

1 General

AZ91 is a magnesium-aluminum-zinc casting alloy that provides an excellent combination of castability and mechanical and physical properties for use at temperatures up to about 300-350F. It is produced in three alloy variations, A, B, and D, for die castings and in two alloy variations, C and E, for sand, permanent-mold, and investment castings. The D and E variations specify lower impurity limits, particularly iron, nickel, and copper, which result in greatly improved corrosion resistance with little effect on mechanical properties. Consequently, the D and E variations are generally preferred for aerospace applications. The less pure variations, A, B, and C, which are less expensive, may be used in applications where corrosion resistance is not an important consideration. Die castings are usually used in the as-cast condition, whereas sand, permanent-mold, and investment castings are normally age-hardened. Primarily in its purer (more corrosion-resistant) variations, the alloy has present and potential aerospace applications in gearbox cases, transmission and engine compressor housings, under-carriage wheels, and cockpit canopy frames (Refs. 11, 19, 20, 21).

1.1 Commercial Designations

AZ91 (A, B, C, D, or E).

1.2 Alternate Designations

UNS Numbers: M11910 (AZ91A), M11912 (AZ91B), M11914 (AZ91C), M11916 (AZ91D), M11919 (AZ91E) (Ref. 11).

1.3 Specifications

1.3.1 [Table] Specifications.

1.4 Composition

1.4.1 [Table] Composition.

1.5 Heat Treatment (Refs. 10, 17, 23)

The conditions of heat treatment for AZ91, as well as of other magnesium casting alloys, are designated as follows: F (as-cast), T5 (artificially aged), T4 (solution heat treated), and T6 (age hardened after solution treatment). The alloy designation AZ91D-F, for example, is indicative of die-cast D alloy variation in the F (as-cast) condition, which is normal for die castings; whereas the designation AZ91E-T6 indicates sand, permanent-mold, or investment casting E alloy variation in the T6 (age-hardened) condition.

1.5.1 Condition T5, artificial aging: age as-cast (F) material at 335F for 16 hours or, alternatively, at 420F for 4 hours, air cool.

1.5.2 Condition T4, solution heat treatment: soak at 775F for 18 hours, fast fan cool to room temperature; alternatively, to minimize grain growth, soak at 775F 6 hours plus 665F 2 hours plus 775F 10 hours, fast fan

cool to room temperature. To prevent possible eutectic melting and its adverse effects on properties, it is suggested that the castings be loaded into the furnace at 500F and brought to the soaking temperature over about a 2-hour period at a uniform rate of heating.

	Mg	
9	Al	
0.7	Zn	

1.5.3 Condition T6, age hardening after solution treatment: soak at 335F for 18 hours, or alternatively at 420F for 5-6 hours, air cool.

The suggested holding times at the various heat treating temperatures are adequate for section thicknesses up to at least 2 in. Longer times may be required for castings with thicker sections.

1.5.4 Furnaces used for heat treating magnesium alloys are usually the air-chamber type and may be electrically heated or oil- or gas-fired. Since magnesium castings are subject to excessive surface oxidation at temperatures of 750F and above, a protective atmosphere containing a minimum of 0.5 percent sulfur dioxide or 3 percent carbon dioxide is recommended for the solution treatment. Inert gases, which are more expensive, may also be used.

If the temperature during solution treatment accidentally exceeds the specified level by an appreciable amount, the castings may ignite and burn, although sulfur-dioxide or carbon-dioxide atmospheres have an inhibiting effect. Once magnesium alloys start to burn, however, the sulfur dioxide or carbon dioxide supplies oxygen to the fire. A magnesium fire in a gas-tight furnace can be extinguished by the introduction of boron trifluoride gas through a small opening.

1.6 Hardness

1.6.1 [Table] Hardness for various heat-treated conditions at room temperature.

1.7 Forms and Conditions Available

Alloy variations A, B, and D are available in the form of die castings, which are used primarily in Condition F (as-cast). The other alloy variations, C and E, are available as sand, permanent-mold, and investment castings; they may be heat treated to Condition T4, T5, or T6, but probably are most often used in the T6 Condition (fully solution-treated and aged).

1.8 Melting and Casting Practice (see AM100A, Code 3410, Section 1.08; see also Section 1.9, first paragraph)

1.9 Special Considerations

For optimum mechanical properties, fine grain size is necessary in AZ91 castings, as well as in other magnesium-alloy castings. During melting operations, grain refinement can be effected either by a controlled

superheat or by carbon inoculation. In superheating, the melt is heated to 1650-1700F, held for about 15 minutes, cooled to the pouring temperature fairly rapidly by removing the crucible from the furnace, and then poured. Carbon inoculation involves the plunging of organic compounds such as hexachloroethane or hexachlorobenzene into the melt, although other carbonaceous materials, such as lampblack, may also be used. Since the organic compounds release chlorine, they function as degasers as well as grain refiners (Refs. 13, 22).

The beneficial effects of grain refinement can be lost as a result of grain growth (also called germination) during solution heat treatment. Sensitivity to this phenomenon is accentuated by very fine, as-cast grain size; by internal stresses, which tend to occur in chilled areas and at saw cuts; and by excessive time at the solution-treating temperature. An effective preventative measure is the alternative (interrupted) solution treatment given in Section 1.5.2 (Refs. 13, 17, 23).

The ignition temperature of magnesium alloys is generally considered to be close to the melting point, but fine shavings, powders, and ribbons can ignite at somewhat lower air temperatures. Magnesium fires cannot be extinguished by water or fire extinguishers of the vaporizing liquid, foam, ordinary dry chemical, or carbon-dioxide types. Their use accelerates burning and may cause an explosion. Magnesium fires can be extinguished only by covering the burning area with a material that will exclude air and not react with burning magnesium. Graphite powder and magnesium melting fluxes are the most commonly used extinguishers (Refs. 13, 17, 24).

AZ91 grows slightly when exposed for long periods of time to temperatures above 200F.

- 1.9.1 [Table] Maximum linear growth of castings due to long-time exposure to 300F.
- 1.9.2 [Figure] Linear growth of castings due to long-time exposures at temperatures from 212 to 425F.

AMS specifications (Refs. 1, 3, 4) prohibit the suppliers of AZ91 castings from repairing defective castings by peening, plugging, welding, impregnation, or other methods unless they obtain written permission from the purchaser.

Although not yet commercially available, AZ91 alloy products made by means of rapid-solidification processing have been shown to have substantially improved mechanical properties with corrosion resistance at least as good as that of conventional AZ91 castings of the same composition. This process involves the production of fine particles or thin ribbons of the alloy rapidly solidified by one of several techniques, such as Free Jet Melt Spinning, Planar Flow Casting, and Atomization. The rapidly solidified material is cold

compacted into bulk material, about 60 percent of theoretical density, for further processing by extrusion, forging, or rolling into final shape and near theoretical density (Refs. 38, 39).

- 1.9.3 [Table] Comparison of the tensile properties and hardness of bars extruded from sand-cast billets with those of bars made by rapid-solidification processing including similar final extruding.

2 Physical Properties and Environmental Effects

2.1 Thermal Properties

- 2.1.1 Melting Range, 875-1105F (Refs. 5, 6, 7, 11).
- 2.1.2 Phase Changes. In the as-cast condition (F), the alloy consists mostly of magnesium-aluminum-zinc solid solution, with massive intergranular and interdendritic magnesium-aluminum compounds known as b-phase. In relatively large sections, because of slow cooling rates from the casting temperature, the b-phase also forms as a lamellar secondary phase along the grain boundaries. Also present in the as-cast alloy are some particles of magnesium-silicon and manganese-aluminum compounds, which are not affected by heat treatment. Solution treatment (T4) dissolves the magnesium-aluminum compounds (b-phase) into the solid solution; subsequent age hardening (T6) induces their precipitation in a discontinuous lamellar network along the grain boundaries (Refs. 15, 16).

2.1.2.1 Time-temperature transformation diagrams.

2.1.3 Thermal Conductivity.

2.1.3.1 [Figure] Effects of temperatures up to 500F on thermal conductivity.

2.1.4 Thermal Expansion. Mean coefficient of thermal expansion of AZ91A and AZ91C from 68 to 392F: $15.1-15.2 \times 10^{-6}$ in. per in. per F (Ref. 14).

2.1.5 Specific Heat.

2.1.5.1 [Figure] Effects of temperatures up to 1400F on specific heat.

2.1.6 Thermal Diffusivity.

2.1.6.1 [Table] Thermal diffusivity at 68F.

2.2 Other Physical Properties

- 2.2.1 Density: 0.0654 lb. per cu. in., 1.81 gr. per cu. cm. (Refs. 5, 6, 7, 8).
- 2.2.2 Electrical Properties.
- 2.2.2.1 [Figure] Effects of temperatures up to 500F on electrical resistivity.
- 2.2.3 Magnetic Properties. Alloy is nonmagnetic.
- 2.2.4 Emittance (see ZK60A, Code 3506, Figure 2.024).

2.2.5 Damping Capacity.

2.2.5.1 [Table] Damping capacity of die castings at various stress levels.

2.3 Chemical Environment

Use of magnesium alloys in aerospace applications has been limited by their susceptibility to corrosion in marine and other aggressive environments. This problem in AZ91 castings has been substantially alleviated by the relatively recent introduction of the high-purity D and E alloy variations with intrinsic corrosion resistance approaching that of aluminum alloys. The improved corrosion resistance of the D and E variations is a result of greatly reduced limits for the heavy-metal impurities—copper, nickel, and iron—plus control of the ratio of iron to manganese contents to a level of 0.032 or less (Ref. 13).

2.3.1 [Figure] Comparison of corrosion rates of AZ91C and E in the T6 Condition with that of A357 aluminum casting alloy both totally immersed in 3.5 percent sodium-chloride solution and in 5 percent salt fog.

2.3.2 [Figure] Comparison of corrosion-pitting depth in AZ91C and E in the T6 Condition with that in A357 aluminum casting alloy after total immersion for 14 days in 3.5 percent sodium-chloride solution.

The corrosion rates for AZ91D-F (die castings) in 5 percent salt fog (ASTM B 117) and totally immersed in 5 percent sodium-chloride solution are about 10 and 45 mil per year, respectively, which compare reasonably well with AZ91E-T6 (sand castings) corrosion rates as shown in Figure 2.3.1 (Ref. 31).

In the older alloy variations (A, B, and C), differences in iron content can have marked effects on corrosion rates in various types of environments (Ref. 31).

2.3.3 [Table] Effects of a variation in iron content on the corrosion rate of AZ91C-T6 sand castings in various types of environments.

Because of the high electrochemical activity of magnesium, galvanic corrosion tends to occur in AZ91, as well as in other magnesium alloys, in areas where they are in electrical contact with most other structural metals in the presence of an electrolyte. Such attack can occur, for example, in areas where magnesium-alloy surfaces are in contact with dissimilar-metal bolts. Use of a nonmetallic sealing compound between all such contact areas can be effective in preventing the attack (Ref. 21).

2.3.4 [Figure] Comparison of corrosion rates of AZ91C and E with that of A357 aluminum casting alloy when galvanically coupled to aluminum and to carbon steel and immersed in 3.5 percent sodium-chloride solution.

Use of ferrous abrasives for surface cleaning can leave iron contamination on casting surfaces, which is detri-

mental to corrosion resistance. Acid pickling can be used to remove such contamination, but use of high-purity alumina, silica, or glass beads is preferable to ferrous abrasives (Ref. 20).

2.3.5 [Table] Effects of heat-treat condition and surface condition on the corrosion rate of AZ91E as a result of 10-day salt-spray testing in accordance with ASTM B 117.

Recent studies have revealed that AZ91 is susceptible to stress corrosion cracking in aqueous environments (Ref. 41).

2.3.6 [Figure] Time to stress-corrosion failure as a function of tensile stress for die-cast specimens in two different environments; and, for comparison, the ultimate tensile strength (F_{tu}) of comparison specimens after similar exposures without stress.

2.4 Nuclear Environment

3 Mechanical Properties

3.1 Specified Mechanical Properties

3.1.1 [Table] AMS specified mechanical properties.

3.1.2 [Table] ASTM specified mechanical properties.

3.2 Mechanical Properties at Room Temperature

3.2.1 Tension Stress-strain Diagrams and Tension Properties.

3.2.1.1 [Figure] Tensile stress-strain curve for die-cast test bar at room temperature.

3.2.1.2 For room-temperature stress-strain curves of sand-cast test bars, see Figure 3.3.1.1.

3.2.1.3 [Table] Typical tensile properties of separately cast test bars at room temperature.

3.2.1.4 [Figure] Effects of exposures up to 1000 hours at 300F on room-temperature tensile properties of sand castings in the T6 condition.

3.2.1.5 [Figure] Effects of long-time exposures at various elevated temperatures on room-temperature tensile yield strength and percent elongation of sand castings in the T4 Condition.

3.2.2 Compression Stress-strain Diagrams and Compression Properties.

3.2.2.1 [Figure] Compressive stress-strain curve for die-cast test bar at room temperature.

3.2.2.2 [Table] Compressive yield strength at room temperature for different alloy variations and heat treatments.

3.2.3 Impact.

3.2.3.1 [Table] Charpy V-notch impact strength at room temperature for die castings and sand castings in various heat-treated conditions.

- 3.2.4 Bending.
- 3.2.5 Torsion and Shear.
 - 3.2.5.1 [Table] Shear strength at room temperature for different alloy variations and heat treatments.
- 3.2.6 Bearing.
 - 3.2.6.1 [Table] Bearing properties at room temperature for different alloy variations and heat treatments.
- 3.2.7 Stress Concentration.
 - 3.2.7.1 Notch properties.
 - 3.2.7.2 Fracture toughness.
- 3.2.8 Combined Properties.
- 3.3 Mechanical Properties at Various Temperatures**
- 3.3.1 Tension Stress-strain Diagrams and Tension Properties.
 - 3.3.1.1 [Figure] Stress-strain curves at room and elevated temperatures for sand-cast test bars.
 - 3.3.1.2 [Figure] Effect of test temperature on tensile properties of sand-cast test bars.
 - 3.3.1.3 [Figure] Effects of test temperature and strain rate on tensile properties of sand-cast test bars in the T6 condition.
- 3.3.2 Compression Stress-strain Diagrams and Compression Properties.
- 3.3.3 Impact.
 - 3.3.3.1 [Table] Charpy V-notch impact strength of sand castings at temperatures from 75 to -320F.
- 3.3.4 Bending.
- 3.3.5 Torsion and Shear.
 - 3.3.5.1 [Figure] Effect of test temperature on shear strength of sand-cast test bars.
- 3.3.6 Bearing.
 - 3.3.6.1 [Figure] Effect of test temperature on bearing properties of sand-cast test bars.
- 3.3.7 Stress Concentration.
 - 3.3.7.1 Notch properties.
 - 3.3.7.2 Fracture toughness.
- 3.3.8 Combined Properties.
- 3.4 Creep and Creep-Rupture Properties**
- 3.4.1 [Figure] Isochronous stress-strain curves at 300 and 400F for sand-cast test bars in the T6 condition.
- 3.4.2 A recent investigation of AZ91A-F die castings has revealed that the alloy is susceptible to creep deformation at room temperatures and stresses below the yield strength (Ref. 40).

3.4.2.1 [Figure] Creep strain of die-cast test bars as a function of time at room temperature and a tensile stress of 19.5 ksi.

3.5 Fatigue Properties

- 3.5.1 [Table] Rotating-beam fatigue strength (R = -1) of different alloy variations at room temperature.
- 3.5.2 [Figure] Fatigue S-N range for sand castings in the T6 Condition.
- 3.5.3 [Figure] Fatigue-crack growth rates for two different sections of a sand casting.

3.6 Elastic Properties

- 3.6.1 Poisson's Ratio, 0.35 (Refs. 11, 25).
- 3.6.2 Modulus of Elasticity.
 - 3.6.2.1 [Figure] Modulus of elasticity at room and elevated temperatures.
- 3.6.3 Modulus of Rigidity, 2.4×10^6 psi (Refs. 11, 25).
- 3.6.4 Tangent Modulus.
- 3.6.5 Secant Modulus.

4 Fabrication

4.1 Forming

4.2 Machining and Grinding

AZ91, as well as other magnesium alloys, has excellent machinability, which enables it to be machined at high speeds and feeds. The low cutting pressures and rapid dissipation of generated heat combine to provide long tool life, dimensional stability, and good surface finish (Ref. 30).

4.3 Joining

Although welding is not recommended for die castings (AZ91A, B, and D), gas-tungsten-arc and gas-metal-arc welding are both applicable for repair and joining of sand, permanent-mold, and investment castings. AZ92A or AZ91C are the recommended filler alloys. Whereas preheat and interpass temperatures of 650-750F are recommended for thin and restrained sections, heavy and unrestrained sections may be welded with little or no preheat (Refs. 11, 32).

- 4.3.1 If the T4 Condition is desired after welding, the castings should be in that condition prior to welding and then postweld treated as follows: 1/2 hour at 775F in protective atmosphere (see Section 1.5.4), fast fan cool (Ref. 32).
- 4.3.2 If the T6 Condition is desired after welding, the castings should be in either the T4 or T6 condition prior to welding and then postweld treated as follows: 1/2 hour at 775F in protective atmosphere (see Section

- 1.5.4), fast fan cool, + 4 hours at 420F or 16 hours at 335F, AC (Ref. 32). The short times at 775F (1/2 hour) for the postweld T4 and T6 treatments are used to avoid germination (see Section 1.9, second paragraph) in the deposited weld metal (Ref. 32).
- 4.3.3 AZ91C and E castings can be welded to most wrought magnesium alloys by the same methods given in Section 4.3, first paragraph. For optimum properties, the castings to be welded should be in the heat-treated condition finally desired. Postweld treatments as given in Sections 4.3.1 and 4.3.2 provide optimum T4 or T6 properties in the casting segment, but may be detrimental to the wrought material depending on the specific alloy (Ref. 32).
- 4.3.4 If optimum mechanical properties are not required, welded castings or cast-wrought weldments should, nevertheless, be stress relieved one hour at 500F in order to prevent stress-corrosion cracking (Ref. 32).
- 4.3.4.1 [Table] Tensile properties of sand-cast plates, both base metal and sections with transverse GMA welds across the gage lengths of the test specimens.
- 4.3.4.2 [Figure] Fatigue S-N curves for sand-cast plates, both base metal and sections with transverse GMA welds across the test areas.
- 4.3.4.3 [Figure] Fatigue-crack growth rates in GMA repair weld deposits made with AZ92A magnesium-alloy electrodes in two different sections of a sand casting.

Gas welding, soldering, brazing, and spot welding are not normally recommended for AZ91 alloy, particularly for critically stressed applications or for service under conditions of vibration or fatigue (Refs. 29, 34).

4.4 Surface Treatment

For corrosion protection during shipping and handling, AZ91, as well as other magnesium-casting alloys, are normally chrome pickled (AMS 2475) or, alternatively, coated with a light corrosion-inhibiting oil by the producing foundries prior to shipment. (Refs. 1, 2, 3, 4). A wide range of chemical and electrochemical cleaning and surface treatments is available for paint adhesion and corrosion protection (Ref. 31, see also AM 100A, Code 3410, Sections 4.042, 4.043, and 4.044 for details).

A study of the effects of various surface treatments and finishes on the rotating-beam fatigue strength of AZ91C-T6 castings showed that acid pickling has detrimental effects on fatigue strength, whereas shot peening has beneficial effects which, in most instances, are sufficient to overcome any detrimental effects of acid pickling or coatings. For the most part, chromate coatings, anodic coatings, and paints have only minor but variable effects on fatigue strength (Ref. 27).

AZ 91

Table 1.3.1 Specifications (Refs. 1-11)

Alloy: AZ91			
Specification	Alloy Variations	Conditions	Form
AMS 4437D	C	T6	Sand Castings
AMS 4446	E	T6	Sand Castings
AMS 4490G	A	F	Die Castings
AMS 4452A	C	T6	Investment Castings
ASTM B 80-90	C, E	F, T4, 5, 6	Sand Castings
ASTM B 94-88	A, B, D	F	Die Castings
ASTM B 199-87	C, E	F, T4, 5, 6	Permanent Mold Castings
ASTM B 403-87	C, E	F, T4, 5, 6	Investment Castings
ASTM B 93-90	A, B, C, D, E	F	Ingot
MIL-M-46062	C	-	Sand and Permanent Mold Castings
QQ-M-56	C	-	Sand Castings
QQ-M-38	A	F	Die Castings
QQ-M-55	C	-	Permanent Mold Castings

Note: In addition to these product specifications, ASTM B 661-90 and MIL-M-6857 cover heat treatment of magnesium alloys including AZ91.

Table 1.4.1 Composition (Refs. 1-9)

Alloy: AZ91										
Alloy Variations	A		B		D		C (a)		E (b)	
Form (c)	Die Cast						Sand, Investment, Permanent Mold Cast			
Specification	AMS (3), ASTM (6)		ASTM (6)		ASTM (6)		AMS (1)		AMS (2)	
Element	Percent		Percent		Percent		Percent		Percent	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Aluminum	8.3	9.7	8.3	9.7	8.3	9.7	8.1	9.3	8.1	9.3
Zinc	0.35	1.0	0.35	1.0	0.35	1.0	0.40	1.0	0.40	1.0
Manganese	0.13	-	0.13	-	-	0.15	0.13	0.30	0.17	0.35
Silicon	-	0.50	-	0.50	-	0.10	-	0.30	-	0.030
Copper	-	0.10	-	0.35	-	0.030	-	0.10	-	0.030
Nickel	-	0.03	-	0.03	-	0.002	-	0.01	-	0.0010
Iron	-	-	-	-	-	0.005	-	-	-	0.005
Others, each	-	-	-	-	-	0.02	-	0.10	-	0.01
Others, total	-	0.30	-	-	-	-	-	0.30	-	-
Magnesium	Remainder		Remainder		Remainder		Remainder		Remainder	

(a) The composition shown for AZ91C is taken from the AMS specification for sand castings (Ref. 1); the AMS specification for investment castings (Ref. 4) and the ASTM specifications for sand (Ref. 5), investment (Ref. 8), and permanent mold (Ref. 7) castings differ only slightly, primarily in the limits for manganese content.

(b) The composition shown for AZ91E is taken from the AMS specification for sand castings (Ref. 2); the ASTM specifications for sand (Ref. 5), investment (Ref. 8), and permanent mold (Ref. 7) castings differ only slightly, primarily in lower maximum limits for silicon and copper contents.

(c) The ASTM specified compositions for ingot in all five alloy variations (Ref. 9) are quite similar to those shown above, the most pronounced differences being somewhat more restricted ranges for the principal alloying elements and in some instances for the residual elements in the ingot specification.

Code 3402

Page 6

Table 1.6.1 Hardness for various heat-treated conditions at room temperature (Refs. 5, 6, 7, 11, 13)

Alloy: AZ91				
Type Casting	Alloy Variation	Condition	Hardness	
			Brinell (a)	Rockwell E
Die	A, B, D	F	63	75
Sand, Permanent Mold, Investment	C, E	F	60	66
		T5	62	-
		T4	55	62
		T6	70	77

(a) 10 mm ball, 500 Kg

Table 1.9.1 Maximum linear growth of castings due to long-time exposure at 300F (Ref. 23)

Alloy: AZ91C	
Form	Castings
Condition	Maximum Linear Growth (in./in.)
F	0.00040
T4	0.00077
T6	0.00055

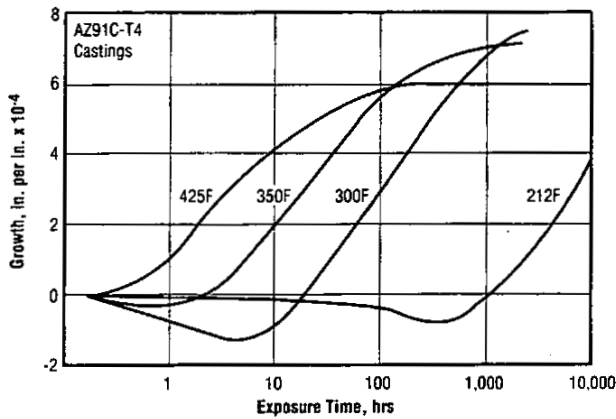


Fig. 1.9.2 Linear growth of castings due to long-time exposures at temperatures from 212 to 425F (Ref. 25)

Table 1.9.3 Comparison of the tensile properties and hardness of bars extruded from sand-cast billets with those of bars made by rapid-solidification processing including similar final extruding (Refs. 38, 39)

Alloy: AZ91E						
Initial Form	Further Processing (a)	Heat Treat	F _{ty} (ksi)	F _w (ksi)	e (percent, 4D)	Hardness Rockwell E
Sand-cast bar	Extruded	None	32.8	45.4	15.6	81
Sand-cast bar	Extruded	T6 (b)	24.2	47.7	11.1	78.5
RS + C (c)	Extruded	None	56.7	66.3	12.1	97.5

(a) Extruded at 480F, extrusion ratio 20, ram speed 0.5 mm per sec

(b) Heat treated after extruding

(c) Rapidly solidified by Free Jet Melt Spinning and compacted

Note: For comparison of the sand-cast and extruded bars with conventional cast test bars see Table 3.2.1.3, in which Condition F and T6, respectively, correspond to heat treatments labeled "None" and "T6" in this table

AZ 91

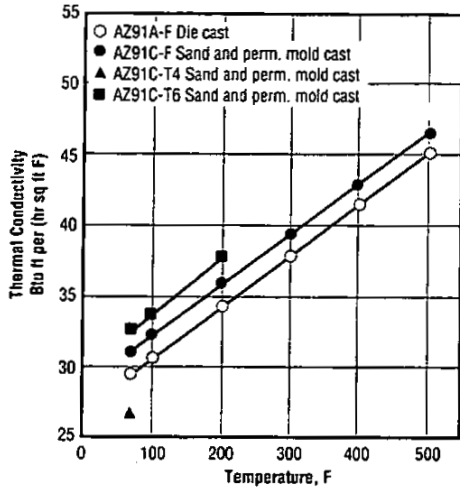


Fig. 2.1.3.1 Effects of temperatures up to 500F on thermal conductivity (Ref. 14)

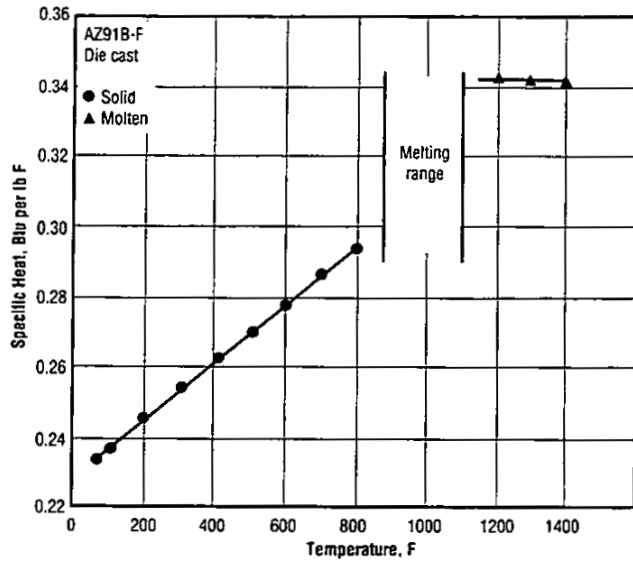


Fig. 2.1.5.1 Effects of temperatures up to 1400F on specific heat (Ref. 14)

Table 2.1.6.1 Thermal diffusivity at 68F (Ref. 14)

Alloy: AZ91			
Alloy Variation	Condition	Casting Type	Diffusivity (sq ft per hr)
A	F	Die	1.12
C	F	Sand & Permanent Mold	1.17
C	T4	Sand & Permanent Mold	1.00
C	T6	Sand & Permanent Mold	1.23

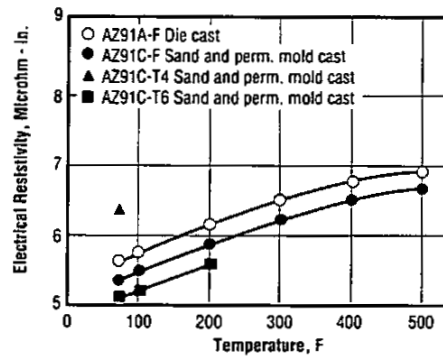


Fig. 2.2.2.1 Effects of temperatures up to 500F on electrical resistivity (Ref. 14)

Table 2.2.5.1 Damping capacity of die castings at various stress levels (Ref. 17)

Alloy: AZ91A, B, D	
Form	Die Castings
Condition	F
Stress (ksi)	Specific Damping Capacity (percent)
1.0	2.67
2.0	5.33
3.0	12.0
3.5	16.0
5.0	29.3

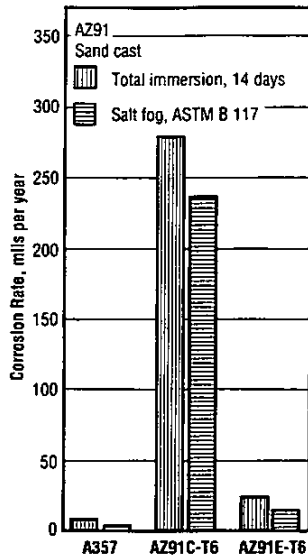


Fig. 2.3.1 Comparison of corrosion rates of AZ91C and E in the T6 condition with that of A357 aluminum casting alloy both totally immersed in 3.5-percent sodium-chloride solution and in 5 percent salt fog (Ref. 21)

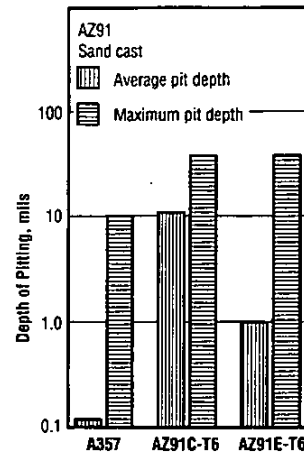


Fig. 2.3.2 Comparison of corrosion-pitting depth in AZ91C and E in the T6 condition with that in A357 aluminum casting alloy after total immersion for 14 days in 3.5-percent sodium-chloride solution (Ref. 21)

Table 2.3.3 Effects of a variation in iron content on the corrosion rate of AZ91C-T6 sand castings in various types of environments (Ref. 31)

Alloy: AZ91C		
Form	Sand Castings	
Condition	T6	
Iron Content (percent)	0.035	<0.005
Environment	Corrosion Rate (mils per year)	
Rural	0.17	0.11
Industrial	0.60	0.55
Marine	0.87	0.25
20% salt spray	3740	27.9

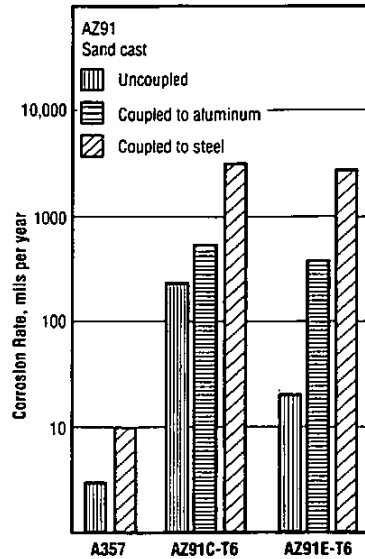


Fig. 2.3.4 Comparison of corrosion rates of AZ91C and E with that of A357 aluminum casting alloy when galvanically coupled to aluminum and to carbon steel and immersed in 3.5-percent sodium-chloride solution (Ref. 21)

AZ 91

Table 2.3.5 Effects of heat-treat condition and surface condition on the corrosion rate of AZ91E as a result of 10-day salt spray testing in accordance with ASTM B 117 (Ref. 20)

Alloy: AZ91E		
Form	Sand Cast	
Heat Treat Condition	Surface Condition	Corrosion Rate (mils per year)
F	(1)	260-277
F	(2)	<14-29
F	(3)	14-29
T4	(3)	5-7
T6	(3)	4-9

- (1) Steel-shot blasted
- (2) Sand blasted, acid etched, and chrome pickled
- (3) Wet-belt abraded with 80-mesh silicon carbide

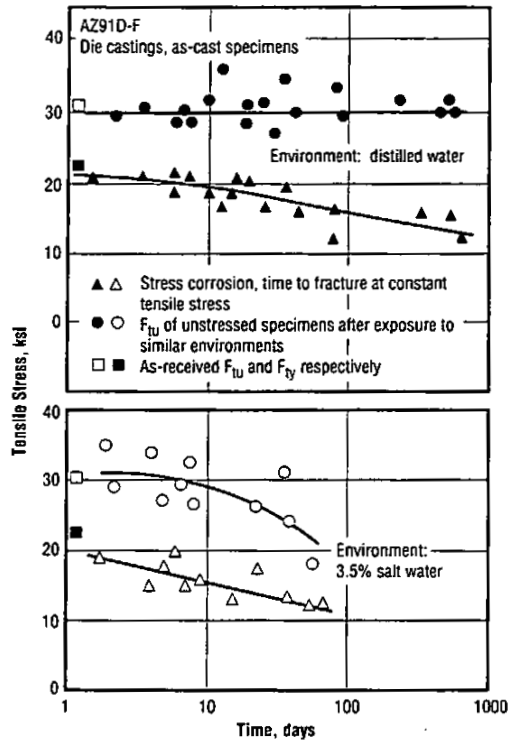


Fig. 2.3.6 Time to stress-corrosion failure as a function of tensile stress for die-cast specimens in two different environments; and, for comparison, the ultimate tensile strength (F_{TU}) of comparison specimens after similar exposures without stress (Ref. 41)

Note 1: The specimens were half submerged in the indicated environments; the stress-corrosion specimens fractured at the air-water interface, but the comparison specimens fractured at random locations in the gage length in subsequent tensile tests.

Note 2: The deterioration in strength of the companion unstressed specimens after about 10 days in salt water was a result of general corrosive attack.

Table 3.1.1 AMS specified mechanical properties (Refs. 1, 2, 4)

Alloy: AZ91						
Condition		T6				
Form (e)	Alloy Variation	Tensile Specimens	F _{ty} (ksi) min	F _{tu} (ksi) min	e (percent, 4D) min	BHN (d)
Sand Cast	C	(a)	16	34.0	3.0	65-85/75-95
		(b)	12	17.0	0.75	65-85/75-95
	E	(a)	16	34.0	3.0	65-85/75-95
		(b)	12	17.0	-	65-85/75-95
		(c)	14.5	25.5	0.75	65-85/75-95
Investment Cast	C	(a)	16	34.0	3.0	-
		(b)	12	17.0	-	-
		(c)	14.5	25.0	1.0	-

(a) Separately cast

(b) Cut from casting, single specimen

(c) Cut from casting, average of four or more specimens

(d) 10 mm ball 500 Kg load/10 mm ball 1000 Kg load; any area of casting except at gate and riser locations

(e) The AMS specification for AZ91A-F die castings (Ref. 3) includes no mechanical-property requirements

Table 3.1.2 ASTM specified mechanical properties (Refs. 5, 7, 8)

Alloy: AZ91					
Tensile Specimens		Separately Cast to Size			
Form (a)	Alloy Variation	Condition	F _{ty} (ksi) min	F _{tu} (ksi) min	e (percent, 2 in.) min
Sand Cast	C	F	11.0	23.0	-
		T4	11.0	34.0	7
		T5	12.0	23.0	2
		T6	16.0	34.0	3
	E	T6	16.0	34.0	3
Investment Cast	C	F	10.0	18.0	-
		T4	10.0	34.0	7
		T5	11.0	20.0	2
		T6	16.0	34.0	3
	E	T6	16.0	34.0	3
Permanent Mold Cast	C	F	11.0	23.0	-
		T4	11.0	34.0	7
		T5	12.0	23.0	2
		T6	16.0	34.0	3
	E	T6	16.0	34.0	3

(a) The ASTM specifications for AZ91A, B, and D-F die castings (Ref. 6) and for AZ91A, B, C, D, and E-F ingot (Ref. 9) include no mechanical-property requirements

AZ 91

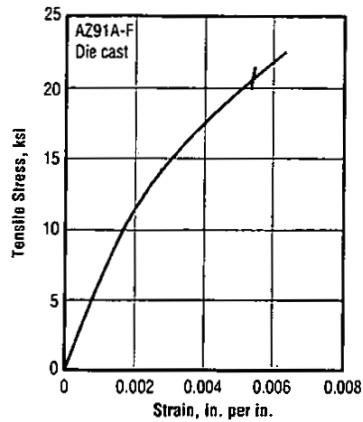


Fig. 3.2.1.1 Tensile stress-strain curve for die-cast test bar at room temperature (Ref. 25)

Table 3.2.1.3 Typical tensile properties of separately cast test bars at room temperature (Refs. 6, 11, 13)

Alloy: AZ91					
Form	Die Cast	Sand, Permanent Mold, Investment Cast			
Alloy Variations	A, B, D	C, E			
Condition	F	F	T4	T5	T6
F_{ty} (ksi)	22-23	14	13	17	21
F_{tu} (ksi)	33-34	24	40	26	40
e (percent, 4D)	3	2.5	15	3	6

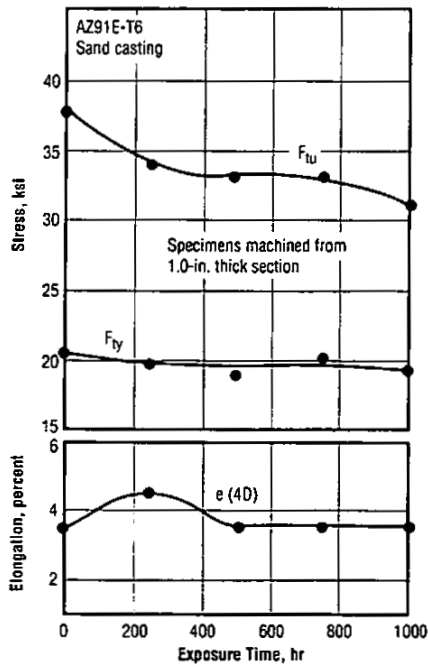


Fig. 3.2.1.4 Effects of exposures up to 1000 hours at 300F on room-temperature tensile properties of sand castings in the T6 condition (Ref. 21)

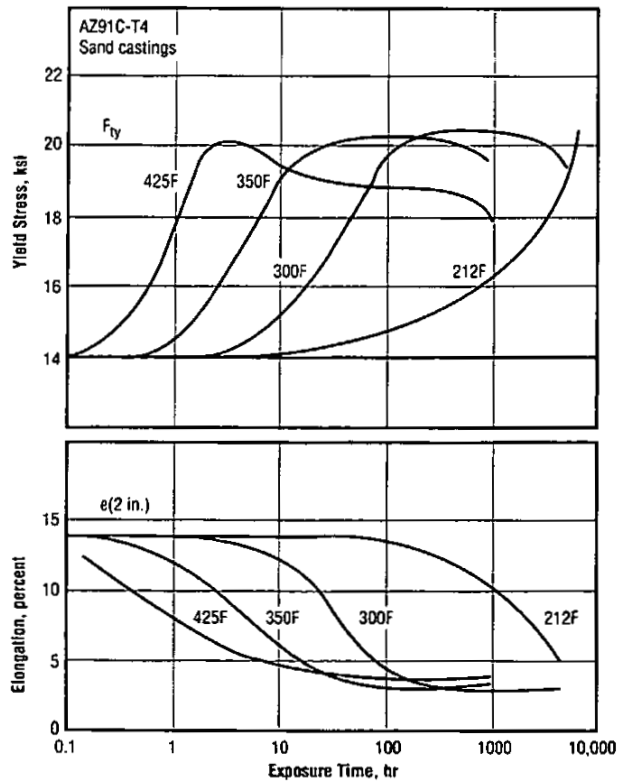


Fig. 3.2.1.5 Effects of long-time exposures at various elevated temperatures on room temperature tensile yield strength and percent elongation of sand castings in the T4 condition (Ref. 25)

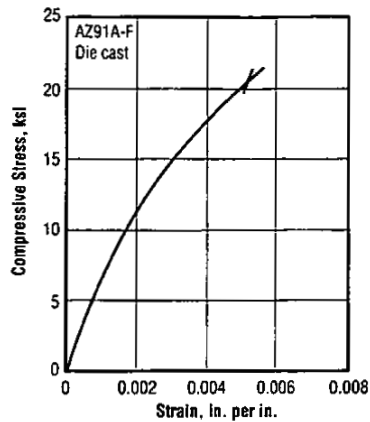


Fig. 3.2.2.1 Compressive stress-strain curve for die-cast test bar at room temperature (Ref. 25)

Table 3.2.2.2 Compressive yield strength at room temperature for different alloy variations and heat treatments (Ref. 11)

Alloy: AZ91			
Form	Alloy Variations	Condition	F _{cy} (ksi)
Die Cast	A, B, D	F	24
Sand, Permanent Mold	C, E	F	14
		T4	13
		T6	19

Table 3.2.3.1 Charpy V-notch impact strength at room temperature for die castings and sand castings in various heat-treated conditions (Ref. 11)

Alloy: AZ91			
Form	Alloy Variation	Condition	Charpy V IE (ft lb)
Die Cast	A, B, D	F	2.0
Sand Cast	C, E	F	0.58
		T4	3.0
		T6	1.0

Table 3.2.5.1 Shear strength at room temperature for different alloy variations and heat treatments (Refs. 11, 33)

Alloy: AZ91			
Form	Alloy Variation	Condition	F _{su} (ksi)
Die Cast	A, B, D	F	20
Sand, Permanent Mold	C, E	F	18
		T4	20
		T6	21

Table 3.2.6.1 Bearing properties at room temperature for different alloy variations and heat treatments (Refs. 11, 25)

Alloy: AZ91				
Form	Alloy Variations	Condition	F _{brv} (ksi)	F _{bru} (ksi)
Sand, Permanent Mold	C, E	F	40	60
		T4	44	60
		T6	52	75

Note: Ratio edge distance to hole diameter, (e/d) = 2.5

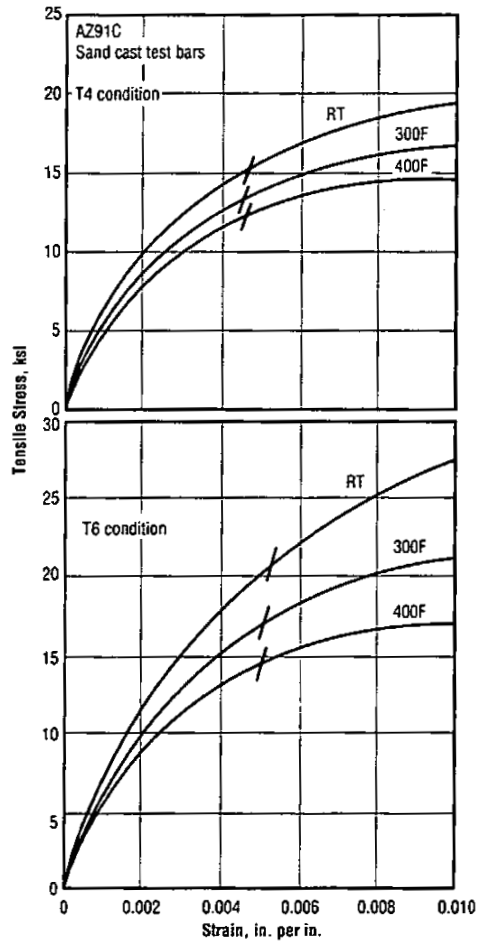


Fig. 3.3.1.1 Stress-strain curves at room and elevated temperatures for sand-cast test bars (Ref. 35)

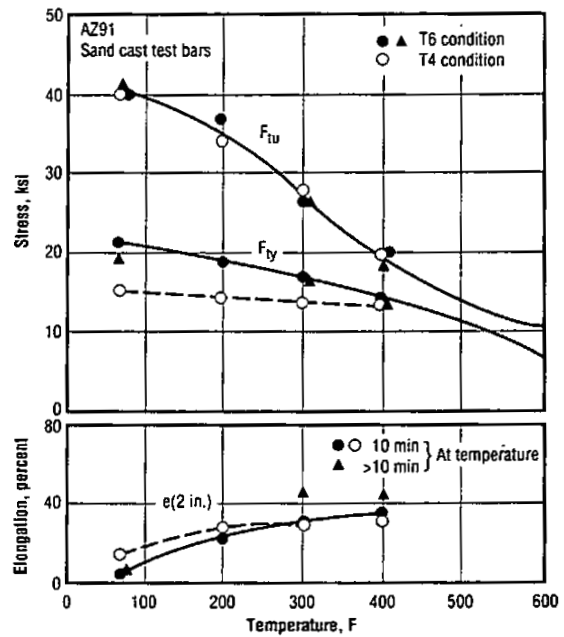


Fig. 3.3.1.2 Effect of test temperature on tensile properties of sand-cast test bars (Refs. 25, 35)

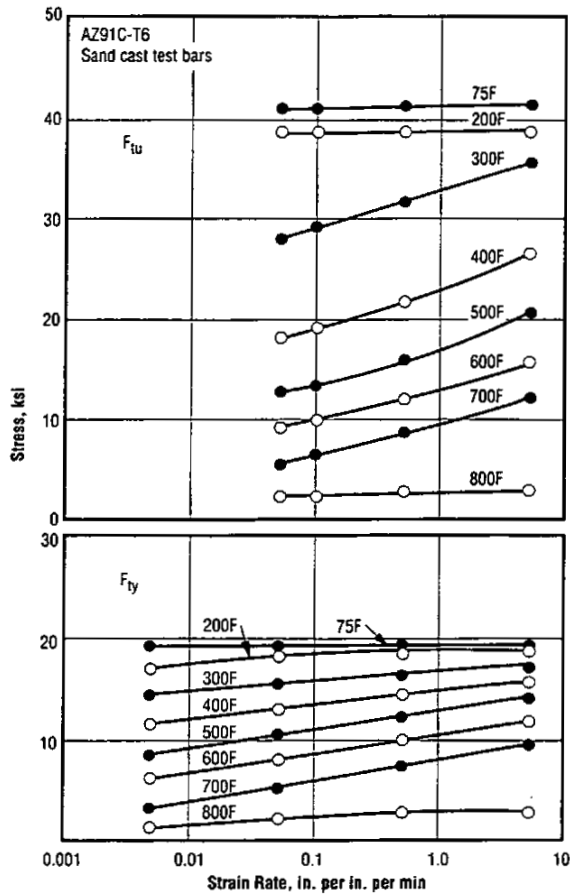


Fig. 3.3.1.3 Effects of test temperature and strain rate on tensile properties of sand-cast test bars in the T6 condition (Ref. 35)

Table 3.3.3.1 Charpy V-notch impact strength of sand castings at temperatures from 75 to -320F (Ref. 29)

Alloy: AZ91C	
Form	Sand Cast
Condition	T6
Temperature (F)	Charpy V IE (ft lb)
75	1
-110	1
-320	3/4

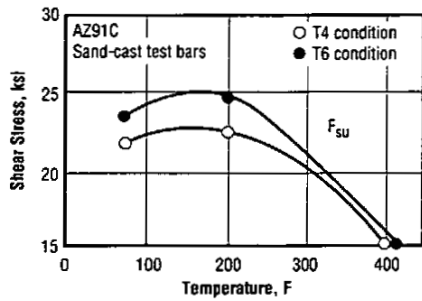


Fig. 3.3.5.1 Effect of test temperature on shear strength of sand-cast test bars (Ref. 36)

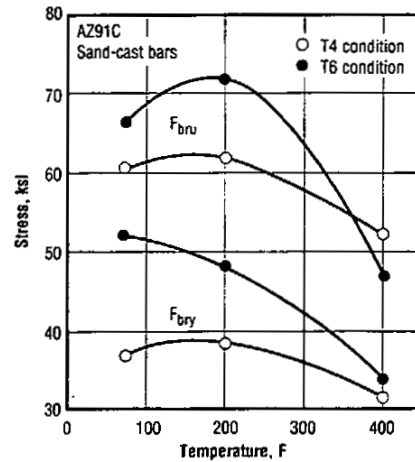


Fig. 3.3.6.1 Effect of test temperature on bearing properties of sand cast test bars (Ref. 36)

AZ 91

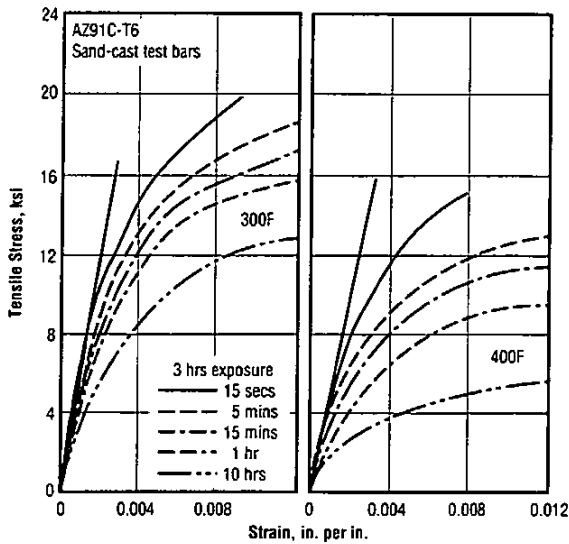


Fig. 3.4.1 Isochronous stress-strain curves at 300 and 400F for sand-cast test bars in T6 condition (Ref. 37)

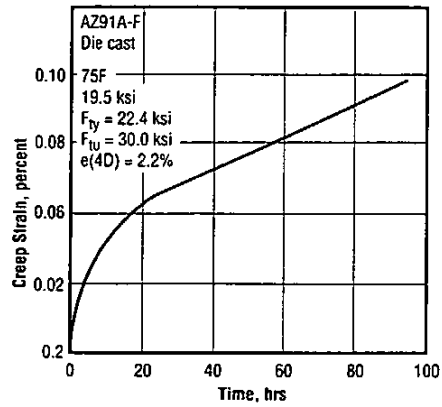


Fig. 3.4.2.1 Creep strain of die-cast test bars as a function of time at room temperature and a tensile stress of 19.5 ksi (Ref. 40)

Table 3.5.1 Rotating-beam fatigue strength (R = -1) of different alloy variations at room temperature (Ref. 11)

Alloy: AZ91				
Form	Alloy Variation	Condition	Cycles to Failure	Maximum Cyclic Stress (ksi)
Die Cast	A, B, D	F	5×10^8	14
Sand, Permanent Mold	C, E	T6	10^8	12-14

Note: Specimen surfaces machined and polished

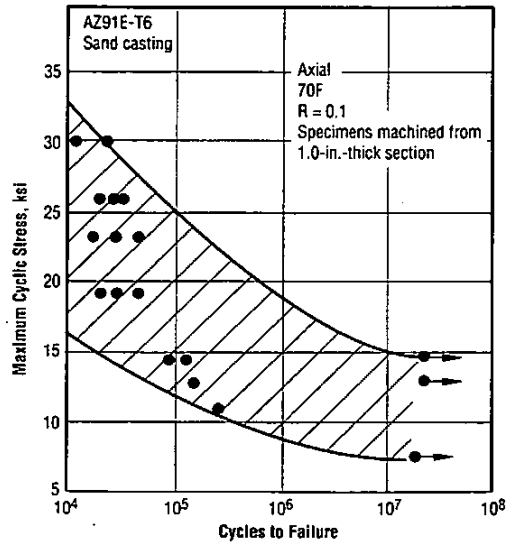


Fig. 3.5.2 Fatigue S-N range for sand castings in the T6 condition (Ref. 21)

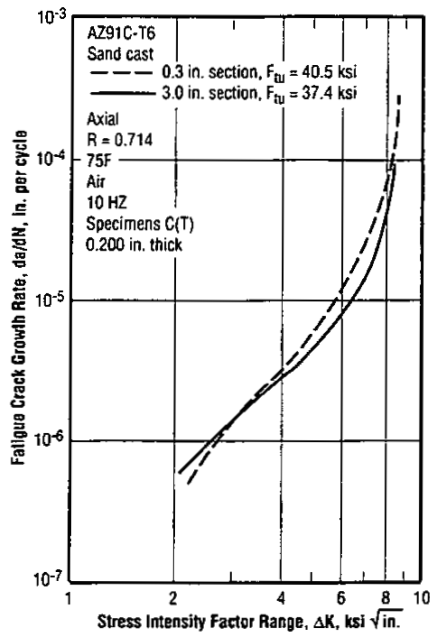


Fig. 3.5.3 Fatigue-crack growth rates for two different sections of a sand casting (Ref. 12)

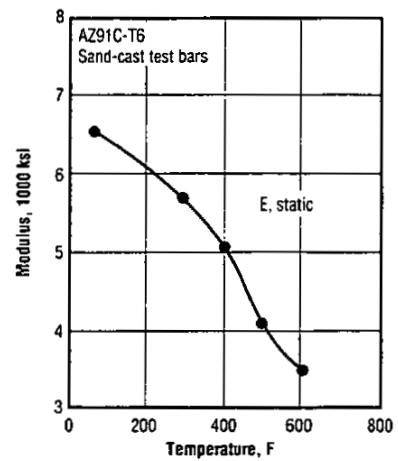


Fig. 3.6.2.1 Modulus of elasticity at room and elevated temperatures (Ref. 28)

Table 4.3.4.1 Tensile properties of sand-cast plates, both base metal and sections with transverse GMA welds across the gage lengths of the test specimens (Ref. 18)

Alloy: AZ91C							
Form	Sand-Cast Plates						
Test Section	Preweld Heat Treatment	Postweld Heat Treatment	Preheat (F)	Filler	F_y (ksi)	F_{tu} (ksi)	e (percent, 2 in.)
Base Metal	T6	T6	400	-	17.9	35.3	3.7
Welded	T6	T6	400	AZ92A	22.1	39.7	4.3
Base Metal	T4	T6	-	-	20.5	41.9	6.5
Welded	T4	T6	-	AZ91C	20.6	34.2	3.3

Note: All tensile properties are the averages of three tests

AZ 91

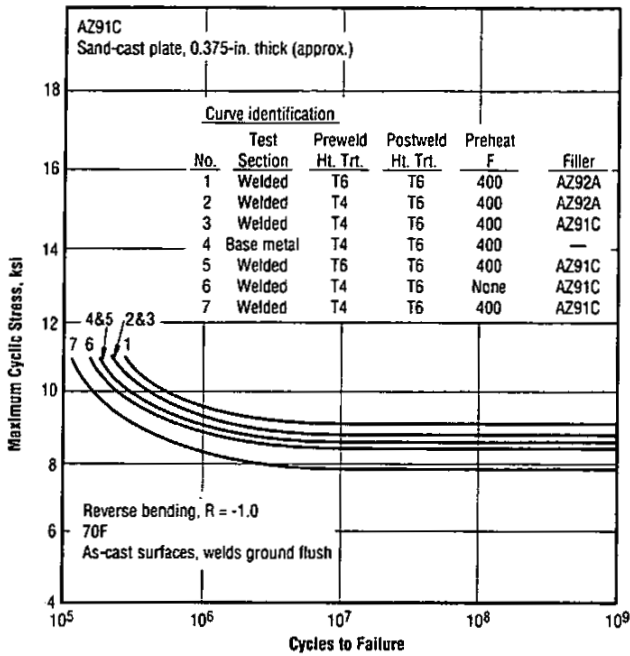


Fig. 4.3.4.2 Fatigue S-N curves for sand-cast plates, both base metal and sections with transverse GMA welds across the test areas (Ref. 18)

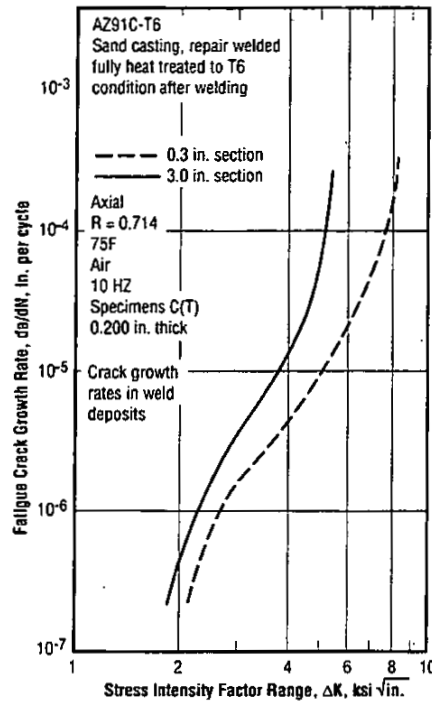


Fig. 4.3.4.3 Fatigue-crack growth rates in GMA repair weld deposits made with AZ92A magnesium alloy electrodes in two different sections of a sand casting (Ref. 12)

Table 4.4.1 Effects of various surface treatments and finishes on the rotating-beam fatigue strength of sand castings at 10 million cycles (Ref. 27)

Alloy: AZ91C		
Form	Sand Castings, 0.625-in. Plates	
Condition	T6 ($F_{T6} = 39.4$ ksi)	
Surface Condition	Fatigue Strength at 10^7 cycles (ksi)	Percent of Control
As polished (control samples)	12	100
Polished, peened	15	125
Polished, alkaline cleaned, pickled	9.5	79
plus, No. 20 chromate conversion coating	10	84
No. 7 chromate conversion coating	9.5	79
HAE light anodic coat	11	92
HAE heavy anodic coat	10	84
No. 17 light anodic coat	8	67
No. 17 heavy anodic coat	9	75
Polished, peened, alkaline cleaned, pickled	15.5	129
plus, No. 20 chromate conversion coating	14.5	121
No. 7 chromate conversion coating	13	108
HAE light anodic coat	14	117
HAE heavy anodic coat	11.5	96
No. 17 light anodic coat	14.5	121
No. 17 heavy anodic coat	11	92
Polished, peened, alkaline cleaned, pickled, HAE heavy anodic coat		
plus, Epoxy primer and lacquer (5 mils total)	12.5	104
Epoxy primer and Alkyd top coat (5.5 mils)	12	100
Epoxy primer and polyurethane (5.4 mils)	11	92
Chloro-rubber and polyurethane (5.3 mils)	12	100
Polished, alkaline cleaned		
plus, HAE light anodic coat	14	117
HAE heavy anodic coat	14	117

Note:

1. Fatigue test conditions: R = -1, 70F, 10,000 cpm
2. Polished: No. 400 polishing paper in longitudinal direction
3. Peened: 0.125-in.-dia steel shot to 5A Almen intensity
4. Pickled: Dilute nitric plus sulfuric acid for 10 sec
5. Alkaline cleaned: immersed in sodium orthosilicate solution

References

1. AMS 4437D, Society of Automotive Engineers (April 1990).
2. AMS 4446, Society of Automotive Engineers (July 1986).
3. AMS 4490G, Society of Automotive Engineers (October 1988).
4. AMS 4452A, Society of Automotive Engineers (April 1985) (R-92).
5. ASTM B 80-90, *ASTM Annual Book of Standards*, Vol. 2.02.
6. ASTM B 94-88, *ibid.*
7. ASTM B 199-87, *ibid.*
8. ASTM B 403-87, *ibid.*
9. ASTM B 93-90, *ibid.*
10. ASTM B 661-90, *ibid.*
11. *ASM International Metals Handbook*, Tenth Edition, Vol. 2 (1990).
12. Kozella, L., and West, D., "Test Results Report and Final Technology Development Report, HLH/STC Transmission Housing Material Evaluation," prepared by Boeing Co. for U.S. Army Aviation Material Laboratory, Fort Eustis, VA (November 1972).
13. "Recommended Practices for Sand Casting Aluminum and Magnesium Alloys," *American Foundrymen's Society*, Second Edition (1965).
14. "Physical Properties of Magnesium and Magnesium Alloys," Dow Chemical Company, Code 2.51 (April 10, 1967).
15. *ASM Metals Handbook*, Eighth Edition, Vol. 7 (1972).
16. Lunder, O., et al, "The Role of Mg₁₇Al₁₂ Phase in the Corrosion of Magnesium Alloy AZ91," *Corrosion*, Vol. 45, pp. 741-746 (September 1989).
17. "Heat Treating Sand and Permanent-Mold Magnesium Castings," Dow Chemical Company (February 1987).
18. "Tensile and Fatigue Strength of Welded AZ91C Magnesium Alloy Castings," Sikorsky Aircraft Report No. SER-50420 (June 11, 1969).
19. Bray, D. J., "Magnesium Alloy Technology for Aerospace Applications," Royal Aerospace Establishment, Farnborough, United Kingdom (August 1989).
20. Fowler, G. A.; King, J. F.; and Lyon, P., "Corrosion Resistant Magnesium Alloys," Preprint No. 21, American Helicopter Society (November 1990).
21. Geary, B., "Corrosion Resistant Magnesium Casting Alloys," paper prepared under the auspices of Westland Helicopter, Ltd. and furnished by Magnesium Elektron, Ltd., Manchester, England.
22. "Crucible Melting of Magnesium Alloys," Dow Chemical Company, Bulletin No. 181-27.
23. "Heat Treating Sand and Permanent Mold Magnesium Castings," Dow Chemical Company, Form No. 141-35-68.
24. "Standard for the Storage, Handling, and Processing of Magnesium," National Fire Protection Association, Form No. 143-152 (May 1961).
25. "Magnesium Design," Dow Chemical Company, Form No. 141-91-457 (1957).
26. Reichel, K. N.; Clark, K. J.; and Hillis, J. E., "Controlling the Salt-Water Corrosion Performance of Magnesium AZ91 Alloy," SAE International Congress and Exposition, Detroit, MI (February 25-March 1, 1985).
27. Bethke, J. J., and Gallaccio, A., "Effect of Corrosion-Resistant Coatings on the Fatigue Strength of Cast Magnesium Alloys," Material and Manufacturing Technology Division, Frankford Arsenal, Report No. MMT-1-77 (August 1977).
28. Fenn, A. W., Jr., "Young's Modulus of Magnesium Alloys as a Function of Temperature and Metallurgical Variables," Dow Chemical Company (1959).
29. Hallowell, J. B., and Ogden, H. R., "An Introduction to Magnesium Alloys," Defense Metals Information Center Report 206 (August 26, 1964).
30. "Machining Magnesium," Dow Chemical Company, Form No. 141-291-65(R) (1965).
31. *ASM International Metals Handbook*, Ninth Edition, Vol. 13 (1987).
32. "Arc Welding Magnesium," Dow Chemical Company, Form No. 141-300-67 (Revised).
33. "Design," Magnesium Elektron Ltd., 1270 Ave. of the Americas, New York City, NY 10020.
34. "Brazing, Bonding, Soldering and Special Welding of Magnesium," Dow Chemical Company, Form No. 141-313-66.
35. "Room and Elevated-Temperature Properties of Magnesium Casting Alloys," Dow Chemical Company, Bulletin No. 141-176 (1958).
36. "Shear, Bearing, and Hardness Data for Cast Alloys," Dow Chemical Company (February 11, 1957).

37. "Isochronous Stress-Strain Curves of Magnesium Casting Alloys," Dow Chemical Company (October 31, 1958).
38. Nussbaum, G.; Gjestland, H.; and Regassoni, G., "Rapid Solidification of Magnesium Alloys," *Light Metal Age*, Vol. 46, pp. 16-19 (August 1988).
39. Das, S. K., and Davis, L. A., "High-Performance Aerospace Alloys via Rapid Solidification Processing," *Materials Science and Engineering*, Vol. 98 (February 1988).
40. Miller, W. K., "Creep of Die-Cast AZ91 Magnesium at Room Temperature and Low Stress," *Metallurgical Transactions*, Vol. 22A, pp. 873-877 (April 1991).
41. Miller, W. K., "Stress Corrosion Cracking of Magnesium Die Casting Alloys," *Materials Research Society Symposium Proceedings*, Vol. 125 (1988).

AZ 91

This page is blank.