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Magnesium Alloys in Aircraft Seats - Engineering Design and Fabrication Recommended Practices

RATIONALE

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FOREWORD

Magnesium metal is used in a diverse range of markets and applications exploiting the unique physical and mechanical properties of the element and its alloys. The light weight properties of magnesium alloys are used as a means of reducing weight, increasing fuel efficiency and reducing greenhouse gas emissions. Compared to magnesium on a volume for volume basis, aluminum weighs one and a half times as much, while steel is four times as heavy.

The use of magnesium in aircraft seat production has been hindered by specification and regulation. There are developments within the SAE and regulatory organizations to remove these restrictions thus allowing magnesium/alloy usage in this and potentially other areas of the aircraft. Due to the existing restrictions, information on the engineering and fabrication of magnesium alloy components is not available. This ARP has been requested by the SAE Aircraft Seat Committee to help define design and fabrication best practices. This document is in support of AIR6160.

Magnesium is well known for its low density, but it also has a number of other beneficial attributes. Magnesium alloys have an excellent strength to weight ratio, good fatigue strength and high damping capacity. Magnesium is non-magnetic, has good thermal and electrical conductivity and offers electromagnetic shielding capabilities that match aluminum in electrical enclosures. Magnesium sheet offers very good dent resistance.

Magnesium can be shaped by all metal working techniques. It can be cast, extruded, processed via powder metallurgy and rolled into sheet and plate. Magnesium is the easiest of all structural metals to machine, and can be formed into shapes by forging, drawing, spinning, stamping, impact extrusion and superplastic forming to mention but a few metalworking processes. Magnesium products can be joined by welding, adhesive bonding, bolting, screwing, and the use of self-piercing rivets.

Attention to surface protection is important; therefore, pre-treatments followed by appropriate paint finishes are utilized to ensure adequate protection. In addition, electroless and electroplating treatments are also possible where a bright chrome finish is desired.

Magnesium has a reputation for being highly flammable. While this may be true for finely divided magnesium powders and ribbon, bulk magnesium does not burn until it has been heated to above its melting point (648 °C/1198 °F for pure metal). Magnesium has been used for over 50 years in demanding high temperature applications such as jet engines and nuclear reactors without any practical flammability issues. In recent times significant effort has been made to demonstrate the safe usage of magnesium and its alloys in aircraft interior applications. Federal Aviation Administration test results have shown that in full scale fuselage flammability tests magnesium posed no additional threat to passenger safety relative to other materials present in the cabin interior. For additional details refer to AIR6160.

TABLE OF CONTENTS

1.	SCOPE.....	5
2.	REFERENCES.....	5
2.1	SAE Publications.....	5
2.2	ASTM Publications.....	5
3.	MAGNESIUM AS A RAW MATERIAL OR SEMI-FINISHED PRODUCT.....	5
3.1	Magnesium Alloys.....	6
3.2	Castings.....	7
3.2.1	Casting Alloys.....	7
3.2.2	Casting Methods.....	8
3.3	Sheet and Plate.....	12
3.3.1	Production of Magnesium Sheet and Plate.....	12
3.3.2	Choosing the Correct Sheet and Plate Alloy.....	12
3.4	Extrusions.....	14
3.4.1	Extrusion Process.....	14
3.4.2	Design.....	15
3.4.3	Choosing the Right Alloy.....	16
3.5	Forgings.....	18
4.	DESIGNING FROM ALUMINUM TO MAGNESIUM.....	23
4.1	Introduction.....	23
4.2	Metallic Materials Property Development and Standardization (MMPDS).....	23
4.3	Modulus of Elasticity.....	24
4.4	Shear Modulus - Modulus of Rigidity - Poisson's Ratio.....	25
4.5	Shear Strength.....	26
4.6	Compressive and Tensile Properties.....	26
4.7	Hardness - Bearing Strength.....	26
4.8	Abrasion Resistance.....	27
4.9	Interference of Shrink Fit Applications.....	27
4.10	Column Strength.....	27
5.	MACHINING.....	28
5.1	Cutting Power and Machinability.....	29
5.2	Speeds, Feed, and Depths of Cuts.....	29
5.3	Tooling.....	30
5.3.1	Tool Material.....	30
5.3.2	Tool Life.....	31
5.3.3	Tool Geometry.....	31
5.3.4	Tooling Manufacturers and Suppliers.....	32
5.4	Clamping, Distortion and Tolerances.....	32
5.5	Cooling.....	32
5.5.1	Dry Machining.....	33
5.5.2	Cooling Gasses.....	33
5.5.3	Mineral Oils.....	33
5.5.4	Water-Miscible Cutting Fluids.....	34
5.5.5	Recommendations for Water-Oil Emulsions.....	35
5.6	Swarf and Chip Handling.....	35
5.6.1	Swarf and Chip Storage.....	35

5.6.2	Dry Chips, Turnings and Swarf	36
5.6.3	Wet Chips, Turnings and Swarf	36
5.6.4	Swarf and Chip Transport	36
5.6.5	Swarf and Chip Disposal and Recycling	36
5.7	Fire Precautions	36
5.8	Machining Operations	37
5.8.1	Turning and Boring	38
5.8.2	Milling	39
5.8.3	Drilling	39
5.8.4	Reaming	41
5.8.5	Tapping	41
5.8.6	Threading	42
5.8.7	End Milling or Countersinking	42
5.8.8	Rounding and Broaching	43
5.8.9	Sawing	43
5.8.10	Filing	43
5.8.11	Grinding and Polishing	43
5.8.12	Storage and Handling of Parts	43
6.	JOINING	45
6.1	Mechanical Joining	45
6.2	Bolted Joints	45
6.2.1	Locking Bolts	45
6.2.2	Self-Clinching Nuts	46
6.2.3	Inserts - Screwed-in	47
6.2.4	Inserts - Press and Shrink Fit	47
6.2.5	Choice of Fasteners and Inserts	48
6.3	Self-Piercing/Self-Tapping Screws	49
6.4	Threaded Fasteners	50
6.4.1	Manufacturers of Fastener Systems for Magnesium	50
6.5	Adhesive Bonding	51
6.5.1	Joint Design	53
6.5.2	Equipment and Materials	55
7.	CUTTING	56
7.1	Sawing	56
7.2	Plasma Arc Cutting Magnesium Plate	58
7.3	Laser Cutting	59
7.4	Water Jet Cutting	59
8.	CORROSION	60
8.1	Corrosion Behavior of Unprotected Magnesium Alloys	60
8.2	The Behavior of Magnesium Components in Service	61
8.2.1	Surface Contamination	61
8.2.2	Unprotected Magnesium Surfaces	63
8.2.3	Galvanic Contacts	64
8.3	Design	64
8.3.1	Method of Assembly	64
8.3.2	The Position of a Component in Service	64
8.3.3	The Effect of Sharp Edges	64
8.3.4	Designing an Assembly Containing Components Fabricated from Magnesium and Other Metals	64
8.4	Summary	69
9.	SURFACE TREATMENT	70
9.1	Protection and Surface Treatment of Magnesium	70
9.2	Temporary Protection for Storage	70
9.3	Application of Coatings	71
9.3.1	Degreasing	71
9.3.2	Surface Cleaning	71



9.3.3	Surface Pretreatments: Conversion Coatings or Anodizing (Plasma Electrolytic Oxidation, PEO, Coatings)	73
9.3.4	Surface Coatings.....	77
9.4	Appendix	79
9.4.1	Related Specifications	79
10.	FLAMMABILITY	79
10.1	General Fire Precautions with Magnesium.....	79
10.1.1	Grinding.....	80
10.1.2	Dust Extraction	80
10.1.3	Machining (see also Section 4).....	81
10.2	Magnesium Storage and Transportation	81
10.2.1	Powder, Chips, Granules, and Turnings.....	82
10.2.2	Transporting Magnesium	82
10.3	If There is a Fire	82
10.3.1	Smothering Agents.....	82
10.4	Employee Training and Response Team	83
11.	REFERENCES.....	83
11.1	Publications and Data Sources.....	83
11.2	Bibliography	83
12.	NOTES.....	84

1. SCOPE

This document is a guide to the application of magnesium alloys to aircraft interior components including but not limited to aircraft seats. It provides background information on magnesium, its alloys and readily available forms such as extrusions and plate. It also contains guidelines for “enabling technologies” for the application of magnesium to engineering solutions including: machining, joining, forming, cutting, surface treatment, flammability issues, and designing from aluminum to magnesium.

2. REFERENCES

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS8049 Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft

AIR6160 Magnesium Alloys in Aircraft Seats - Developments in Magnesium Alloy Flammability Testing

2.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM B80 Standard Specification for Magnesium-Alloy Sand Castings

ASTM B90/B90M Standard Specification for Magnesium-Alloy Sheet and Plate

ASTM B94 Standard Specification for Magnesium-Alloy Die Castings

ASTM B107/B107M Standard Specification for Magnesium-Alloy Bars, Rods, Profiles, Tubes, and Wire

ASTM B199 Standard Specification for Magnesium-Alloy Permanent Mould Castings

ASTM B293 Standard Practice for Temper Designations of Magnesium Alloys, Cast and Wrought

ASTM B403 Standard Specification for Magnesium-Alloy Investment Castings

ASTM B661 Standard Practice for Heat Treatment of Magnesium Alloys

ASTM B951 Standard Practice for Codification of Unalloyed Magnesium and Magnesium Alloys, Cast and Wrought

3. MAGNESIUM AS A RAW MATERIAL OR SEMI-FINISHED PRODUCT

Magnesium is available in three basic forms for aerospace applications; alloyed ingot for casting, extrusions in the forms of standard bar and rod, as well as tailor designed profiles; and sheet and plate. Note that forging feed stock is also available, but this is generally cast billet or pre-extruded bar. Similarly, cast block for machining can be obtained.

3.1 Magnesium Alloys

The following relates to all product forms including castings, extrusion, sheet and plate:

The American Society for Testing and Materials (ASTM) has a standardized designation system for all magnesium alloys. All alloy designations are characterized by two letters and two numbers, which are followed by a series letter. In certain cases a temper designation is included. The initial two letters indicate the primary and secondary alloying elements and their nominal content in weight percent rounded to the nearest integer is shown by the two numbers respectively. This is followed by a serial letter to indicate any revision to the alloy composition, i.e., WE43C is an alloy with 4 wt.% yttrium; 3 wt.% rare earths, and is the third alloy registered with that basic composition. Table 1 shows alloying elements and their associated letter used in the ASTM designation. Following the alloy designation, it is common for the temper of the material to be indicated as shown in Table 2 which contains the definitions of the temper letters.

The temper designations used are similar to those used in wrought aluminum alloys.

Table 1 - Alloy nomenclature

A	Aluminum	N	Nickel
B	Bismuth	P	Lead
C	Copper	Q	Silver
D	Cadmium	R	Chromium
E	Rare Earths	S	Silicon
F	Iron	T	Tin
H	Thorium	V	Gadolinium
J	Strontium	W	Yttrium
K	Zirconium	X	Any Other
L	Lithium	Y	Antimony
M	Manganese	Z	Zinc

Table 2 - Alloy temper definition

General Divisions	Subdivisions of -H	Subdivisions of -T	
F - as fabricated.	H1, plus one digit - strain hardened only.	T1 - cooled and naturally aged.	T6 - solution heat treated and artificially aged.
O - annealed (wrought process).	H2, plus one digit - strain hardened and partially annealed.	T2 - annealed (cast products only).	T7 - solution heat treated and stabilized
H - strain hardened.		T3 - solution treated and cold worked.	T8 - solution heat treated, cold worked and artificially aged.
T - thermally treated to a stable temper (other than those above).	H3, plus one digit - strain hardened and thermally stabilized.	T4 - Solution heat treated.	T9 - solution heat treated, artificially aged, and cold worked.
W - solution heat treated (unstable).		T5 - cooled and artificially aged.	

For further information on magnesium alloy specifications, refer to the following ASTM documents:

- ASTM B80 Standard Specification for Magnesium-Alloy Sand Castings
- ASTM B90/B90M Standard Specification for Magnesium-Alloy Sheet and Plate
- ASTM B94 Standard Specification for Magnesium-Alloy Die Castings
- ASTM B107/B107M Standard Specification for Magnesium-Alloy Bars, Rods, Profiles, Tubes, and Wire
- ASTM B199 Standard Specification for Magnesium-Alloy Permanent Mould Castings

- ASTM B293 Standard Practice for Temper Designations of Magnesium Alloys, Cast and Wrought
- ASTM B403 Standard Specification for Magnesium-Alloy Investment Castings
- ASTM B661 Standard Practice for Heat Treatment of Magnesium Alloys
- ASTM B951 Standard Practice for Codification of Unalloyed Magnesium and Magnesium Alloys, Cast and Wrought

3.2 Castings

Metal casting offers the designer a method of making a component that can be complex in shape and contain internal passageways that are extremely difficult to manufacture by other methods. The process is reproducible and competent foundries are capable of making castings ranging from a few grams to several hundred kilograms in weight. Use of magnesium alloys offers a considerable weight reduction while maintaining good mechanical properties.

3.2.1 Casting Alloys

A large range of magnesium alloys are available for cast applications, however, not all alloys are suitable for production by casting methods. Optimum properties are achieved when an appropriate alloy and casting method is selected. Some alloys are more suited to sand casting or permanent mould casting whereas other alloys perform better when die cast.

Although the magnesium-aluminum and magnesium-aluminum-zinc alloys are generally easy to cast, they are limited in certain respects. They exhibit micro-shrinkage when sand cast, and they are not suitable for applications in which temperatures of over 95 °C (200 °F) are experienced. The magnesium-rare earth-zirconium alloys were developed to overcome these limitations and sand castings in the zirconium grain refined alloys also have excellent pressure tightness.

For normal, moderate temperature applications (up to 160 °C, or 32 °F), the two alloys ZE41A and EZ33A find the greatest use. They are very castable and can be used to make very satisfactory castings of considerable complexity. In addition, they have the advantage of requiring only a T5 heat treatment.

For applications that operate at higher temperatures or require greater corrosion resistance the modern yttrium and rare earth containing alloys are more suitable; i.e., WE43B and WE54A. These alloys have superior elevated-temperature properties and a corrosion resistance similar to the high-purity magnesium-aluminum-zinc types (AZ91E).

The latest alloy is EV31A, which has good elevated temperature performance, good corrosion resistance and improved ease of casting. The alloys used for investment casting are very similar to those used for the sand casting process. See Tables 3A and 3B.

Table 3A - Typical properties of cast alloys - Metric units

Design Attribute	EV31A	WE43B	WE54A	ZE41A	EZ33A	AZ91E
Density (g/cm ³)	1.82	1.84	1.85	1.84	1.80	1.83
Yield Strength (0.2% PS MPa)	170	185	205	148	94	131
Specific Strength (kNm/kg)	93	101	111	80	52	72
Youngs Modulus (GPa)	44.8	45.0	44.1	44.1	44.1	44.1
Specific Stiffness (MNm/kg)	24.2	23.9	23.8	23.9	24.4	24.0
Damping Capacity		0.09	0.17	0.28	1.89	0.27
Creep Resistance at 200 °C (MPa) ¹	80	85			50	
Thermal Conductivity (W/m°C)	116	51	52	109	100	84
Tensile Strength (MPa)	280	265	280	218	161	247
Elongation (%)	5	7	4	4.5	4.5	2.5
Compressive Strength (MPa)	168	187	165 - 175	130 - 150	85 - 120	130
Fatigue Strength (MPa at 5e ⁷ cycles)	95 - 105	8	97	95	70	70
Brinell Hardness	70	85	85	65	55	75
Thermal Expansion (x10 ⁻⁶ /K)	26.3	26.7	27.0	27.1	26.8	27.0
Specific Heat (J/kg/K)	1086	966	960	960	1040	1000
Corrosion Rate (mpy)	10 - 3	<75	<75	320 - 480	270	4 - 14
Impact Value (Joules) (Unnotched)	6			4 - 4.5	6 - 7	3 - 4
Shear Strength (MPa)	170	160	150	140	140	145

¹0.1% creep strain after 1000 hours.

Table 3B - Typical properties of cast alloys - English units

Design Attribute	EV31	WE43B	WE54A	ZE41A	EZ33A	AZ91E
Density (lb/ft ³)	113.6	114.9	115.5	114.9	112.4	114.2
Yield Strength (0.2% PS ksi)	24.7	26.8	29.7	21.5	13.6	19.0
Specific Strength (ksi/lb.in ³)	375.4	403.0	444.6	323.3	209.2	287.4
Youngs Modulus (x10 ³ ksi)	6.53	6.53	6.38	6.38	6.38	6.38
Specific Stiffness (ksi/lb.in ³)	57.5	56.8	55.2	55.0	56.8	55.9
Damping Capacity		0.09	0.17	0.28	1.89	0.27
Creep Resistance at 390 °F (ksi) ¹	11.6	12.3			7.3	
Thermal Conductivity (Btu/ft h °F)	67	30	30	63	58	49
Tensile Strength (ksi)	40.6	38.4	40.6	31.6	23.4	35.8
Elongation (%)	5	7	4	4.5	4.5	2.5
Compressive Strength (ksi)	24.4	27.1	23.9 - 25.4	18.9 - 21.8	12.3 - 17.4	18.9
Fatigue Strength (ksi at 5e ⁷ cycles)	13.8 - 15.2	12.3	14.1	13.8	10.2	10.2
Brinell Hardness	70	85	85	65	55	75
Thermal Expansion (x10 ⁻⁶ /F)	14.6	14.8	15.0	15.1	14.9	15.0
Specific Heat (Btu/lb°F)	0.259	0.231	0.229	0.229	0.248	0.239
Corrosion Rate (mpy)	10 - 30	<75	<75	320 - 480	270	
Impact Value ((ft lb) (Unnotched)	4.4			3.0 - 3.3	4.4 - 5.2	2.2 - 3.0
Shear Strength (ksi)	24.7	23.2	218	20.3	20.3	21.0

¹0.1% creep strain after 1000 hours.

3.2.2 Casting Methods

3.2.2.1 Sand Casting

Magnesium alloy sand castings are used in aerospace and other high specification applications because they offer a clear weight advantage over aluminum and other materials. A considerable amount of research and development has resulted in improvements in properties of modern casting alloys compared with the earlier aluminum-zinc (AZ) alloys. Although there is still a large volume of castings for aerospace being produced in the older AZ alloys, there is now increasing use of the newer zirconium containing alloy systems, such as WE43B and EV31, which have high strength and long term temperature stability at temperatures up to 482 °F (250 °C), see Table 4. A schematic of the sand casting process is shown in Figure 1.

Table 4 - AMS magnesium alloys - Comparison of elevated temperature properties

Alloy	AMS Specification	At Elevated Temperature		Conditions	Cut from Castings or Integral Coupons			
		°F	°C		YS ksi	UTS ksi	YS MPa	UTS MPa
AZ91E	4466	70	21	Any bar	12.0	17.0	83	117
				Average of 4 bars minimum	14.5	25.5	100	176
ZE41A	4439	70	21	Any bar or integral coupon	17.5	26.0	121	179
QE22A	4418	400	204	Any bar or integral coupon	18.0	24.0	124	165
EV31*	4429	400	204	Typical properties	22.5	33.0	155	228
WE43B	4427	480	249	Any bar or integral coupon	18.5	25.5	128	176

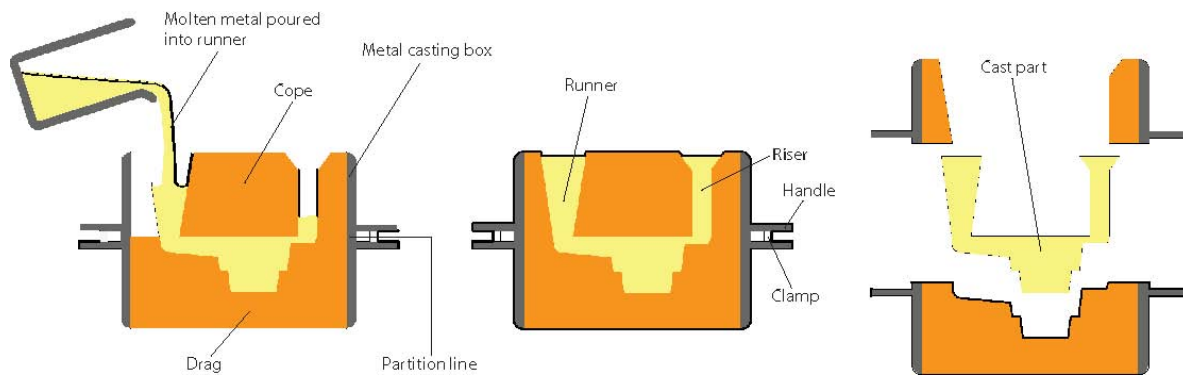


Figure 1 - Sand casting process

3.2.2.2 Pressure Sand Casting

Several magnesium foundries now use a pressure system when making certain castings. The sand mould is placed on a steel plate located on top of the crucible containing the prepared alloy. A vertical pipe is lowered through a hole in the steel plate and immersed into the liquid metal and the top of the pipe is sealed into the sand mould running system.

The high pressure system requires that the crucible has a sealed lid incorporating the pipe. The atmosphere above the melt is pressurized and liquid metal is forced up the pipe and into the mould cavity. Once the metal has solidified sufficiently then the pressure is released and the pipe assembly removed.

3.2.2.3 Investment Casting

Throughout the history of magnesium alloy castings, designs involving cast components that were very complex, embraced very thin wall sections, had fine surface finish, and attained tight dimensional tolerances became the market for investment casting.

The gap between modern sand casting and investment casting has been considerably narrowed. However, the investment casting process is still capable of producing castings of tighter tolerances and thinner wall sections than those of sand castings. The disadvantages of the investment process are the cost of the casting in terms of both capital equipment and cost per casting. There is also a much greater restriction on the size of the casting that can be produced.

The same alloys can be cast by this process as with sand casting. The processes used are mainly the lost wax type. This gives, among other things, a general improvement in dimensional accuracy by the elimination of the parting line. The introduction of newer alloys such as EV31 with reduced reactivity has resulted in renewed interest in this form of casting.

Investment cast magnesium components are already being used in areas of motorsport, commercial automotive prototyping and civil and defense man-portable systems. Investment cast EV31 is also currently being evaluated for civil aerospace applications, a major potential new market. EV31 offers most of the property benefits of WE43B, including good corrosion resistance and elevated temperature performance. An important additional aspect for precision casting is that EV31 has low oxidation characteristics, which may reduce reaction with mould material and certainly facilitates easy molten metal handling for the foundry. Wherever the combination of lightweight and strength are required, investment cast magnesium can be a solution. See Figure 2.

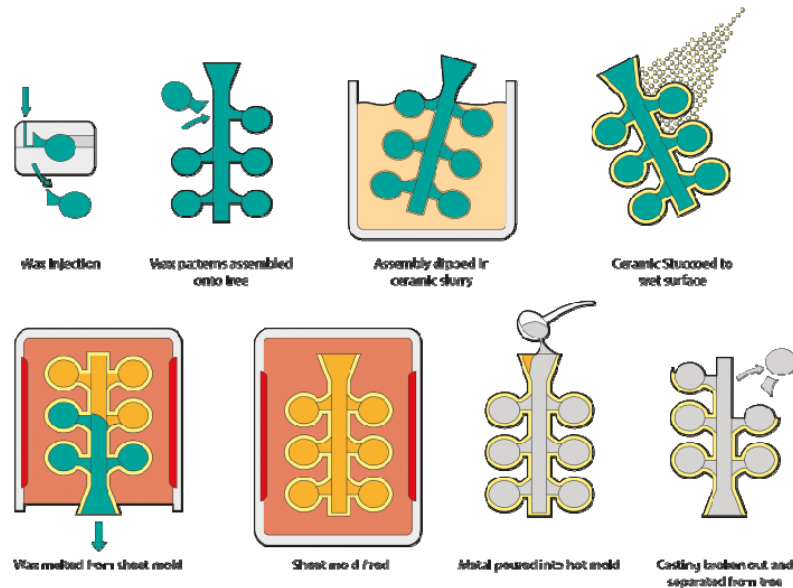


Figure 2 - Investment casting process

For full exploration of Magnesium precision cast parts, one must also compare properties of aluminum based alloys.

It is apparent from Table 5 that EV31 has the ability to compete with some of the aluminum alloys currently in use.

Table 5 - Typical properties of EV31 versus aluminum alloys

Typical Properties	Yield Strength MPa (ksi)	Tensile Strength MPa (ksi)	Elongation (%)	Casting Process
EV31 - T6	166 (24)	248 (36)	4	Precision cast
A357 - T6	213 (30.9)	283 (41)	2.5	Data from thin wall investment casting
A356 - T6	165 (23.9)	230 (33.4)	3.5	Typical Sand Cast - source: ASM Metals Handbook Vol. 2.
Specification Minimums				
EV31 - T6	145 (21)	248 (36)	2	Sand Cast to AMS4429 & MMPDS
A357 T62 Class 11	214 (31)	283 (41)	3	ASM Handbook
D357 - T6	248 (36)	310 (45)	2	Castings to AMS4241C

3.2.2.4 Shell Moulding

Shell mould castings are available from a number of foundries to dimensional tolerances similar to those of shell mould castings in other metals

3.2.2.5 Permanent Mould Casting

In general, the alloys normally sand cast are also suitable for permanent mould casting. The exception are older alloys of the magnesium-zinc-zirconium type, for example ZK51 and ZK61A, which exhibit strong hot-shortness tendencies and are consequently unsuitable for processing by this method, so aluminum-zinc alloys are preferred for larger castings.

The fact that a mould or die can be repeatedly reused is an advantage over sand casting. However, the total number of castings required from a die must be capable of amortizing the high initial capital cost of the die. In general, the surface finish and dimensional tolerances are superior to those obtainable from a comparable sand casting. A distinct disadvantage to the process is the high cost of modifying the casting design or running system, once the die is constructed.

3.2.2.6 Die Casting

The die casting process is ideally suited to high-volume production. The high cost of the die can be amortized by the large production volume. The process is a fast production method capable of a high degree of automation, one for which certain magnesium alloys are ideally suited. The number of alloys that can successfully be cast by die casting is more restricted than with sand casting. Schematics of both low pressure and high pressure die casting are shown in Figures 3 and 4 respectively.

Two advantages of magnesium die castings are that molten magnesium does not solder onto the die in the same way as does aluminum; therefore, the expensive dies last much longer; two to three times longer than with aluminum alloys. Also, magnesium can be machined four times faster than aluminum. These factors, combined with the fact that magnesium is only two-thirds the weight of aluminum, account for the growing popularity of magnesium die casting, particularly in the automotive field.

The most common alloys from which die castings are made are the magnesium-aluminum and magnesium-aluminum-zinc type, for example AZ91, AM50, and AM60. More advanced alloys include AJ52, and AJ62 containing strontium, AS41B containing silicon and AE44 containing rare earths. These have improved high temperature properties and good corrosion resistance. An overview of the mechanical properties of these alloys is given in Table 6.

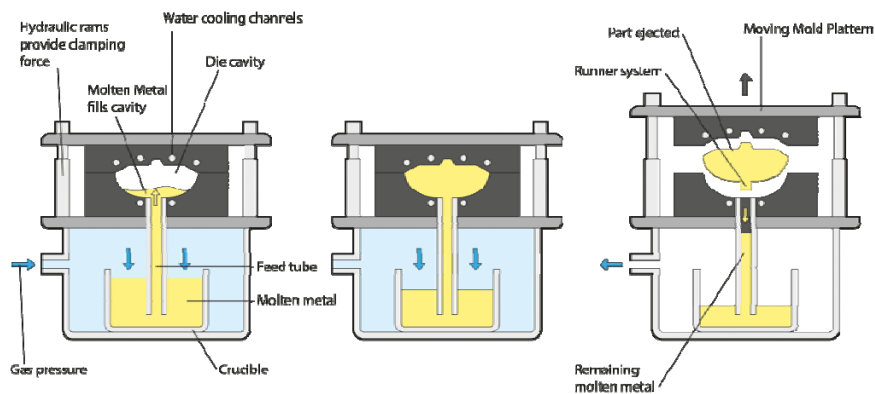


Figure 3 - Low pressure die casting process

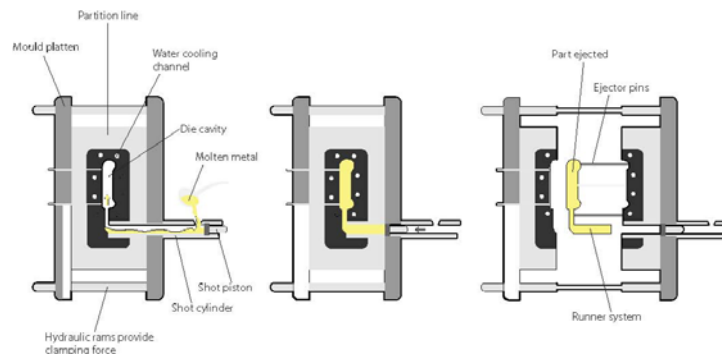


Figure 4 - High pressure die casting

Table 6 - Mechanical properties for die casting alloys

	AZ91D	AM50A	AM60B	AJ62A
Typical Tensile Properties at 68 °F (20 °C)				
0.2% Tensile Yield Strength MPa (ksi)	150 (23)	120 (18)	130 (19)	114 (17)
Ultimate Tensile Strength MPa (ksi)	230 (34)	220 (32)	220 (32)	240 (35)
Elongation (%)	3	6 - 10	6 - 8	5 - 9
Typical Compressive Properties at 68 °F (20 °C)				
0.1% Yield Strength MPa (ksi)	165 (24)	-	130 (19)	-
Ultimate Strength MPa (ksi)	400 (58)	-	-	-
Typical Shear Properties				
Ultimate Shear Strength MPa (ksi)	140 (20)	-	-	-
Fatigue Properties				
Rotating bend test 5×10^7 cycles MPa (ksi)	70 (10)	70 (10)	70 (10)	60 (9)
Creep Properties				
0.05% strain at 347 °F (175 °C) for 200 hours MPa (ksi)	-	-	-	50 (7)
Typical Tensile Properties at 350 °F (177 °C)				
0.2% Tensile Yield Strength MPa (ksi)	115 (17)	-	90 (13)	103 (15)
Ultimate Tensile Strength MPa (ksi)	150 (22)	-	110 (16)	165 (24)

3.3 Sheet and Plate

Magnesium sheet and plate is available in a number of alloys. Each with unique properties that lend them to different applications. These include AZ31B, ZE10A, and WE43C.

3.3.1 Production of Magnesium Sheet and Plate

Magnesium sheet and plate products are produced using the same process as their aluminum counterparts. Flat products start from direct chill (DC) cast ingot with dimensions up to 400 mm x 1200 mm x 2100 mm (15.7 inches x 47.2 inches x 82.7 inches) in the region of 1.5 to 2t in weight. These are scalped and homogenized before rolling. In the production of plate products up to 2 m (78.7 inches) in width, the slab will receive a degree of hot cross rolling (to widen the 1200 mm/47.2 inch direction) before longitudinal hot rolling to final thickness on a 4-High reversing break down mill. Hot rolling refers to rolling above the re-crystallization temperature of the alloy.

Products with a final thickness <10 mm (0.394 inch), will receive a separate finishing operation on a 4-High coil rolling mill at elevated temperature (>392 °F/200 °C) to achieve both the necessary gauge tolerance and mechanical properties.

Magnesium sheet can also be produced via twin roll casting in which liquid magnesium alloy is fed into the roll bite and directly solidified into sheet in a continuous casting process which normally produces a coil of similar thickness to the reversing breakdown operation found in the processing of DC cast slab, around 6 mm (0.236 inch). This yields a sheet that has a cast structure with a small amount of deformation. The coiled sheet is then processed via warm finish rolling to achieve the final product gage and improve the mechanical properties.

3.3.2 Choosing the Correct Sheet and Plate Alloy

The magnesium-aluminum-zinc alloy AZ31B and the magnesium-zinc-rare earth-zirconium alloy ZE10 are readily available as rolled sheet products. AZ31B and the magnesium yttrium rare earth alloy, WE43C, are readily available as plate material. WE43C has good flammability resistance and strength at elevated temperatures making it particularly suitable for high temperature aerospace applications as plate and parts machined from plate.

AZ31B is suitable for use at room temperature up to 200 °F (100 °C) and is also available in a number of tempers. AZ31B in the cold rolled and partially annealed condition (H23, H24) will have maximum yield strength at the expense of some ductility. Annealed and re-crystallized (-O) material will have a lower yield strength but greater ductility than H23-H24 rolled sheet.

Magnesium tooling plate offers a light weight, ultra flat, fully stress relieved, rigid material suitable for use in jigs, fixtures, gauges and other tools and is often used in fast moving reciprocating machinery due to its low inertia and good machinability. In addition to the excellent machinability and weldability, tooling plate also offers a guaranteed flatness tolerance in a wide range of sizes. See Tables 7, 8A, 8B, and 9.

Table 7 - Properties of wrought sheet and plate alloys (typical properties in brackets, all others are spec min.)

Typical Chemical Composition Major Alloying Elements (%)	Alloy	Tensile Properties			Compressive Properties	Hardness	Description
		0.2% Proof Stress (ksi)	Tensile Strength (ksi)	Elongation (%)	0.2% Proof Stress (ksi)	Vickers Pyramidal Number	
Al 3.0 Zn 1.0 Mn 0.3	AZ31B Sheet - O	15.2 - 8.1	31.9	11	12.3	50 - 65	Medium strength sheet and extrusion alloy. Good formability. Weldable.
	Plate - H24	29.0	39.2	5	23.9	-	
	0.25 - 1 inches	21.8 - 26.1	36.3 - 37.7	7	13.1 - 20.3	-	
	1 - 3 inches	18.1 - 19.6	34.1	7	8.7 - 10.2	-	
Al 3.0 Zn 1.0	AZ31B Tooling Plate 0.25 - 1 inches	(14.5)	(29.0)	(8)	-	-	Moderate strength plate with excellent flatness and dimensional stability.
Zn 1.0 RE 0.5 Zr 0.2	ZE10A Sheet - O	18	30	15	-	-	Medium strength sheet. Good superplastic forming and deep drawability
Y 4.0 RE 3.0 Zr 0.5	WE43C						High strength plate and extrusion alloy. Weldable.
	WE43C-T5 Plate 0.25 - 1.25 inches 1.26 - 3.0 inches	(38) (35)	(54) (55)	(20) (17)	(35.0 - 37.3) (35.0 - 37.3)	75 - 95 75 - 95	

Table 8A - Magnesium alloy specifications (British/American) - See Table 8B for German/French/Europe

Alloy Designation, Product Form And Condition	BRITISH		AMERICAN			
	B S Series		ASTM Alloy Designation & Temper	ASTM	Federal	AMS
	Aircraft	General Engineering				
AZ31	-	3370 MAG S-1110	AZ31B-O	B90	QQ-M-44B	4375
Sheet: soft	-	-	AZ31B-H24	B90	QQ-M-44B	4377
Sheet: half hard	-	-	AZ31B-O	B90	QQ-M-44B	4375
Plate: soft	-	-	AZ31B-H24	B90	QQ-M-44B	4377
Plate: half hard	-	-	AZ31B-O	B90	-	4382
Plate: extra flat	-	-	ZE10A	B90	-	-
ZE10	-	-	WE43C	-	-	4371
WE43C	-	-				

Table 8B - Magnesium alloy specifications (German/French/European)

Alloy Designation, Product Form And Condition	GERMAN		FRENCH			EUROPEAN
	Aircraft #	DIN 9715 #	Commercial Designation	AIR9052	AFNOR	AECMA
AZ31	W.3504	3.5312	F3	G-A3Z1	G-A3Z1	MG-P-62
Sheet: soft	-	-	-	-	-	-
Sheet: half hard	-	-	-	-	-	-
Plate: soft	-	-	-	-	-	-
Plate: half hard	-	-	-	-	-	-
Plate: extra flat	-	-	-	-	-	-

Table 9 - Physical properties of magnesium wrought alloys

Physical Properties of Magnesium Wrought Alloys					
Alloy	Specific Gravity (20 °C)	Coefficient of thermal expansion 10 ⁻⁶ K ⁻¹ (20 - 200 °C)	Thermal conductivity Wm ⁻¹ K ⁻¹ (20 °C)	Electrical resistivity nΩm (20 - 100 °C)	Specific heat Jkg ⁻¹ K ⁻¹ (20 - 100 °C)
AZ31	1.77	26.0	76	100	1040
ZEK10	1.75	26.0	137.9	63	1082
WE43C	1.84	26.7	51	148	966

3.4 Extrusions

3.4.1 Extrusion Process

Extrusion involves pushing a preheated magnesium alloy billet using hydraulic loads from 350-3500t in an extrusion press through a steel die to form a long length of symmetrical shape of profile. Magnesium alloys are readily extruded into an almost unlimited variety of solid bars, hollow tubes, structural or special shapes. Some of these are standard items, but others are designed specifically for one end use. The cost of an extrusion die is relatively low allowing the designer to custom make his engineered solution. See Figures 5 and 6.

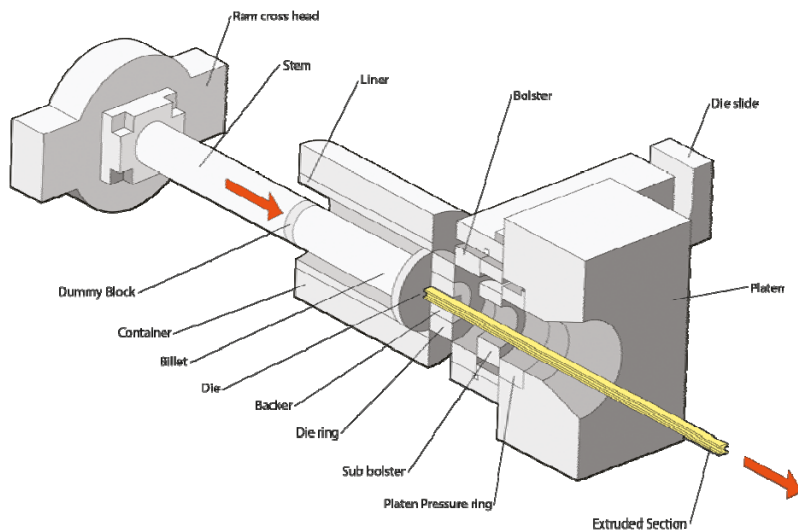


Figure 5 - Typical extrusion press schematic

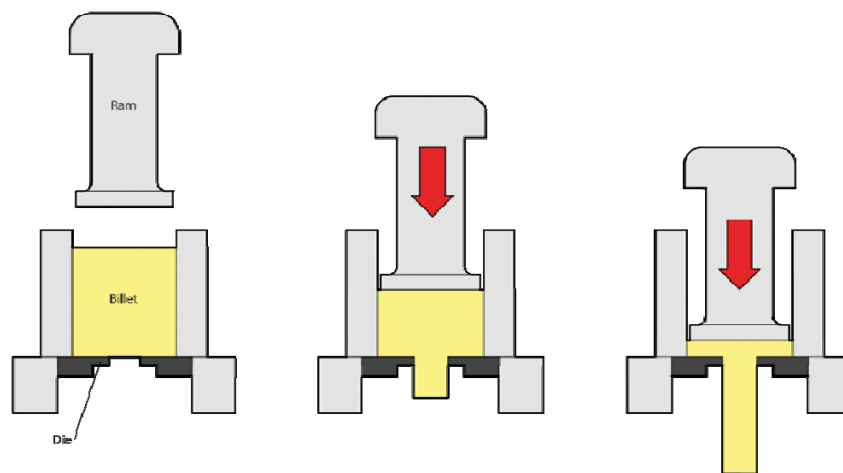


Figure 6 - The extrusion process

The billet may be derived from primary magnesium or recycled alloy scrap and is cast in lengths generally in excess of 4 m (13.2 feet). The extrusion billet is cut to short lengths both to fit the container on the extrusion press, which is generally less than 1 m (3.3 feet) in length, and to contain the extruded length on the press run out table. It is normal for the extrusion ratio (cross sectional area of billet divided by cross sectional area of output extrusion), to be in the range 35-60, and so a 1 m (3.3 feet) billet will yield 35 to 60 m (115 to 197 feet) of extruded product.

In order to soften the billet prior to extrusion, it will normally be preheated in the temperature range of 572 to 842 °F (300 to 450 °C), depending upon alloy and the extruded section will exit the press at 662 to 752 °F (350 to 400 °C). Some alloys require simple air blast cooling on the run out table to reduce distortion in handling, while others which are capable of being age hardened, may be air or water quenched as they exit the extrusion die in order to maximize mechanical properties in the extruded section.

After cooling, the extruded sections may be stretched to straighten and relieve stress, and subject to the alloy, may be age hardened in a furnace at a low temperature 302 to 482 °F (150 to 250 °C) prior to cutting to length.

Extrusion speeds vary from 1 to 3 m (3.3 to 10 feet) per minute for complex age hardenable alloys and to 50 m (164 feet) per minute for softer non-heat treatable commercial alloys. Speeds are usually limited by the available press pressure at the lower end and by the tendency of the surface of the extrusion to hot tear at the upper end of the speed range. Most magnesium extrusion is performed using direct extrusion presses where the billet is pushed through the die with a fixed container, and in this operation the frictional heating of the container has an impact on the exit temperature of the extrusion. Indirect extrusion presses force the die in the billet and so the billet is stationary relative to the container eliminating this frictional heating effect.

3.4.2 Design

A wide variety of special shapes can be extruded to the user's design within reasonable limits of size and complexity. Extrusion is generally chosen as the preferred route for manufacture where:

1. Several extrusions or a combination of sheet and extrusion are used to form an assembly.
2. Shapes are desired that cannot be roll formed or simply machined from castings.
3. Mechanical properties cannot be met by machining from solid cast or forged parts.

Extrusion dies are relatively inexpensive and can be used for small quantities, but the complexity of an extrusion will affect the yield and ultimately the cost, however, factors such as re-entrant angles and undercuts, thin walled tubing in large diameters, variations in section thickness, and the ability to put metal where it is needed almost without restrictions helps to make parts produced by extrusion a complex profile.

Probably the most important factor in the extrudability of a shape is symmetry about both the X and Y axis. Although the designer has considerable freedom in placing metal where it will be most effective, there are some things that should be avoided for good extrudability.

Figure 7 gives an indication of preferred design characteristics and things to be avoided, while more difficult shapes can often be extruded, the designer should satisfy themselves that asymmetry and thin sections are required as they will doubtless add to cost.

- a. Very thin sections with a large circumscribing area, should be avoided, the optimum aspect ratio (width/thickness) for magnesium extrusion is generally less than 20.
- b. The thick wedge tapering to a thin edge should be avoided, as metal will not fill the thin edge of the die properly during extrusion.
- c. The thin leg attached to a thick body should be limited to a length not exceeding ten times the thickness.
- d. Semi-closed shapes involving long thin slots should be avoided; the length of the tongue should be no more than 3 to 5 times its width.

- e. Shapes requiring unsymmetrical die tongues do not make for easy extrusion.
- f. Hollow shapes with unsymmetrical voids or having inadequate section thickness between them are undesirable.

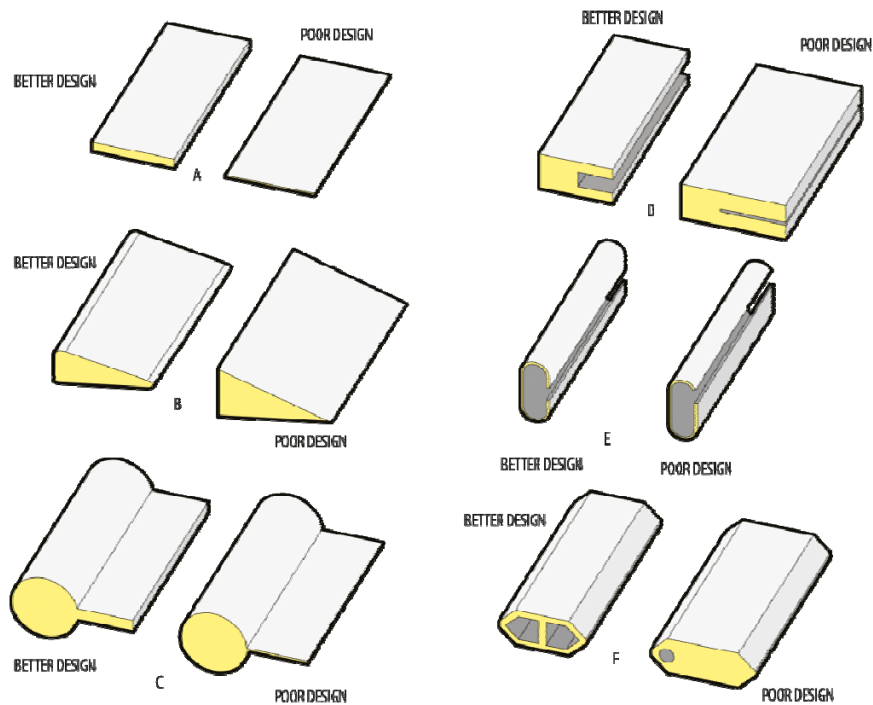


Figure 7 - Examples of good and bad design of extrusion profiles

3.4.3 Choosing the Right Alloy

The magnesium-aluminum zinc alloys AZ31B, AZ61A and AZ80A and the magnesium-zinc-zirconium alloys ZK30A (ZW3) and ZK60A are readily available as extruded products. The higher aluminum alloys generally increase in strength with alloy content as do the zinc containing alloys with higher zinc contents, but as alloying content increases, the difficulty of extrusion tends to increase the cost of manufacture. Tubes and hollow shapes are not normally available in AZ80A due to their poor weldability using a porthole die. The higher strength alloys are capable of limited precipitation hardening by aging heat treatments after extrusion (T5 temper) and so these alloys may be offered in the F (as manufactured) or T5 condition. The F-temperatures tend to offer higher ductility as compared with the fully aged tempers and may be more suitable for bending applications or where impact damage is anticipated, and as a feedstock for forging operations.

For magnesium alloys, there is generally a difference between compressive and tensile yield strengths due to the alignment of the crystal structure during working which makes twinning favorable in compression along the extrusion axis, but not in tension. In AZ alloys, the ratio of the yield strength in compression to that in tension in the extrusion direction can be as low as 0.6 for AZ31B and 0.9 for AZ80A in the T5 temper. Conversely, if the section is large enough to take tensile tests perpendicular to the extrusion direction, the tensile yield may be 30 to 40% lower than that in the extrusion direction. For Elektron 43, the difference is reduced to more like 20%. See Tables 10A and 10B.

Table 10A - Directional mechanical properties of magnesium alloys - Metric units

		ED Tensile Properties (parallel)			TD Tensile Properties (perpendicular to ED)			Ratio Tensile YS/TD/ED	Compressive YS (MPa)	Ratio Compressive YS/Tensile ED
Alloy	Temper	YS (MPa)	UTS (MPa)	E (%)	YS (MPa)	UTS (MPa)	E (%)			
AZ31A	F	180	250	14	110	225	13	61%	110	61%
AZ61A	F	220	300	12	140	295	12	64%	130	59%
AZ80A	F	240	340	10	170	325	11	71%	145	60%
ZK30(ZW3)	T6	240	290	14	220	280	16	92%	190	79%
ZK60A	T6	280	320	12	250	310	14	89%	230	82%
Elektron 43	T5	240	350	11	250	305	10	76%	252	105%

Table 10B - Directional mechanical properties of magnesium alloys - English units

		ED Tensile Properties (parallel)			TD Tensile Properties (perpendicular to ED)			Ratio Tensile YS/TD/ED	Compressive YS (ksi)	Ratio Compressive YS/Tensile ED
Alloy	Temper	YS (ksi)	UTS (ksi)	E (%)	YS (ksi)	UTS (ksi)	E (%)			
AZ31A	F	26.1	36.3	14	16.0	32.9	13	61%	15.9	61%
AZ61A	F	31.9	43.5	12	20.3	42.8	12	64%	18.9	59%
AZ80A	F	34.8	49.4	10	24.7	47.1	11	71%	21.0	60%
ZK30(ZW3)	T6	34.8	42.1	14	31.9	40.1	16	92%	27.6	79%
ZK60A	T6	40.6	46.4	12	36.3	45.0	14	89%	33.4	82%
Elektron 43	T5	34.8	50.8	11	26.4	44.2	10	76%	36.5	105%

Higher strength alloys are the rare earth containing alloys Elektron 43 and Elektron 675. These new generation Elektron alloys have good flammability resistance and strength at elevated temperatures making them particularly suitable for high temperature aerospace applications. They are much more isotropic than the simpler alloys, a huge advantage when machining a component from a solid extrusion of the alloy. See Table 11.

Elektron 675 extruded bar properties exceed those of aluminum alloys AA2024 and AA7075 above 200 °C (392 °F) making this alloy a competitor with titanium for elevated temperature aerospace applications. See graph in Figure 8.

Table 11 - Elevated temperature mechanical properties of Elektron 43

ELEKTRON 43 TYPICAL TENSILE PROPERTIES				
Extruded				
		0.2% Proof Stress MPa (ksi)	Tensile strength MPa (ksi)	Elongation %
T5	68 °F (20 °C)	240 (34.8)	350 (50.8)	11
	482 °F (250 °C)	200 (29.0)	268 (38.9)	22

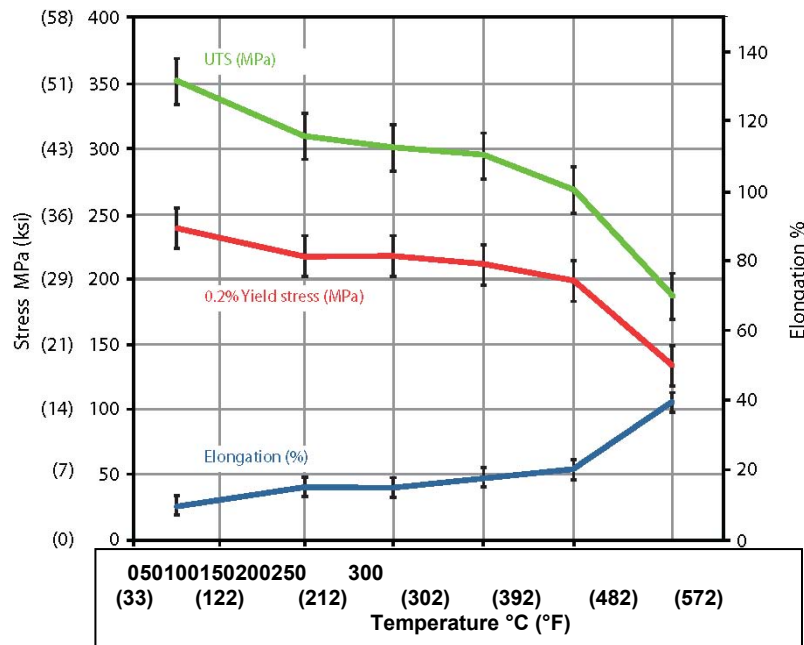


Figure 8 - Graph showing elevated temperature mechanical properties of Elektron 43

3.5 Forgings

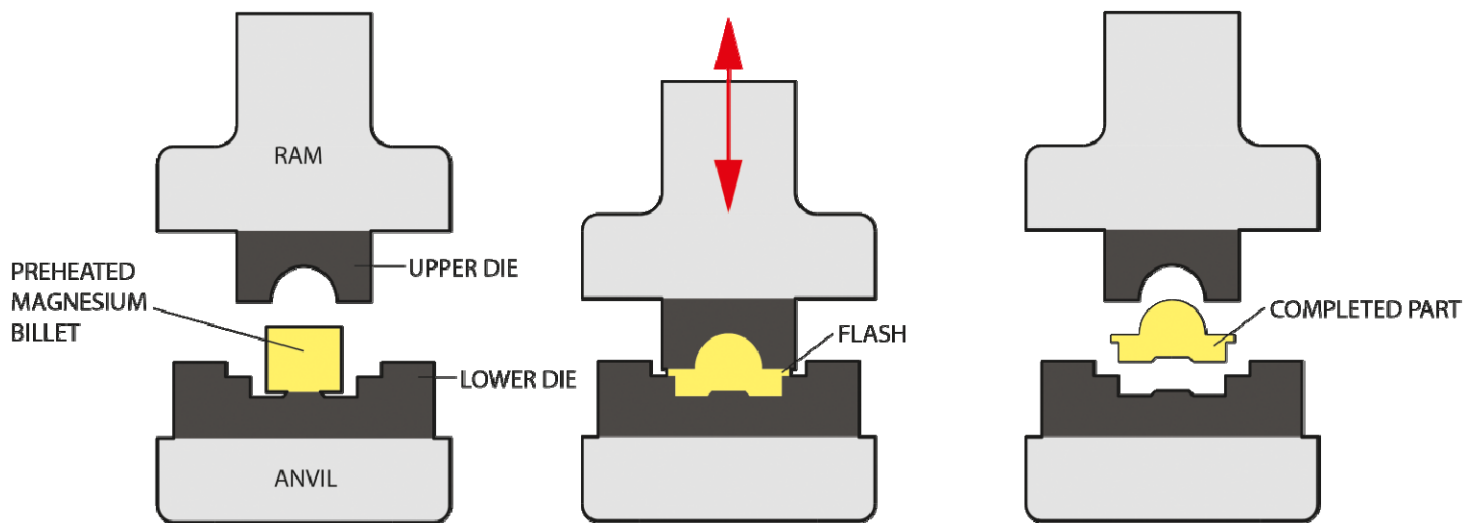


Figure 9 - Closed die forging process

Although metals are forged, as is done by the old-fashioned blacksmith, by pounding with a hammer from various directions until the desired contour is obtained, the usual method is to shape the piece by forcing the metal into die cavities, see Figure 9. Because large strains are the rule, forging is performed at elevated temperatures for all metals. Magnesium forgings are almost always die forgings made on hydraulic presses; hammer forging is seldom used.

As large strains are imposed, a metal develops a preferred orientation both in the crystallographic sense, and in the sense that second phase particles and the long axis of individual grains line up in the direction of the strain. Mechanical properties in the finished piece depend upon the direction of measurement with respect to the preferred orientation; in general properties measured parallel to the direction of strain are higher. An important part of forging design is to assure that metal flow during forging is directed so that maximum properties are developed where needed in the final part.

The mechanical properties developed in a part depend upon the alloy composition, the degree of work hardening present, the grain size, and the state of heat treatment. Forging, which is done at elevated temperatures, lends itself to control of all these factors, with an accompanying high degree of control over mechanical properties the forging schedule for a specific part should be chosen so that properties are maximized through optimization of the metallurgical variables.

As forging consists of webs, ribs, bosses, cavities, and holes. Ribs and bosses are stiffeners or bearing surfaces for such things as bolts. Cavities and holes serve to lighten the structure or to accommodate other parts. Webs hold all of the features together into one part. The important design features for forging are the height, length and width of ribs and bosses. The thickness of all sections, radii of curvature where two walls meet at an angle less than 180 degrees (fillets), and radii of curvature where two walls meet at an angle greater than 180 degrees (corners).

Both fillets and corners can be horizontal or vertical with respect to the plane of forging. Since the shape is formed in a die cavity, draft on the walls is usually required to allow extraction of the finished piece from the die. A draft angle of 5 degrees is normally used for magnesium, although it is possible to forge even with zero draft. Since greater care and closer tolerances are required for zero draft than for a forging with draft, the costs of a more expensive forging compared to those for machining the extra stock of the draft must be compared. Because the design of the forging influences not only the service characteristics but also metal flow during forging, there is a strong interaction between the design on the mechanical properties developed in the finished piece. It is critically important that the designer consults with the forger at an early stage so that the design and the process will both be optimized to produce the best possible part for its projected service conditions.

Table 12 shows section thickness recommendations for magnesium forgings. Minimum corner and fillet radii are given in Tables 13 and 14. In the latter case in particular, the minima should be observed. In many cases, larger radii will be preferable, either because of serviceability or productibility. The advice of the forger should be sought before the final design is determined. See Figure 10.

The flow patterns developed during forging are dependent not only on the forging practice but also on the starting material. If an extruded bar is used, for example as the starting material for forging flow patterns already developed in the extrusion affect the flow results in the forging. Selection of the correct starting material can be important.

Table 12 - Thickness recommendations for forgings

W x L		W (maximum)		T ₁ (minimum)	
mm ²	inch ²	mm	inch	mm	inch
<650	1	180	7	3	0.12
650 - 1300	1.0 - 2.0	30	12	5	0.2
1300 - 2600	2.0 - 4.0	500	20	5.5	0.22
2600 - 5200	4.0 - 8.0	800	30	6.5	0.25

Note: t_2 varies from 3.0 mm (0.12 inch) at $D = 6.5$ mm (0.25 inch) to 6.5 mm (0.25 inch) for $D > 50$ mm (2 inches). The ratio of rib thickness to rib height varies from 1:2 for ribs less than 5 mm (0.2 inch) in height to 1:5 for ribs over 50 mm (1.6 inch) in height.

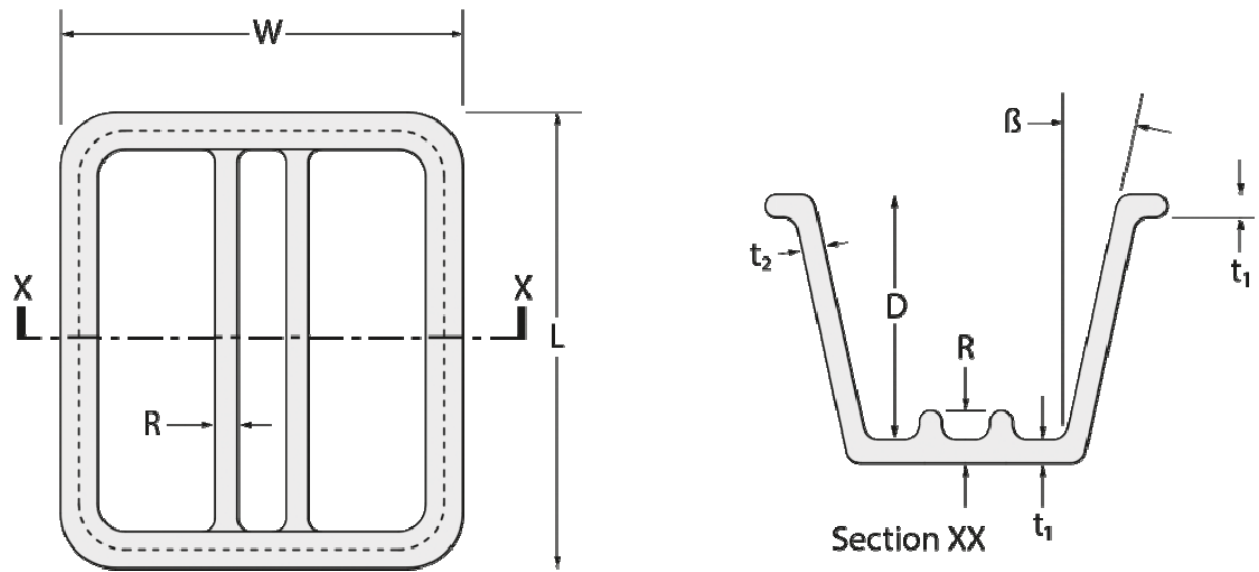
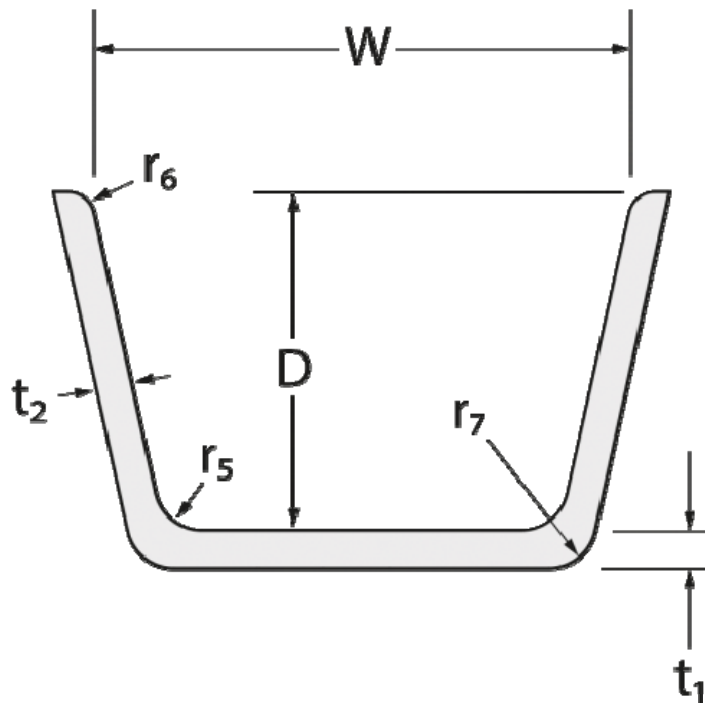


Figure 10 - Forging key dimensions

Table 13 - Minimum corner radius and fillet radii for forgings - C channel sections



W mm		<16	16-20	20-25	25-32	32-40	40-50	50-63	63-75	75-100	100-130
D mm	r_6 mm	r_5 mm									
<10	1.5	3.0	3.0	4.0	4.0	4.0	6.5	6.5	10.0	10.0	10.0
10-13	1.5		4.0	4.0	4.0	6.5	6.5	6.5	10.0	10.0	10.0
13-16	3.0			4.0	4.0	6.5	6.5	6.5	10.0	10.0	10.0
16-21	3.0				6.5	6.5	10.0	10.0	10.0	10.0	16.0
21-25	3.0					6.5	10.0	10.0	10.0	10.0	16.0
25-33	10.0						10.0	10.0	10.0	16.0	16.0
33-50	6.5								16.0	16.0	20.0

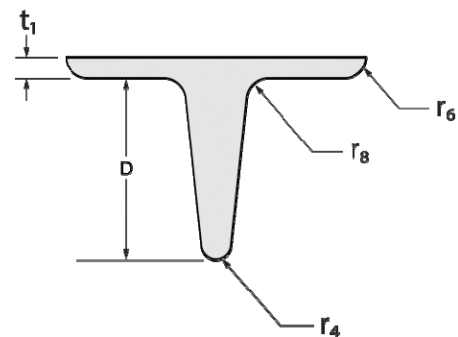
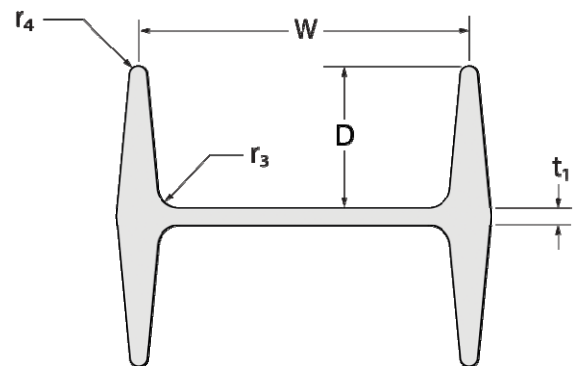
W inches		<6.2	0.62-0.79	0.79-1	1-1.26	1.26-1.57	1.57-1.97	1.97-2.48	2.48-2.95	2.95-3.94	3.94-5.12
D in	r_6 in	r_5 in									
<0.254	0.059	0.118	0.118	0.157	0.157	0.157	0.256	0.256	0.394	0.394	0.394
0.254-0.512	0.059		0.157	0.157	0.157	0.256	0.256	0.256	0.394	0.394	0.394
0.512-0.623	0.118			0.157	0.157	0.256	0.256	0.256	0.394	0.394	0.394
0.623-0.827	0.118				0.256	0.256	0.394	0.394	0.394	0.394	0.630
0.827-0.984	0.118					0.256	0.394	0.394	0.394	0.394	0.630
0.984-1.299	0.394						0.394	0.394	0.394	0.630	0.630
1.299-1.968	0.256								0.630	0.630	0.787

Note: $r_7 = r_5 + t_1$

Table 14 - Minimum corner radius and fillet radii for forgings - I and T sections

mm				
I - sections			T - sections	
D	r_3	r_4	D	r_8
10.0	6.5	1.5	1.5	1.5
12.5	7.0	1.5	6.5	6.5
16.0	8.5	1.5	8.0	8.0
19.0	10.0	2.0	8.7	8.5
22.0	11.0	2.5	22.2	9.5
25.5	12.0	3.0	25.4	10.5
28.5	12.5	3.0	28.6	11.0
32.0	14.5	4.0	31.8	12.5
38.0	16.0	5.0	36.1	15.0
44.5	18.5	5.5	44.5	16.5
51.0	20.5	6.5	50.8	19.0
57.0	22.0	7.0	57.1	21.5
63.5	24.0	8.0	63.5	23.0
70.0	27.0	8.5	70.0	25.5
76.0	28.5	9.5	76.2	27.0

inches				
I - sections			T-sections	
D	r_3	r_4	D	r_8
0.394	0.256	0.059	0.059	0.059
0.492	0.276	0.059	0.256	0.256
0.630	0.335	0.059	0.315	0.315
0.748	0.394	0.079	0.343	0.335
0.866	0.433	0.098	0.874	0.374
1.004	0.472	0.118	1.000	0.413
1.122	0.492	0.118	1.126	0.433
1.260	0.571	0.157	1.252	0.492
1.496	0.630	0.197	1.421	0.591
1.752	0.728	0.217	1.752	0.650
2.008	0.807	0.256	2.000	0.748
2.244	0.866	0.276	2.248	0.846
2.500	0.945	0.315	2.500	0.906
2.756	1.063	0.335	2.756	1.004
2.992	1.122	0.374	3.000	1.063



The values given for r_3 and r_4 apply when the W/D ratio is approximately 2 to 1. For W/D ratios $> 2:1$ the radii should be increased and for lower W/D ratios the Radii may be decreased also see images.

4. DESIGNING FROM ALUMINUM TO MAGNESIUM

4.1 Introduction

Magnesium has the lowest density of all common structural metals. A direct replacement of an AA6061 component with magnesium can lead to a 30% weight saving. However, an understanding of magnesium and its alloys is needed to optimize the performance of magnesium components to ensure their successful performance in service. The actual achievable weight saving is dependent upon the mechanical properties of the competing materials being replaced by magnesium alloy and the operational requirements of the part in question.

The following section highlights a number of aspects of magnesium engineering characteristics to aid design engineers better understand methods with which to optimize component geometries to gain maximized weight savings when replacing aluminum components with magnesium.

4.2 Metallic Materials Property Development and Standardization (MMPDS)

An excellent resource for mechanical and physical properties of metals used in aerospace applications is the Metallic Materials Property Development and Standardization (MMPDS) Handbook. MMPDS is directly supported by the FAA and run by Battelle. Its goal is to provide detailed and reliable property data for all metallic materials used in aerospace, including magnesium alloys.

The data contained within the MMPDS Handbook includes the properties listed in Table 15. These include the statistical -A and -B basis minima for a range of properties. These are the values that are employed by FEA software packages, amongst others, that allow the modelling of stresses and strains engineering components. The Handbook contains detailed stress strain curves, fatigue and fracture toughness data as well as a significant amount of analysis to aid in the understanding and prediction of the materials behavior in service.

The MMPDS handbook is available from Battelle and can be found at <http://projects.battelle.org/mmpds/>.

Table 15 - List of mechanical and physical properties contained in MMPDS Handbook

Property	MMPDS Symbol	Property	MMPDS Symbol
Ultimate Tensile Strength	Ftu-L	Bearing Ultimate Strength, e/D=1.5	Fbru e/D=1.5 L
Ultimate Tensile Strength	Ftu-LT	Bearing Ultimate Strength, e/D=1.5	Fbru e/D=1.5 LT
Yield Strength	Fty-L	Bearing Ultimate Strength, e/D=2.0	Fbrue/D=2.0 L
Yield Strength	Fty-LT	Bearing Ultimate Strength, e/D=2.0	Fbrue/D=2.0 LT
Compressive Yield Strength	Fcy-L	Elongation	e-L
Compressive Yield Strength	Fcy-LT	Elongation	e-LT
Ultimate Shear Strength	Fsu-L-T	Young's Modulus (tensile)	E
Ultimate Shear Strength	Fsu-T-L	Young's Modulus (compression)	Ec
Bearing Yield Strength, e/D=1.5	Fbry e/D=1.5 L	Shear Modulus	G
Bearing Yield Strength, e/D=1.5	Fbry e/D=1.5 LT	Poisson's Ratio	u
Bearing Yield Strength, e/D=2.0	Fbry e/D=2.0 L	Density	w (density)
Bearing Yield Strength, e/D=2.0	Fbry e/D=2.0 LT	Fatigue	
		Fracture toughness	

4.3 Modulus of Elasticity

The Young's Modulus of magnesium alloys is 44 GPa (6500 ksi), as compared with 70 GPa for aluminum alloys (10 000 ksi) and 207 GPa (30 000 ksi) for mild steel. The modulus generally reduces with increasing temperature but is only slightly affected by alloy condition and composition. For a given design load and allowable deflection it is necessary to redesign magnesium components to achieve equal stiffness as compared with parts made from materials with a higher modulus (e.g., aluminum or steel).

Deflection (δ) of a rectangular beam of length L , width B , and height H , simply supported at each end under a force F is given by:

$$\delta = \frac{F \cdot L^3}{48 \cdot E \cdot I}$$

where:

E = Young's Modulus and

I = Moment of inertia = $BH^3/12$ (for a rectangular section)

With magnesium structures it is generally necessary to design with an increased moment of inertia relative to those of aluminum or steel. The moment of inertia of a section, and its stiffness, increases in proportion to the cube of its depth (height) but only linearly in proportion to its width. Thus, increasing the section depth will achieve the maximum saving in weight.

A magnesium section is about 22% as stiff as steel of the same thickness, but if the depth of the magnesium section is increased to twice that of the steel, then the magnesium section will be 70% more rigid and yet only weigh half as much. See Figure 11, 12, and 13.

Similarly on the basis of equal rigidity, a magnesium section need weigh only 75% of the aluminum one, or when compared on the basis of equal weight the magnesium will be twice as stiff.

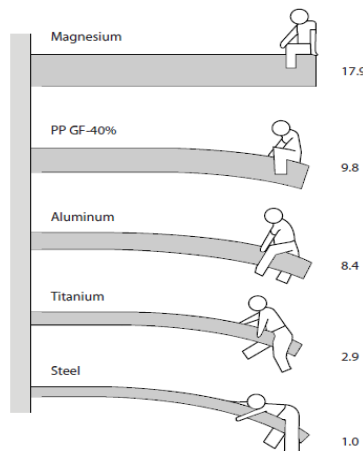


Figure 11 - Relative stiffness of bars with the same weight and width

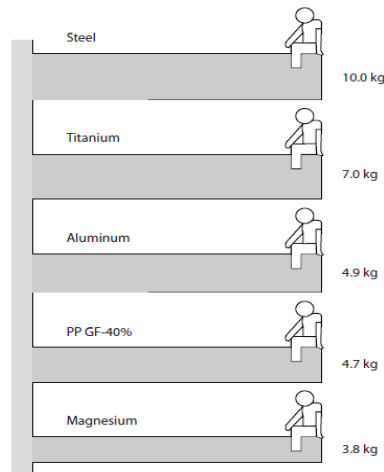


Figure 12 - Weight of bars with the same stiffness and width

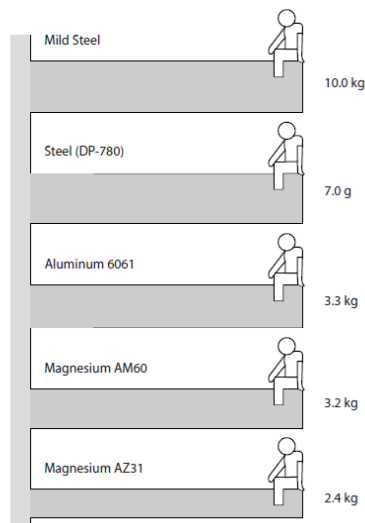


Figure 13 - Weight of bars with constant yield strength and width

Increase in cross section frequently solves a magnesium design problem, and small increases in cross section judiciously placed and involving relatively little increase in weight, may result in great increases in strength and stiffness. In this way, weight savings of 20 to 25% and 65 to 70% are possible in comparison with beams of equal stiffness in aluminum and steel respectively.

When increases in dimensions are permissible, it may be that the ability to use a greater bulk of magnesium for the same weight may remove local instability which may be the governing factor for other materials. Although greater local stiffness can be achieved by attaching stiffening elements such as angled gussets, webs and corrugated sections such additions may add to the fabrication cost.

4.4 Shear Modulus - Modulus of Rigidity - Poisson's Ratio

The shear modulus of magnesium (modulus of rigidity) and its alloys is similar to that of aluminum and the Poisson's ratio is 0.33 to 0.35 as compared with 0.33 for most aluminum alloys. See Table 16.