T6-Chill(Fantetti)

Stress Level (MPa)	Primary		Secondary	
	Sample #	Cycles	Sample #	Cycles
120	436	6.3×10^4	166	5.9×10^4
120	176	4.5×10^4	106	6.2×10^4
120	206	1.0×10^5	246	6.3×10^4
120	156	5.4×10^4	96	1.7×10^6
115	346	$>1.2 \times 10^7$ *	386	1.8×10^5
115	506	$>1.2 \times 10^7$ *	496	9.1×10^4
110	246	2.7×10^6	206	$>1.0 \times 10^7$ *
110	136	1.7×10^6	346	7.4×10^6
110	296	9.7×10^6		

* did not break

Figure 5.3.4: Fatigue strength of virgin and recycled AM60(Guy)

Figure 5.3.5: Fatigue strength of virgin and recycled AM60B(Albright)

(a)

(b)

Figure 5.4.1: SEM micrographs of the (a) surface layer and (b) center of a 1mm thick AZ91D die casting (Dunlop)

Figure 5.4.2: SEM micrographs of the interdendritic area in etched die cast AZ91D.
 α -Mg supersaturated with aluminum surrounds the β -Mg₁₇Al₁₂ (Dunlop)

Figure 5.4.3: Profile of grain size across a die cast AM60B tensile bar at x500

Figure 5.4.4: Relationship between porosity and section size in AZ91D and AM60B fatigue specimens(Rodrigo)

Sample Nominal Thickness	Sample No.	Distance to Gate (cm)	Sample Width (cm)	Porosity Zone Width (cm)	Width%	δ (mm)
1mm	904-1					
2mm	462-3	3.2	2.6	2	77%	0.33
	462-2	4.6	1.9	1.5	79%	0.28
	462-1	5.9	1.3	0.9	69%	0.18
	462-5	7.1	1.8	1.5	83%	0.28
	468-3	3.3	2.5	2.1	84%	0.37
	468-2	4.8	1.8	1.5	83%	0.31
	468-1	5.9	1.3	0.9	69%	0.17
	468-5	7.1	1.8	1.5	83%	0.31
5mm	149-1	3.3	2.5	1.8	72%	1.8
10mm	467-1	3.2	2.6	0.9	35%	3.6

Figure 5.4.5: Porosity as a function of distance from the gate in AM60B fatigue specimens (Rodrigo)

Figure 5.4.6: Porosity distribution across a AM60B fatigue specimen (Rodrigo)

Figure 5.4.7:Effect of Al content on hot tearing sensitivity in Mg-Al-1%Zn system (Sasaki)

Figure 5.4.8: Segregated areas in squeeze cast AZ91D (Sasaki)

(a)

(b)

(c)

Figure 5.4.9: (a,b) Bands in die cast AZ91D (c) Tearing in a segregation band (Dunlop)

Figure 5.4.10: Strength as a function of solid fraction in a solidifying alloy

Figure 5.4.11: The evolution of fraction solid over a cross section (a) and the corresponding strength profile (b). (c) represents the microstructure obtained due to the applied pressure forcing flow of the central plug where the shear band is enriched with solute.

Figure 5.4.12: (a) The evolution of fraction solid over a cross section, and the corresponding strength profile (b). (c) represents the microstructure obtained when the applied pressure forces the flow of the central pug at higher solid fractions resulting in tearing along the shear plane.

Figure 5.5.3: UTS and yield strength of die cast AM type alloys (Albright)

Figure 5.5.4: Elongation of die cast AM type alloys (Albright)

Figure 5.5.5: Variation of tensile strength with aluminum content (Greibetz)

Figure 5.5.6: Effect of section thickness on UTS and YS of AZ91D (Dunlop)

Figure 5.5.7: Inter-dendritic spacing in a permanent mold cast AZ91D (Avishai)

Figure 5.5.8: Typical stress-strain curves for vacuum cast AM50 (Albright)

Figure 5.5.9: Effect of vacuum application on impact strength of AM50 (Albright)

TABLE 2 AM60B MAGNESIUM FINAL TEST BAR RESULTS

Testing Lab	Average Elongation (%)	Average Tensile Strength (psi)	Average Yield Strength (psi)*	Average Impact Strength (ft-lbs) **	Metallography	
					Surface	Core
Current Industry Standards	8%	31,900	18,850	4.3	N.A.	N.A.
Spartan Results	22.6%	39,199	N.A.	N.A.	N.A.	N.A.
Outside Lab Results	23.1 %	38,924	21,512	21.25	<1% voids	2% voids

*Yield taken at .2% offset

**Unnotched

Figure 5.5.10: Effect of vacuum and improved die design on properties of AM60B (Dierks)

Figure 5.5.11: Improved elongation in AM60B obtained at Spartan by application of vacuum and die design (Dierks)

Figure 5.5.12: Improved Charpy impact in AM60B obtained at Spartan by application of vacuum and die design (Dierks)

Figure 5.5.13: Improved elongation in AM50B obtained at Spartan by application of vacuum and die design (Dierks)

Figure 5.5.14: Improved fatigue properties in AM60B obtained at Spartan by application of vacuum and die design (Dierks)

Table 4 Recommended solution-treating and aging schedules for magnesium alloy castings and wrought products

For castings up to 50 mm (2 in.) in section thickness; heavier sections may require longer times at temperature.

Alloy	Final temper	Aging(a)			Solution treating(c)					Aging after solution treating		
		Temperature		Time, h	Temperature		Time, h	Maximum temperature		Temperature		Time, h
		°C, ±6(b)	°F, ±10(b)		°C, ±6(b)	°F, ±10(b)		°C	°F	°C, ±6(b)	°F, ±10(b)	
Magnesium-aluminum-zinc castings(d)												
AM100A	T5	232	450	5	...	...	...	...	...	...	...	...
	T4	...	...	...	424(e)	795(e)	16–24(e)	432	810	...	...	...
	T6	...	...	...	424(e)	795(e)	16–24(e)	432	810	232	450	5
	T61	...	...	...	424(e)	795(e)	16–24(e)	432	810	218	425	25
AZ63A	T5	260(f)	500(f)	4(f)	...	...	...	...	...	...	...	...
	T4	...	...	...	385	725	10–14	391	735	...	...	...
	T6	...	...	...	385	725	10–14	391	735	218(f)	425(f)	5(f)
AZ81A	T4	...	...	...	413(e)	775(e)	16–24(e)	418	785	...	...	...
AZ91C	T5	168(g)	335(g)	16(g)	...	...	...	...	...	...	...	...
	T4	...	...	...	413(e)	775(e)	16–24(e)	418	785	...	...	...
	T6	...	...	...	413(e)	775(e)	16–24(e)	418	785	168(h)	335(h)	16(h)
AZ92A	T5	260	500	4	...	...	...	...	...	...	...	...
	T4	...	...	...	407(i)	765(i)	16–24(i)	413	775	...	...	...
	T6	...	...	...	407(i)	765(i)	16–24(i)	413	775	218	425	5
Magnesium-zinc-copper castings												
ZC63A(j)	T6	...	...	...	440	825	4–8	445	835	200	390	16
Magnesium-zirconium castings												
EQ21A(j)	T6	...	...	...	520	970	4–8	530	985	200	390	16
EZ33A	T5	175	350	16	...	...	...	...	...	...	...	...
QE22A(j)	T6	...	...	...	525	980	4–8	538	1000	204	400	8
QH21A(j)	T6	...	...	...	525	980	4–8	538	1000	204	400	8
WE43A(j)	T6	...	...	...	525	980	4–8	535	995	250	480	16
WE54A(j)	T6	...	...	...	527	980	4–8	535	995	250	480	16
ZE41A	T5	329(k)	625(k)	2(k)	...	...	...	...	...	...	...	...
ZE63A(l)	T6	...	...	...	480	895	10–72	491	915	141	285	48
ZK51A	T5	177(m)	350(m)	12(m)	...	...	...	...	...	...	...	...
ZK61A	T5	149	300	48	...	...	...	...	...	...	...	...
	T6	...	...	...	499(n)	930(n)	2(n)	502	935	129	265	48
Wrought products												
ZK60A	T5	150	300	24	...	...	...	...	...	...	...	...
AZ80A	T5	177	350	16–24	...	...	...	...	...	...	...	...
ZC71A(j)	T5	180	355	16	...	...	...	...	...	...	...	...
ZC71A(j)	T6	...	...	...	430	805	4–8	435	815	180	355	16

(a) Aging to the T5 temper is done from the as-fabricated (f) condition. (b) Except where quoted differently. (c) After solution treatment and before subsequent aging, castings are cooled to room temperature by fast fan cooling, except where otherwise indicated. Use carbon dioxide, sulfur dioxide, or 0.5 to 1.5% sulfur hexafluoride in carbon dioxide as a protective atmosphere above 400 °C (750 °F). (d) For solution treating, Mg-Al-Zn alloys are loaded into the furnace at 260 °C (500 °F) and brought to temperature over a 2-h period at a uniform rate of temperature increase. (e) Alternative treatment to prevent germination (excessive grain growth): 6 h at 413 ± 6 °C (775 ± 10 °F), 2 h at 352 ± 6 °C (665 ± 10 °F), 10 h at 413 ± 6 °C (775 ± 10 °F). (f) Alternative treatment: 5 h at 232 ± 6 °C (450 ± 10 °F). (g) Alternative treatment: 4 h at 216 ± 6 °C (420 ± 10 °F). (h) Alternative treatment: 5 to 6 h at 216 ± 6 °C (420 ± 10 °F). (i) Alternative treatment to prevent germination (excessive grain growth): 6 h at 407 ± 6 °C (765 ± 10 °F), 2 h at 352 ± 6 °C (665 ± 10 °F), 10 h at 407 ± 6 °C (765 ± 10 °F). (j) Quench from solution-treating temperature either in water at 65 °C (150 °F) or in other suitable medium. (k) This treatment is adequate for development of satisfactory properties; it may be followed by 16 h at 177 ± 6 °C (350 ± 10 °F) to provide very slight improvements in mechanical properties. (l) Alloy ZE63A must be solution treated in a special hydrogen atmosphere because its mechanical properties are developed through hydriding of some of its alloying elements. Hydriding time depends on section thickness; as a guide, 6.4 mm (¼ in.) sections require approximately 10 h, and 19 mm (¾ in.) sections require about 72 h. Following solution treatment, ZE63A should be quenched in oil, water spray, or air blast. (m) Alternative treatment: 8 h at 218 ± 6 °C (425 ± 10 °F). (n) Alternative treatment: 10 h at 482 ± 6 °C (900 ± 10 °F).

Figure 5.6.1: Typical heat treating conditions for magnesium alloys

Figure 5.6.2: Aging curves for AZ91D (Ito)