Age-hardening wrought Al-alloys

Description

Image

Caption

1. A close-up of building cladding made from wrought aluminum alloy . © John Fernandez 2. Chassis of a personal computer. © Chris Lefteri 3. The 2000 and 7000 series age-hardening aluminum alloys are the backbone of the aerospace industry.

The material

The high-strength aluminum alloys rely on age-hardening: a sequence of heat treatment steps that causes the precipitation of a nano-scale dispersion of intermetallics that impede dislocation motion and impart strength. This can be as high as 700 MPa giving them a strength-to-weight ratio exceeding even that of the strongest steels. This record describes for the series of wrought Al alloys that rely on age-hardening requiring a solution heat treatment followed by quenching and ageing. This is recorded by adding TX to the series number, where X is a number between 0 and 8 that records the state of heat treatment. They are listed below using the IADS designations (see Technical notes for details).2000 series: Al with 2 to 6% Cu -- the oldest and most widely used aerospace series.6000 series: Al with up to 1.2% Mg and 1.3% Si -- medium strength extrusions and forgings.7000 series: Al with up to 8% Zn and 3% Mg -- the Hercules of aluminum alloys, used for high strength aircraft structures, forgings and sheet. Certain special alloys also contain silver. So this record, like that for the non-age hardening alloys, is broad, encompassing all of these.

Compositional summary

2000 series: Al + 2 to 6% Cu + Fe, Mn, Zn and sometimes Zr
6000 series: Al + up to 1.2%Mg + 0.25% Zn + Si, Fe and Mn
7000 series: Al + 4 to 9 % Zn + 1 to 3% Mg + Si, Fe, Cu and occasionally Zr and
Ag

General properties

Density	156	-	181	lb/ft^3
Price	* 1	-	1.15	USD/lb
Date first used	1916			

Mechanical properties

Young's modulus	9.86	-	11.6	10^6 psi
Shear modulus	3.63	-	4.06	10^6 psi
Bulk modulus	9.28	-	10.2	10^6 psi
Poisson's ratio	0.32	-	0.36	

Yield strength (elastic limit)	13.8	-	88.5	ksi
Tensile strength	26.1	-	89.9	ksi
Compressive strength	13.8	-	88.5	ksi
Elongation	1	-	20	% strain
Hardness - Vickers	60	-	160	HV
Fatigue strength at 10^7 cycles	8.27	-	30.5	ksi
Fracture toughness	19.1	-	31.9	ksi.in^0.5
Mechanical loss coefficient (tan delta)	1e-4	-	0.001	

Thermal properties

Melting point	923	-	1.18e3	°F
Maximum service temperature	248	-	392	°F
Minimum service temperature	-460			°F
Thermal conductor or insulator?	Good conductor			
Thermal conductivity	68.2	-	101	BTU.ft/h.ft^2.F
Specific heat capacity	0.213	-	0.244	BTU/lb.°F
Thermal expansion coefficient	12.2	-	13.3	µstrain/°F

Electrical properties

Electrical conductor or insulator?	Good conductor			
Electrical resistivity	3.8	-	6	µohm.cm

Optical properties

Transparency	Opaque

Processability

Castability	4	-	5
Formability	3	-	4
Machinability	4	-	5
Weldability	3	-	4
Solder/brazability	2	-	3

Durability: water and aqueous solutions

Water (fresh)	Excellent
Water (salt)	Acceptable
Soils, acidic (peat)	Unacceptable
Soils, alkaline (clay)	Excellent
Wine	Excellent

Durability: acids

Acetic acid (10%)	Limited use
Acetic acid (glacial)	

	Unacceptable
Citric acid (10%)	Acceptable
Hydrochloric acid (10%)	Acceptable
Hydrochloric acid (36%)	Unacceptable
Hydrofluoric acid (40%)	Unacceptable
Nitric acid (10%)	Limited use
Nitric acid (70%)	Limited use
Phosphoric acid (10%)	Unacceptable
Phosphoric acid (85%)	Unacceptable
Sulfuric acid (10%)	Unacceptable
Sulfuric acid (70%)	Unacceptable

Durability: alkalis

Sodium hydroxide (10%)	Unacceptable
Sodium hydroxide (60%)	Unacceptable

Durability: fuels, oils and solvents

Amyl acetate	Excellent
Benzene	Excellent
Carbon tetrachloride	Excellent
Chloroform	Excellent
Crude oil	Excellent
Diesel oil	Excellent
Lubricating oil	Excellent
Paraffin oil (kerosene)	Excellent
Petrol (gasoline)	Excellent
Silicone fluids	Excellent
Toluene	Excellent
Turpentine	Excellent
Vegetable oils (general)	Excellent
White spirit	Excellent

Durability: alcohols, aldehydes, ketones

Acetaldehyde	Excellent
Acetone	Excellent
Ethyl alcohol (ethanol)	Acceptable
Ethylene glycol	Excellent
Formaldehyde (40%)	Excellent
Glycerol	Limited use
Methyl alcohol (methanol)	Acceptable

Durability: halogens and gases

Chlorine gas (dry)	Limited use
Fluorine (gas)	Unacceptable
O2 (oxygen gas)	Excellent
Sulfur dioxide (gas)	Acceptable

Durability: built environments

Industrial atmosphere	Excellent
Rural atmosphere	Excellent
Marine atmosphere	Excellent
UV radiation (sunlight)	Excellent

Durability: flammability

Flammability	Non-flammable

Durability: thermal environments

Tolerance to cryogenic temperatures	Excellent
Tolerance up to 150 C (302 F)	Acceptable
Tolerance up to 250 C (482 F)	Unacceptable
Tolerance up to 450 C (842 F)	Unacceptable
Tolerance up to 850 C (1562 F)	Unacceptable
Tolerance above 850 C (1562 F)	Unacceptable

Geo-economic data for principal component

Annual world production, principal component		3.63e7			ton/yr
Reserves, principal component		4.67e10	-	5.16e10	l. ton

Primary material production: energy, CO2 and water

Embodied energy, primary production	*	2.15e4	-	2.37e4	kcal/lb
CO2 footprint, primary production	*	12.2	-	13.4	lb/lb
Water usage	*	137	-	151	gal(US)/lb
Eco-indicator 95		780			millipoints/kg
Eco-indicator 99		710			millipoints/kg

Material processing: energy

Extrusion, foil rolling energy	*	1.11e3	-	1.22e3	kcal/lb
Rough rolling, forging energy	*	568	-	627	kcal/lb
Wire drawing energy	*	4.05e3	-	4.47e3	kcal/lb
Metal powder forming energy	*	2.19e3	-	2.65e3	kcal/lb
Vaporization energy	*	1.68e6	-	1.85e6	kcal/lb
Coarse machining energy (per unit wt removed)	*	132	-	146	kcal/lb

Fine machining energy (per unit wt removed)	* 856	-	946	kcal/lb
Grinding energy (per unit wt removed)	* 1.66e3	-	1.83e3	kcal/lb
Non-conventional machining energy (per unit wt removed)	1.68e4	-	1.85e4	kcal/lb

Material processing: CO2 footprint

Extrusion, foil rolling CO2	* 0.764	-	0.844	lb/lb
Rough rolling, forging CO2	* 0.393	-	0.434	lb/lb
Wire drawing CO2	* 2.81	-	3.1	lb/lb
Metal powder forming CO2	* 1.62	-	1.96	lb/lb
Vaporization CO2	* 1.16e3	-	1.28e3	lb/lb
Coarse machining CO2 (per unit wt removed)	* 0.0913	-	0.101	lb/lb
Fine machining CO2 (per unit wt removed)	* 0.593	-	0.655	lb/lb
Grinding CO2 (per unit wt removed)	* 1.15	-	1.27	lb/lb
Non-conventional machining CO2 (per unit wt removed)	11.6	-	12.8	lb/lb

Material recycling: energy, CO2 and recycle fraction

Recycle	✔			
Embodied energy, recycling	* 3.63e3	-	4.01e3	kcal/lb
CO2 footprint, recycling	* 2.63	-	2.91	lb/lb
Recycle fraction in current supply	33	-	55	%
Downcycle	✔			
Combust for energy recovery	✘			
Landfill	✔			
Biodegrade	✘			
Toxicity rating	Non-toxic			
A renewable resource?	✘			

Environmental notes

Aluminum ore is abundant. It takes a lot of energy to extract aluminum, but it is easily recycled at low energy cost.

Supporting information

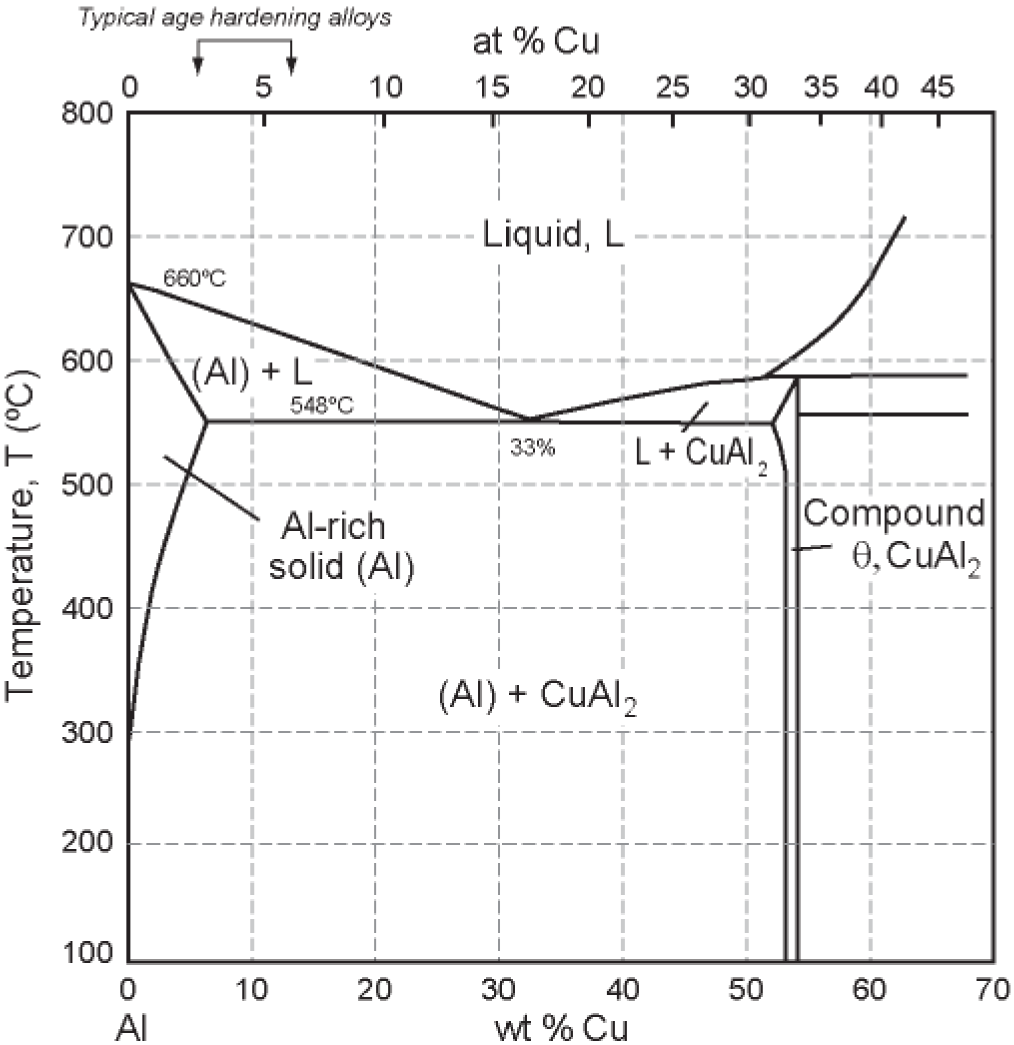
Design guidelines

The age-hardening alloys have exceptional strength at low weight, but the origin of the strength -- age hardening -- imposes certain design constraints. At its simplest, age-hardening involves a three step heat treatment.
Step 1: the wrought alloy, as sheet, extrusion or forging, is solution heat treated -- held for about 2 hours at around 550 C (it depends on the alloys) to make the alloying elements (Cu, Zn, Mg, Si etc) dissolve.
Step 2: the material is quenched from the solution-treatment temperature, typically by dunking or spraying it with cold water. This traps the alloying elements in solution. Quenching is a savage treatment that can cause distortion and create internal stresses that may require correction, usually by rolling.
Step 3: the material is aged, meaning that it is heated to between 120 and 190 C for about 8 hours during which the alloying elements condense into nano-scale dispersions of intermetallics (CuAl, CuAl2, Mg2Si and the like). It is this dispersion that gives the strength.
The result is a material that, for its weight, has remarkably high strength and corrosion resistance. But if it is heated above the solution treatment temperature -- by welding, for example -- the strength is lost. This means that assembly requires fasteners such as rivets, usual in airframe construction, or adhesives. Some 6000 series alloys can be welded, but they are of medium rather than high strength.

Technical notes

Until 1970, designations of wrought aluminum alloys were a mess; in many countries, they were simply numbered in the order of their development. The International Alloy Designation System (IADS), now widely accepted, gives each wrought alloy a 4-digit number. The first digit indicates the major alloying element or elements. Thus the series 1xxx describe unalloyed aluminum; the 2xxx series contain copper as the major alloying element, and so forth. The third and fourth digits are significant in the 1xxx series but not in the others; in 1xxx series they describe the minimum purity of the aluminum; thus 1145 has a minimum purity of 99.45%; 1200 has a minimum purity of 99.00%. In all other series, the third and fourth digits are simply serial numbers; thus 5082 and 5083 are two distinct aluminum-magnesium alloys. The second digit has a curious function: it indicates a close relationship: thus 5352 is closely related to 5052 and 5252; and 7075 and 7475 differ only slightly in composition. To these serial numbers are added a suffix indicating the state of hardening or heat treatment. The suffix F means 'as fabricated'. Suffix O means 'annealed wrought products'. The suffix H means that the material is 'cold worked'. The suffix T means that it has been 'heat treated'. More information on designations and equivalent grades can be found on the Granta Design website at www.grantadesign.com/designations

Phase diagram



Phase diagram description

The 2000 series of wrought aluminum alloys are based on aluminum (Al) with 2.5 - 6% copper (Cu). This is the relevant part of the phase diagram.

Typical uses

2000 and 7000 series: aerospace structures, pressure vessels, ultralight land-based transport systems; sports equipment such as golf clubs and bicycles.
6000 series: cladding and roofing; medium strength extrusions, forgings and welded structures for general engineering and automotive such as connecting rods.

Links

Reference

ProcessUniverse

Producers