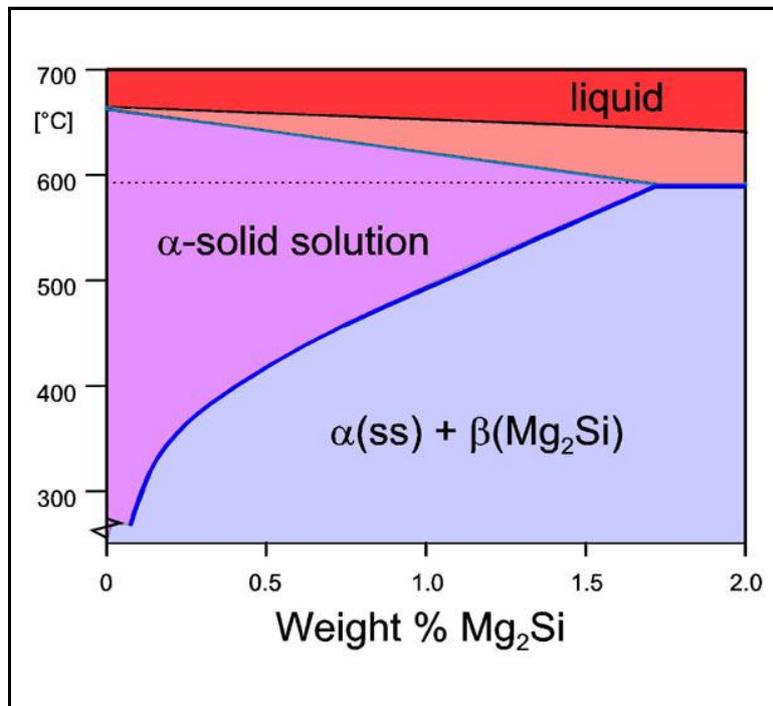


Materials – Alloy constitution

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2 Alloy constitution



Equilibrium phase diagram of the Al-Mg₂Si system

2.1 Understanding properties, behaviour and heat treatment

Literature:

- ⤴ Altenpohl, D., Aluminium von innen, Düsseldorf: Aluminium-Verlag, 1994, ISBN 3-87017-235-5
- ⤴ Altenpohl, D.G., Aluminium: Technology, applications, and environment - A profile of a metal, Washington, D.C.: The Aluminum Association, and Warrendale, Pa.: The Minerals, Metals & Materials Society (TMS), 1998, ISBN 0-87339-406-2
- ⤴ Hatch, J. E. (ed.), Aluminium: properties and physical metallurgy, Metals Park, Ohio: American Society for Metals, 1984, ISBN 0-87170-176-6
- ⤴ Ostermann, F., Anwendungstechnologie Aluminium, Berlin, Heidelberg, London, New York, Tokyo: Springer-Verlag, 1998, ISBN 3-540-62706-5

Unalloyed, pure aluminium is very soft and ductile. For structural and other uses **alloying elements** are added to impart desired properties, such as strength, toughness, corrosion resistance and physical properties.

According to the theories of metallurgical thermodynamics alloying elements can enter the crystal structure as solid solution or build various **constituent phases** depending on composition, temperature and on the kinetics of nucleation and growth processes. The types of phases existing in an alloy of given composition and at various temperature regimes are mapped in **phase diagrams**.

The parameters of the complete chain of thermo-mechanical processes in the production of a cast or wrought product influence the type and distribution of alloying elements and constituent phases in the microstructure and thereby determine the **properties** and **behaviour** of the product.

Knowledge of the **alloy constitution** is therefore the basis for alloy selection and for understanding the properties and behaviour during fabrication and service.

THE Aluminium Automotive MANUAL

This chapter describes the effects of the main **alloying elements** in automotive aluminium alloys, the **strengthening mechanisms** employed as well as the basic effects of **heat treatment** during manufacturing at the materials' supplier and during fabrication at the user's end.

Improvement of cold formability, ductility or strength by heat treatments depends on the constitution of the individual aluminium alloys and their products.

2.2 Basic aluminium alloy groups

See also:

- ⤴ AAM – Materials – 3 Designation system
- ⤴ AAM – Products – 1 Rolled products
- ⤴ AAM – Products – 2 Extruded products
- ⤴ AAM – Products – 6 Cast alloys and products > Alloys

Casting alloys & wrought alloys

It is useful to distinguish between casting and wrought alloys, since their constitution is typically different according to the respective requirements of **castability** (fluidity, solidification characteristic and resistance to hot cracking) and **hot formability** (homogeneous α -solid solution for optimum behaviour during hot rolling, extruding and forging).

Accordingly and traditionally, there is a different **designation system** for these two groups of **aluminium alloys** in various national and international standards.

Age-hardening alloys & strain-hardening alloys

Wrought alloys and casting alloys may be also distinguished by their prevalent strengthening mechanism, which is reflected by the **temper designation**:

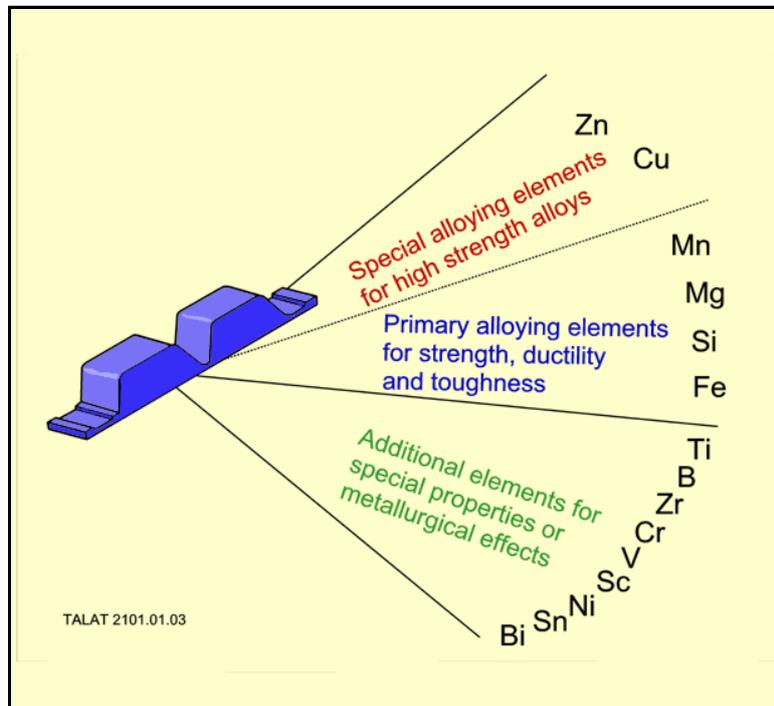
- ⤴ **Non-age-hardening alloys** are solid solution strengthened. Wrought alloys may be further strengthened by work-hardening (**H-temper**s).
- ⤴ **Age-hardening alloys** are precipitation strengthened and afford a special heat treatment (**T-temper**s)

Process dependence of alloy constitution

The alloy composition also reflects the type of processes used to manufacture the casting or the semi-finished wrought product. Alloys are specifically designed for a particular casting method (sand, die, high-pressure die casting, etc.) as well as for the type of hot (and cold) forming methods (rolling, extruding, forging).

Therefore, alloys used with specific semi-product manufacturing processes should be selected from the respective lists provided in the Manual's section "**Products**".

2.3 Elements



Source: Vocational TALAT, ATS 1999

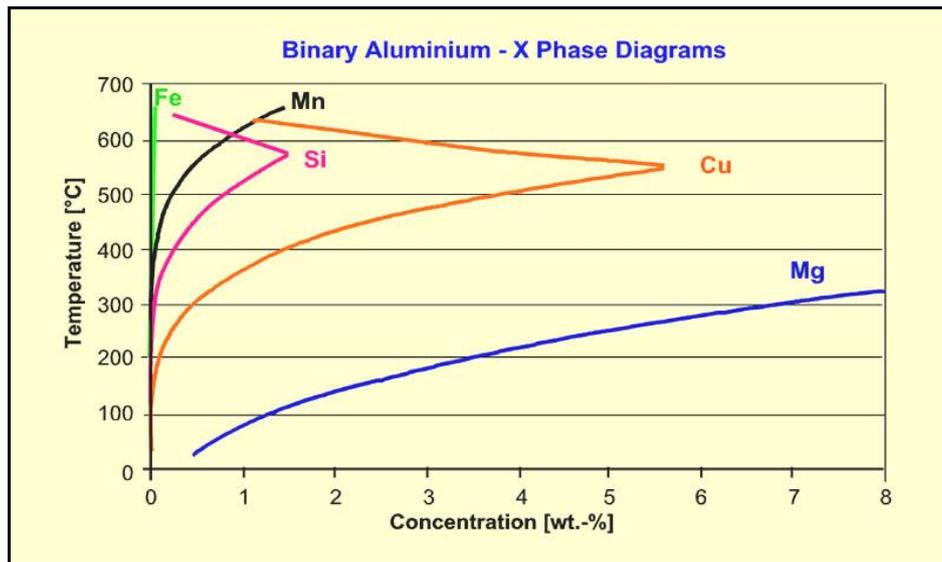
2.3.1 Solid solubility of alloying elements in aluminium

Most alloying elements have limited solubility in solid Al.

Beyond the limit demarcated by the solvus on the phase diagram, further amounts lead to formation of intermetallic phases.

	Element	Max. Solubility (wt. %)
High Solubility	Zn	70
	Mg	17.4
	Cu	5.65
	Mn	1.8
	Si	1.65
Low Solubility	Ti	1.3
	Cr	0.77
	Zr	0.28
	Fe	0.05

The table (above) and the diagram (below) show that different alloying elements have different solubilities in solid Al.



Binary phase diagrams showing differing solute solubility in Al

2.3.2 Strengthening of alloying elements in α -solid solution

See also:

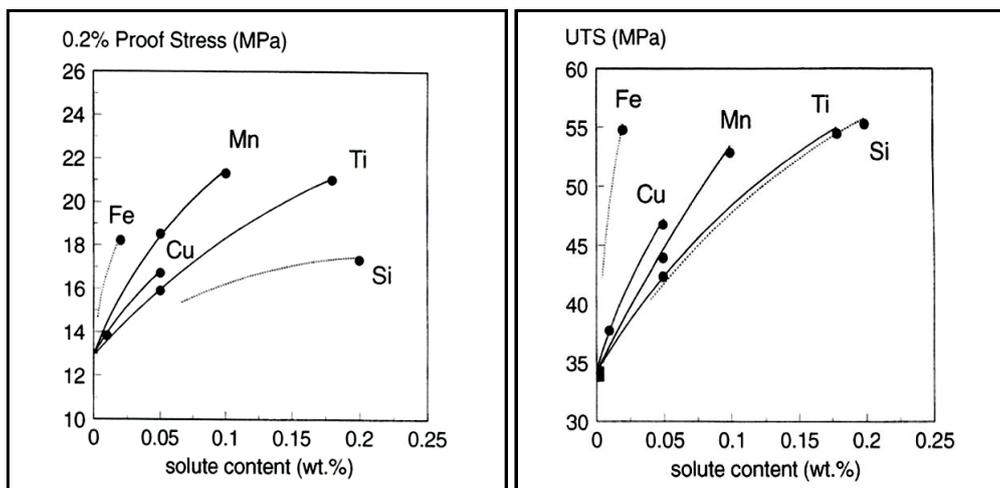
- ▲ AAM – Materials – 2 Alloy constitution > Strengthening mechanisms

Literature:

- ▲ Mondolfo, L.F.: Aluminium Alloys-Structure and Properties, Butterworths, 1979.
- ▲ Mahon, G.J., Marshall, G. J.: Microstructure Property Relationships in O-Temper Foil Alloys, JOM, vol 48(6), 1996, pp. 39-42.

Alloying elements are added in Al for different purposes. Si is added to improve the fluidity of molten Al and Ti (on its own or as TiB₂ or TiC grain refiners) are added to improve castability. Most other elements are added to improve strength of the final product in different ways.

The figures below show the effect of strengthening of different alloying elements in super pure binary Al alloys.



Graphs showing the effect of alloying additions on strengthening super pure Al binary alloys

Slow and fast diffusing elements in aluminium

See also:

- ▲ AAM – Materials – 2 Alloy constitution > Heat treatment

Literature:

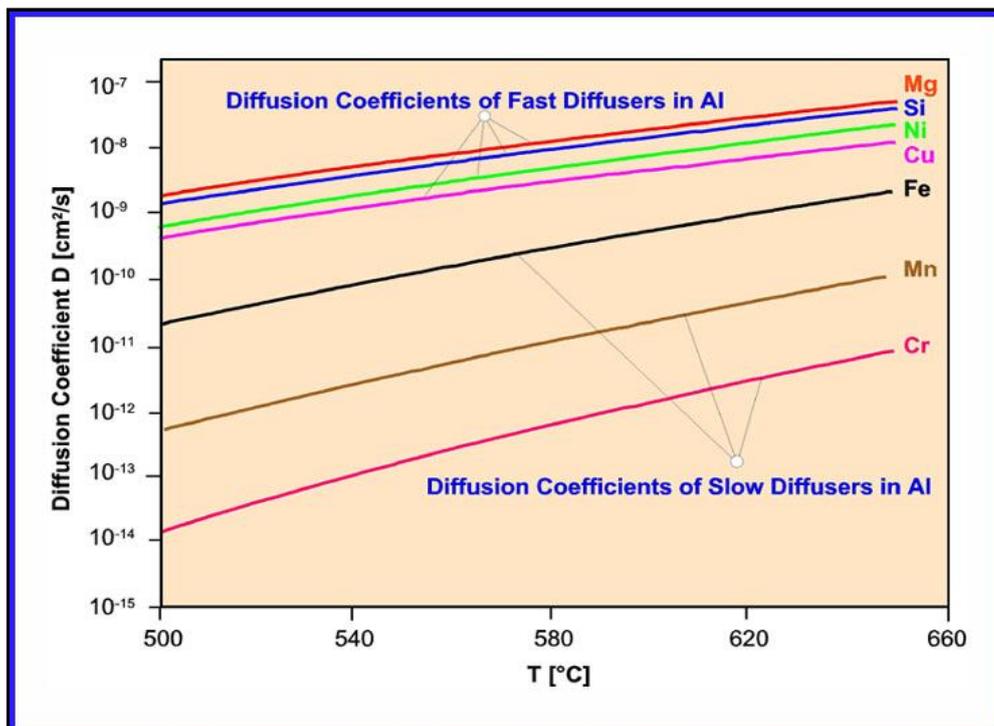
- ▲ Smithells Metals Reference Book (eds: E.A. Brandes, G.B. Brook), Butterworth-Heinemann Publishing, 7th edition, 1992, chapter 13.

The **atomic sizes** of different alloying elements in Al vary compared to that of aluminium. Consequently, different alloying elements **diffuse at different rates** in Al during **heat treatments**.

Element	Atomic Radius (nm)
Al	0.118
Si	0.146
Zn	0.153
Cu	0.157
Mg	0.160
Fe	0.172
Mn	0.179
Cr	0.185
Ti	0.200
Zr	0.216

Figure (below):

Diffusion coefficients of fast and slow diffusers in aluminium. Alloys containing **slow diffusers** need longer heating times compared to those containing **fast diffusers**. For a given temperature, diffusion coefficients of fast and slow diffusers vary by many orders of magnitude.



2.3.3 Major and minor alloying elements

See also:

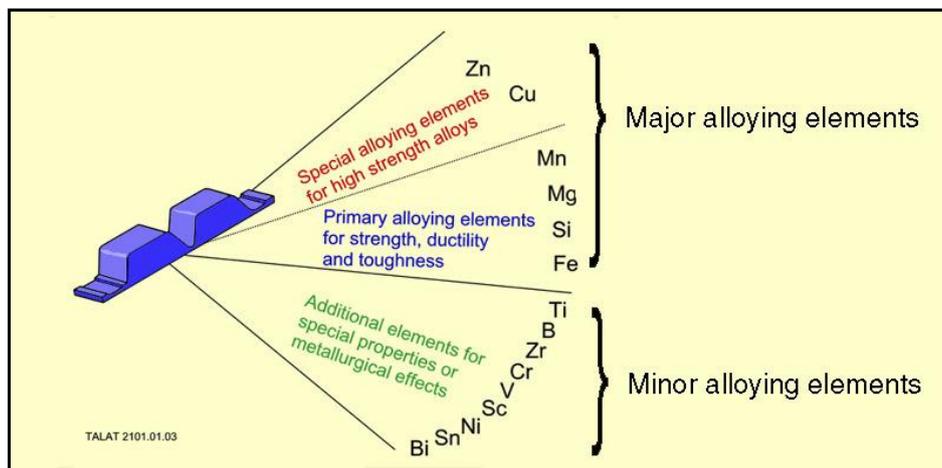
- ⤴ AAM – Materials – 3 Designation system > Cast alloys > Designation system for casting alloys – EN 1780-1
- ⤴ AAM – Materials – 3 Designation system > Wrought alloys > Alloy designation system for wrought alloys (EN 573)

Literature:

- ⤴ Polmear, I. J.: Light Alloys-Metallurgy of the Light Metals, 3rd edition, chapters 3 and 4

Major alloying elements are specially added to the alloy to introduce certain specific properties (solid solution strengthening, strain hardening, precipitation or age hardening, ease of casting etc.) during use.

Minor alloying additions - usually those with low solid solubility - form coarse and fine intermetallic phases and indirectly affect properties, e.g. by grain refining during casting or heat treatments.



Major and minor alloying elements in aluminium

	Alloy Group	Major Alloying Element	Solution Hardening	Work Hardening	Precipitation Hardening	
Wrought Alloys EN AW-	1xxx	None				non-heat treatable alloys
	3xxx	Mn	X	X		
	4xxx	Si				
	5xxx	Mg				heat treatable alloys
	6xxx	Mg + Si				
	2xxx	Cu	X	(X)	X	
	7xxx	Zn				
	8xxx	Others (Fe, Li)				
	9xxx	unused				
Casting Alloys EN AC-	1xxxx	Min. 99% Al				non-heat treatable alloys
	4xxxx	Si	X			
	5xxxx	Mg				
	3xxxx	Si + Mg (Cu)				heat treatable alloys
	2xxxx	Cu				
	7xxxx	Zn	X		X	
	8xxxx	Sn				
9xxxx	unused					

2.3.4 Major alloying elements in 6XXX automotive wrought alloys

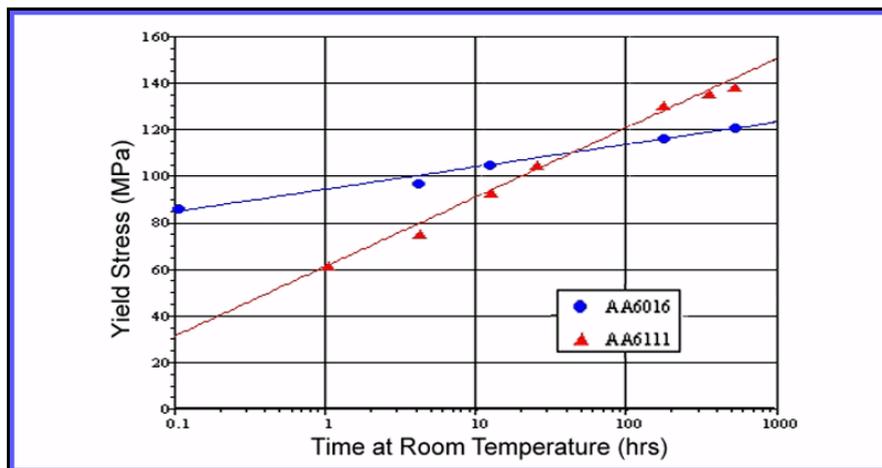
Literature:

- △ Hamerton, R.G., Hirth, S.M., Gatenby, K.M., Court, S.A., Ricks, R.A.: Al-Mg Alloys for Automotive Applications - Design Considerations and Mat'ls Selection, Proc. Intern'l Body Eng'g Conf. (IBEC97) (ed: S.G. Kelkar), 30/9 - 02/10 '97, Stuttgart, pp.1-6

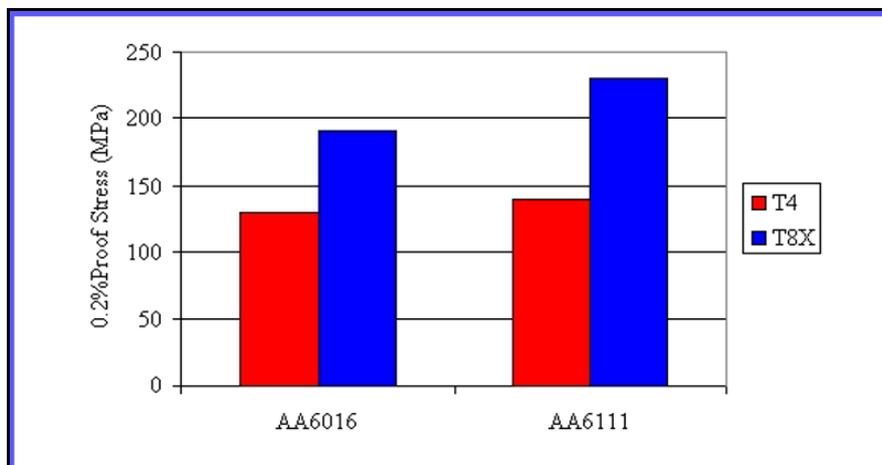
Al-Mg-Si and Al-Mg-Si-Cu

Mg, Si and **Cu** are the major alloying elements in Al automotive alloys. Mg and Si combine to form Mg₂Si which affects natural ageing behaviour (slightly) and all three affect paint bake response during curing of 6XXX alloys, the natural (T4) and artificial (T6/T8) ageing response of body sheet alloys.

AA6016 and **AA6111** are shown in figures below. **Cu** confers additional strength to the 6XXX automotive alloys. T4 refers to as supplied sheet. The paint bake response is measured by testing the sheet after subjecting it to a 2% elongation followed by heating to 180 °C for 30 minutes (T8X).



This picture shows the response of alloys AA6016 and AA6111 to natural ageing



Typical Longitudinal Proof Stresses for AA6016 and AA6111

Source: Hamerton et al, IBEC97, pp.1-6

2.3.5 Major alloying elements in 5XXX automotive wrought alloys

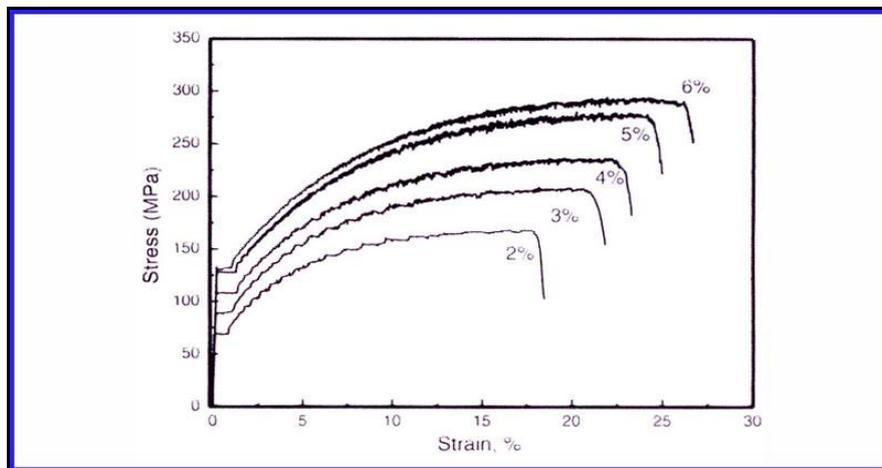
Literature:

- △ Gatenby, K.M., Court, S.A.: Aluminium Magnesium Alloys for Automotive Applications - Design Considerations and Materials Selection, Proc. Internat'l Body Engineering Conf. (IBEC97) (ed: S.G. Kelkar), 30/9 - 02/10 '97, Stuttgart, Germany, pp.137-143

Al-Mg and Al-Mg-Mn

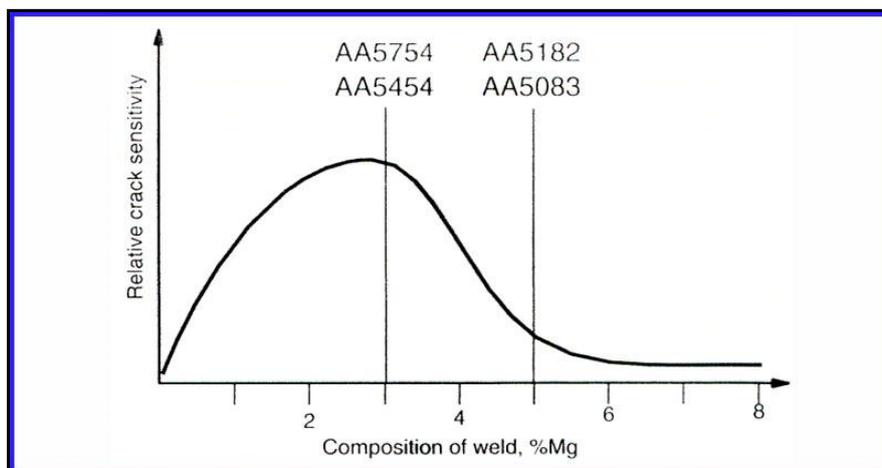
Mg also increases strain hardening, tensile strength (0.2%PS and UTS) and formability (uniform and total elongation). However, these beneficial properties to the sheet must be balanced by increasing difficulty to roll the higher Mg containing alloys as they strengthen on rolling.

The weldability of 5XXX alloys is very composition sensitive and may be related, in particular, to the level of Mg within the alloy although the level of Mn and/or Cr may also be important.



Stress strain curves from Al-Mg model alloys containing 2-6% Mg

Source: Gatenby and Court IBEC97, p.137-143



This picture shows the weldability of Al-Mg alloys as a function of Mg content

Source: Gatenby and Court IBEC 97, pp. 137-143

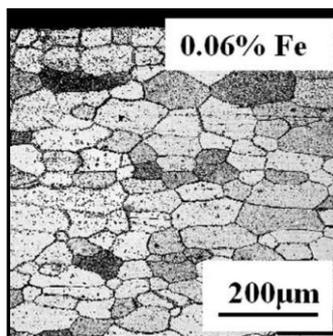
2.3.6 Minor alloying elements in automotive alloys

Literature:

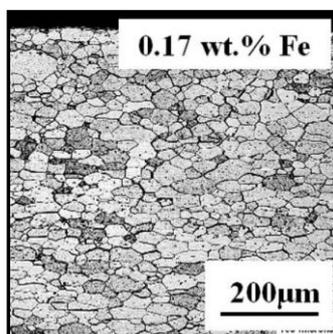
- △ Hamerton, R.G., Hirth, S.M., Gatenby, K.M., Court, S.A., Ricks, R.A.: Al-Mg Alloys for Automotive Applications - Design Considerations and Mat'ls Selection, Proc. Intern'l Body Eng'g Conf. (IBEC97) (ed: S.G. Kelkar), 30/9 - 02/10 '97, Stuttgart, pp.1-6

Elements with low solubility such as **Mn** and **Fe**, and minor alloying elements such as **Cr**, **Zr** and **Ti** also have an important role to play in the development of properties of Al automotive alloys. Being of low solubility these elements form relatively coarse intermetallic particles during casting and pre-heating prior to hot rolling. In small quantities, these particles play critical roles in controlling the grain structure which develops during subsequent hot and cold rolling and final gauge annealing of the sheet.

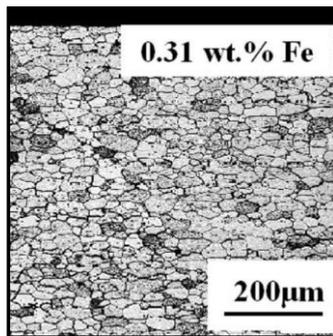
On the other hand, if the levels of these elements are too high, there can be detrimental effects on properties. E.g., Fe levels can influence properties: formability is reduced if higher levels of Fe and hence more Fe containing particles are present. However, low Fe levels are costly to achieve and also impose constraints on the use of recycled alloys. Optimisation of alloy composition must balance the technical requirements of the end application, for example the need to be able to form complex parts, against the commercial considerations and practicalities.



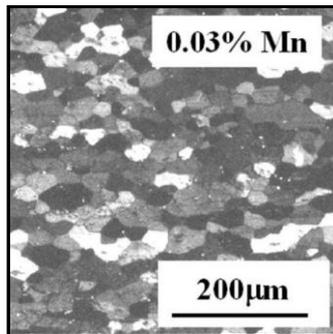
Optical micrograph showing grains in AA6111 base alloy with 0.06%Fe



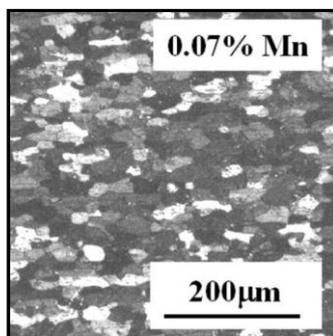
Optical micrograph showing grains in AA6111 base alloy with 0.17%Fe



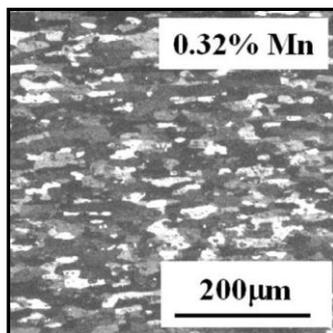
Optical micrograph showing grains in AA6111 base alloy with 0.31%Fe



Optical micrograph showing grains in AA6016 base alloy with 0.03%Mn

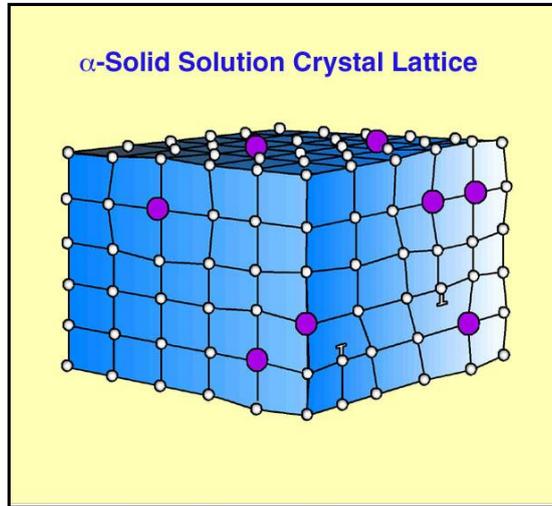


Optical micrograph showing grains in AA6016 base alloy with 0.07%Mn



Optical micrograph showing grains in AA6016 base alloy with 0.32%Mn

2.4 Strengthening mechanisms



2.4.1 Work hardening / Solid solution hardening / Precipitation hardening

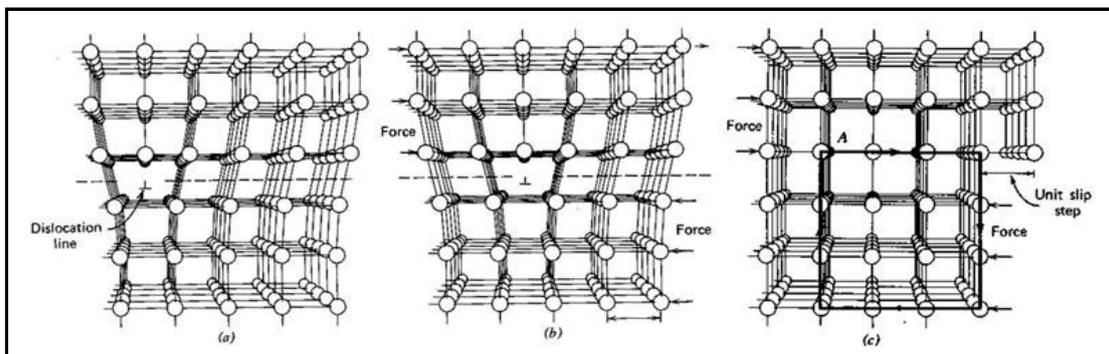
(for details on metallurgy see AluMatter and TALAT databases)

Annealed 99.8% pure aluminium has a yield strength of less than 20 MPa and a tensile elongation of more than 40%. In order to make it versatile for structural application it is essential to introduce strengthening effects.

Plastic deformation of metals is due to the existence of linear lattice defects - the dislocations. Plastic deformation proceeds by movement and multiplication of dislocations (see figure below).

Strengthening occurs when obstacles for dislocation movement are introduced into the lattice.

In aluminium three basic strengthening mechanisms are effective. These are classified as **work hardening**, **solid solution hardening** and **precipitation hardening**. In turn, aluminium alloys are classified according to prevailing strengthening mechanisms.



Plastic deformation by movement ("slip") of a dislocation line through the lattice of a ductile metal

2.4.2 Strengthening of aluminium alloys

Work Hardening

Dislocations move in the most densely packed lattice planes - slip planes. Due to the cubic symmetry of aluminium four equivalent slip planes with three equivalent slip directions each exist - resulting in 12 slip systems. Depending on prevailing stress conditions several slip systems are normally active. Interactions of dislocations like cutting will be a frequent process. Thus, dense tangles of dislocations develop, forming extended obstacles with intense local stress fields. This mechanism is operating in all alloys subject to plastic deformation.

Solid Solution Hardening

Alloying elements in solid solution interact with dislocations mainly by local stress fields providing additional friction forces during dislocation movement. This strengthening mechanism increases the effect of work hardening. 3XXX and 5XXX alloys are typical examples of solid solution hardened alloys.

Precipitation Hardening

Precipitates of secondary phases in aluminium are very effective obstacles for dislocations depending on size and distance. Small coherent precipitates may be cut by dislocations. With growing size and/or loss of coherency within the lattice structure the obstacle strength of a precipitate particle increases. Assuming constant volume fraction of precipitates the distance between particles increases during maturation. This allows dislocations to bow out between precipitates. If near semicircular shape is attained neighbouring dislocation segments may combine and proceed leaving a dislocation loop at the precipitate. Thus, the increase to peak hardness during isothermal ageing is easily explained by progress of precipitation with increasing precipitate strength. Decrease of hardness by overageing is due to the increase of distance between particles.

2.5 Heat treatment

2.5.1 Thermal treatments for specific properties



Source: AluNorf

The properties of aluminium and aluminium alloy products are governed by their microstructural state, which develops as a result of all **thermo-mechanical processing steps** during the complete processing chain of product fabrications.

Heat treatment of aluminium and aluminium alloy materials - as treated in this chapter - comprises a number of different **thermal cycles**, which are used to achieve **specific properties** for further processing or service behaviour.

A thermal cycle is characterised not only by **time at temperature**, but also by **heating and cooling rates**.

Thermal treatments are used to revert the hardened state of a material to a softer state or to strengthen by precipitation hardening:

- ⤴ **Recrystallisation anneal**: forming a new grain structure which yields the softest, thermodynamically highly stable state with best formability.
- ⤴ **Recovery anneal**: improving formability of a **strain-hardened** material without significant loss of strength.
- ⤴ **Solution annealing and ageing** treatments are used to achieve a precipitation-hardened state with or without intermediate cold working (only applicable to **age-hardening alloys**).

For **improved formability of age-hardened alloys** (e.g. T4, T6 or T7 tempers) the following methods retain the age-hardening capability:

- ⤴ **Resolution treatments** recovering the as-quenched state by any solution heat treatment, including reversion and retrogression treatments.
- ⤴ **Reversion treatment** can be applied to T4 tempers. It is a flash anneal at intermediate temperatures.
- ⤴ **Retrogression treatment** can be applied to T6 tempers. It is a flash anneal at higher temperatures.

2.5.2 Guidance for heat treatments

See also:

- ▲ AAM – Manufacturing – 3 Forming > Semi-hot forming
- ▲ AAM – Products – 6 Cast alloys and products > Tempers and mechanical properties

Thermal Treatments of Components				
Requirement	Starting material temper	Alloys	Type of treatment	Reference chapter
Improved formability	Hard tempers (H14...)	3xxx, 5xxx sheet alloys	recrystallisation anneal	LINK 1
	Hard tempers (H12...)	3xxx, 5xxx sheet alloys	recovery anneal	LINK 1
	Cold-worked			LINK 1
	F, O, H tempers	3xxx, 5xxx sheet alloys	semi-hot forming	LINK 2
	T4, T6, T7 tempers	2xxx, 6xxx, 7xxx alloys	resolution treatment + quench	LINK 3
	T4 temper	2xxx, 6xxx, 7xxx alloys	reversion heat treatment	LINK 3
Improved static strength	T6 temper	2xxx, 6xxx, 7xxx alloys	retrogression heat treatment	LINK 4
	T4 temper	6xxx extrusions & sheet	age-hardening to T6, T7	LINK 5
Improved dent resistance	T4* temper	6xxx-T4* formed sheet parts	bake-hardening	LINK 6
Improved crashworthiness	F temper	4xxxx castings	homogenisation	LINK 7
	T6 temper	6xxx extrusions	T7-overaging (whole or local)	LINK 8
Stress relieve (castings)	F temper	4xxxx castings	anneal, slow cool	LINK 9

2.5.3 Annealing

Recovery and recrystallisation

See also:

▲ AAM – Materials – 3 Designation system > Wrought alloys

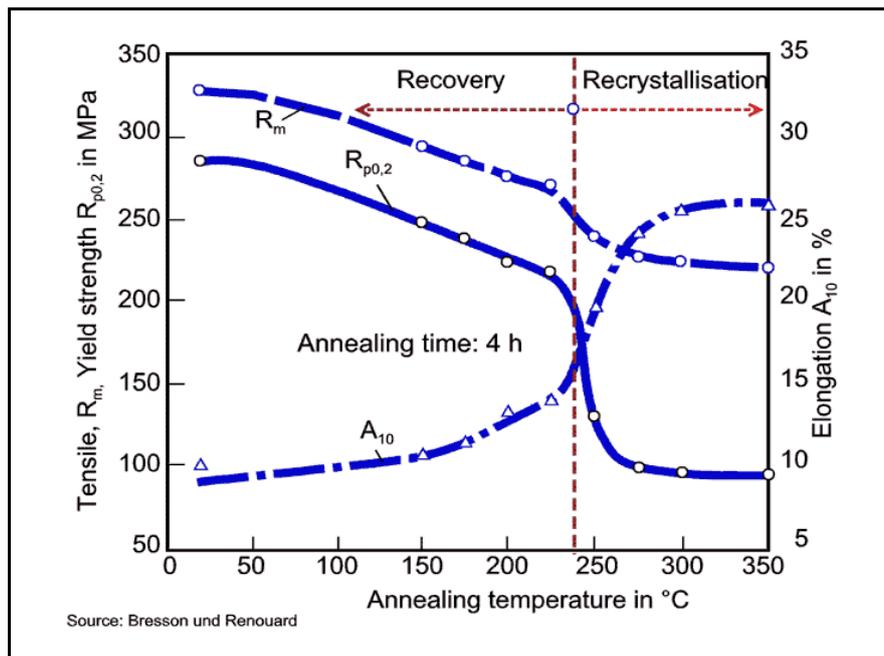
Recovery anneal

Purpose: Softening of work-hardened wrought alloys with the aim to improve formability and toughness. Moderate decrease in yield and ultimate strength with increase in elongation. No recrystallisation. Temperature regime: $MT < 240\text{ °C}$. Temper designation: "H2X".

Recrystallisation anneal:

Purpose: Obtain stable temper with highest formability at sacrifice of strength. Highest strain-hardening rate (n-value) compared to any other temper. Growth of grains out of deformed grain structure. Note: grain size depends on amount of prior cold-work, annealing temperature and time. Temperature regime: $MT = 300 - 400\text{ °C}$. Slow cooling from MT advised for 5xxx alloys. Temper designation: "O".

MT = metal temperature



Annealing response of AlMg3 H18

2.5.4 Solution treatment and ageing

Process sequence

See also:

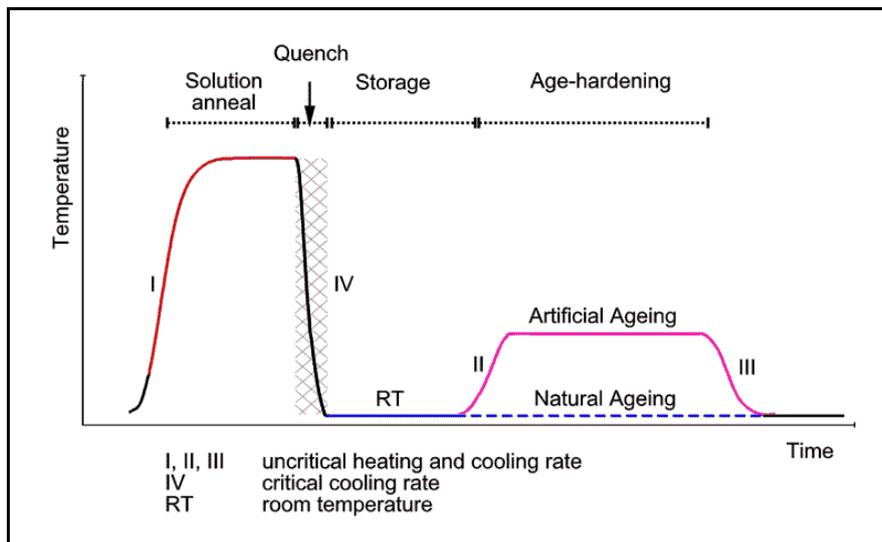
- ⤴ AAM – Materials – 3 Designation system > Wrought alloys > Temper designation system for wrought alloys (EN 515)
- ⤴ AAM – Materials – 3 Designation system > Wrought alloys > T-Tempers for heat-treatable wrought alloys (EN 515)

Age-hardening is the most important strengthening mechanism for wrought and casting alloys. Virtually all automotive structural extrusions are made from age-hardening 6xxx and 7xxx alloys and are usually supplied in the fully heat-treated T6 temper, i.e. they have been subjected to the process cycle (s. fig.below): solution anneal + quench + RT storage + artificial ageing.

Immediately after quenching the materials is in a very soft state ("W" temper) permitting straightening and forming operations at RT.

Within a short time (approx. 1 hr.) after quenching the alloy begins to harden over a period of a week or longer, depending on the alloy system. This is called "natural ageing", the final temper being designated T4.

Various variations of the principle process scheme exist, e.g. quenching from a sufficiently high extrusion or forging temperature.



Various heat treatment phenomena of practical relevance and the metallurgical background are explained in the following pages.

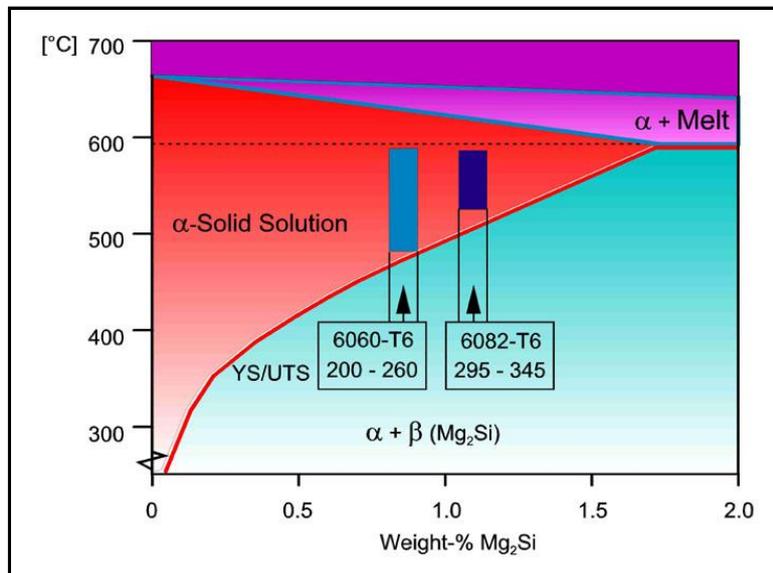
Solution treatment

In order to achieve significant hardening, second phase particles have to be much smaller than 1 μm in size, uniformly distributed throughout the grains and sufficient in volume to hinder dislocation motion.

Formation of such fine intermetallic particles from solid solution by suitable ageing treatments requires a highly supersaturated solid solution of alloying elements in the aluminium α -phase as a prerequisite for precipitation.

Aluminium age-hardening alloy systems exhibit a large increase of solubility for the age-hardening phase in the α -matrix with increasing temperature, s. figure at right.

The figure illustrates the quasi-binary Al-Mg₂Si equilibrium phase diagram and shows two common 6xxx alloys within the system. On annealing these alloys around 500 to 550 °C the β -phase (Mg₂Si) is completely dissolved ("solution anneal").



Quasi-binary Al-MgSi equilibrium phase diagram

Source: ATS/Ostermann

Quenching

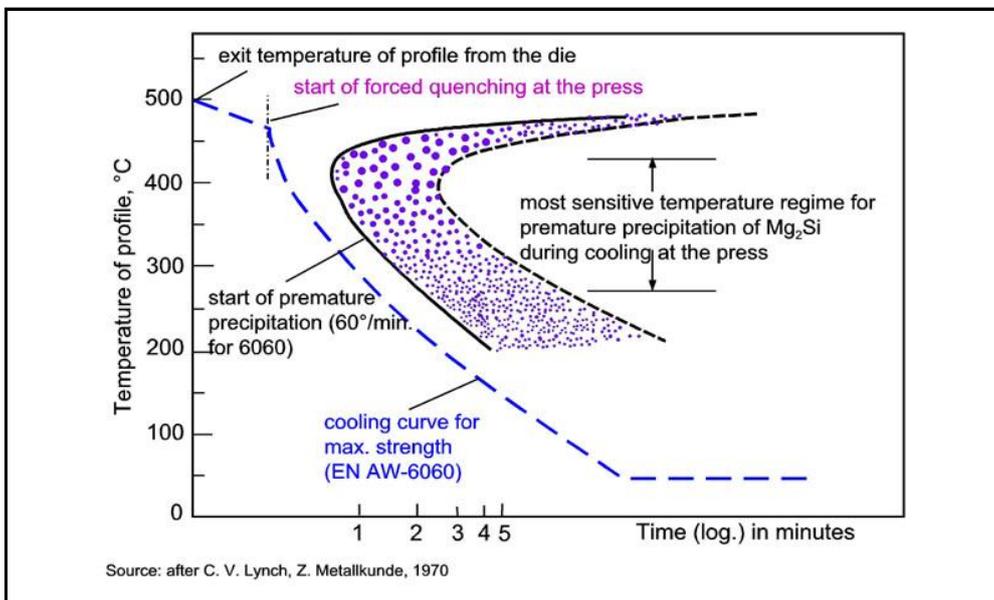
(cooling from solution annealing temperature)

Purpose: to obtain a supersaturated state at room temperature requires a sufficiently rapid cooling rate after solution anneal.

Insufficient cooling rate causes premature precipitation of intermediate phases within grains and at grain boundaries, which reduces age-hardening capacity, ductility and also corrosion resistance, s. TTP diagram and micrographs for extruded 6060 alloy. Increasing alloy concentration requires higher quenching rates (increased quench sensitivity).

High cooling rates generate thermally induced residual stresses which cause distortion. Wrought alloys are stretched beyond the yield point to remove residual stresses. Castings are quenched sufficiently slowly to avoid distortion, internal stresses and cracking.

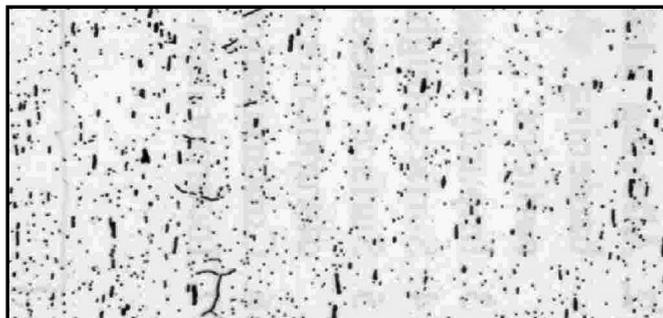
To suit metallurgical requirements, quenching rates can be varied (air cool, air blast, cold water, hot water, oil and mixtures of water with polymers).



TTP diagram for alloy 6060 extrusions

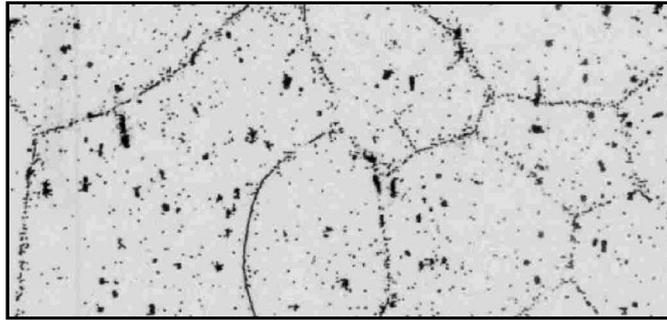
Source: after C.V. Lynch, Z. Metallkunde

6060 alloy with and without grain-boundary phase:



Correctly quenched 6060 extrusion - no grain boundary precipitation

Source: Alcan



Grainboundary precipitation due to slow cooling

Source: Alcan

THE Aluminium Automotive MANUAL

Ageing

(precipitation from supersaturated α -solid solution)

See also:

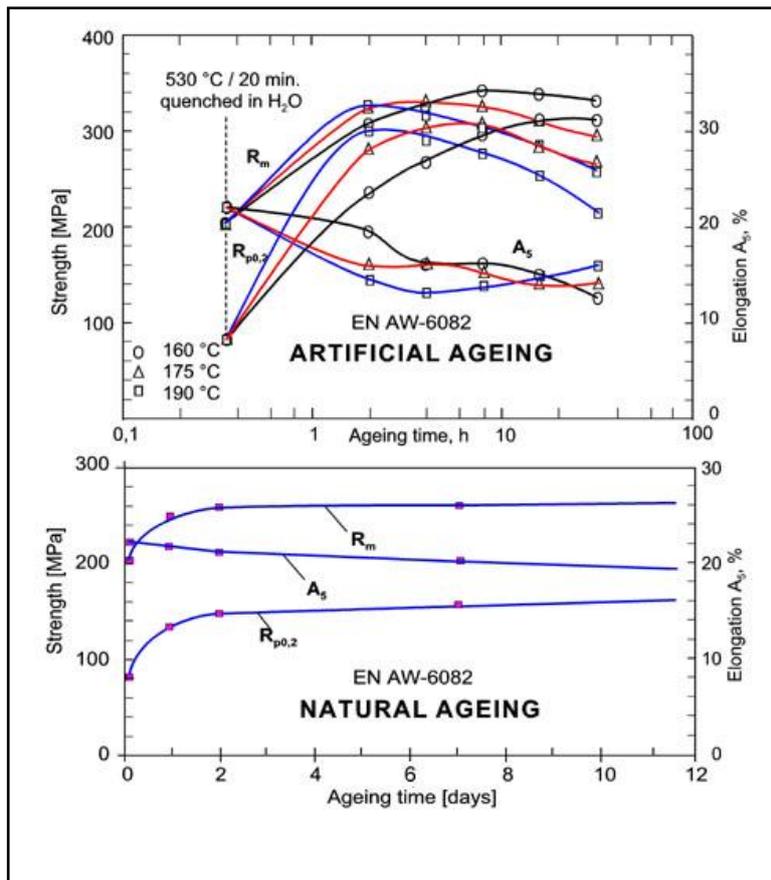
- ▲ AAM – Products – 1 Rolled products > Thermal stability > T4 temper stability for 6xxx series alloys (AlMgSi type)

The segregation of alloying elements from supersaturated solid solution (α_{SS}) at lower ambient temperatures occurs as a non-equilibrium process by nucleation and growth of metastable, intermediate second phases. This process is controlled by diffusion rate and by the activation energy for formation and growth of precipitate nuclei. As a consequence and depending on the ambient temperature various different intermediate second phases are formed, which have different influence on the rate and magnitude of hardening.

RT – 60°C: Formation of "clusters" (Guinier-Preston zones) coherent with the α_{SS} aluminium lattice. This process is called "natural ageing" and results in tempers T1, T4.

60°C – 220°C: Formation of intermediate coherent and semi-coherent second phases (designated e.g. β'' and β' in 6xxx alloys). This process is called "artificial ageing" and results in tempers T5, T6.

The ageing curves (s. fig) show the effect of ageing temperatures on the strength and fracture elongation properties of extruded alloy EN AW-6082 (AlSi1MgMn).



Natural and artificial ageing curves for alloy 6082 (extrusion)

Source: VAW and Ostermann/ATS

Note the higher ductility and lower strength after ageing at room temperature.

Special ageing effects in 6xxx alloys: stabilised T4 tempers (T4*)

Literature:

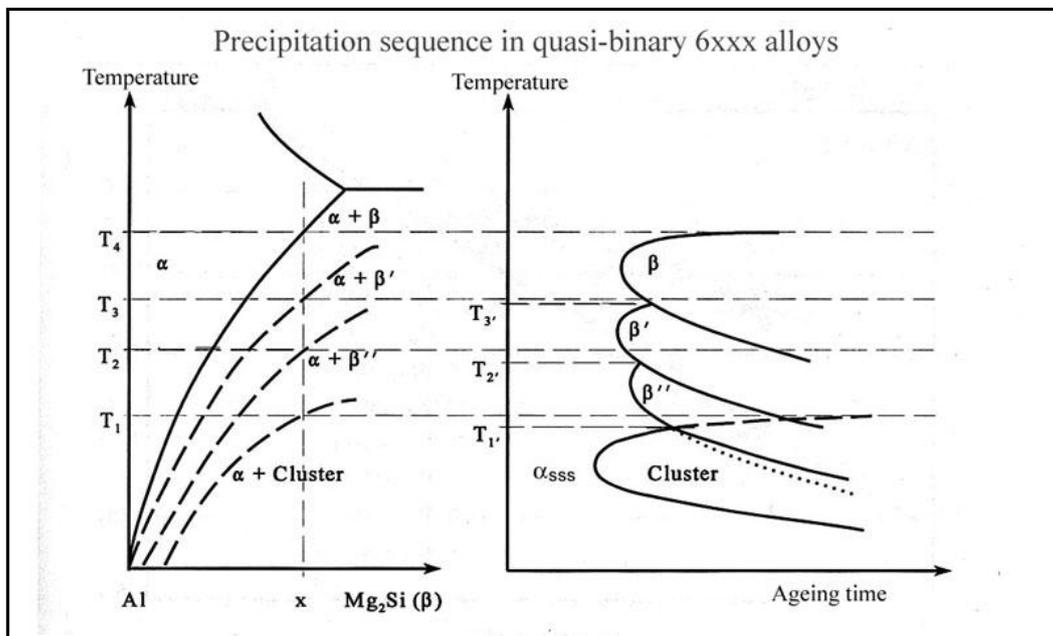
- ▲ Huppert-Schemme, G.: AlMgSi-Bleche für den Fahrzeugbau - Metallkunde und Fertigungstechnik. Düsseldorf: Aluminium-Verlag GmbH, 1997, ISBN 3-87017-255-X

Al-Mg-Si alloys are often supplied in T4 temper for more extensive formability of sheet or extruded profiles. Subsequent ageing to higher strength by T6 tempering or by a paint bake cycle does not give max. T6 strength, or only after longer ageing times.

The reason is that T4 strength is mainly caused by 'clusters' (s. fig. below) which reduce and retard nucleation and growth of more stable T6 secondary phases (β'' , β').

Therefore, various special T4 treatment schemes have been developed - depending on the specific alloy composition and product form - which suppress cluster formation and instead produce β'' - and β' -nuclei. This improves ageing response time and strength during paint bake or T6 ageing treatments.

These special T4 tempers are called "**stabilised**" tempers (T4*) and are not standardised, since the stabilising treatment depends on composition, semi-product form and production method. - *Suppliers should be contacted for details.*



Beta solvus curves (left) and TTP curves (right) in 6xxx alloys

Source: G. Huppert-Schemme, 1997

Optimum paint bake response of AA6016-T4* car body sheet material

See also:

- ⤴ AAM – Materials – 3 Designation systems > Wrought alloys > T-Tempers for heat-treatable wrought alloys (EN 515)

Literature:

- ⤴ Furrer, P. and Bloeck, M.: Aluminium-Karosseriebleche. Landsber: Verl. Moderne Industrie, 2001, (Die Bibliothek der Technik; Bd. 220) ISBN 3-478-93250-5
- ⤴ Janse, J.E., Zhuang, L., Mooi, J., De Smet, P.: Evaluation of the effect of Cu on the paint bake response of pre-aged AA6xxx. Proc. ICAA8 (2002)
- ⤴ Zhuang, L., Janse, J.E., De Smet, P., Chen, J.H., Zandbergen, H.W.: Natural ageing effect on the bake hardening response in Al-Si-Mg alloys. Proc. TMS2001, (2001)
- ⤴ Zhuang, L., de Haan, R., Bottema, J., Lahaye C.T.W., De Smet, P.: Improvement in bake hardening response of Al-Si-Mg alloys. Proc. of ICAA7, Materials Science Forum, Vols. 331-337, pp.1309-1314 (2000)

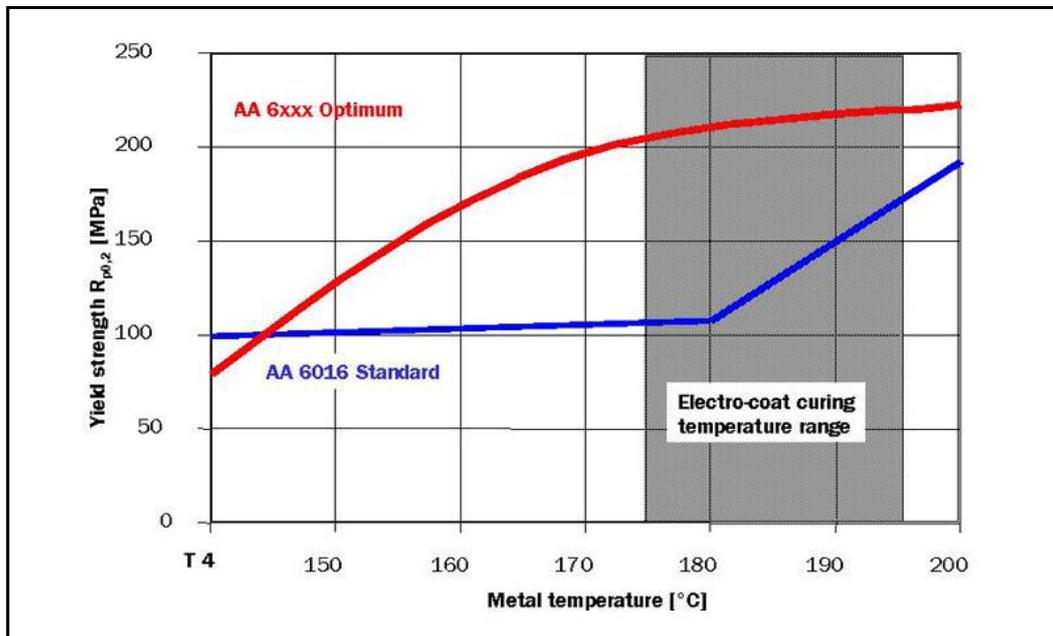


The requirements for automotive sheet are **high formability** (to allow the forming of complex parts) and **high yield strength** in service application (to provide high dent resistance).

Rolled sheet made of age-hardenable **AA 6xxx** alloys are deformed in the T4 temper. Maximum strength is then reached by artificial ageing treatment of the deep drawn sheet at its final geometry in the temperature range around 200°C. For economic reasons, it is desirable to age-harden the material during lacquer curing, which is however performed at lower temperatures that do not lead to an optimum age hardening effect. Therefore a special treatment is applied after solution anneal (T4* -temper) leading to an accelerated age hardening effect at 160-190°C, s. figure below.

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Diagram: red curve shows the more rapid ageing response of 6016-T4* material (1 hr at temperature) vs. the behaviour of standard 6016-T4 material (blue curve).



Optimised bake-hardening response of AA6016-T4 by special processing

Source: Alcan

Tempers for extrusions: high formability, high strength, high crash performance

Literature:

- ▲ Schwelling, P.; Lutz, E.: Aluminiumprofilwerkstoffe für energieabsorbierende Bauteile im Fahrzeugbau; Zeitschrift Werkstoffe im Automobilbau 98/99 (Sonderausgabe)



AA6014-T7 extruded profile with optimised crash behaviour

Source: Alcan

Alloy AA6014 extrusions are supplied in either

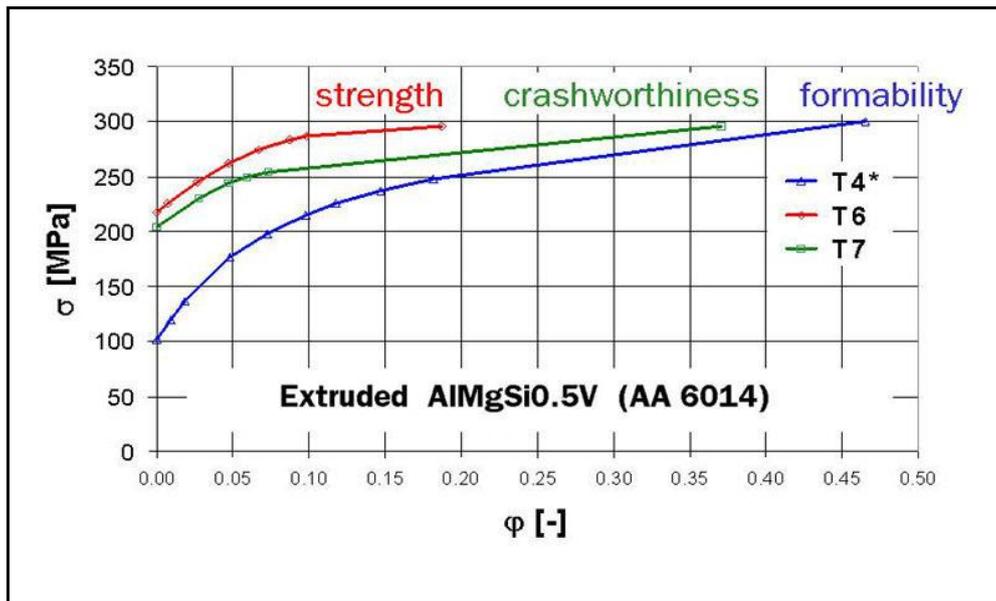
- ▲ **T7** temper for **best crash performance**,
- ▲ **T6** temper for **maximum strength**, or
- ▲ **T4*** temper for **best formability**.

The flow curves (true stress - true strain) for the various tempers are illustrated in the figure below.

Crash properties of extruded components depend strongly on composition, processing conditions and temper. To ensure a high energy absorption and to prevent the forming of cracks during the crash, the **microstructure** (i.e. the intermetallic particle distribution and the grain size) has to be properly adjusted.

To obtain optimum crash worthiness strength, ductility and fracture toughness have to be adjusted to a joint maximum level.

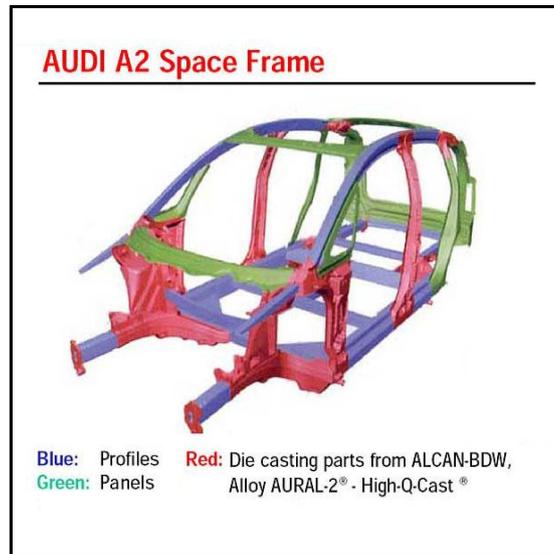
T7 is an overageing treatment resulting in slightly reduced strength, yet improved ductility.



True stress - true strain curves for AA6014 extruded profiles in various different tempers

Source: Alcan

Shape casting: solution annealing (homogenisation) and ageing of crash relevant parts



To produce structural cast components with **excellent crash worthiness**, apart from the **casting technology**, the **alloy composition** and the following **thermal treatment** are most important to obtain the desired microstructure.

The optimised thermal treatment of this B-pillar is done in two steps:

- ⤴ The first step is done at high temperature (>400°C) to **homogenise** the alloying elements and to globularize the eutectic phase particles (s. fig.). To limit the amount of distortion during quenching, the **soak temperature is decreased** as much as possible and the **cooling rate** is kept relatively slow.
- ⤴ The second step is artificial ageing at temperatures around 200°C to **increase the strength**.



B-pillar of Audi A2: crash relevant shape part

Aluminium casting with high ductility – Microstructure of the B-pillar shown at right

Source: Alcan

2.5.5 Resolution treatment

Resolution treatments for age-hardened alloys

(to improve formability)

See also:

- ▲ AAM – Materials – 2 Alloy constitution > Heat treatment > Retrogression heat treatment
- ▲ AAM – Materials – 2 Alloy constitution > Heat treatment > Solution treatment and ageing > Special ageing effects in 6xxx alloys: stabilised T4 tempers (T4*)

Resolution Treatment (general):

Age-hardening (T4, T6) of aluminium alloys is a reversible process. By re-heating the age-hardened material above the solvus line the precipitate phase is dissolved. Subsequent quenching and ageing restore the mechanical properties of the age-hardened state. The freshly quenched state (-W temper) offers improved formability.

In general, resolution treatments involve re-heating the part into the temperature region for solution annealing, which depends on alloy composition. To avoid destruction of the material's properties by overheating, solution annealing temperatures must be precisely controlled within a narrow process window.

High solution annealing temperatures and quenching are not generally suited for in-line processes of manufacturing lines. In particular for shaped components, care must be taken to avoid geometrical distortions during quenching.

Reversion Treatment (only T4 temper):

Alternatively, age-hardened alloys in the T4 temper may be treated by a reversion treatment, which involves a flash anneal at much lower temperatures.

The temperatures involved depend on the solvus line for the metastable GP-zones. The following temperature regimes are suitable:

2xxx alloys: 220 to 275 °C

6xxx alloys: 200 to 250 °C

7xxx alloys: 160 to 220 °C

Annealing times must be less than 5 minutes and can be as short as 30 seconds.

Reversion treatments may, therefore, be suited for in-line processing, when higher formability is required than available in the T4 temper.

2.5.6 Retrogression heat treatment

Characteristics of RHT

Literature:

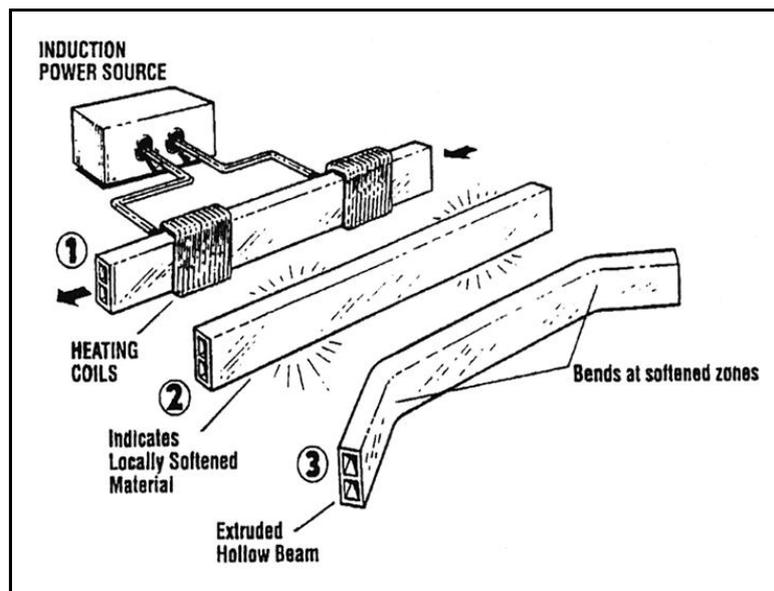
- ⤴ Benedyk, J. C. / Alumax Extrusions, Inc.: "Method for forming a metallic material"; United States Patent No. 5 911 844; June 15, 1999
- ⤴ Benedyk, J. C. / Alumax Extrusions, Inc.: "Process for formation of high strength aluminum ladder structures"; United States Patent No. 4 766 664; August 30, 1988
- ⤴ Benedyk, J. C. / Alumax Extrusions, Inc.: "Space frame apparatus and process for the manufacture of same"; United States Patent No. 5 458 393; October 17, 1995
- ⤴ Benedyk, J. C., Sheldon Mostovoy, S., McKenzie, S.R.: "Retrogression Heat Treatment Applied to Aluminum Extrusions for Difficult Forming Applications"; Part I, II and III; Light Metal Age; October 1996, February 1997, June 1997

Retrogression Heat Treatment * is applied to age-hardened (T6) extrusion alloys.

Characteristics of RHT are:

- ⤴ Rapid heating usually by induction
- ⤴ RHT temperatures of 350°C to 450°C are higher than original aging temperatures but below normal solutionizing temperatures.
- ⤴ RHT times are very short (several seconds)
- ⤴ After subsequent water quench the treated parts or areas of parts are softened.
- ⤴ The biggest benefit of RHT is a localized increase in elongation by up to several hundred percent.
- ⤴ RHT makes extensive forming operations possible.
- ⤴ Changes induced by RHT recover within hours to days by natural aging.

* patent of Alumax, held by Alcoa, s. Literature



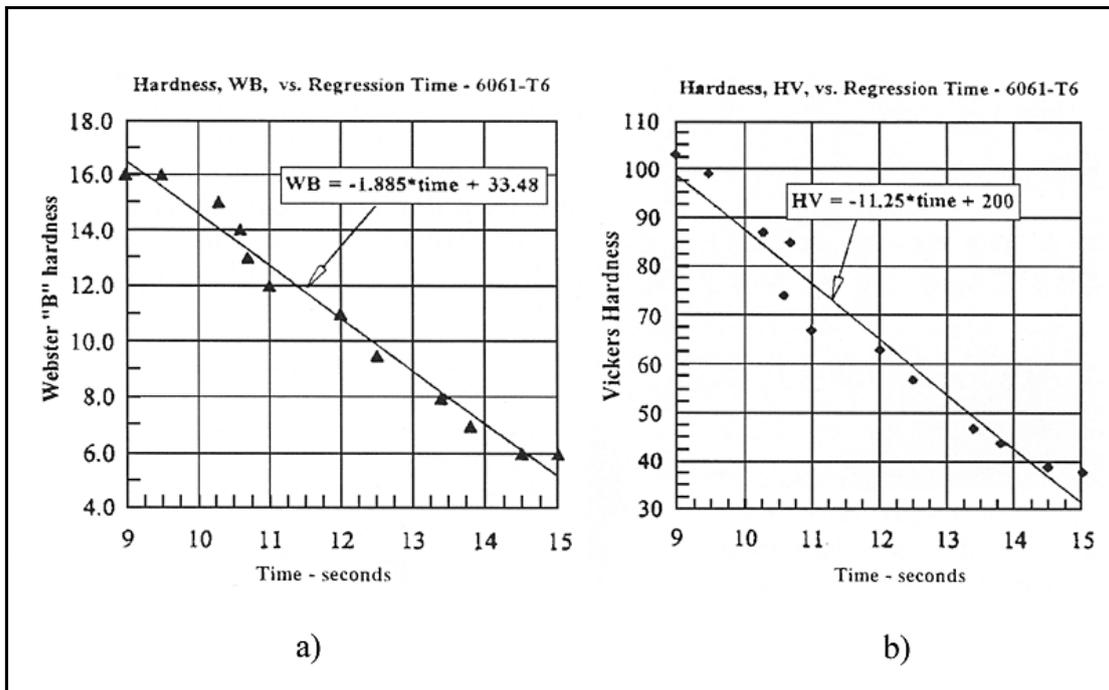
Schematic application of localized RHT to bending of a bumper beam

Principles of RHT: Metallurgy

Hardness versus RHT time in seconds

The term retrogression or reversion in metallurgy commonly refers to resolution of GP zones and/ or precipitates in age-hardened alloys by heating them to a temperature above the original aging temperature but below the solutionizing temperature.

The figure below shows as-quenched hardness measurements on 6061-T6 extruded plate as a function of RHT time. (a - Webster "B" or WB hardness change; b - Vickers hardness or HV change). Hardness decreased linearly as a function of residence time in the induction coil down to an asymptotic value equal to 6 WB (39.5 HV).

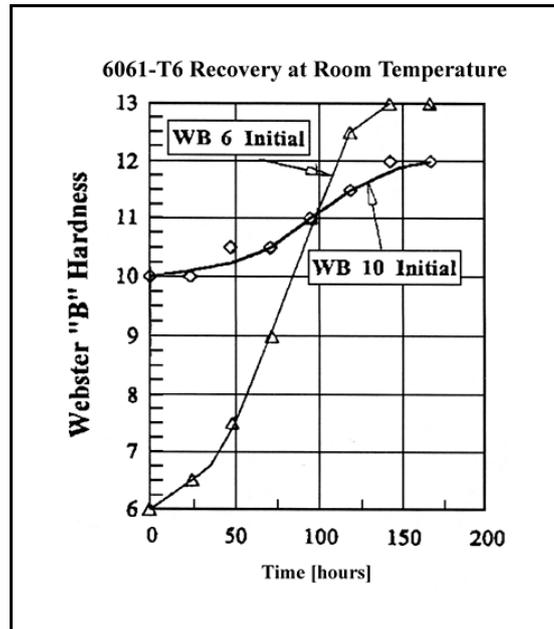


As-quenched hardness of 6061-T6 extruded plate as a function of induction heating time used in RHT

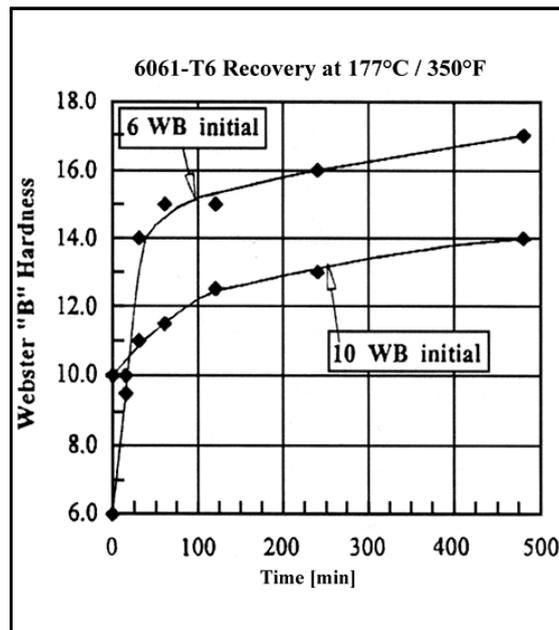
Although the asymptotic value for both 6005-T5 and 6061-T6 materials was equivalent, the 6005 material softened at a faster rate for the same power level on the induction unit.

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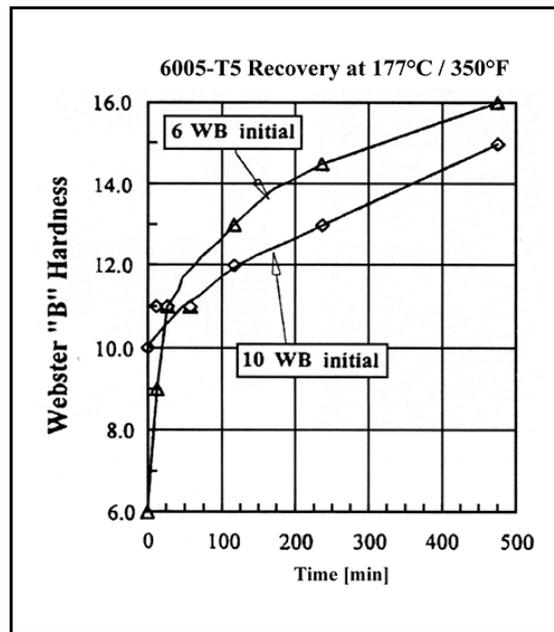
Aging curves at room temperature and at 177°C (350°F)



Aging curves: WB hardness versus time at room temperature, 6061-T6



Aging curves: WB hardness versus time at 177°C (350°F), 6061-T6



Aging curves: WB hardness versus time at 177°C (350°F), 6005-T5

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Applications of RHT: Forming

Small radii in rotary draw bending

RHT has been successfully applied to the forming of 6000- and 7000-series aluminium alloy extrusions in various tempers and especially the -T6 temper. With this method of processing, for example, thin walled tubes of 6061-T6 have been successfully bent in a rotary draw bending operation to an internal radius of one tube diameter without cracking (see picture).



Photograph of a 6061-T6 thin wall tube bent to a radius to the 1.D. of one tube diameter

In this case, the localized process took only a few seconds and was incorporated in line with the bending operation. Normally, a tube of this cross section and temper would require an internal bend radius of six tube diameters or more.

Hardness recovery without cold work

In 6000-series aluminium alloys, the precipitation hardenable aluminium alloys most commonly used in automotive applications, RHT usually involves localized heating by induction to temperatures of 315 to 535 °C within a few seconds, quenching by air, spray or water, then fabricating within a time period of hours or days, depending on the degree of deformation imparted by the fabrication operation. Cold work from the fabrication operation accelerates natural or artificial ageing.

Heating Temp.	Cycle Time	Webster "B" hardness after natural aging					
		0 Hr.	2 Hr.	2 Days	3 Days	4 Days	10 Days
[°C]	[Sec.]						
204	1	16	16	16	16	16	16
260	1.25	14-15	15	15	15	15	15
316	1.5	9-13	9-13	9-13	9-13	9-13	9-13
343	1.75	0-5	6-7	8-9	9	10	10
371	2.5	0-1.5	6	8	9	10	10
427	3	0-1.0	6	8	10	10	10

Room temperature aging

Although RHT response is dependent on alloy composition and other factors, a typical hardness-time response profile for an extruded 6XXX-T6 alloy under natural aging conditions

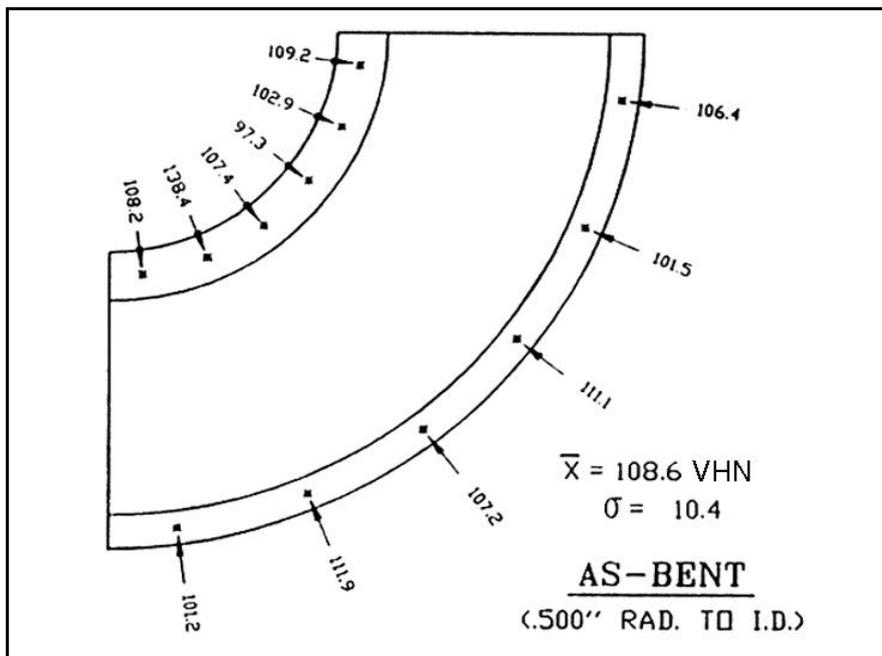
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with no cold work introduced in the RHT zone is presented in the table: For a significant effect, RHT temperatures of 343°C have to be reached.

Hardness recovery with cold work

The degree of hardness or strength recovery after RHT depends on the temperature-time cycle of the RHT and subsequent deformation in the forming operation(s). Generally, the combination of RHT and forming deformation can result in a formed zone that has substantially better properties than the original -T6 material.

In the case of the bent tubes, the hardness recovery after RHT in the bent region was high (see *figure below*) due to the combined effects of cold work and natural aging.



Wall thickness hardness reading

Consequently, artificial aging was not required after forming to achieve minimum -T6 properties. The figure shows diamond pyramid hardness distribution in 6061 -T6 bent tubes. The average hardness was 108.6 VHN (100 g load) in bent portion that previously underwent RHT.

Bending with and without RHT



Bending of 6061-T6 thinwall tube with RHT



Bending of 6061-T6 thinwall tube with RHT
Radius = 1D is possible!



Bending of 6061-T6 thinwall tube WITHOUT RHT

RHT makes bendings possible that otherwise lead to cracking. Also a very promising application of RHT is springback reduction of sheet material. Due to the principles behind RHT it should be applicable to T4 tempers as well.

Applications of RHT: Joining

See also:

- △ AAM – Joining – 5 Mechanical joining

Compression Fit (CF) Joint *

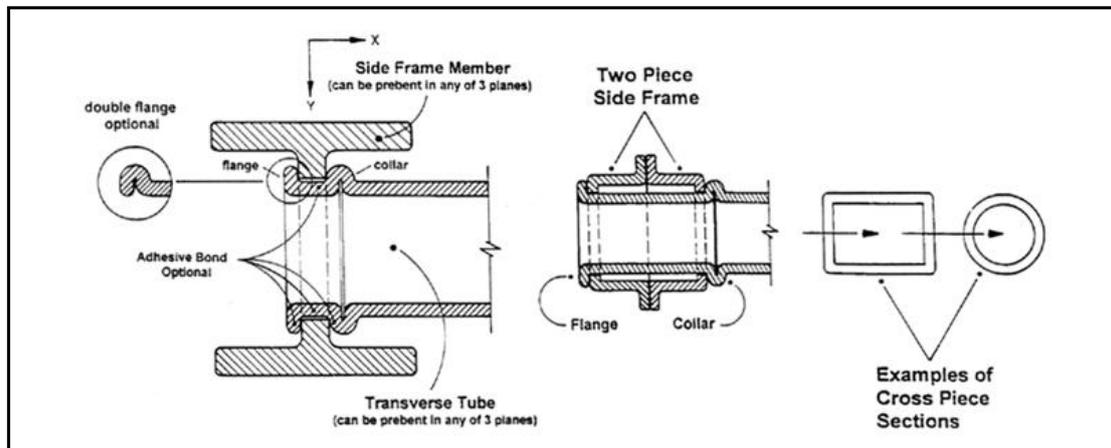
Localized RHT has been applied to form a special joint, called a Compression Fit (CF) joint, that has been successfully utilized in building aluminium ladders and vehicle frames.

Simple tooling and pressure application are used in making these joints. In principle, the CF joint has many possible configurations, and two simple modifications are shown schematically in the figures below.

* patented by Alumax, held by Alcoa

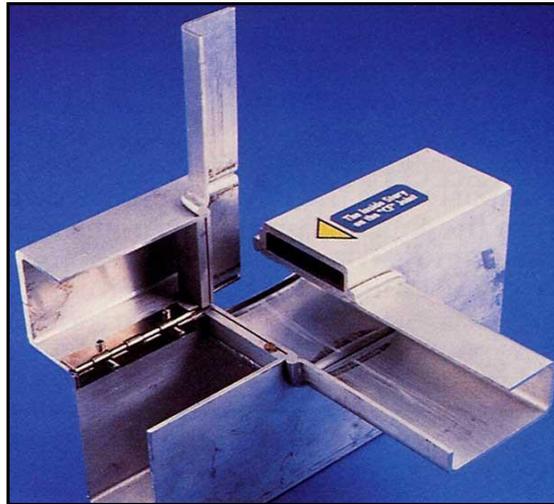
Left: RHT used to make a collar and flange CF joint in a simple I-beam side frame member.

Right: Collar / flange CF joint made in a two piece side frame with the aid of RHT to facilitate forming in the cross member.

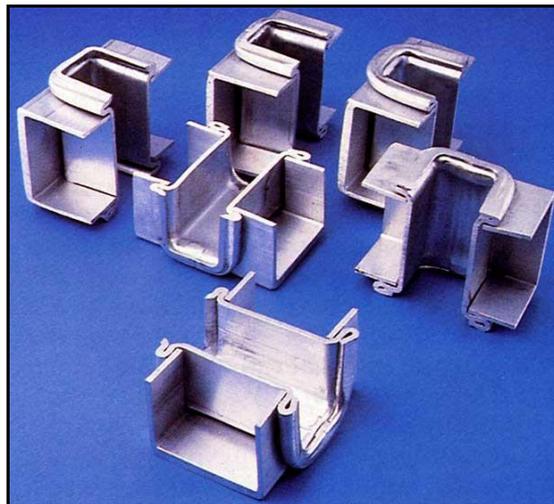


Collar and flange CF joints

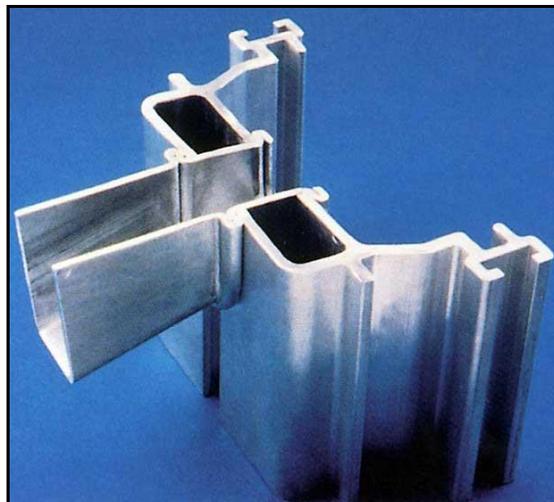
Examples of CF Joints



Cross section of a CF joint made in 6061-T6 extrusions using RHT and an internal sleeve



Sections of CF joints made in 6061-T6 hollow rectangular extrusions with RHT



Applications of RHT in series production

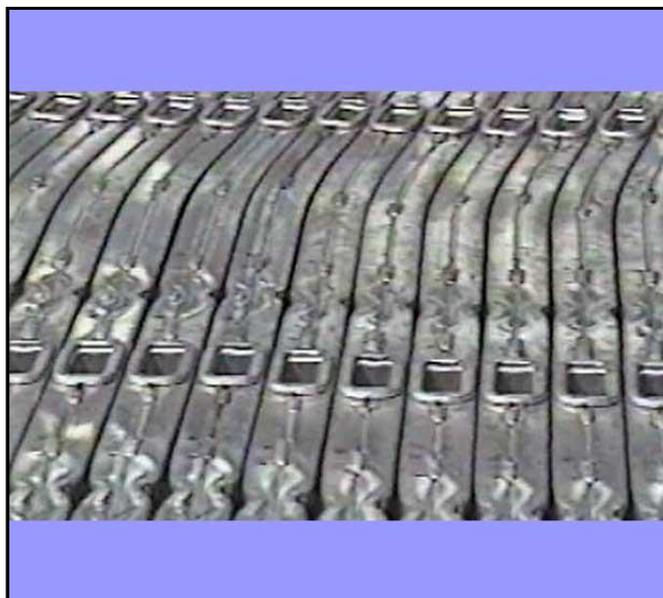
Literature:

- ▲ N.N.: "Panoz AIV Roadster - Leader in the Lightweight Class"; Light Metal Age; October 1996

In the USA: CF joints used in Panoz AIV Roadster Spaceframe



RHT in series production: Panoz AIV Roadster frame



RHT in series production: Panoz AIV Roadster frames



Panoz AIV Roadster

The Roadster chassis is made of four large tubular aluminium extrusions which are joined by Compression-Fit technology, the rails are then bent to Panoz's specifications using RHT technology. These are combined with a boxed-in aluminium backbone and the entire structure is tied together with steel subframes in key areas such as the bulkhead.