

## Products – Cast alloys and products

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## 6 Cast alloys and products

### 6.1 General characteristics of castings



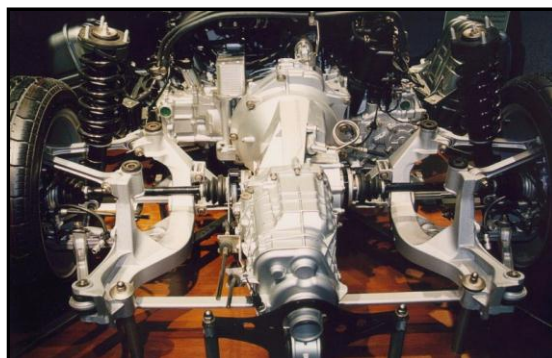
A collection of parts made via semi-solid forming

#### Advantages

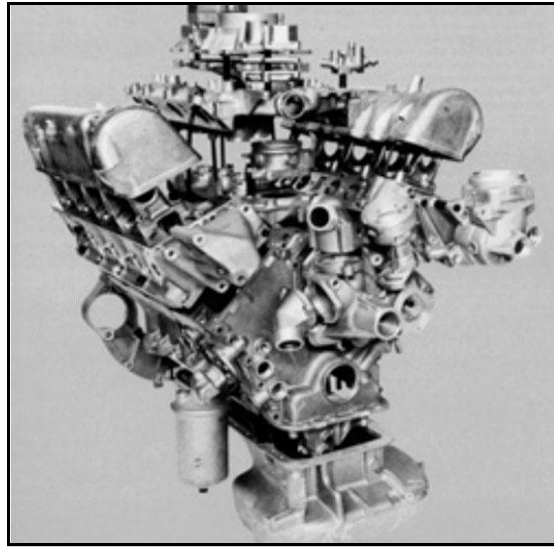
- ⤴ A single operation process; casting is the least costly manufacturing route for a wide range of parts.
- ⤴ Complex three-dimensional shapes can be produced with intricate internal passages. Powertrain components take maximum advantage of this feature for cylinder heads and blocks. Many such components cannot be made economically otherwise.
- ⤴ Part consolidation is a large advantage in that a single casting can replace an assembly of parts produced by other means. This reduces tooling costs, eliminates joining operations, and ensures close tolerances.

#### Disadvantages

- ⤴ The properties of a casting are - apart from alloy composition and heat treatment - strongly influenced by the casting process and part design.
- ⤴ Mechanical properties will vary with the local freezing rate from location to location within a single casting. Exact mechanical performance data can thus be difficult to obtain in forms other than minimum and typical values and FE analysis is difficult.
- ⤴ Close co-operation between the part designer, foundryman, and metallurgist is needed very early in the design process in order to ensure a successful outcome.

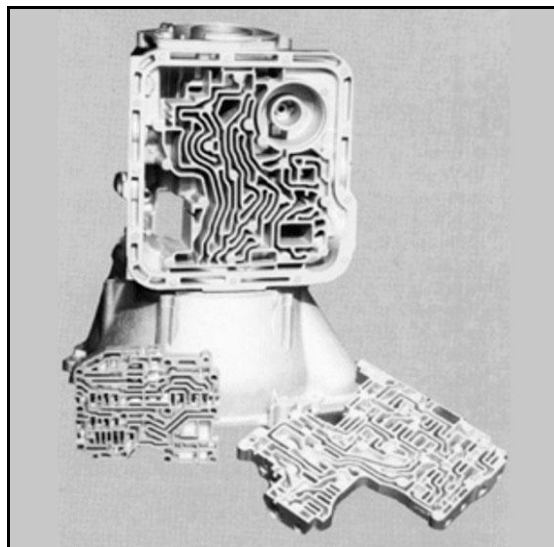


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**Mercedes 450 SLC-5-1 Engine**

**Source: Gesamtverband der Aluminium-Industry e.V.**

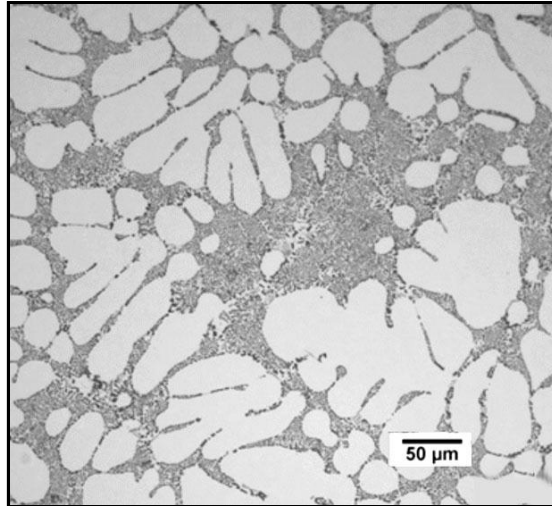


**7 kg GD-AlSi8Cu3 Transmission Case**

**Source: Gesamtverband der Aluminium-Industry e.V.**

## 6.2 Alloys

### 6.2.1 Foundry alloys – Characteristics and use



**Typical hypoeutectic AlSi7Mg (AA A356) Microstructure: Al dendrites surrounded by Al+Si eutectic**

**Aluminium Foundry Alloys** can be tailored to cover a wide range of mechanical performance via chemistry and/or process control.

- ⤴ There are four main families based on Al-Si(-Cu), Al-Cu, Al-Mg(-Si), and Al-Zn(-Si)-Mg systems
- ⤴ The vast majority of cast Al components are based on the Al-Si system because of its good castability.
- ⤴ Some Al-Cu, Al-Mg and Al-Zn alloys exhibit better properties than Al-Si alloys, but their casting properties are generally poor. In particular, they show a high tendency to hot tearing.

#### **Al-Mg Alloys**

- ⤴ Highly corrosion resistant, these alloys polish to a high shine and can be anodised. Good strength/ductility compromise without need for high temperature heat treatment.
- ⤴ Used to produce high-pressure die cast automotive steering wheels and structural components.

#### **Al-Zn-Mg Alloys**

- ⤴ Used to avoid quench distortions, as these alloys are subject to age hardening at room temperature without previous solution treatment.

#### **Al-Mg-Si and Al-Zn-Si-Mg Alloys**

- ⤴ The addition of Si to these alloy systems in adequate quantities gives better casting properties. Various alloys have been developed or are under development.

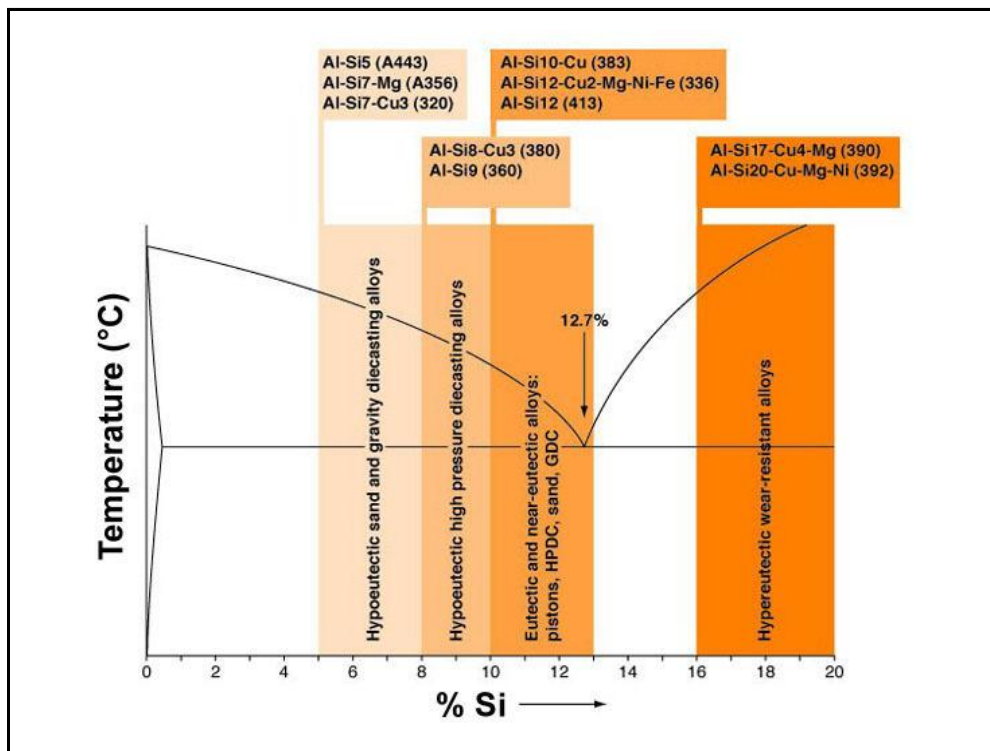
#### **Al-Cu Alloys**

- ⤴ The strongest of the casting alloys, the Al-Cu family sees use mostly in the aerospace industry.
- ⤴ They also see service as automotive suspension knuckles, high-end turbocharger impellers, etc.
- ⤴ The alloys are very hot short and difficult to cast in complex shapes.
- ⤴ Limited to low volume production for sports cars and other exotic vehicles.

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### Al-Si Alloys

- ⤴ The most popular alloys of the casting industry world-wide.
- ⤴ Exhibiting **excellent castability** these alloys feed well, resist hot tearing, and are in general the most manufacturable casting alloys.
- ⤴ Addition of **Mg** results in good mechanical properties after heat treatment, addition of **Cu** gives a better machinability and increases strength at temperature.
- ⤴ **Al-Si-Mg** alloys are used for **wheels, structural castings and suspension parts** requiring moderate to high strength and good ductility.
- ⤴ **Al-Si-Cu(-Mg)** alloys dominate the market for power train components such as **engine blocks, cylinder heads, pistons, and die castings** where strength at temperature and/or wear resistance is more important than ductility.

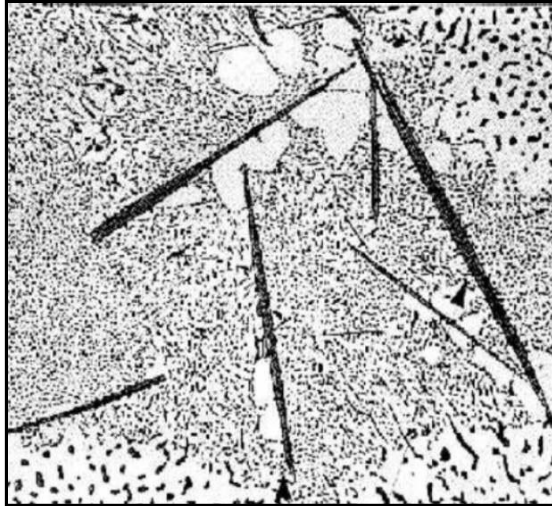


Schematic Al-Si phase diagram showing the composition ranges for the most common foundry alloys

## 6.2.2 Foundry Alloys – Primary and Secondary Alloys

See also:

- ⤴ AAM – Materials – 1 Resources > Secondary aluminium



**FeSiAl5 needles in a 1% Fe-containing permanent mould cast Al Si12**

- ⤴ **Primary alloys** are produced from **pure aluminium**, melted with addition elements.
- ⤴ **Secondary alloys** are produced at a lower cost from **scrap** (end-of-life recycled) aluminium materials, which are remelted after classifying, with adjustment for main elements.

Secondary alloys have relatively high levels of impurities, esp. **Fe**, as most available scraps are contaminated with iron or steel components (e.g. bolts, rings, etc.). **Fe** is detrimental to many properties, mainly **castability** and **ductility**, and must be kept at levels as low as possible, with an exception for pressure die casting.

### **Alloys for sand and permanent mould applications**

For applications requiring **high ductility**, **Fe** content is generally specified < **0.20 %**, which requires **primary** alloys.

When ductility is not a criterion, the Fe level may be raised, and the criterion can be **castability** or **machinability**, and secondary alloys can be selected with Fe content as high as 0.5 %, or higher if acceptable.

### **Alloys for pressure die casting applications**

- ⤴ In this case Fe is a "wanted impurity", as it lowers the tendency of aluminium alloys to stick to the mould surface.
- ⤴ For this reason Fe content is specified with a **minimum** value, generally **0.6 %** or more, and **secondary** alloys are quite suitable.
- ⤴ The maximum value depends on **ductility** requirements, it is generally around **1 %**, up to **1.3 %**.

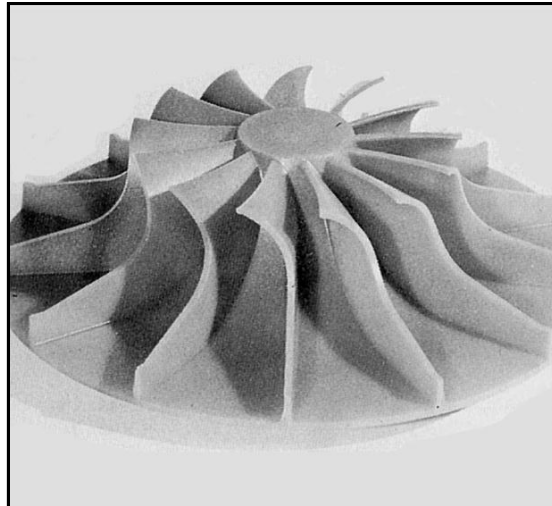


## 6.2.3 Composition

### Foundry Fluidity – Definition and process parameters

See also:

- ⤴ AAM – Products – 6 Cast alloys and products > Alloys > Typical application areas
- ⤴ AAM – Applications – 1 Power train > Cylinder block > Alloys: composition and heat treatment



**Thin-veins or intricate thin walled structures require a high degree of fluidity to avoid misruns**

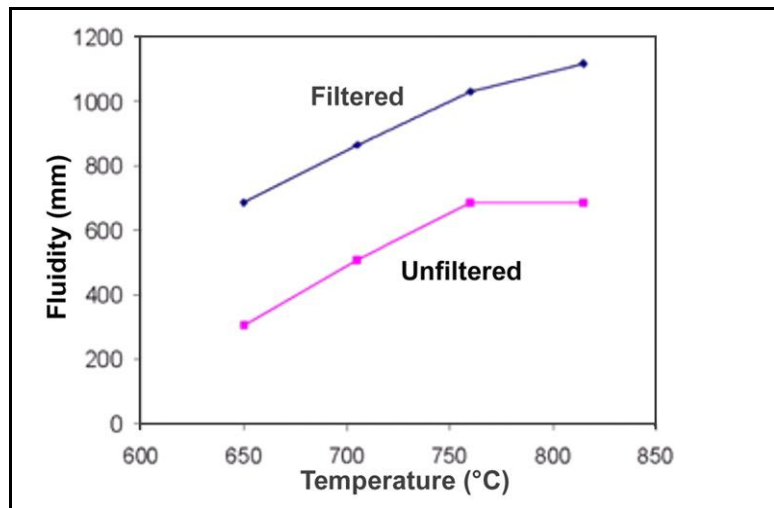
### Foundry Fluidity – Defined

- ⤴ Fluidity as a foundry term differs from the scientific definition. In science fluidity is the reciprocal of viscosity and, as such is an exact measurable quantity.
- ⤴ Foundry Fluidity is defined as the distance that a liquid metal will flow into a mould cavity and is thus a relative term.
- ⤴ As molten metal is introduced into a mould cavity it loses thermal energy to the walls of the mould as it flows. Eventually it begins to freeze and at some point the metal will cease to flow.

### Process Factors:

- ⤴ The initial metal temperature.
- ⤴ The heat extracting power of the mould material including the effect of any insulating die coatings that are applied.
- ⤴ Kinetic energy of the metal. Gravity die casting, sand casting, etc., all rely on the metal flowing downhill under its own weight and momentum. Low pressure or high pressure diecasting conditions impart a different, and adjustable, pressure to be applied to the metal to cause it to flow.
- ⤴ Metal Cleanliness also has a large impact and, while a quality of the metal, is largely process dependent.

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**Filtered (Clean) versus Unfiltered (Dirty) metal fluidity comparison**

**Source: F. Major, Alcan**



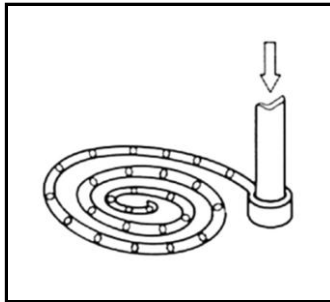
## Foundry Fluidity – Test methods

### Implications of Fluidity

- ⤴ Insufficient fluidity may result in misruns (incompletely filled castings) and poor replication of details.
- ⤴ Excessive fluidity may cause sand penetration or excessive flashing of molten metal along parting lines.
- ⤴ In practice it is controlled via alloy choice, casting and mould temperatures.
- ⤴ Changes in fluidity may be an indication of dirty metal.
- ⤴ Changes in fluidity can be expected when trace impurities change, most important are changes in grain refining or modifying practice.

### Spiral Fluidity Test (below)

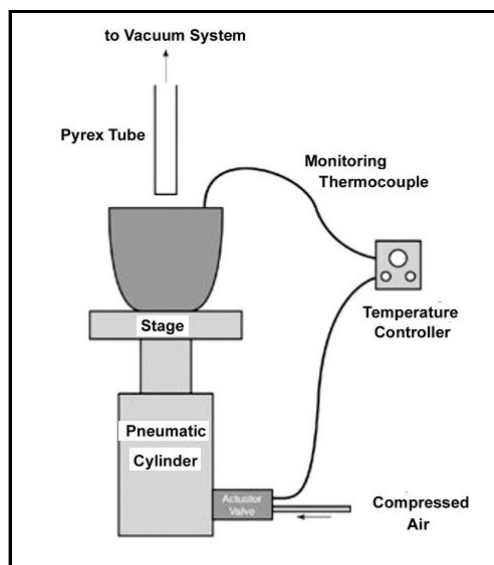
- ⤴ The oldest of the fluidity tests, the spiral is moulded in sand. Metal at a carefully controlled temperature is poured into the mould and, after shakeout, the distance that the metal flows is measured.



**The fluidity spiral, or sand spiral, is one of the oldest and simplest fluidity tests**

### Vacuum Fluidity Testing (below)

- ⤴ A pyrex or quartz tube is connected to a vacuum system. The test melt is presented to the tube at the same time that the vacuum is applied; again, at a set temperature. The distance up, or along, the tube that the metal flows is measured as the fluidity.

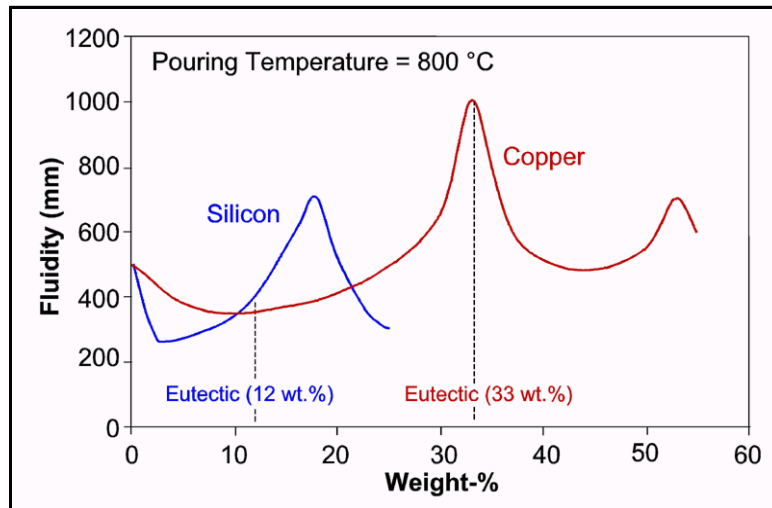


**Vacuum fluidity testing is more complex, but eliminates variables associated with moulded sand**

## Foundry Fluidity – Effects of alloying elements

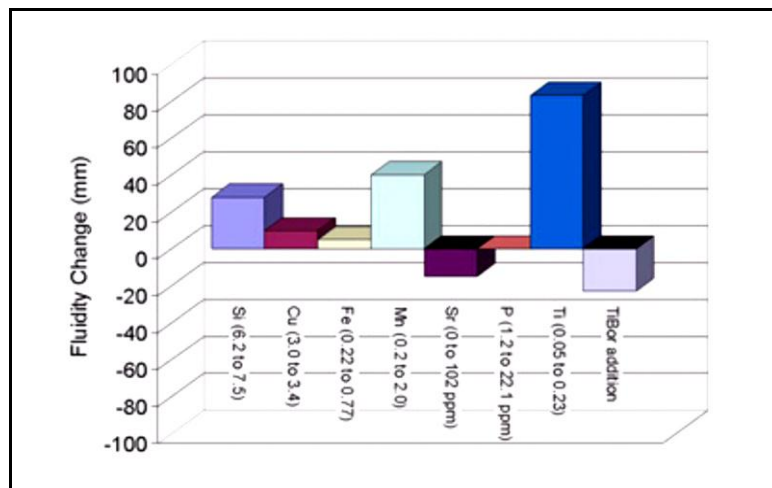
### Effect of Alloy Elements

- Alloying elements such as Cu or Si significantly influence the foundry fluidity of aluminium alloy melts (s. diagram below).



**Foundry fluidity of Al with Si or Cu content**

- Elements modifying the eutectic morphology (e.g. Sr), grain refiners (Ti, TiB, etc.) and impurity elements such as Fe also impact fluidity (s. diagram below).

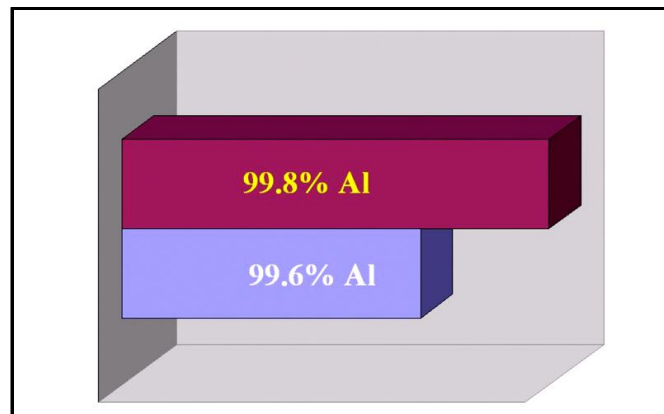


**Effects on AA 320 alloy of changes in trace elements or master alloy additions**

### High Purity Metal

- The fluidity of aluminium is very sensitive to chosen purity level as shown in the schematic diagram (below).

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**Rapid change in fluidity of pure Al with impurity content**

- ⤴ This is most important when casting electrical motor rotors or conductors.

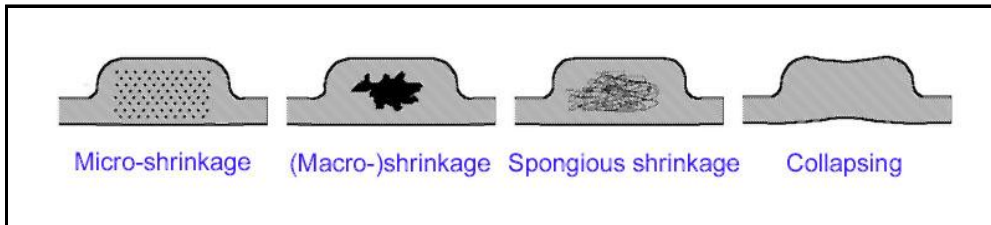
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### Shrinkage – Influence of alloying elements

**Aluminium shrinks** during solidification, as its density in the liquid state is 6.5 % less than in the solid state. Cast parts generally solidify from the surface to the centre. Therefore, any lack of material will appear there if not compensated by feeding (mould design, alloy selection, temperature regime, etc.).

The composition of the alloy has an influence on the volume and type of the shrinkage, see table:

- ⤴ silicon is the only suitable additional element that reduces shrinkage as silicon expands 8 % when solidifying;
- ⤴ alloys having a low eutectic ratio present scattered "micro-shrinkage" and "collapsing";
- ⤴ elements such as phosphorus, sodium, antimony and strontium, which determine the shape of silicon particles during solidification of the aluminium-silicon alloys, have at the same time an effect on the type of shrinkage observed in alloys with high silicon contents.



Alloy designation	Eutectic ratio (%)	Usual form	Total shrinkage (%)
EN AC- 21000 Al Cu5MgTi	9	1+3	6.4
41000 Al Si2MgTi	12	1+3	6.1
42100/200 Al Si7Mg0.3/0.6	50	1	5.2
43300 Al Si9Mg	72	1+3	4.8
44000 Al Si11(Mg)	83	3	4.5
44100 Al Si12	100	2 or 4*	4.2
45100 Al Si5Cu3Mg	38	3	5.5
46300 Al Si7Cu3Mg	54	3	5.1
46000 Al Si9Cu3	80	3	4.8
48000 Al Si12CuNiMg	95	2 or 4*	4.3
51000 Al Mg3	15	1+3	6.4
71000 Al Zn5Mg	10	1+3	6.3

\* 2 when sodium modified, 4 when phosphorus modified

### Hot tearing

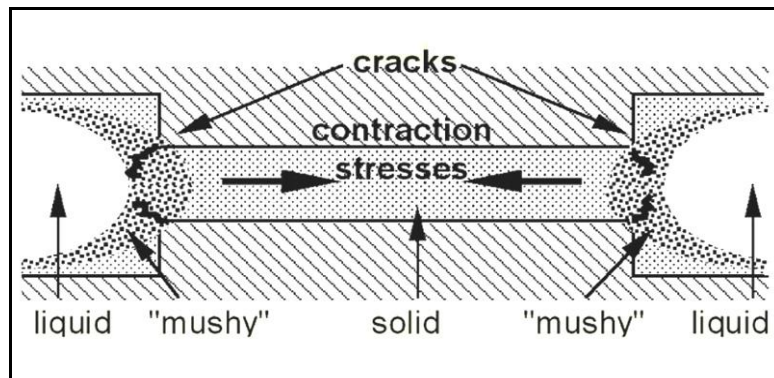
Cracks (hot tearing) may appear in cast parts after solidification.

Stresses applied on still "mushy" areas are generated by the contraction of already solidified zones. Cracks appear when the "mushy" zone is too thick and the quantity of liquid available is too small to fill the resulting gap.

The composition of the alloy has a major influence on this phenomenon, as the selected alloy determines the possibility for the liquid eutectic phase to progress through the solidifying metal - "mushy" zone - to feed stressed areas.

There are also other factors that the foundry man will take into account to control the "hot tearing" defect, among which are:

- ⤴ design of the part,
- ⤴ grain refinement of the alloy,
- ⤴ stiffness of the mould.



**Shrinkage stresses causing hot tearing**

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### Hot Tearing – Influence of alloying elements

See also:

- △ AAM – Materials – 3 Designation system > Cast alloys > Designation system for casting alloys – EN 1780-1

The sensitivities of main alloys to hot tearing, coded from 0 to 6, are compared in the table below. The relation between sensitivity and the ratio of eutectic phase and the freezing range of the alloy is obvious.

Silicon plays a major role in this respect, as it is the only practical alloying element that reduces the contraction of the alloy in the solid state.

Alloy designation	Eutectic	Solidif.	Hot tearing	
EN AC-	EN AC-	ratio (%)	range (°C)	tendency
21000	Al Cu5MgTi	9	120*	4,2
41000	Al Si2MgTi	12	90	3,9
42100/200	Al Si7Mg0,3/0,6	50	60	0
43300	Al Si9Mg	72	45	0
44000	Al Si11(Mg)	83	30	0
44100	Al Si12	100	0	0
45100	Al Si5Cu3Mg	38	110	2,8
46300	Al Si7Cu3Mg	54	100	0
46000	Al Si9Cu3	80	80	0
48000	Al Si12CuNiMg	95	30	0
51000	Al Mg3	15	190*	4,2
71000	Al Zn5Mg	5	50*	5,6

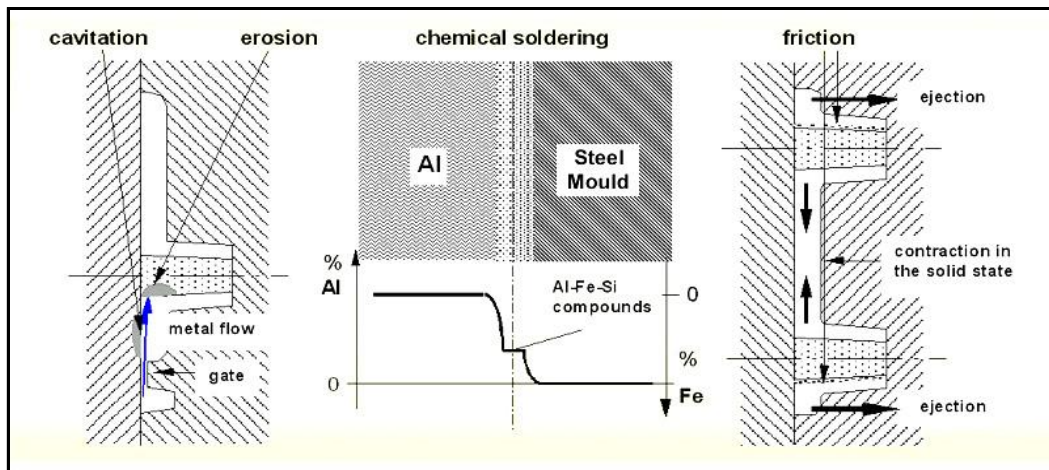
\* depends on cooling rate, typical values

## Mould sticking

**Mould sticking** is a defect observed in pressure die casting which leads to surface defects on the part and progressive deterioration of the mould.

"Mould sticking" may be in fact the consequence of four different phenomena, as shown below:

- ⤴ cavitation
- ⤴ erosion
- ⤴ chemical soldering
- ⤴ friction





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### Mould Sticking – Influence of alloying elements

The **composition of the alloy** may have an influence on mould sticking with two elements:

- ⤴ **Iron** is generally considered to be a harmful impurity in gravity casting, mainly towards ductility. For pressure die casting applications, on the other hands, the solubility for iron originating from the mould in liquid aluminium lowers with the iron content of the molten alloy, and 0.5 % is considered as a minimum towards problems of sticking by soldering of the steel mould.

In newer alloy developments, iron is partially replaced by manganese which has a similar effect and reduces also mould sticking with less deterioration of the mechanical properties.

- ⤴ **Silicon** content may have an effect on sticking by friction as it modifies the contraction factor: a high content lowers the contraction of the part.

<b>Causes and prevention of mould sticking</b>			
<b>origin</b>	<b>due to</b>	<b>preferential areas</b>	<b>solution</b>
(chemical) soldering of steel	excessive solubility of iron in liquid aluminium	overheated areas	alloy : Fe content
			design
(hydraulics) erosion of iron	excessive speed of the liquid metal	gates, corners	design (gates) process
	cavitation	widenings	design (gates) process
(wear) sticking of aluminium	friction during extraction of the part	areas with too low draft angles	alloy : Si content draft

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### Other properties of cast parts

Different other properties of cast parts are also depending on the composition of the alloy. Typical values for electrical resistivity, thermal conductivity and thermal expansion are indicated in table for the as cast condition.

Alloy designation		Density	Thermal conduct.	Electrical resistivity	Expansion coef.
EN AC-	EN AC-	g/cm <sup>3</sup>	W/m. °C	μΩ.cm	°C <sup>-1</sup> × 10 <sup>6</sup>
21000	Al Cu5MgTi	2.80	140	6	23
41000	Al Si2MgTi	2.70	150	4	22
42100/200	Al Si7Mg0.3/0.6	2.68	160	4	22
43300	Al Si9Mg	2.65	160	4.5	20.5
44000	Al Si11(Mg)	2.65	160	4.5	20.5
44100	Al Si12	2.65	165	4.5	20
45100	Al Si5Cu3Mg	2.75	120	5	22
46300	Al Si7Cu3Mg	2.75	115	6	21.5
46000	Al Si9Cu3	2.75	105	7	20.5
48000	Al Si12CuNiMg	2.72	115	6	19
51000	Al Mg3	2.67	145	6	24
71000	Al Zn5Mg	2.80	140	6	23

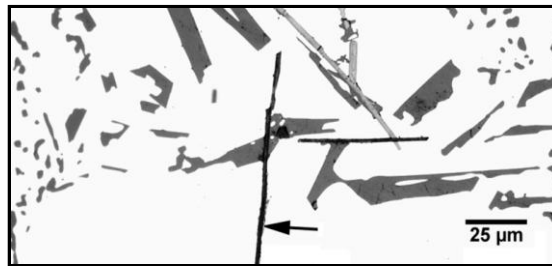
Thermal conductivity and electrical resistivity, which are correlated, depend also on the temper:

- △ thermal conductivity is maximal in the as cast (and annealed) condition, and minimum after a solution treatment, and the opposite for resistivity.

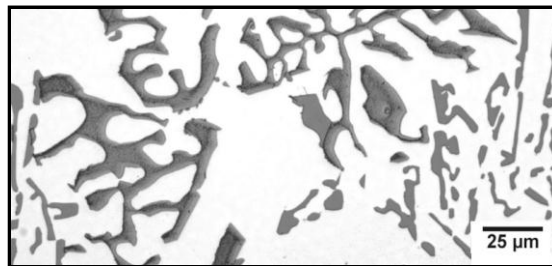
## Influence of Fe-content on mechanical properties

### Effects of AlFeSi intermetallic phases

- ⤴ Fe is the main trace impurity responsible for degrading the ductility of conventional casting alloys.
- ⤴ The phase which forms from the liquid in high Si foundry alloys is  $\beta$ -FeSiAl<sub>5</sub>.
- ⤴ Acicular, or needle-like, in morphology, these particles are commonly referred to as  $\beta$ -AlFeSi needles, but they are actually plates.
- ⤴ Adding Mn at levels equal to roughly half the Fe content corrects the phase to script  $(\text{Fe,Mn})_3\text{Si}_2\text{Al}_{15}$  or  $\beta$ -AlFeSi.



$\beta$ -AlFeSi needles

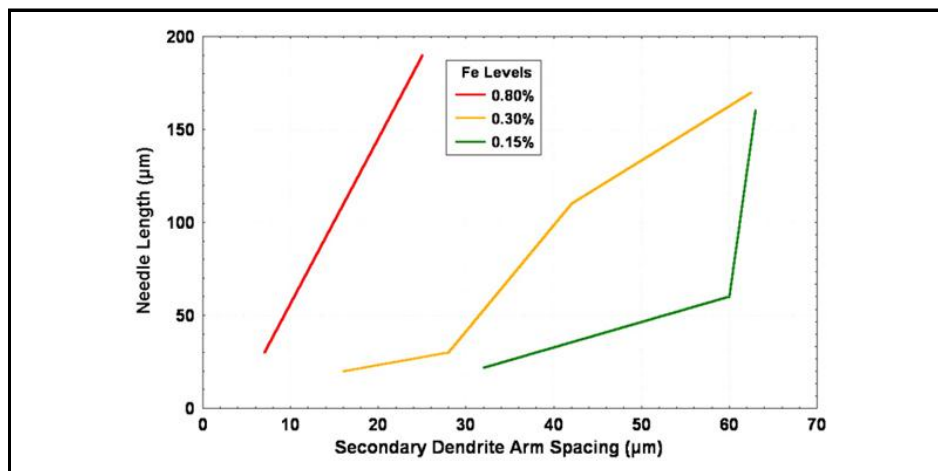


Alpha-Fe Script Phase  $(\text{Fe,Mn})_3\text{Si}_2\text{Al}_{15}$  in 357

Less harmful than  $\beta$ -AlFeSi needles but still embrittling

### $\beta$ -AlFeSi needle length

- ⤴ The length of the  $\beta$ -AlFeSi needles is a function of the cooling rate (of which the secondary dendrite arm spacing is a measure).
- ⤴ The  $\beta$ -AlFeSi needle length also increases with the Fe content.

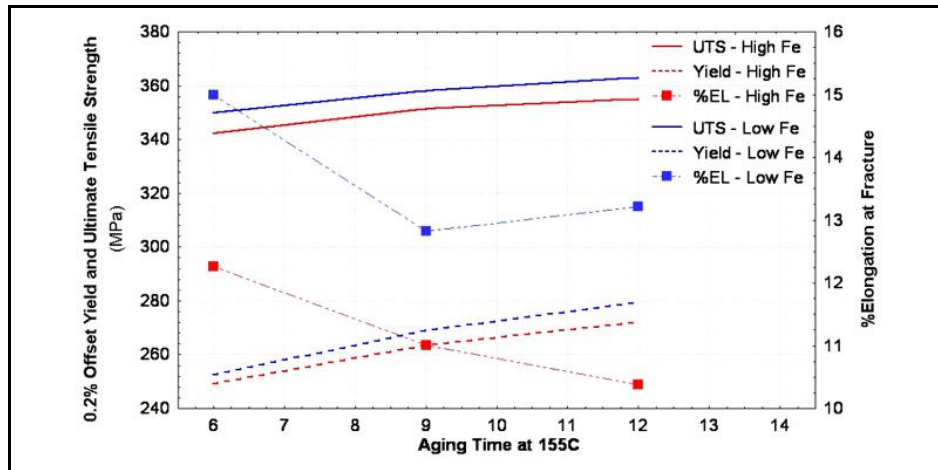


$\beta$ -AlFeSi needle length as function of secondary dendrite arm spacing

Source: Biswal et al.

## Impact of Fe on mechanical properties

- ⤴ The presence of  $\beta$ -AlFeSi needles will degrade the mechanical properties of the alloys.
- ⤴ The ductility is the most strongly impacted property, particularly in secondary alloys with high Fe-content.

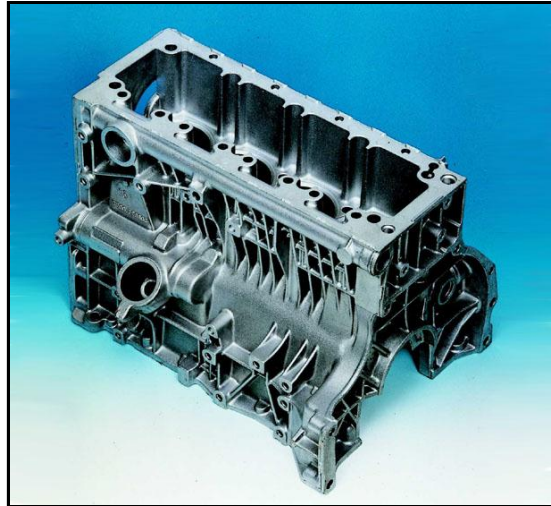


Comparison of low vs. high Fe 357 alloys (0.093% Fe vs. 0.055% Fe)

Source: F. Major, Alcan

## 6.2.4 Typical application areas

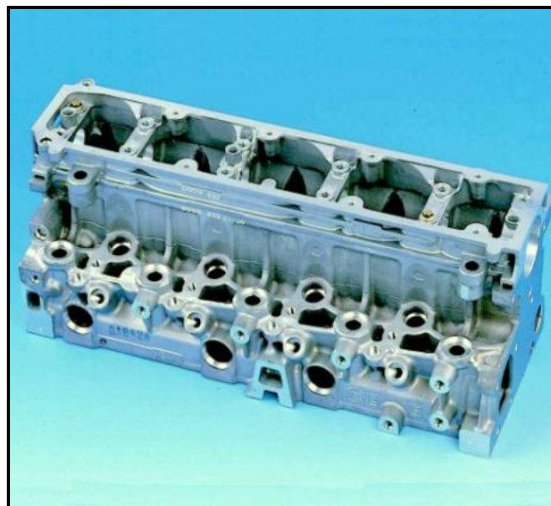
### Main Foundry Alloys and their applications



Renault Safrane cylindre block

Source: Renault

Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
<p><b>Al-Si-Cu Alloys for Power train Applications</b></p> <ul style="list-style-type: none"> <li>The primary requirements include elevated temperature strength and hardness.</li> <li>Ductility is generally low.</li> </ul>	<p>EN AC-Al Si5Cu3(Mg)(Mn)</p> <p>EN AC-Al Si7Cu3Mg EN AC Al Si8Cu3 (AA 319 / AA320)</p> <p>EN AC-Al Si9Cu3Fe (AA 380) EN AC-Al Si11Cu2 (AA 383)</p>	<ul style="list-style-type: none"> <li>Gravity diecasting (with sand cores)</li> <li>Lost foam</li> <li>Cosworth</li> <li>Low pressure</li> <li>Conventional or vacuum high pressure diecasting</li> </ul>	<p>4.5 - 8.5% Si 3 - 4% Cu 0 - 0.5% Mg &lt; 0,5 (0.8)% Fe Na, Sr, or Sb refinement</p> <p>8-11% Si 2-4% Cu 0,05 - 0,55% Mg &lt; 1.3% Fe</p>	<ul style="list-style-type: none"> <li>Hydraulically cooled engine blocks and cylinderheads.</li> <li>Closed deck cylinderhead design</li> <li>Large inline 4 or 5 cylinder blocks</li> <li>V6 and V8 cylinderblocks</li> <li>Small to medium 4 cylinder engine blocks with open deck design.</li> <li>Transmission cases</li> </ul>

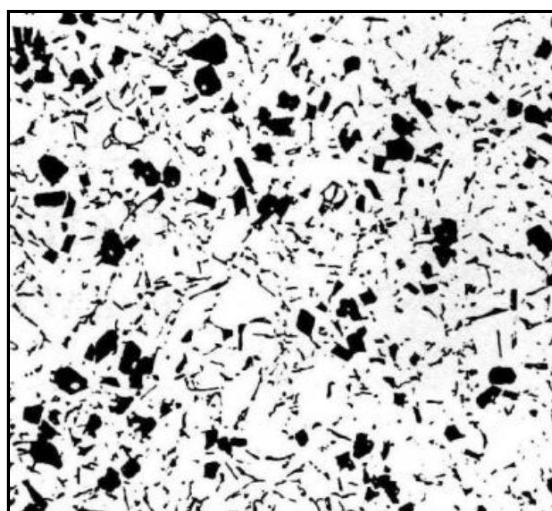


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Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
<b>Al-Si-Mg Alloys for Powertrain Applications</b> <ul style="list-style-type: none"> <li>Thermal fatigue resistance, and/or strength and ductility.</li> </ul>	EN AC-AI Si7Mg EN AC-AI Si7Mg0,3 (AA 356 / AA A356)  EN AC-AI Si9Mg EN AC-AI Si10Mg (AA 359 / AA 360)	<ul style="list-style-type: none"> <li>Gravity diecasting (with sand cores)</li> <li>Low pressure diecasting</li> </ul>	7-10 % Si 0,25-0,5% Mg < 0,2% Fe (1) < 0,1% Cu (1) < 0,6% Fe (2) < 0,3% Cu (1) Na, Sr, or Sb ref.	<ul style="list-style-type: none"> <li>Heavily stressed diesel engine cylinderheads</li> <li>Differential carriers</li> </ul> (1) = primary alloys (2) = secondary alloys
<b>Al-Si-Mg Alloys for Suspension Components</b> <ul style="list-style-type: none"> <li>Ductility, fracture toughness</li> <li>Safety critical components</li> </ul>	EN AC-AI Si7Mg0,3 EN AC-AISi7Mg0,5 (AA A356 / AA A357)	<ul style="list-style-type: none"> <li>Gravity diecasting</li> <li>Low pressure diecasting</li> <li>Squeeze casting</li> <li>Semi-solid forming</li> </ul>	6,5-7,5% Si 0,2 – 0,6% Mg < 0,2% Fe < 0,1% Cu Na, Sr, or Sb refinement	<ul style="list-style-type: none"> <li>Upper and lower suspension control arms.</li> <li>Rear knuckles</li> <li>Front steering knuckles</li> <li>Cross-members</li> </ul>

Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
<b>Al-Cu Alloys for Automotive Suspension Parts</b>	EN AC-AI Cu4MgTi (AA A206 / AA 206)	<ul style="list-style-type: none"> <li>Premium quality sand casting</li> <li>Gravity diecasting</li> </ul>	4,2-5,0% Cu 0,15-0,35% Mg < 0,35% Fe 0,15-0,30% Ti	<ul style="list-style-type: none"> <li>Simply shaped knuckles or control arms for speciality automotive applications: sports cars and other limited volume high price cars.</li> </ul>
<b>Al-Si-Mg and Al-Si Alloys for Wheels</b>	EN AC-AI Si7Mg0,3 (AA A356)  EN AC-AI Si11	<ul style="list-style-type: none"> <li>Gravity diecasting</li> <li>Low pressure diecasting</li> </ul>	6,5-7,5% Si < 0,05% Cu 0,25 – 0,45% Mg < 0,20% Fe  Sr or Sb refinement 10,5-12,5% Si < 0,05% Cu < 0,45% Mg < 0,20 % Fe Sr modification	<ul style="list-style-type: none"> <li>General purpose fully heat treated automotive wheels.</li> <li>Lightly loaded non-heat-treated automotive wheels.</li> </ul>

Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common and Alternative Processes	Typical Composition	Application Notes
<b>Al-Si and Al-Mg Alloys for Steering Wheel Cores</b> <ul style="list-style-type: none"> <li>Impact energy absorption</li> <li>High ductility requirement</li> <li>Safety critical part</li> </ul>	AA B443 (Al Si5Fe) (no EN equivalent)  EN AC-AI Mg3 (AA 511)	<ul style="list-style-type: none"> <li>High pressure diecasting</li> <li>High pressure diecasting</li> </ul>	4,5– 6,0% Si < 0,15% Cu < 0,05% Mg < 0,35% Mn < 0,8% Fe  2,5–3,5 % Mg < 0,55% Si < 0,55% Fe < 0,45% Mn	<ul style="list-style-type: none"> <li>High pressure diecast steering wheel cores where high ductility at moderate strength is required.</li> <li>High pressure diecast steering wheel cores where very high ductility at low strength is required.</li> </ul>



**Primary Si particles in a P-refined hypereutectic Al-Si alloy**

Source: F. Major, Alcan



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Automotive Alloys by Family and Application	Most Commonly Used Alloys	Common Processes	Typical Composition	Application Notes
<b>Al-Si-Cu-Mg Alloys for Automotive Pistons</b> <ul style="list-style-type: none"> <li>Hypoeutectic, eutectic, and hypereutectic compositions are all commonly used.</li> <li>Hot Hardness and Wear Resistance are the primary requirements.</li> <li>Thermal Fatigue is also critical.</li> </ul>	<b>AA 332</b> (Al Si10Cu3Mg) <sup>*)</sup> <ul style="list-style-type: none"> <li>Commonly used alloy for light duty pistons</li> </ul> <b>EN AC-AI Si12CuNiMg</b> (AA 336) <ul style="list-style-type: none"> <li>Increased elevated temperature strength.</li> </ul> <b>AA A390</b> (Al Si17Cu4Mg) <sup>*)</sup> <ul style="list-style-type: none"> <li>Highest wear resistance</li> </ul>	Gravity Diecasting  <b>Notes:</b> <sup>*)</sup> no EN equivalent  <sup>**)</sup> when fine scattered Si primary particles are needed	8.5 – 10.5% Si 2.0 – 4.0% Cu 0.5 – 1.5% Mg < 1.2% Fe; < 0.5% Mn  10.5 – 13.5% Si 0.8 – 1.5% Cu 0.8 – 1.5% Mg 0.7 – 1.3% Ni < 0.7% Fe; < 0.35% Mn Na modif., or P ref. <sup>**)</sup>  16.0 – 18.0% Si 4.0 – 5.0% Cu 0.45 – 0.65% Mg < 0.50% Fe, P refinement	<ul style="list-style-type: none"> <li>The complexity of these alloys varies with the piston type. The more heavily loaded the piston is, mechanically or thermally, the more highly alloyed it must be to survive the service environment.</li> <li>Both gasoline and diesel engine pistons are commonly cast.</li> <li>Many proprietary compositions exist.</li> <li>The more highly alloyed compositions have a high intermetallic compound content, which gives the wear, and scuff resistance in a very demanding environment.</li> <li>The intermetallic content also helps to give the alloys hot hardness and strength at elevated temperatures.</li> <li>When requested, the presence of Si primary particles gives the alloy the wear behaviour of a natural composite.</li> </ul>

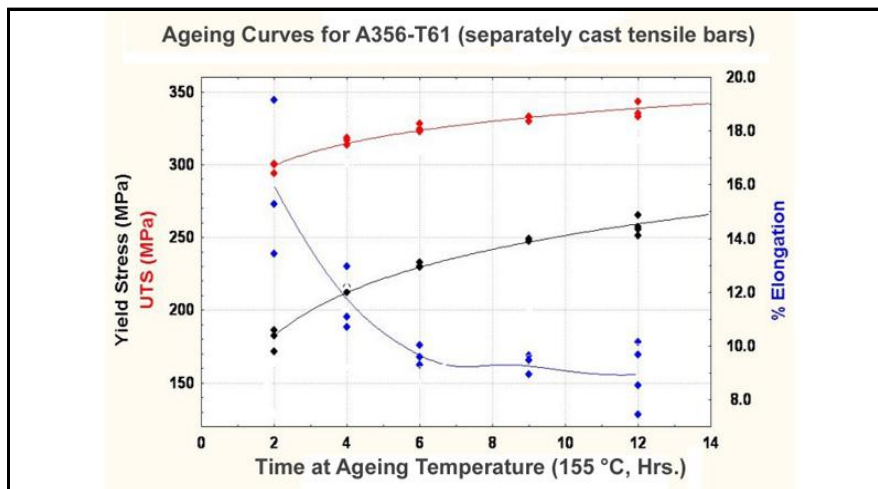


## 6.3 Tempers and mechanical properties

### 6.3.1 Strengthening mechanisms in casting alloys

#### Strengthening Mechanisms in Casting Alloys

- ⤴ Castings are generally not strengthened by work hardening.
- ⤴ **Solid solution strengthening** occurs and is largely determined by the alloy composition.
- ⤴ **Precipitation hardening** is the most commonly applied and flexible strengthening mechanism.
- ⤴ The alloy is solution annealed at high temperature to dissolve the elements which will be used to create the precipitates.
- ⤴ The alloy is then hot-water quenched to create a super-saturated solid-solution with minimal quench-distortion.
- ⤴ Sub-microscopic intermetallic compounds are precipitated throughout the Al alloy matrix. The concentration of the hardening elements determines the strength of response.
- ⤴ The super-saturated solid solution is heated to a low temperature to allow enough atomic mobility for the pre-precipitation hardening elements to form into precipitates.
- ⤴ The mechanical result is an **ageing curve** in which the yield and ultimate strengths gradually increase as the ductility comes down. The process is halted when the desired properties are achieved.



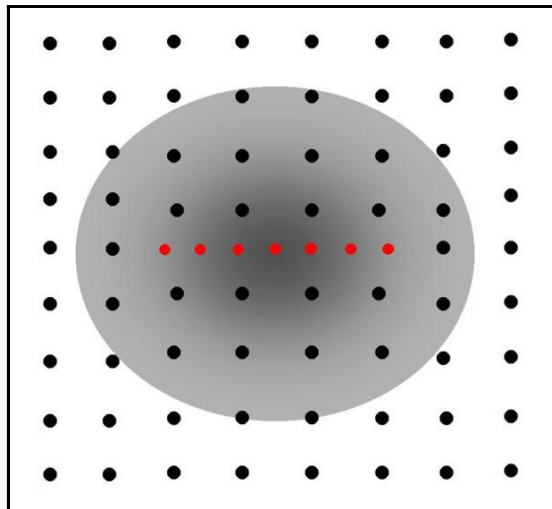
Classic Aging curve for A356-T61

Source: F. Major, Alcan

#### General Precipitation Sequence:

Super-saturated solid solution → GPZ →  $\theta''$  →  $\theta'$  →  $\theta$

- ⤴ Super-saturated solid solution: low strength and soft
- ⤴ GPZ (Guinier-Preston zones): stronger
- ⤴  $\theta'' + \theta'$  (increasingly large precipitates): stronger still
- ⤴  $\theta$  (large end-stage particles): soft again (overaged)



Schematic diagram of a Gunier-Preston Zone

Differences in atomic sizes induce a lattice strain field which hampers dislocation motion

#### Possible Precipitation Hardening Chemistries:

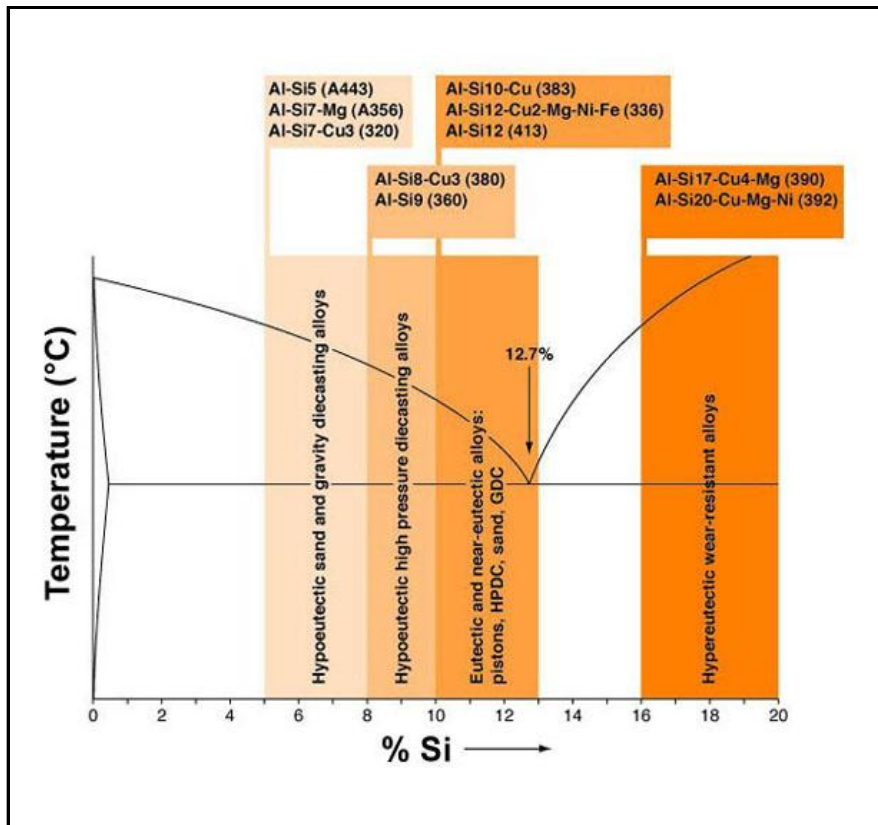
- ⤴ Al-Cu; end stage is  $\text{CuAl}_2$
- ⤴ Al-Mg; end stage is  $\text{Mg}_2\text{Si}$
- ⤴ Al-Cu-Mg; end stage is  $\text{CuMgAl}_2$
- ⤴ Al-Zn-Mg; end stage is  $\text{MgZn}_2$  ( $\text{Zn} > \text{Mg}$ )
- ⤴ Al-Mg-Zn; end stage is  $\text{Mg}_3\text{Zn}_3\text{Al}_2$  ( $\text{Zn} < \text{Mg}$ )

#### Engineering Aspects of Precipitation Strengthening

- ⤴ Quenching of cast parts from temperatures in the vicinity of  $500^\circ\text{C} - 540^\circ\text{C}$  may cause warpage of the castings. A straightening operation before artificial ageing, when the casting is in its softest condition, is not uncommon.
- ⤴ The precipitation hardening process may cause growth of the castings. This occurs because of the volume change associated with the formation of precipitates from solid solution. Alloys may be aged for strengthening reasons or they may be aged to stabilize them dimensionally.
- ⤴ Note that the Al-Zn-Mg and Al-Mg-Zn systems do not grow.

## 6.4 Microstructure and porosity

### 6.4.1 Microstructure – The Al-Si Eutectic System



Schematic diagram of the Al-Si eutectic system

#### The Al-Si Eutectic System

##### Importance

As shown in the schematic Al-Si phase diagram, the majority of commercial foundry alloys are based on this alloy system.

- ⤴ **Hypoeutectic Alloys** (<11% Si) are composed of a forest of Al dendrites surrounded by interdendritic Al-Si eutectic (1:1 ratio depending on alloy)
- ⤴ **Eutectic or near eutectic alloys** (11 < Si < 13) may consist almost entirely of eutectic.
- ⤴ **Hypereutectic alloys** (>13% Si) will consist of a eutectic matrix together with wear resistant primary Si.

#### Eutectic Morphology Control

##### Why?

- ⤴ Aluminium is a **ductile** metallic element which can be alloyed to give a wide range of combinations of strength and ductility.
- ⤴ Silicon is a glassy, hard, **brittle** semi-conductor whose presence in foundry alloys is important during solidification as it makes the alloy castable.
- ⤴ Once solid, these alloys are in-situ composites.
- ⤴ An alloy in which the Al-Si eutectic has been well modified may show a **ductility** up to three times higher than the same alloy unmodified.

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### How?

- ⤴ The shape of the Si may be changed by cooling rate. At high freezing rates this is called **quench modification**
- ⤴ The shape of the Si may be changed by a solutionizing heat treatment. This is **thermal modification**.
- ⤴ Chemical additions of elements like Na, Sr, Sb, or P may be made to the melt. This is **chemical modification**

## 6.4.2 Microstructure – Morphologies of the Al-Si-eutectic

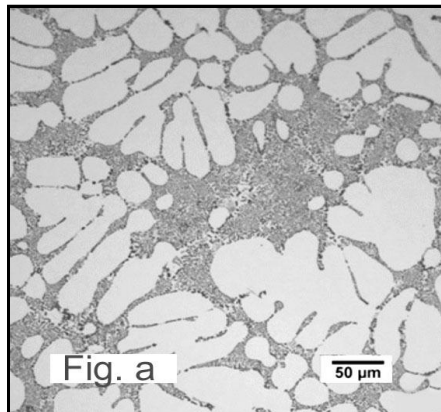
Fig. a: Typical as-cast microstructure with dendrites and eutectic.

Fig. b: Eutectic composition solidified vertically upwards at a slow rate, then quenched and the Al phase etched back.

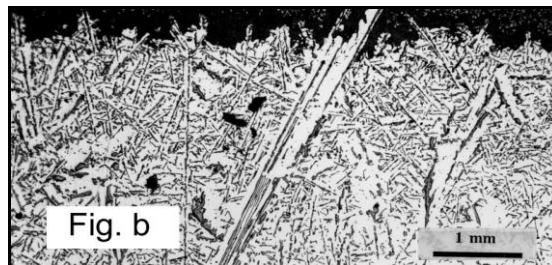
Fig. c: Large faceted acicular Si plates. The fine white structures surrounding it are quench modified Si fibres.

Fig. d: Chemically modified Al-Si eutectic also forms as extremely fine fibres (F temper).

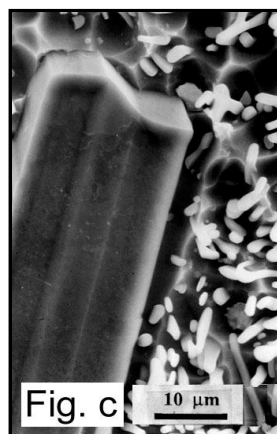
Fig. e: Solution heat treatment (T6 temper) causes brittle fibres to coagulate into discontinuous particles.



**Micrograph of hypoeutectic A356 alloy showing the typical dendrite plus eutectic structure**

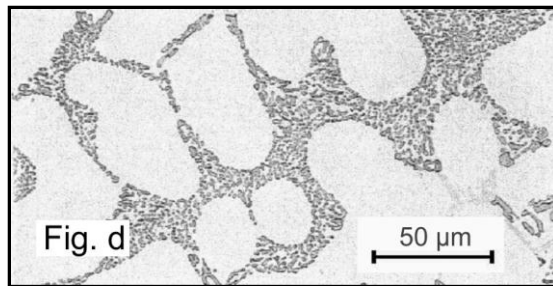


**Classic unmodified acicular Al-Si eutectic  
Quenched solid-liquid interface at top**

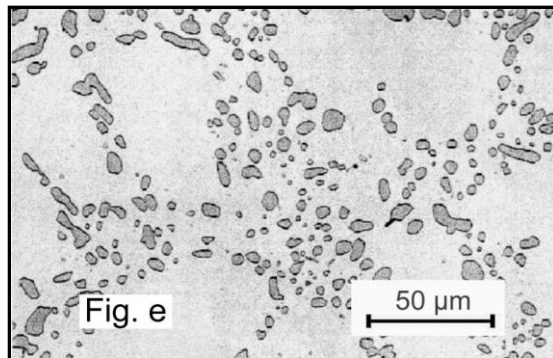


**Slowly solidified and then quenched**

**This SEM micrograph shows the scale of both acicular and fibrous Si**



**Micrograph of modified A356 alloy as-cast**  
**A fine, hard to resolve fibrous eutectic**



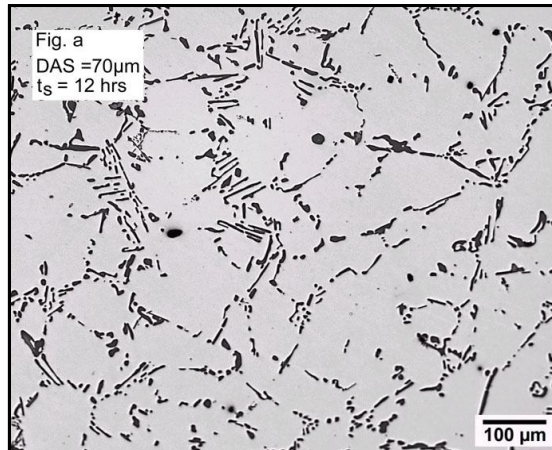
**Micrograph of modified A356 alloy in the T6 temper**  
**Discontinuous spheroidised eutectic**



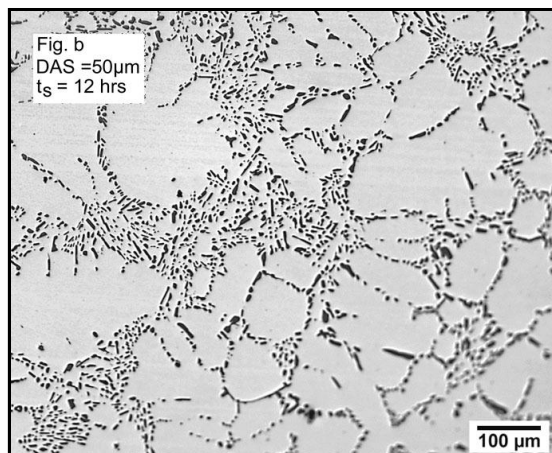
### 6.4.3 Microstructure – Thermal modification of the Al-Si-eutectic

**Effects of solidification rate (DAS)** on thermal modification treatment: Before chemical modifiers were discovered, heat treatment was used to round and spheroidise the Si phase in order to improve mechanical properties. Some legacy heat treatment cycles still call for lengthy solutionising times.

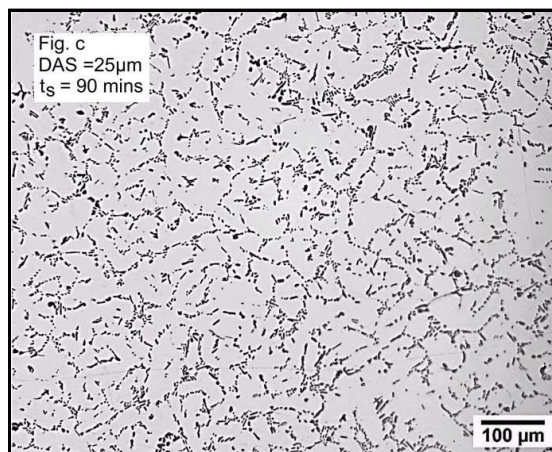
**Below:** Very coarse microstructures (DAS = 70  $\mu\text{m}$ ) cannot be thermally modified.



**Below:** Medium coarse microstructure (DAS 50  $\mu\text{m}$ ) 12 hours is enough.



**Below:** Fine microstructures (DAS 25  $\mu\text{m}$ ) thermally modify quickly.





## 6.4.4 Modification of the Al-Si-eutectic by chemical modifiers and refining agents

### Sodium (Na)

- ⤴ One of the first chemical modifiers discovered.
- ⤴ Na is the strongest of the chemical modifiers in terms of amount required to modify. 30 ppm will completely modify most Al-Si alloys.
- ⤴ The major disadvantage is the fade rate. Na is lost from the melt by volatilisation in as little as 20 minutes.
- ⤴ Na can be added elementally via Na metal. Packed in sealed cans or foil packs, the master alloy must be kept dry and handled carefully as it is a hazardous material.
- ⤴ Na can be added by fluxes as well.

### Strontium (Sr)

- ⤴ Strontium is a slightly weaker modifier and amounts ranging from 80ppm to 200ppm may be required depending on the alloy and the cooling rate.
- ⤴ Generally available in two master alloys: Al-10%Sr and Sr-10%Al. The first is the most popular with foundries as it is inert and easy to handle while the second is reactive and flammable.
- ⤴ Sr is known to cause a reduction in the feeding distance and a greater tendency towards porosity.
- ⤴ Sr is more popular with many foundries as it fades much more slowly: hours rather than minutes.

### Antimony (Sb)

- ⤴ Sb refines the Si phase as opposed to modifying it. I.e. the microstructure remains acicular but becomes much finer; thermal modification then renders it indistinguishable from modified material.
- ⤴ Sb does not fade but is incompatible with Sr or Na.

### Phosphorous (P)

- ⤴ Phosphorous poisons the other modifiers/refiners where the Al-Si eutectic is concerned.
- ⤴ P is added to hypereutectic alloys to refine primary Si for wear resistance.

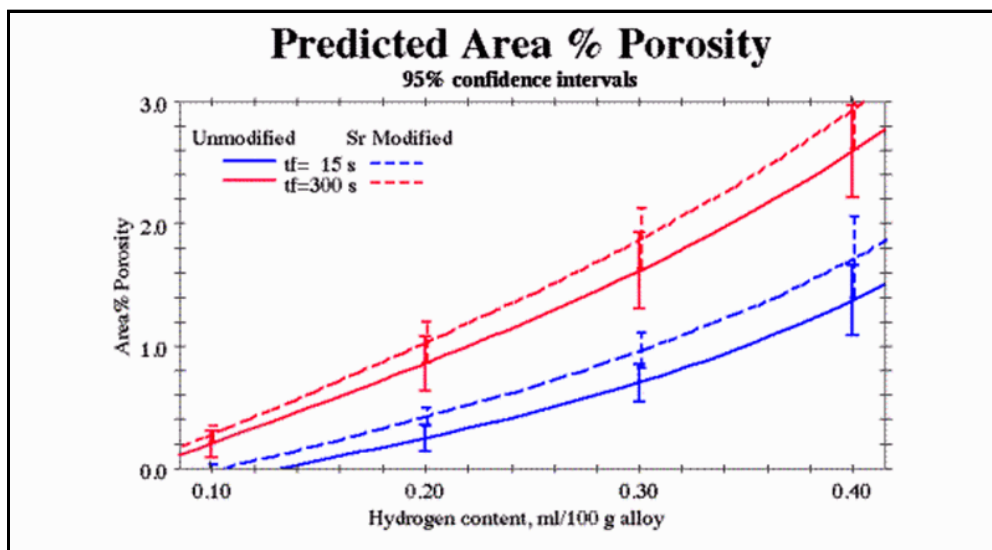
### 6.4.5 Porosity – Factors affecting hydrogen porosity

Literature:

- △ Tynelius K., Major J.F., and Apelian D.: A Parametric Study of Microporosity in the A356 Casting Alloy System, AFS Transactions, 93-166, 1993, pp. 401-413

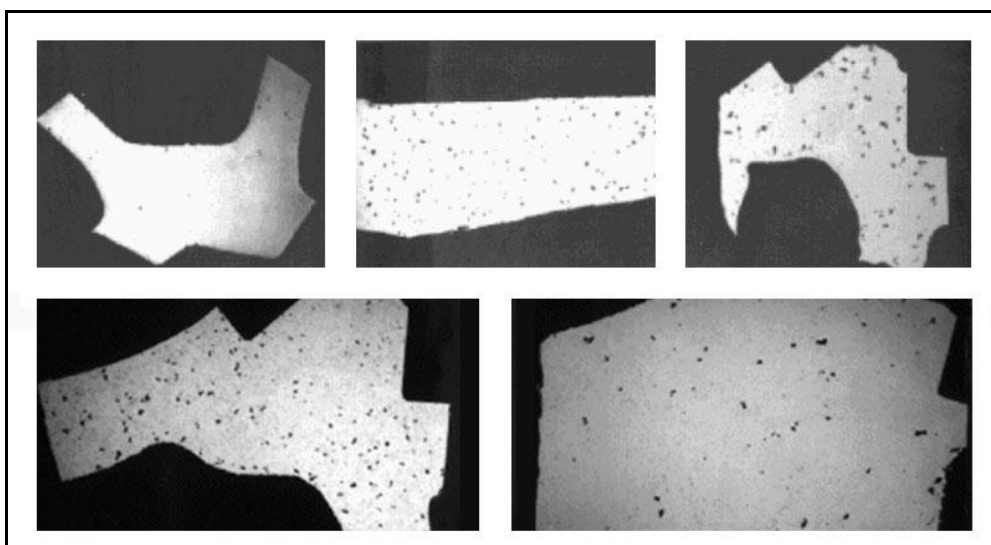
Many factors influence hydrogen porosity formation in Al alloy castings:

- △ The amount and size of porosity which will actually form at any given gas level is a function of metallurgical factors such as the Sr content and use of particulate grain refiners.
- △ Local process parameters such as the total freezing time (tf) will also influence the quantity of porosity.



Results from a parametric study of porosity in the AISi7 (A356) alloy system

Source: F. Major, Alcan



Combustion bridge sections from a number of commercially produced cylinderheads showing pores

### 6.4.6 Porosity – Factors affecting elongation

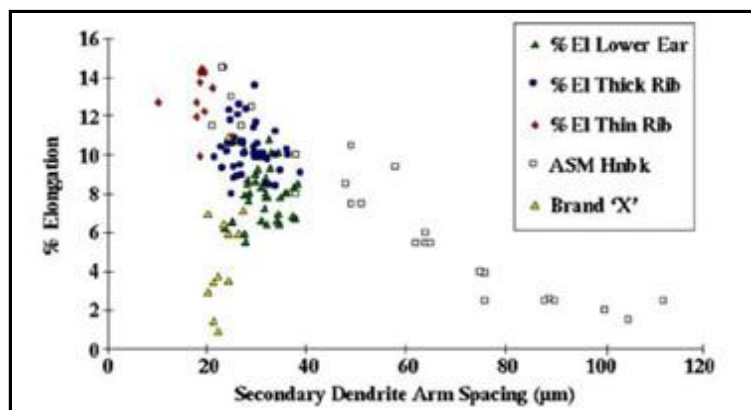
Literature:

- ^ Major, J.F., Makinde, A., Lee, P.D., Chamberlain, B., Scappaticci, T., Richman, D., The Lincoln Mark VIII Cast Aluminium Suspension Control Arm, in Vehicle Suspension System Enhancements, SAE SP-1031, Techn. Paper 940874, pp. 117-128



**Lower Suspension Control Arm with Regions of Varying Thickness Marked for Comparison**

One of the easiest microstructural features to measure or predict the secondary dendrite arm spacing (DAS) correlates with the ductility of the alloy unless porous (as in Brand "X"). The secondary dendrite arm spacing (DAS) varies with cooling rate and hence with part thickness. QA data from the three regions in the casting above are shown below.

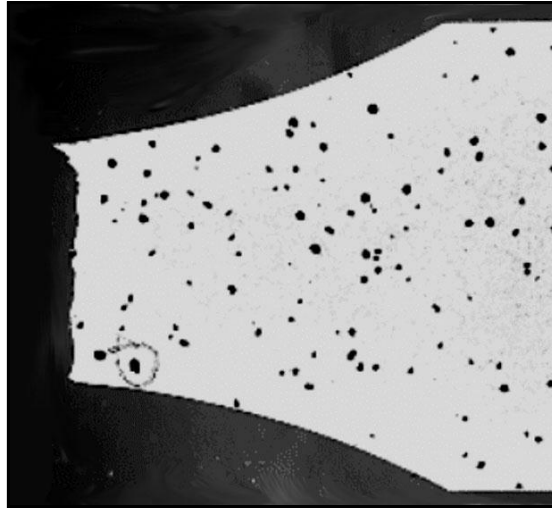


**Casting QA data is compared to the handbook curve of DAS vs % Elongation for A356-T6**

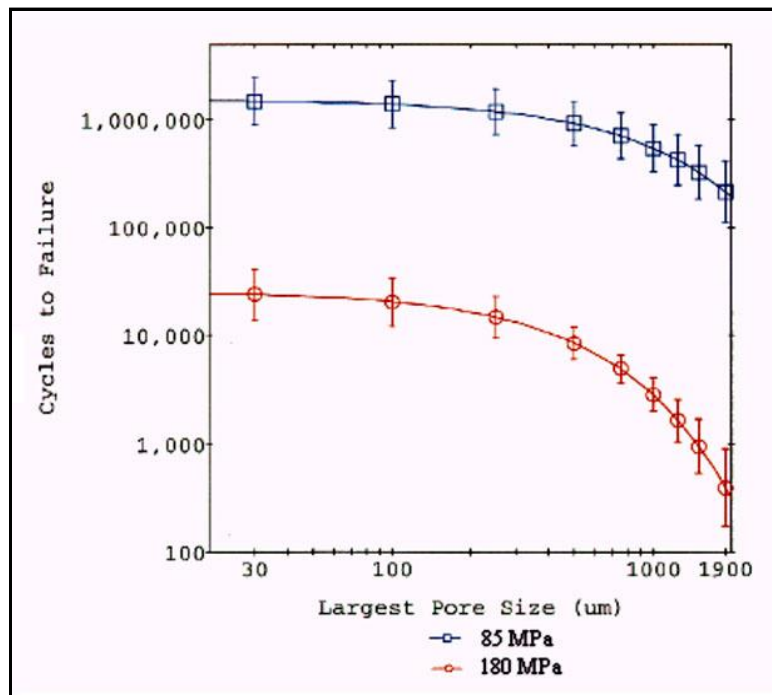
### 6.4.7 Porosity – Factors affecting fatigue life

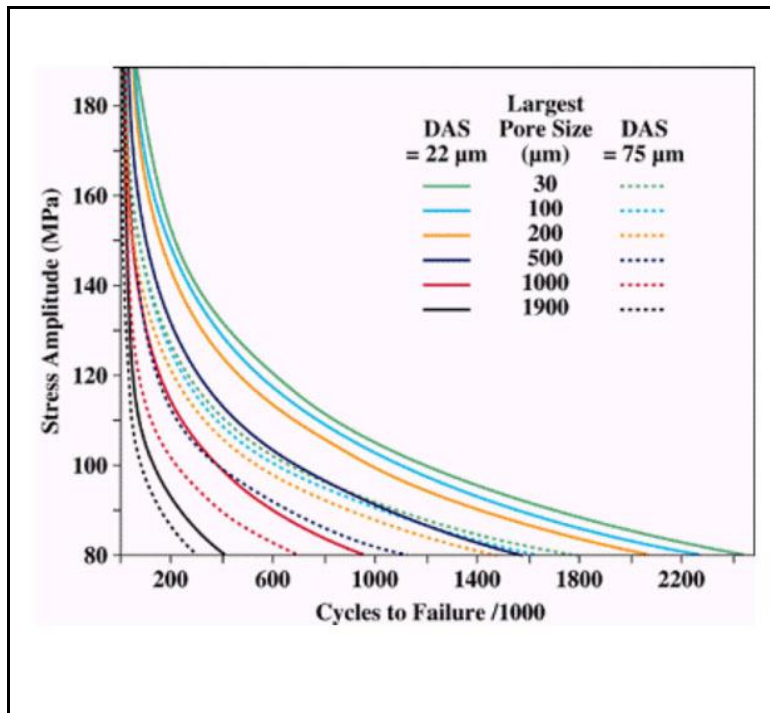
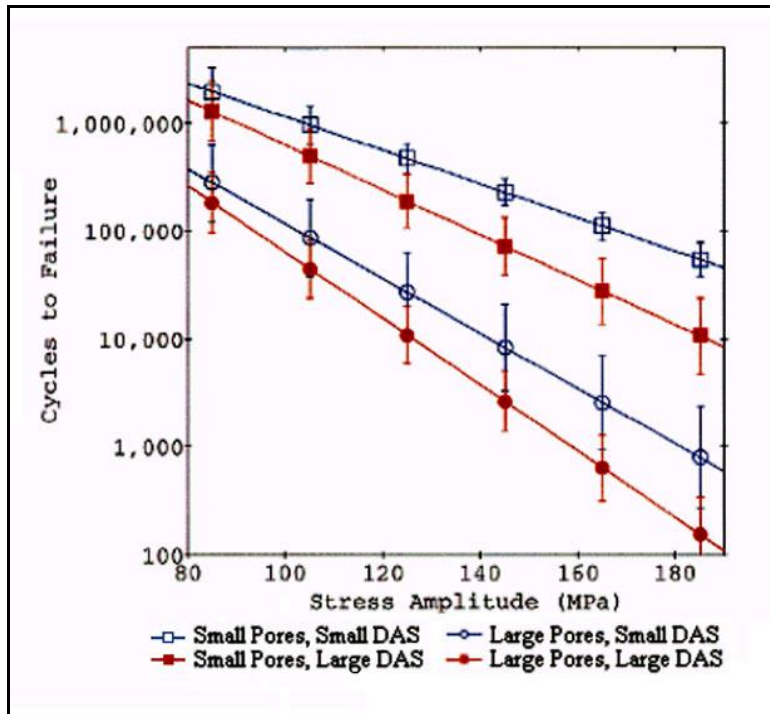
Literature:

- ^ Major J.F.: Porosity Control and Fatigue Behaviour in A356-T61 Aluminum Alloy, AFS Transactions, 97-94, 1997, pp. 901-906



Tested sample for determining fatigue life of casting with varying porosity levels





Source: F. Major, Alcan (s. Lit.)

Fatigue properties are strongly impacted by porosity. The largest pore size in a sample will limit the fatigue life.

The scale of the microstructure is also important and the fatigue life will correlate inversely with the secondary dendrite arm spacing or DAS.

## **6.5 Thermal stability**

*Work in progress*

## **6.6 Crashworthiness**

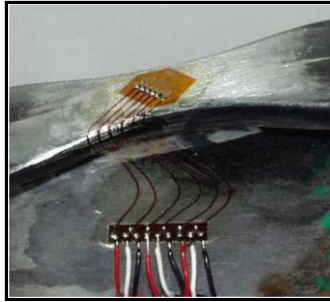
*Work in progress*

## 6.7 Fatigue of components

### 6.7.1 Fatigue of cast components

Literature:

- ⤴ Terjesen, G.: Effects of elevated temperatures on tensile properties and fatigue strength of an AlSi10Mg alloy. ALUMINIUM 78, 2002, p. 464-469



Aluminium castings have had for long a reputation of low fatigue strength.

However, aircraft builders were interested since the 80' in replacing riveted multi-components structures by single castings and tested them: it was demonstrated every time that the casting had a better fatigue resistance than the equivalent riveted part.

A wide spread application has been for years designed and tested upon fatigue criteria: **car wheels**.

#### Quality of castings and fatigue strength

- ⤴ The actual fatigue performances of castings, compared to values obtained on test-bars, can be lowered mainly by surface or sub-surface defects that act as local stress raisers and crack initiators.
- ⤴ The more detrimental defects are **oxides**, when in the shape of films, and cold shuts.
- ⤴ The critical dimension of defects is about 300  $\mu\text{m}$ , defects under 100  $\mu\text{m}$  have usually no detrimental influence.

#### Design and production process provisions

"Hot spots" of maximal stresses must be indicated to the foundry, so that particular care be taken in these areas.

