

Materials for Automobiles

Aluminium Alloys

Lec 14

Aluminium (Introduction)

Density

2.7 g/cm³, approximately one-third as much as steel (7.83 g/cm³), copper (8.93 g/cm³), or brass (8.53 g/cm³)

Corrosion Resistance

Excellent corrosion resistance in most environments, including atmosphere, water (including salt water), petrochemicals, and many chemical systems

Electrical conductivity

excellent, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors.
Aluminum is often selected for its electrical conductivity, which is nearly twice that of copper on an equivalent weight basis. The requirements of high conductivity and mechanical strength can be met by use of long-line, high-voltage, aluminum steel cored reinforced transmission cable

Thermal conductivity

.The thermal conductivity of aluminum alloys, about 50 to 60% that of copper, is advantageous in heat exchangers, evaporators, electrically heated appliances and utensils, and automotive cylinder heads and radiators.

Table 3.1 Data for Young's modulus, E

<i>Material</i>	<i>E (GNm⁻²)</i>	<i>Material</i>	<i>E (GNm⁻²)</i>
Diamond	1000	Niobium and alloys	80-110
Tungsten carbide, WC	450-650	Silicon	107
Osmium	551	Zirconium and alloys	96
Cobalt/tungsten carbide cermets	400-530	Silica glass, SiO ₂ (quartz)	94
Borides of Ti, Zr, Hf	450-500	Zinc and alloys	43-96
Silicon carbide, SiC	430-445	Gold	82
Boron	441	Calcite (marble, limestone)	70-82
Tungsten and alloys	380-411	Aluminium	69
Alumina, Al ₂ O ₃	385-392	Aluminium and alloys	69-79
Beryllia, BeO	375-385	Silver	76
Titanium carbide, TiC	370-380	Soda glass	69
Tantalum carbide, TaC	360-375	Alkali halides (NaCl, LiF, etc.)	15-68
Molybdenum and alloys	320-365	Granite (Westerly granite)	62
Niobium carbide, NbC	320-340	Tin and alloys	41-53
Silicon nitride, Si ₃ N ₄	280-310	Concrete, cement	30-50
Beryllium and alloys	290-318	Fibreglass (glass-fibre/epoxy)	35-45
Chromium	285-290	Magnesium and alloys	41-45
Magnesia, MgO	240-275	GFRP	7-45
Cobalt and alloys	200-248	Calcite (marble, limestone)	31
Zirconia, ZrO ₂	160-241	Graphite	27
Nickel	214	Shale (oil shale)	18
Nickel alloys	130-234	Common woods, to grain	9-16
CFRP	70-200	Lead and alloys	16-18
Iron	196	Alkyds	14-17
Iron-based super-alloys	193-214	Ice, H ₂ O	9.1
Ferritic steels, low-alloy steels	196-207	Melamines	6-7
Stainless austenitic steels	190-200	Polyimides	3-5
Mild steel	200	Polyesters	1.8-3.5
Cast irons	170-190	Acrylics	1.6-3.4
Tantalum and alloys	150-186	Nylon	2-4
Platinum	172	PMMA	3.4
Uranium	172	Polystyrene	3-3.4
Boron/epoxy composites	80-160	Epoxies	2.6-3
Copper	124	Polycarbonate	2.6
Copper alloys	120-150	Common woods, ⊥ to grain	0.6-1.0
Mullite	145	Polypropylene	0.9
Vanadium	130	PVC	0.2-0.8
Titanium	116	Polyethylene, high density	0.7
Titanium alloys	80-130	Foamed polyurethane	0.01-0.06
Palladium	124	Polyethylene, low density	0.2
Brasses and bronzes	103-124	Rubbers	0.01-0.1
		Foamed polymers	0.001-0.01

Cast Aluminum Alloys ANSI Designation

	<i>Number Series Alloy Type</i>
1XX.X	99.0% minimum aluminum content
2XX.X	Al + Cu
3XX.X	Al + Si & Mg, or Al + Si & Cu, or Al + Si & Mg & Cu
4XX.X	Al + Si
5XX.X	Al + Mg
7XX.X	Al + Zn
8XX.X	Al + Sn
zero (0) one (1) two (2)	<p>The digit that follows the decimal in each alloy number indicates the product form.</p> <p>the cast product itself (die casting, for instance).</p> <p>the chemistry limits for ingot used to make the XXX.0 product.</p> <p>indicates ingot used to make that XXX.0 product, but ingot of somewhat different (usually tighter) chemistry limits than XXX.1.</p> <p>While not always the case, XXX.1 often indicates secondary alloy chemistry limits whereas XXX.2 would indicate primary alloy chemistry limits.</p>

Aluminum – Casting Alloys Examples

Alloy	Form	Si	Fe	Cu	Mn	Mg	Zn	Ti	Others	
									Each	Total
A360.0	die casting	9.0 - 10.0	1.3 max	0.6 max	0.35 max	0.40 - 0.6	0.50 max	-	-	0.25 max
A360.1	ingot	9.0 - 10.0	1.0 max	0.6 max	0.35 max	0.45 - 0.6	0.40 max	-		- 0.25 max
A360.2	ingot	9.0 - 10.0	0.6 max	0.10 max	0.05 max	0.45 - 0.6	0.05 max	-	0.05 max	0.15 max

Aluminium -Effects of Alloying Elements

Major elements	silicon (Si), copper (Cu) and magnesium (Mg)
Minor elements	nickel (Ni) and tin (Sn) -- found largely in alloys that likely would not be used in high integrity die castings
Microstructure modifying elements	titanium (Ti), boron (B), strontium (Sr), phosphorus (P), beryllium (Be), manganese (Mn) and chromium (Cr)
Impurity elements	iron (Fe), chromium (Cr) and zinc (Zn).

Aluminium - Major Elements : Effect of Silicon

Silicon

Silicon's high heat of fusion contributes immensely to an alloy's "fluidity"

- silicon has limited solid solubility (maximum 1.65%) and yet forms a eutectic with aluminum increases significant strength without thermal contraction - very important to avoiding hot tearing or hot cracking issues.
- The more silicon content, the lower is its thermal expansion coefficient.
- Silicon is a very hard phase, thus improves alloys wear resistance.
- Silicon combines with other elements to improve an alloy's strength and to make alloys heat treatable.

Strength — Silicon alone contributes very little to the strength of aluminum casting alloys. However, when combined with magnesium to form Mg_2Si , Si provides a very effective strengthening mechanism in aluminum castings.

Wear Resistance — Silicon also increases an alloy's wear resistance, which has often made aluminum silicon alloy castings attractive substitutes for gray iron in automotive applications. The hypereutectic Al-Si alloys, such as B390, are used extensively in premium aluminum base-bore engine blocks, for example, as well as in numerous pumps, compressors, pistons and automatic transmission components.

Silicon and Cutting Tool Wear — As silicon increases, especially into the hypereutectic range, the greater the tool wear during machining, Hence polycrystalline diamond cutting tools are used.

Aluminium Effect of Silicon

Thermal Expansion coefficient reduction	Pure aluminum has Thermal expansion coefficient up to $23.5 \times 10^{-6} / ^\circ\text{C}$. To reduce the thermal expansion coefficient, aluminum alloys containing Si as high as 12% or 19% are generally used. The alloyed Si reduces the thermal expansion coefficient because that of Si is as low as $9.6 \times 10^{-6} / ^\circ\text{C}$.
Density Reduction	Si has additional advantages when alloyed in aluminum. It lowers the alloy's density and decreases the piston weight. Pure Al has a density of 2.67 g/cm ³ , while pure Si 2.33 g/cm ³
Improved wear resistance	Silicon also raises wear resistance. The alloyed Si is also very effective in preventing seizure of the piston ring to the ring groove. Si has a Vicker's hardness value in the range of 870 to 1350 HV. Hard Si is a semi-metal, showing similar properties to those of ceramics

Aluminium -Major Alloying Elements

Copper

Copper (Cu) has the single greatest impact of all alloying elements on the strength and hardness of aluminum casting alloys, both heat-treated and not heat-treated.

Copper also improves the machinability of alloys by increasing matrix hardness, making it easier to generate small cutting chips and fine machined finishes.

On the downside, copper generally reduces the corrosion resistance of aluminum; and, in certain alloys and tempers, it increases stress corrosion susceptibility.

Aluminum-copper alloys that do not also contain at least moderate amounts of silicon have relatively poor fluidity and resistance to hot tearing during solidification.

Magnesium

Magnesium's (Mg) role is also to strengthen and harden aluminum castings. As mentioned earlier in this section, silicon combines with magnesium to form the hardening phase, Mg_2Si that provides the strengthening and heat treatment basis for the popular 356 family of alloys.

Magnesium is also the strengthening ingredient in the high magnesium 5XX alloys that contain very little silicon; those alloys too depend on Mg_2Si , but gain additionally from other magnesium-bearing phase.

Aluminium - Microstructure Modifying Elements

Titanium & Boron

Titanium (Ti) and boron (B) are used to **refine primary aluminum grains**. Grain refining efficiency is better when titanium and boron are used in combination. Master alloys of aluminum with 5% titanium and 1% boron are commonly used additives for this purpose.

Strontium Sodium, Calcium and Antimony

These elements (one or another, and not in combination) are added to eutectic or hypoeutectic aluminum silicon casting alloys to **modify the morphology of the eutectic silicon phase**. Without the benefit of a modifying treatment, eutectic silicon solidifies in a relatively coarse continuous network of thin platelets which reduces strength and ductility.

Manganese & Chromium

Alone or in combination, manganese (Mn) and/or chromium (Cr) change the **morphology of the iron-rich Al_5FeSi phase from its typical platelet/acicular form to a more cubic $Al_{15}(MnFe)_3Si_2$ form** that is less harmful to ductility

Aluminium – Casting Alloys :

General Applications of Alloy Families

1XX alloy family

The 1XX alloys are used commercially to cast electric motor rotors. Rotors are usually cast on vertical high-pressure die casting type machines especially designed for the purpose

2XX alloy family Cu

The 2XX alloys include the highest strength aluminum casting alloys available today. The 2XX alloys also tend to retain their strength better than other alloy systems at elevated service temperatures. Alloys 206 and A206 include military and aerospace hardware where the highest tensile and impact properties are required. They are also used for a variety of structural castings on trucks and trailer

3XX alloy family Si + Mg Cu

The 3XX alloys are the true workhorses of the aluminum casting industry because of their superior casting characteristics and good strength. Al-Si-Cu alloys are the most prevalent and the higher-copper versions are fully heat treatable. When full heat treatment is desired, the Al-Si-Cu-Mg alloys provide the highest strength and hardness, at both ambient and elevated temperatures. Alloys 319 and B319 are used in numerous commercial casting applications and have been extensively used in recent years for automotive engine crankcases, intake manifolds and cylinder heads. They are also used to cast oil pans for autos and trucks. A356 has long been the material of choice for cast aluminum automobile wheels in North America and has become the standard for most automotive chassis and suspension castings as well

Aluminium : General Applications of Alloy Families

3XX alloy family	The 380 family of alloys have long been the workhorses of the die casting industry, probably accounting for 85% or more of all die cast aluminum. Die casting large, thin-walled automotive body, chassis and suspension components that must have both strength and ductility
5XX alloy family	The 5XX alloys have the best corrosion resistance of the aluminum casting alloys. They also polish to bright finishes and they tend to anodize with a pleasing natural aluminum appearance.
7xxx	The 7XX alloys have good impact properties and they develop reasonably high strength without a need for heat treatment.. The 7XX alloys are not intended for die casting. Large machine tool parts, furniture, garden tools, textile and office machine castings, trailer parts and mining equipment parts.
8xxx	Bearings :cast bushings and journal bearings. They have excellent compressive properties and unique lubricating properties under over-heat conditions. The unique ingredient in 8XX alloys is tin (Sn). Tin resides in the solidified casting largely as small globules of the essentially-pure element. If normal lubrication fails and causes overheating of a bushing/bearing, the tin phase melts at 231°C (its normal low melting temperature) and provides emergency liquid-tin lubrication .

Aluminium Alloys – Hardening Mechanisms

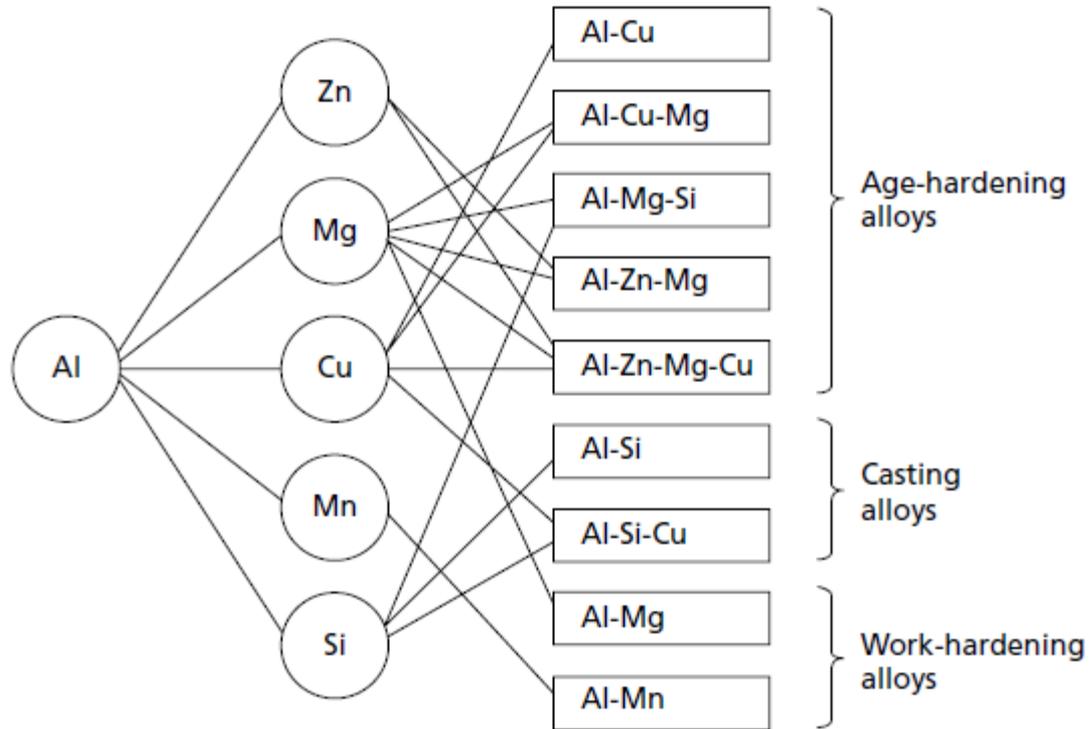


FIG. 20.7 Major aluminum alloy systems (Hatch, J.E., Ed., *Aluminum: Properties and Physical Metallurgy*, © 1984. Reprinted with permission of ASM International (R). All rights reserved. www.asminternational.org)

Engine Crankcase Materials : CI and Casting Aluminium Alloys

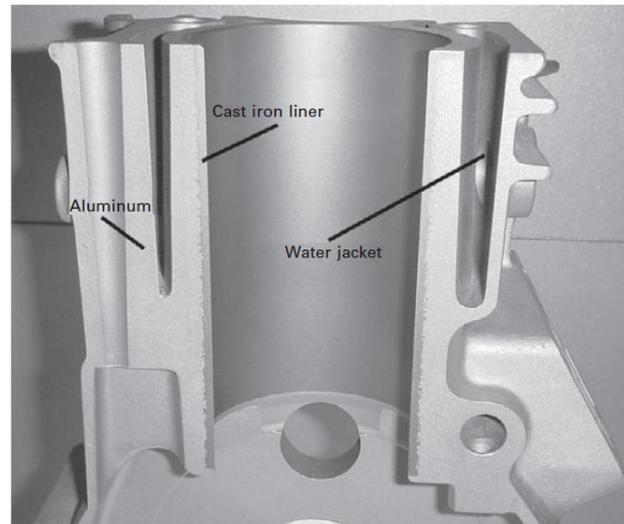
Table 2.1 Cylinder structures

Type	Structure	Processing	Characteristics
Monolithic (linerless)	(1) Cast iron integrated type.	Monolithic block (typically, JIS-FC 200) with sand casting. The water passage is formed using expendable shell core. Laser or induction hardening is sometimes used on the bore surface to give durability.	Low cost but heavy.
Heterogeneous (dry liner)	(2) Cast iron block enclosing cast iron liner.	High-P cast iron liner is slip-fitted in JIS-FC200 block.	Hard liner gives durability.
Heterogeneous (cast-in liner)	(3) Aluminum block enclosing cast iron liner.	Liner is enclosed in block (typically, JIS-ADC12 die casting, JIS-AC4B shell molding) by casting-in with various casting methods.	Better cooling performance than type (1).
Heterogeneous (cast-in liner)	(4) Aluminum block enclosing PM-aluminum liner.	PM aluminum liner is enclosed in block (typically, JIS-ADC12 diecasting) by casting-in with high-pressure die casting.	Better cooling performance than type (3).
Heterogeneous (dry liner)	(5) Aluminum block enclosing cast iron or hyper-eutectic Al-Si liner with press-fitting.	Liner is inserted in block (typically, JIS-ADC12 die casting, JIS-AC4B shell molding) by press-fitting or shrunk-in.	Accurate roundness at elevated temperatures.
Quasi-monolithic (linerless)	(6) Aluminum block with plated bore surface.	Monolithic block having a coated bore by porous-Cr or Ni-SiC plating. The block material is typically JIS-AC4B shell molding or JIS-ADC12 high-pressure die casting.	High cooling performance. Bore pitch can be shortened in multi-bore engines.
Quasi-monolithic (linerless)	(7) Aluminum block with metal-sprayed bore surface.	Wire explosion or plasma spraying (steel base alloy) on the aluminum bore wall.	Cooling performance is the same as (6).
Monolithic (linerless)	(8) Hyper-eutectic Al-Si block without coating.	Low-pressure die casting using A390 alloy. The bore surface is either etched or mechanically polished to expose Si.	The wear-resistant coating is necessary on the piston side.
Quasi-monolithic (linerless)	(9) Fiber or particle reinforced Al alloy composite.	Preform of fibers (Sapphire+carbon) or Si particle is cast into aluminum by squeeze die casting.	The rigidity of the cylinder bore increases.

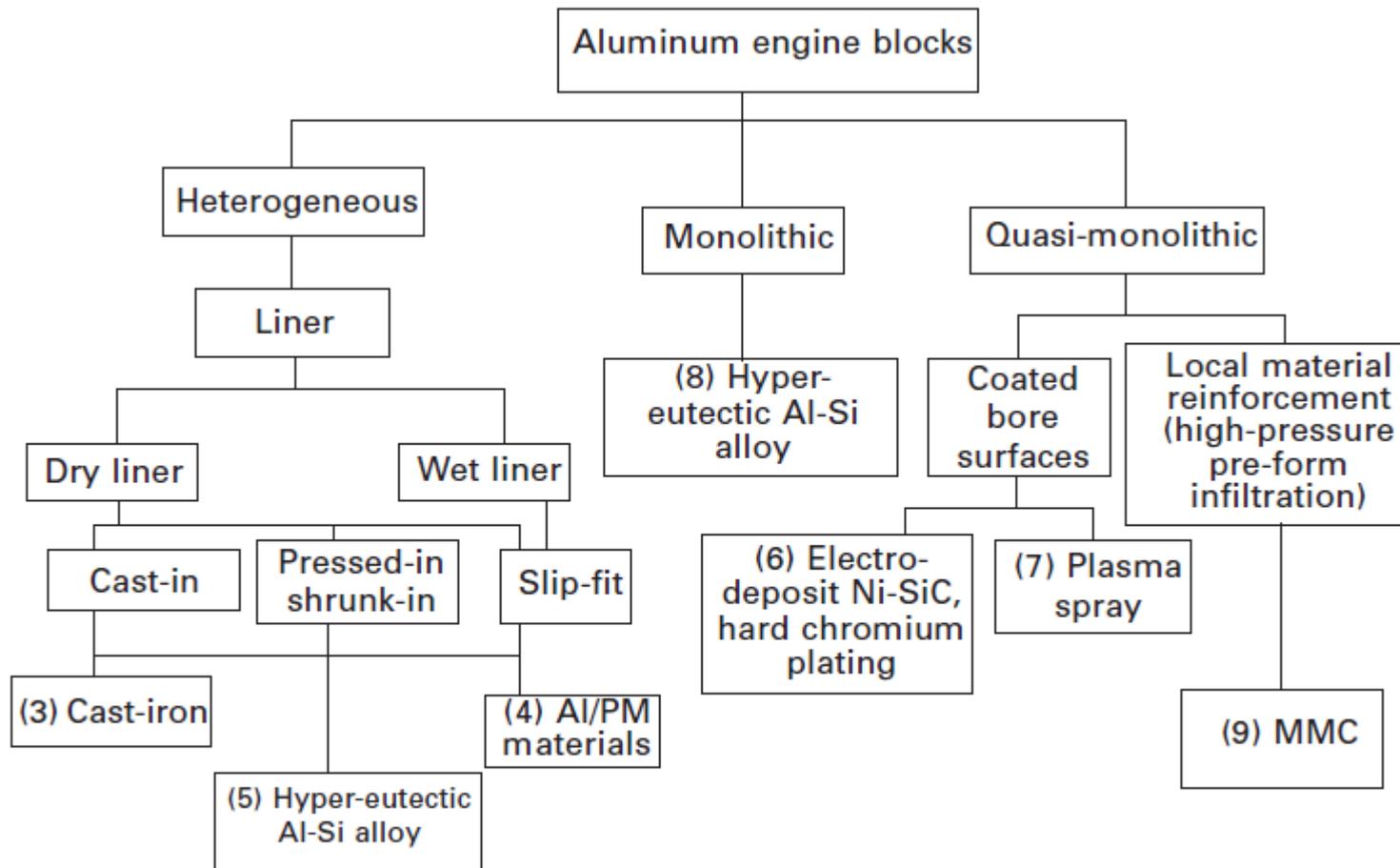
Materials for Cylinder Blocks

Table 2.2 Chemical compositions (%). JIS-FC200 is a flake graphite cast iron having a strength of 200 MPa. JIS-AC4B and ADC12 are aluminum alloy for castings. A 390 is a hyper-eutectic Al-Si alloy

Material	Si	Fe	Cu	Mn	Mg	Zn	Ni	Ti	Cr	Al	C	P	V
JIS-FC200	2.0	Balance	-	0.8	-	-	-	-	-	-	3.2	-	-
High-V cast iron	2.0	Balance	-	0.8	-	-	-	-	-	-	3.2	-	0.3
High-P cast iron	2.0	Balance	-	0.8	-	-	-	-	-	-	3.2	0.3	0.3
JIS-AC4B	8.0	1.0	0.3	0.4	0.3	0.5	0.1	0.2	0.1	Balance	-	-	-
JIS-ADC12	11.0	1.3	2.0	0.5	0.3	1.0	0.5	-	-	Balance	-	-	-
A390	18.0	0.5	4.0	0.1	0.5	-	-	0.2	-	Balance	-	-	-



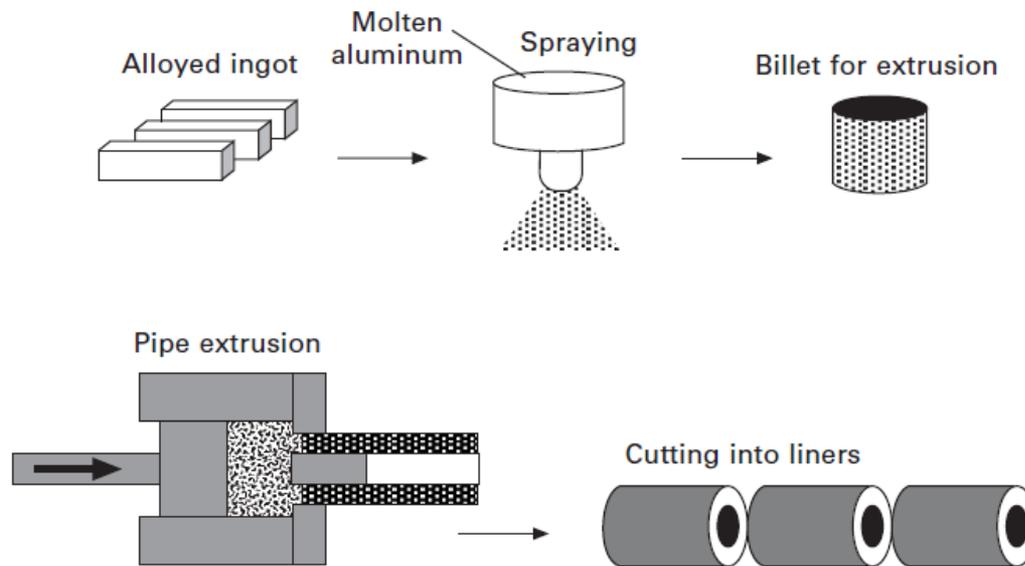
2.21 Cutaway of an aluminum block enclosing a cast iron liner having dimpled outer surface.



2.19 Aluminum engine block designs. The numbers correspond to the numbers in Table 2.1.

Process for Aluminium Cylinder liner manufacture

The molten alloy is sprayed and rapidly cooled into a powder first. The powder has a very fine microstructure during spraying. Next, the powder is canned in vacuum to make a billet for extrusion. Finally, the heated billet is hot-extruded into a tube. A spray forming process that directly deposits the sprayed powder to form a billet shape is also used. The powder particles weld together to form a bulk material during extrusion. The extruded tube is then cut into liners. The process generates the hardness and wear resistance needed for a liner.



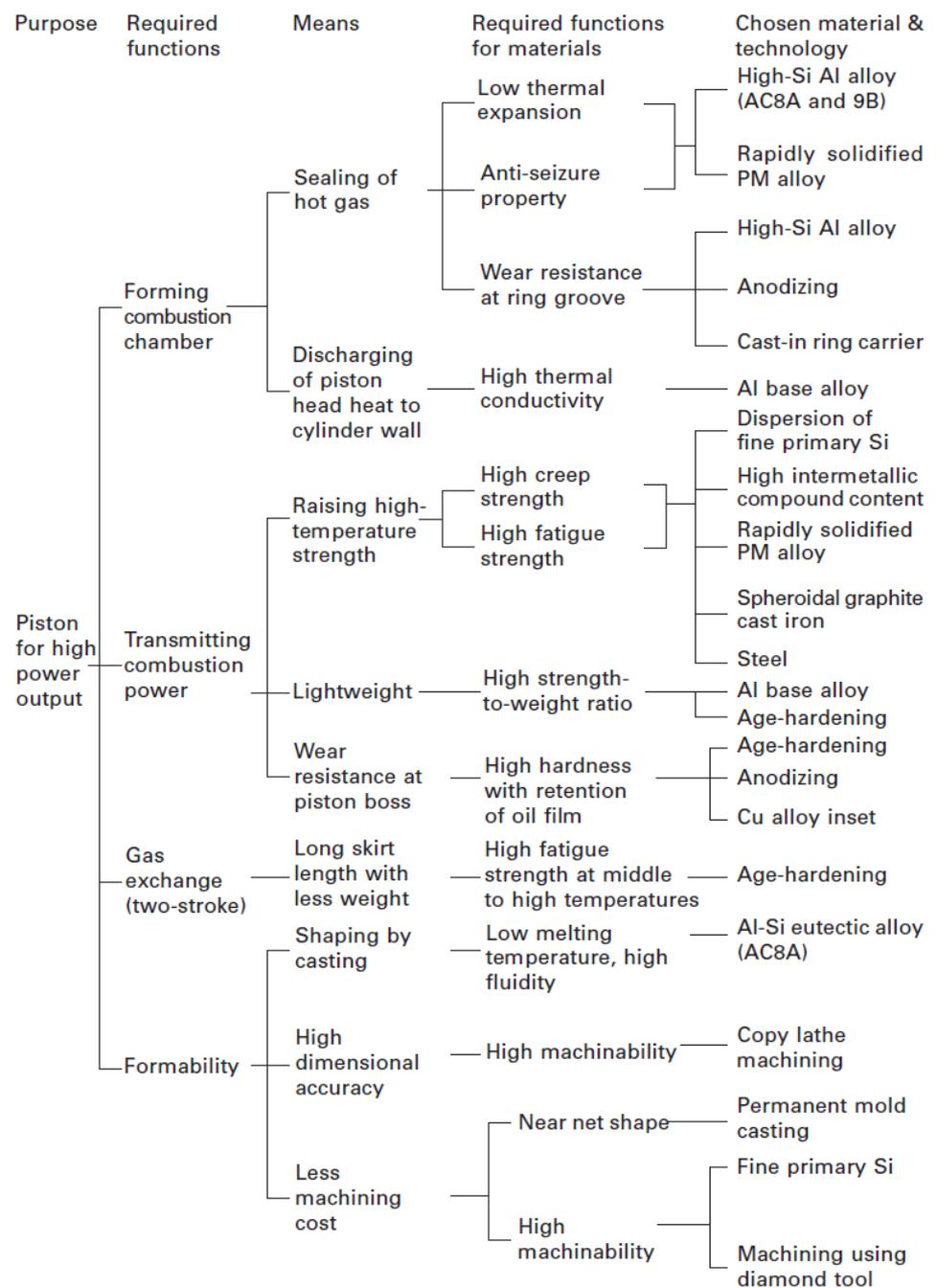
2.24 Manufacturing process of PM aluminum liner including spraying and extrusion.

Process for Aluminium Cylinder liner manufacture

Honda has marketed a motorcycle engine using cylinder liners made from a rapidly solidified powder metallurgical (PM) aluminum alloy. The chemical composition of the liner is Al-17% Si-5 Fe-3.5 Cu-1 Mg-0.5 Mn containing Al₂O₃ and graphite. The hard Si particles (1200 HV) as well as finely dispersed intermetallic compounds embedded in the aluminum matrix give increased wear resistance. The liner is cast in by high-pressure die casting.

Daimler- Chrysler has also used a PM alloy cylinder liner¹³ in its car engine. It is cast in by high-pressure die casting. This process is considered to be far more cost effective and it avoids the difficulties in tribological control of the hyper-eutectic Al-Si block .

Piston Property Development



3.5 Functions of a piston for high output power.

Aluminum Piston



3.6 Aluminum piston for a direct injection diesel engine. The edge of the combustion bowl is fiber-reinforced. The top ring groove is reinforced with a Niresist ring carrier.

Table 3.1 Chemical compositions of piston alloys (%). JIS-AC8A and AC9B are for a cast piston. AFP1 is a rapidly solidified powder-metallurgical alloy for a forged piston

Piston alloy	Cu	Si	Mg	Fe	Ni	Al	SiC	Zr
JIS-AC8A	1	12	1	–	1	Balance	–	–
JIS-AC9B	1	19	1	–	1	Balance	–	–
AFP1	1	17	1	5.2	–	Balance	2	0.9

Aluminium Piston Materials

I.C. ENGINE PISTON DESIGN

Piston materials

The % composition of typical eutectic piston alloys is shown below:-

	<i>Gasoline pistons %</i>	<i>Diesel pistons %</i>
Silicon	10.0–13.0	11.0–12.5
Copper	0.7–1.5	0.7–1.5
Magnesium	0.8–1.5	0.7–1.3
Iron	1.0 max	0.5 max
Manganese	0.5 max	0.25 max
Zinc	0.5 max	0.1 max
Aluminium	remainder	remainder

Precipitation Hardening (Age Hardening)

In Al-Cu system, the solute atom (copper) has a diameter about 12 percent larger than the aluminum atom.

In the other systems { Al-Ag). Al-Zn), the solute atom differs in size from that of the solvent by only about one percent.

As the solubility is less at room temperature, excess solute precipitates out of the solution. The precipitate often passes through several stages before a final stable structure appears

Aluminum containing 4 percent copper may pass through three different intermediate precipitation stages before the final stable phase (CuAl_2) is attained.

The first of these stages involves local clustering of the solute atoms to form what are commonly called *Guinier-Preston* or *GP zones*.

The shape that these clusters or zones take is strongly influenced by the amount of the misfit that occurs when the solute atom is placed in the parent lattice.

When this is small, the GP zones tend to be spherical in shape.

On the other hand, the misfit much the GP zones tend to form as very thin, two-dimensional plates oriented parallel to the $\{100\}$ aluminum lattice planes.

Precipitation Hardening

However, X-ray diffraction studies have revealed that the second rise is accompanied by the formation of a new structure.

Originally, this intermediate structure was called GP(2), but later authors have tended to identify it by the symbol θ since it has the characteristics of a three-dimensional ordered phase. It also consists of plates that lie along aluminum {100} planes, but these plates now have a thickness of several atomic layers. It is interesting to note that the sizes or diameters of the θ plates are larger than those of the GP zones.

In this specific alloy they may become at least four to five times larger in diameter than the GP zones. As indicated in Fig. 16.11, the GP zone and θ structures can be seen to overlap each other for a short part of the cycle.

Precipitation Hardening Process

To age harden our Al–4 wt% Cu alloy we use the following schedule of heat treatments:

- (a) Solution heat treat at 550°C. This gets all the Cu into solid solution.
- (b) Cool rapidly to room temperature by quenching into water or oil (“quench”).
- (c) Hold at 150°C for 100 hours (“age”).

Separate hardening mechanisms are at work during the ageing process:

(a) **Solid solution hardening**

At the start of ageing the alloy is mostly strengthened by the 4 wt% of copper that is trapped in the supersaturated α . But when the GP zones form, almost all of the Cu is removed from solution and the solution strengthening virtually disappears .

(b) **Coherency stress hardening**

The coherency strains around the GP zones and θ'' precipitates generate stresses that help prevent dislocation movement. The GP zones give the larger hardening effect.

(c) **Precipitation hardening**

The precipitates can obstruct the dislocations directly. But their effectiveness is limited by two things: dislocations can either *cut through* the precipitates, or they can *bow around* them .Resistance to cutting depends on a number of factors, of which the shearing resistance of the precipitate lattice is only one. In fact the cutting stress *increases* with ageing time

Bowing is easier when the precipitates are far apart. During ageing the precipitate spacing increases from 10 nm to 1 μm and beyond.

Age Hardening

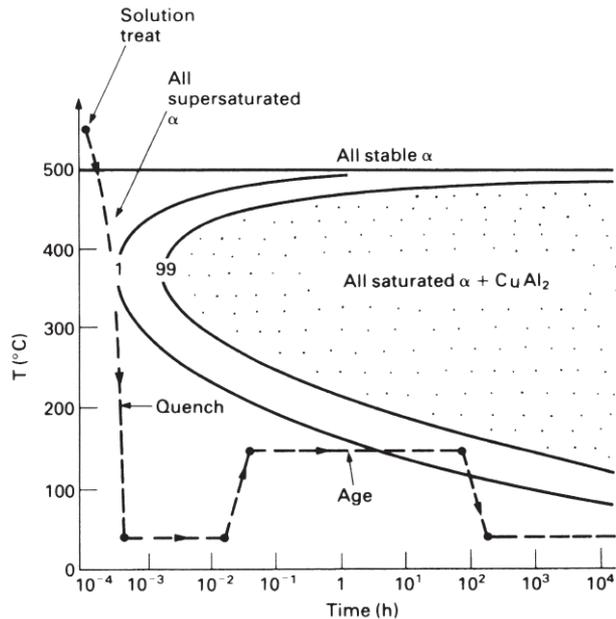


Fig. 10.5. TTT diagram for the precipitation of CuAl_2 from the Al + 4 wt% Cu solid solution. Note that the equilibrium solubility of Cu in Al at room temperature is only 0.1 wt% (see Fig. 10.3). The quenched solution is therefore carrying $4/0.1 = 40$ times as much Cu as it wants to.

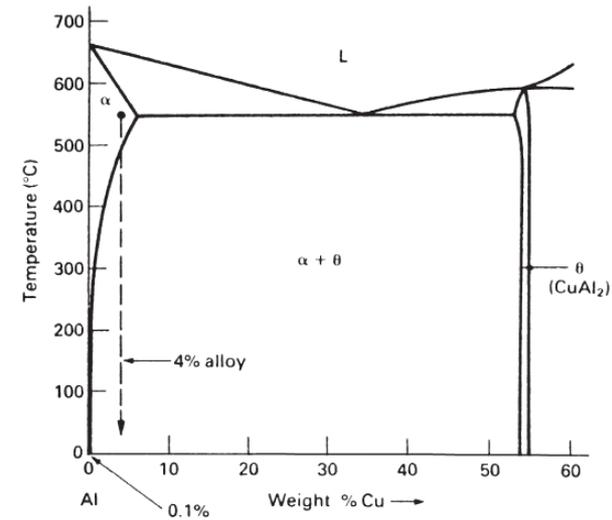


Fig. 10.3. The aluminium end of the Al-Cu phase diagram.

Precipitation Hardening Stages

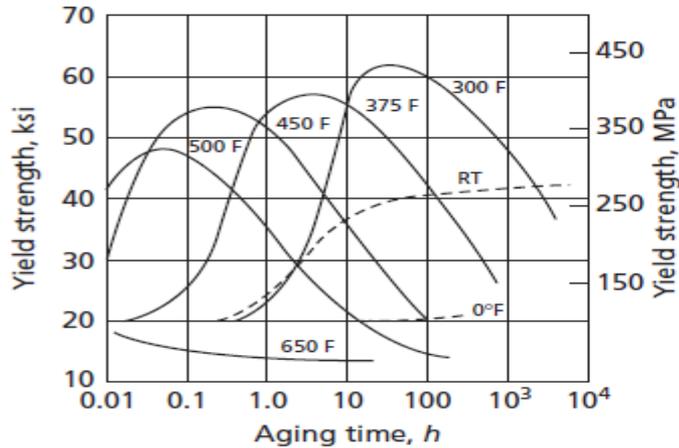


FIG. 16.10 Representative isothermal aging curves of the aluminum alloy 2014-T4. (From Hatch, J.E., Ed., *ALUMINUM Properties and Physical Metallurgy*, American Society for Metals, Metals Park, Ohio, 1984. Reprinted with permission of ASM International (R). All rights reserved. www.asminternational.org)

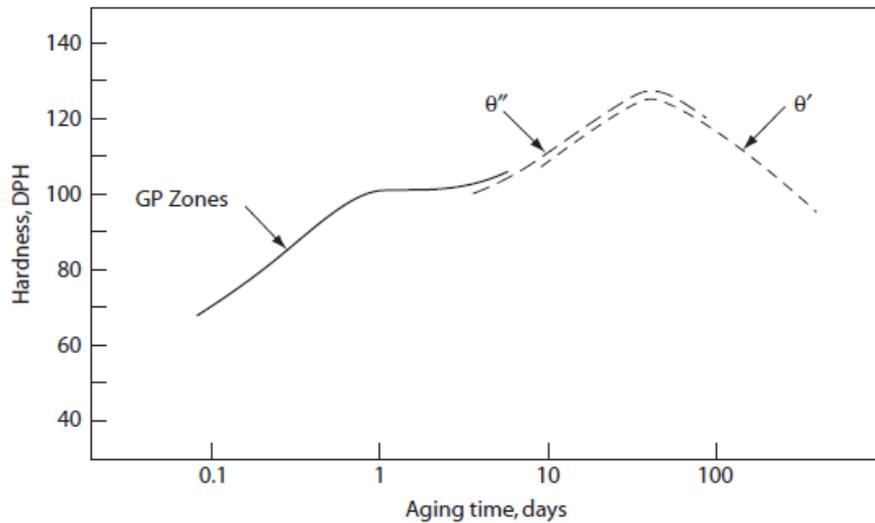


FIG. 16.11 Isothermal aging curve, Al-4 pct Cu at 130°C. (After Silcock, J. M., Heal, T. J., and Hardy, H. K., *J. Inst. Met.*, **82** 239 [1953-4].)

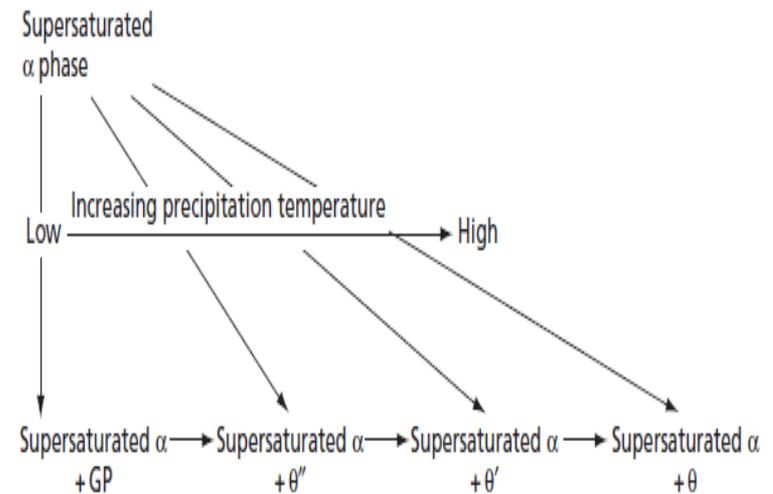


FIG. 16.12 Precipitation sequence in Al-Cu alloys

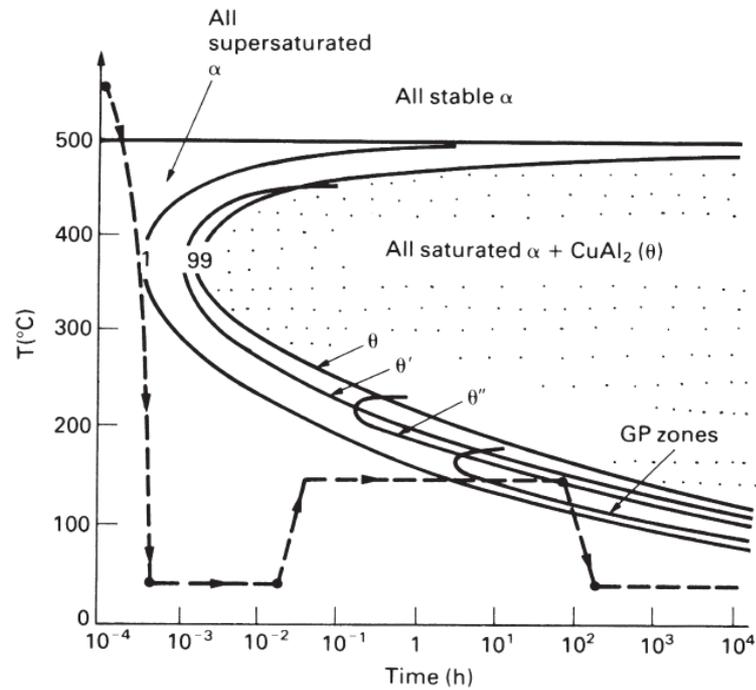


Fig. 10.10. Detailed TTT diagram for the Al-4 wt% Cu alloy. We get peak strength by ageing to give θ'' . The lower the ageing temperature, the longer the ageing time. Note that GP zones do not form above 180°C: if we age above this temperature we will fail to get the peak value of yield strength.

Table 10.4 Yield strengths of heat-treatable alloys

Alloy series	Typical composition (wt%)	σ_y (MPa)	
		Slowly cooled	Quenched and aged
2000	Al + 4 Cu + Mg, Si, Mn	130	465
6000	Al + 0.5 Mg 0.5 Si	85	210
7000	Al + 6 Zn + Mg, Cu, Mn	300	570

Table 10.5 Yield strengths of work-hardened aluminium alloys

<i>Alloy number</i>	σ_y (MPa)		
	<i>Annealed</i>	<i>"Half hard"</i>	<i>"Hard"</i>
1100	35	115	145
3005	65	140	185
5456	140	300	370

PDC Machine

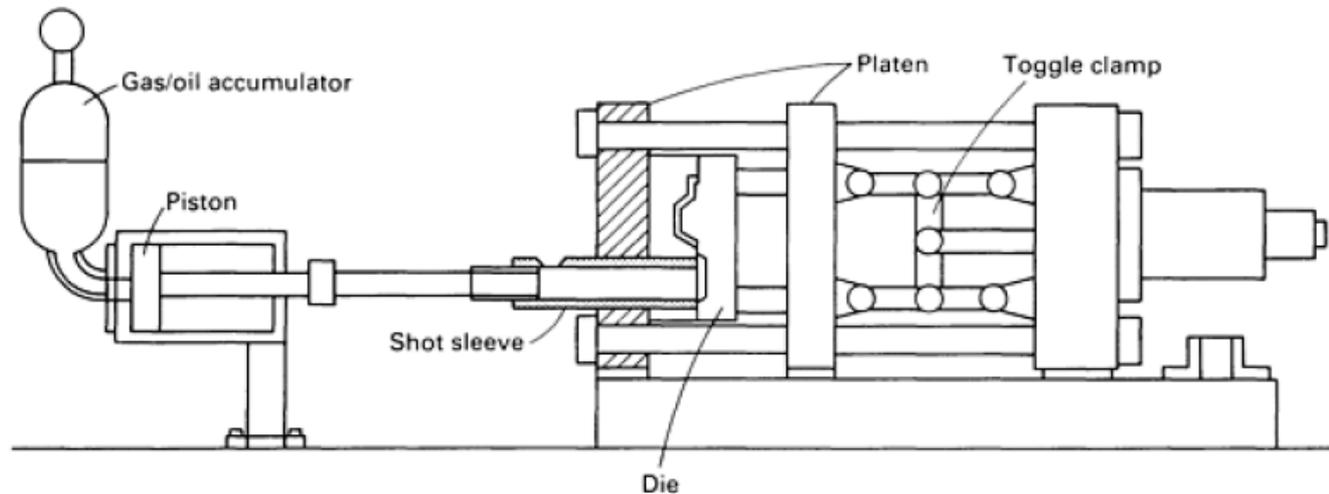
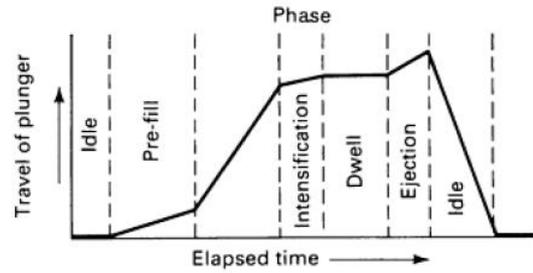


Fig. 2 Schematic showing the principal components of a cold chamber die casting machine

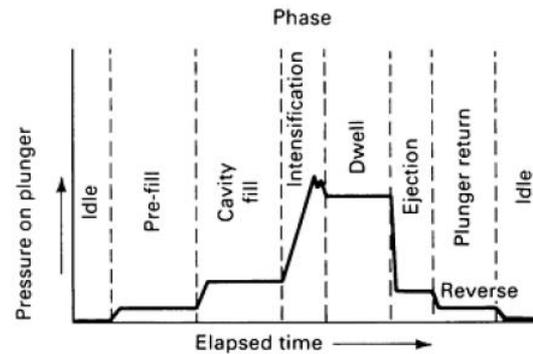
Direct injection extends the technology used for lower-melting polymers to metals by taking the hot chamber intimacy to the die cavity with small nozzles connected to a manifold, thus eliminating the gating and runner system. This process, however, is still under development.

Process control in die casting to achieve consistent high quality relates to timing, fluid flow, heat flow, and dimensional stability. Some features are chosen in die and part geometry decisions and are therefore fixed; others are defined by the process at the machine and can be adjusted in real time. All are related and therefore must be dealt with in parallel; the best die castings result from an intimate interrelationship between product design and process design.

Pressure Die Casting (Process Parameters)



(a)



(b)

Fig. 6 Curves for plunger travel versus time (a) and plunger pressure versus time (b) indicating the various phases of a shot

Pressure Die Casting Defects

Mechanically induced defects such as galling or drag marks on the casting surface occur during ejection of the casting and are usually caused by insufficient draft in the die, poor ejector system alignment, and inadequate slide or core alignment. Improper machine setup with uneven tie bar loading can cause the die to shift upon closing and opening and therefore create galling. Distorted or cracked castings are the result of extreme cases of poor mechanical design.

Metallurgical Defects. The four principal factors are alloy composition, dissolved gas content, entrained solids (such as oxides and intermetallic compounds), and improper temperatures.

The results can be poor fluidity, die soldering, shrinkage porosity, hot cracking, and gas porosity. Metallurgical factors interact directly with the primary causes of casting defects: heat flow and fluid flow.

Pressure Die Casting Defects

	Interaction of Heat Flow and Fluid Flow.
<i>Cold shuts</i>	Unfilled regions because of early solidification
<i>Gas porosity</i>	<p>consists of discrete, separate holes that have two sources: entrained air and, less frequently, dissolved gas.</p> <p>The latter source is entirely a metallurgical control problem, while the former has a variety of process causes. Built-in causes of excessive entrained gas are:</p> <ul style="list-style-type: none">· Too empty a shot sleeve (excessive diameter or length)· Inadequate venting· Excessive use of lubricant· Residual moisture from sprays· Poor metal flow patterns that prevent venting
<i>Shrinkage porosity</i>	<p>is a series of interconnected holes created by a lack of feed metal at the end of solidification.</p> <p>Shrinkage is confined to the thermal center of a section</p>
<i>Soldering</i>	<p>is the adherence of the molten metal to the die surface; this results in tearing of the casting surface upon ejection. The condition appears where impingement of the flowing metal causes local overheating of the die. This special soldering problem can be avoided by maintaining the iron content of aluminum die casting alloys between 0.8 and 1.1%.</p>
<i>Heat check fins</i>	<p>are replica die cracks created by thermal fatigue. Thermal fatigue cracking (heat checking) is the result of the temperature cycles experienced at the die surface</p>

Parameters to be considered for Effective Die Design for PDC

Various methods have been developed to provide the die caster with tools to address the problem on a sound, consistent basis. All of these methods attempt to take into account the influence of the following key variables:

- Part shape
- Internal quality
- Surface quality
- Mechanical properties
- Die temperature
- Die erosion
- Die material
- Die venting
- Metal temperature
- Metal fluidity
- Metal heat content
- Metal microstructure

Since the invention of the die casting process, many die castings have been successfully made with gating systems

Minimum Wall Thickness for PDC

Table 2 Minimum section thicknesses for die castings

Surface area of casting ^(a)		Minimum section thickness for:					
		Tin, lead, and zinc alloys		Aluminum and magnesium alloys		Copper alloys	
cm ²	in. ²	mm	in.	mm	in.	mm	in.
Up to 25	Up to 3.875	0.635	0.025	0.81	0.032	1.52	0.060
25-100	3.875-15.5	1.02	0.040	1.27	0.050	2.03	0.080
100-500	15.5-77.5	1.52	0.060	1.78	0.070	2.54	0.100

Aluminium Wrought Alloys

- 1xxx Controlled unalloyed (pure) compositions
- 2xxx Alloys in which copper is the principal alloying element, though other elements, notably magnesium, may be specified
- 3xxx Alloys in which manganese is the principal alloying element
- 4xxx Alloys in which silicon is the principal alloying element
- 5xxx Alloys in which magnesium is the principal alloying element
- 6xxx Alloys in which magnesium and silicon are principal alloying elements
- 7xxx Alloys in which zinc is the principal alloying element, but other elements such as copper, magnesium, chromium, and zirconium may be specified
- 8xxx Alloys including tin and some lithium compositions characterizing miscellaneous compositions
- 9xxx Reserved for future use

Aluminium – Wrought Alloys

1xxx

These grades of aluminum are characterized by

- excellent corrosion resistance,
- high thermal and electrical conductivities,
- low mechanical properties, and excellent workability.

Moderate increases in strength may be obtained by strain hardening.

Iron and silicon are the major impurities.

Typical uses include chemical equipment, reflectors, heat exchangers, electrical conductors and capacitors, packaging foil, architectural applications, and decorative trim.

2xxx Series.

Copper is the principal alloying element , often with magnesium .

These alloys require solution heat treatment to obtain optimum properties; which are close to low-carbon steel.

In some instances, precipitation heat treatment (aging) is employed to further increase mechanical properties.

The alloys in the 2xxx series do not have as good corrosion resistance as most other aluminum alloys. Therefore, these alloys in the form of sheet usually are clad with a high-purity aluminum or with a magnesium-silicon alloy of the 6xxx series,.

Alloys in the 2xxx series are particularly well suited for parts and structures requiring high strength-to-weight ratios and are commonly used to make truck and aircraft wheels, truck suspension parts, aircraft fuselage and wing skins, and structural parts.

Aluminium – Wrought Alloys

3xxx Series.

Manganese is the major alloying element. These alloys generally are non-heat treatable but have about 20% more strength than 1xxx series .
These applications include beverage cans, cooking utensils, heat exchangers, storage tanks, awnings, furniture, highway signs, roofing, siding, and other architectural applications.

4xxx Series.

The major alloying element is silicon, which can be added in sufficient quantities (up to 12%) to cause substantial lowering of the melting range without producing brittleness.
These are used in welding wire and as brazing alloys for joining aluminum. Alloy 4032 has a low coefficient of thermal expansion and high wear resistance, and thus is well suited to production of forged engine pistons.

5xxx Series.

The major alloying element is magnesium. When it is used as a major alloying element or with manganese, the result is a moderate-to-high-strength work-hardenable alloy
Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmospheres. However, certain limitations should be placed on the amount of cold work and the safe operating temperatures permissible for the higher-magnesium alloys) to avoid susceptibility to stress-corrosion cracking. Uses include architectural, ornamental, and decorative trim; cans and can ends; household appliances; streetlight standards; boats and ships, cryogenic tanks; crane parts; and automotive structures.

Aluminium – Wrought alloys

6xxx Series.

Alloys in the 6xxx series contain silicon and magnesium approximately in the proportions required for formation of magnesium silicide (Mg_2Si), thus making them heat treatable. Although not as strong as most 2xxx and 7xxx alloys, 6xxx series alloys have good formability, weldability, machinability, and corrosion resistance, with medium strength.

Alloys in this heat-treatable group may be formed in the T4 temper (solution heat treated but not precipitation heat treated) and strengthened after forming to full T6 properties by precipitation heat treatment.

Uses include architectural applications, bicycle frames, transportation equipment, bridge railings, and welded structures.

7xxx Series.

Zinc, in amounts of 1 to 8% is the major alloying element in 7xxx series alloys, and when coupled with a smaller percentage of magnesium results in heat-treatable alloys of moderate to very high strength. Usually other elements, such as copper and chromium, are also added in small quantities.

7xxx series alloys are used in airframe structures, mobile equipment, and other highly stressed parts.

Aluminium Temper Designations

Table 3.8. Aluminum-alloy temper designation⁷

Letter	Description
F	As manufactured or fabricated
O	Annealed
H	Strain hardened (wrought products only) : H1x: Strain hardened only H2x: Strain hardened only and partially annealed to achieved required temper H3x: Strain hardened only and stabilized by low-temperature heat treatment to achieve required temper H12, H22, H32: Quarter hard, equivalent to about 20–25% cold reduction H14, H24, H34: Half hard, equivalent to about 35% cold reduction H16, H26, H36: Three quarter hard, equivalent to about 50–55% cold reduction H18, H28, H38: Fully hard, equivalent to about 75% cold reduction
W	Solution heat treated
T	Thermally treated to produce stable tempers other than F, H, and O. Usually solution heat treated, quenched, and precipitation hardened. T1: Cooled from elevated-temperature shaping process and aged naturally to a substantially stable condition T2: Cooled from elevated-temperature shaping process, cold worked, and aged naturally to a substantially stable condition T3: Solution heat treated, cold worked, and aged naturally to a substantially stable condition T4: Solution heat treated and aged naturally to a substantially stable condition T5: Cooled from elevated-temperature shaping process, and then aged artificially T6: Solution heat treated, then aged artificially T7: Solution heat treated, then stabilized (overaged) T8: Solution heat treated, cold worked, then aged artificially T9: Solution heat treated, aged artificially, then cold worked T10: Cooled from an elevated- temperature shaping process, artificially aged, then cold worked

Note: A large number of numeric additions have been introduced to indicate specific variations.

Table 3.9. Physical properties of selected wrought aluminum alloys

AA designation	Average chemical composition (x/% wt.)	Density ($\rho/\text{kg}\cdot\text{m}^{-3}$)	Temper	Young's modulus (E/GPa)	Yield strength 0.2% proof ($\sigma_{0.2}/\text{MPa}$)	Ultimate tensile strength ($\sigma_{\text{UTS}}/\text{MPa}$)	Elongation (Z/%)	Brinell hardness (/HB)	Liquidus range(/°C)	Thermal conductivity ($k/\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	Specific heat capacity ($c_p/\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	Coefficient linear thermal expansion ($\alpha/10^{-6}\text{K}^{-1}$)	Electrical resistivity ($\rho_l/\mu\Omega\cdot\text{cm}$)
1199	99.992	2710	H18	69	12	85	43	28	660	234	917	23.6	2.70
1050	99.50	2705	O	69	30	70	43	19	645–655	222–230	920	23.5	2.80
1100	99.00	2710	O	69	35	90	35–45	23	643–655	222	917	23.6	3.0
			H18		150	165	5–15	44		170			2.80
2014	Al-4.5Cu-0.85Si-0.7Fe-0.5Mg-0.25Zn	2800	O	73	95	185	18	45	507–638	193	962	23.0	3.50
			T6		415	485	13	135		154			4.30
2017	Al-4.0Cu-0.7Fe-0.6Mg-0.5Si-0.25Zn	2790	O	72	70	180	22	45	513–640	193	920	23.6	3.5
			T4		315	420	12	120		134			5.15
2024	Al-4.4Cu-1.5Mg-0.6Mn-0.5Si-0.5Fe-0.25Zn	2780	O	73	95	185	22	47	503–638	193	920	23.2	3.50
			T6		415	495	13	135		151			4.50
2219	Al-6.3Cu-0.3Mn-0.2Si-0.3Fe-0.25Zr	2840	O	73	75	175	18	n.a.	543–643	172	920	22.3	4.00
			T62		290	415	10	n.a.		121			5.80
3003	Al-1.5Mn-0.6Si-0.7Fe-0.2Cu	2730	O	69	40	110	30–40	28	643–655	193	920	23.2	3.50
			H12		125	130	10–20	35		163			4.15
3004	Al-1.25Mn-1.1Mg-0.7Fe-0.3Si-0.25Zn	2720	O	69	70	180	20–25	45	630–655	163	920	23.9	4.15
3105	Al-0.35Mn-0.7Fe-0.6Si-0.6Mg-0.3Cu-0.25Zn	2730	O	69	55	115	24	85	635–655	172	920	23.6	3.8
4032	Al-12Si-1Mg-1Ni-1Fe-0.9Cu-0.25Zn	2680	O	79	n.a.	n.a.	n.a.	n.a.	532–570	154	950	19.4	4.30
			T6		315	380	9	120		138			5.00

Table 3.9. (continued)

AA designation	Average chemical composition (x/% wt.)	Density (ρ /kg.m ⁻³)	Temper	Young's modulus (E/GPa)	Yield strength 0.2% proof (σ_{YS} /MPa)	Ultimate tensile strength (σ_{UTS} /MPa)	Elongation (Z/%)	Brinell hardness (/HB)	Liquidus range(/°C)	Thermal conductivity (k/W.m ⁻¹ .K ⁻¹)	Specific heat capacity (c _p /J.kg ⁻¹ .K ⁻¹)	Coefficient linear thermal expansion (α /10 ⁻⁶ .K ⁻¹)	Electrical resistivity (ρ /μΩ.cm)
4043	Al-5Si-0.8Fe-0.3Cu	2690	O	71	75	130	20	n.a.	575–632	163	920	22.1	4.15
5052	Al-2.5Mg-0.4Fe	2680	O	70	90	195	25–30	47	607–650	138	962	23.75	5.00
5083	Al-4.5Mg-0.4Mn-0.5Si-0.25Zn	2660	O	71	145	290	22	77	590–638	117	962	23.75	6.00
6061	Al-1Mg-0.6Si-0.3Cu	2700	O	69	55	125	25–30	30	580–650	180	962	23.6	3.65
			T6		275	310	12–17	95		167			4.00
6063	Al-0.5Mg-0.5Si-0.35Fe	2700	O	69	50	90	n.a.	25	615–655	218	962	23.4	3.20
			T6		215	240	12	73		200			3.30
7075	Al-5.7Zn-2.6Mg-1.6Cu	2810	T6	72	105	230	16–17	60	475–635	130	962	23.6	5.15
7178	Al-6Zn-2.5Mg-2Cu-0.3Cr	2830	T6	n.a.	n.a.	n.a.	n.a.	n.a.	475–630	125	962	23.4	5.50
8017	Al-0.6Fe-0.2Cu	2710	H12	n.a.	n.a.	n.a.	n.a.	n.a.	645–655	n.a.	n.a.	23.6	2.8
			H212	n.a.	n.a.	n.a.	n.a.	n.a.		n.a.	n.a.		3.0
8176	Al-0.1Si-0.7Fe-0.1Zn	2710	H24	n.a.	n.a.	n.a.	n.a.	n.a.	645–655	230	962	23.6	2.8
8081	Al-1Cu-0.7Si-0.7Fe	2700	H24	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	230	962	23.6	2.8

Table 3.11. Applications and uses of selected aluminum alloys

Aluminum alloy	Major characteristics	Applications and uses
1100	Excellent forming qualities, weldability, electrical conductivity, and resistance to corrosion	Chemical equipment, tank cars, heat exchanges, storage tanks, sheet-metal work, dials and name plates, cooking utensils, reflectors
2011	Good machining, unexcelled for free cutting qualities with good mechanical properties	Screw machine products, machine parts, atomizer and hose parts, pipe stems, tube fillings
2017	Relative high strength, combined with fair workability and good machinability	Screw machine products, tube fittings, pulleys, gages, coat hangers, tube & tube fittings
2024	A high strength material of adequate workability has largely superseded 2017 for structural applications. 2024-0 not recommended unless subsequently heat treated	Aircraft parts, truck wheels, piano hinges, luggage, scientific instruments, ski poles, fasteners, orthopedic braces
2219	Excellent combination of cryogenic, room-temperature, and elevated-temperature mechanical properties. Excellent resistance to stress-corrosion cracking in standard artificially aged tempers	Welded tanks for cryogenic liquids, high-strength structural weldments, and elevated-temperature application in 200 – 250°C range
3003	Similar to 1100 but with slightly higher strength and good workability, weldability, and resistance to corrosion. Low cost. Moreover, 3003 H112 plates meet ASME Unfired Pressures Vessel Code	Ductwork, ice-cube trays, garage doors, awning slats, trailer and truck panels, refrigerator panels, gas lines, gas tanks, heat exchanges, storage tanks, utensils, drawn and spun parts; very versatile metal
5005	Properties similar to 3003 but with finer grain structure. Good finishing characteristics	Identical to those of 3003 but when excessive finishing costs are encountered in the use of 3003 alloys due to surface roughness upon drawing
5052	Very good corrosion resistance, good workability, weldability, and strength	Used for aircraft fuel tanks, storm shutters, refrigerator liners, utensils, electronic mounting plates and panels, fan blades
5083	High-strength, high resistance to corrosion, suitable for welding	Welded structures, pressure vessels, storage tanks, truck and marine applications, armor plate

Aluminum alloy	Major characteristics	Applications and uses
5086	Properties similar to 5083, high strength, high resistance to corrosion, good weldability	Medium-strength welded structures
5456	High strength, high resistance to corrosion, very suitable for welding	High-strength welded structures, pressure vessels, storage tanks, truck and marine applications, armor plate
6061	Excellent forming qualities, weldability, electrical conductivity, resistance to corrosion	Chemical equipment, boats, truck and bus bodies, scaffolding, transmission towers, marine equipment, fire ladders. 6061T6 is used for tankage, tank fittings, and general structural and high-pressure applications
7075	Very high strength and hardness	Used where strengths higher than 2024 are required. Especially used in aircraft parts

AA designation	Average chemical composition (x/% wt.)	Density (ρ /kg.m ⁻³)	Young's modulus (E/GPa)	Yield strength 0.2% proof ($\sigma_{0.2}$ /MPa)	Ultimate tensile strength (σ_{UTS} /MPa)	Elongation (Z/%)	Brinell hardness (/HB)	Melting point or liquidus range(/°C)	Thermal conductivity (k/W.m ⁻¹ .K ⁻¹)	Specific heat capacity (c _p /J.kg ⁻¹ .K ⁻¹)	Coefficient linear thermal expansion (α /10 ⁻⁶ .K ⁻¹)	Electrical resistivity (ρ /μΩ.cm)
100.1	99.9	2700	69	30	80	30	25	n.a.	218	n.a.	24.0	3.0
201.0	Al-4.6Cu-0.7Ag-0.35Mg-0.35Mn-0.25Ti	2750	71	170–215	225–295	8	90	535–650	121	920	22.5	3.6
204.0	Al-4.6Cu-0.25Mg-0.17Fe-0.17Ti	2750	70	200	225	26	118–137	570–650	121	920	19.3	5.40
356.0	Al-7Si-0.35Mg-0.2Fe-0.2Cu	2685	73	195–210	240–290	6	90	555–615	167	963	21.5	4.01
359.0	Al-9Si-0.6Mg	2700	72	180	230	1	105	555–615	138	963	20.9	4.00
360.0	Al-9.5Si-2Fe-0.6Cu-0.5Zn-0.5Ni	2740	71	170	305–320	2.5–3.5	55–60	555–595	93	963	20.88	6.16
383.0	Al-10.5Si-2.5Cu-0.5Mn	2740	71	172	310	3.5	75	515–580	96–100	n.a.	21.1	6.6
390.0	Al-17Si-4.5Cu-0.6Mg	2731	88	248	317	1	120	505–650	134	n.a.	18.0	8.6
413.0	Al-11.5Si-2Fe-1Cu-0.5Ni-0.5Zn	2657	71	145–280	200–297	2.5	80–125	650–760	121–142	963	20.34	5.3
443.0	Al-5.5Si-0.8Fe	2670	71	60–70	125–155	5–6	n.a.	575–630	159	963	21.0	4.1
512.0	Al-4Mg-2Si-0.3Fe	2600	70	n.a.	n.a.	n.a.	n.a.	n.a.	134	963	22.0	5.1
514.0	Al-4Mg	2650	71	95	145	3.0	50	585–630	146	963	24	4.93
518.0	Al-8Mg-1.8Fe	2570	n.a.	180–190	295–340	12–18	85–95	535–620	96.2	n.a.	24.1	6.89
535.0	Al-6.5Mg-0.2Mn	2620	71	100	160–215	6–10	60–65	550–630	130	n.a.	23.6	5.6
712.0	Al-5.8Zn-0.6Mg-0.5Cr-0.2Ti	2810	71	170	220	5	70	570–615	138	963	24.7	4.93

Porosity Remedial Action

Impregnation. Porosity in a die casting can lead to a lack of pressure tightness. Although porosity can be minimized by proper process design or control, it is sometimes necessary or cost effective to fill voids by using an impregnation process. Sodium silicate and anaerobic organic compounds are among the impregnants available. The typical procedure is as follows:

- Clean the casting
- Place in an autoclave and draw a vacuum of 710 mm (28 in.) of mercury for 15 min
- Introduce the sealant and apply hydrostatic pressure for 15 min
- Pump out and remove the castings
- Wash and dry