Welding of Aluminium-Selection of Filler Metals

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Aluminium alloys find wide applications in all kind of industries. Emphasis on lighter vehicles has especially encouraged use of aluminium in transport sector and in automobile industry. Lower density is the prime reason for their preference in this sector but good thermal conductivity is another major consideration some applications. Transport sector accounts for nearly 18% of the total aluminium consumption in India.

(1) Aluminium alloys are widely used for aeronautical applications because of high strength weight ratio.
(2) For automobiles for reducing weight of the vehicle thus reducing fuel consumption.
(3) For electrical conductors including overhead transmission lines.
(4) For Packaging of food and medicines because of non toxic nature and good corrosion resistance.
(5) House hold and consumer applications such as utensils and white goods.
(6) In buildings and for architectural applications such as windows, doors and railings. .
(7) For surface transport such as fittings in railway coaches and buses.
(8) For heat exchanger purposes because of the good thermal conductivity.
(9) Marine applications.
(10) Use as sacrificial anode.
Applications of pure aluminium however are rather limited.

Classification

Aluminium alloys can be can be classified into :

(i) Wrought alloys
(ii) Cast alloys
Each of these alloys can be further classified into :
(a) Non heat treatable alloys
(b) Heat treatable alloys

Heat Treatment for Age hardening

Heat treatable aluminium alloys are hardened by Precipitation or Age hardening treatment. Heat Treatment of such alloys consist of

1) Solution Treatment: Heating the alloy in single phase region so as to take second phase into solution, temperature of solution treatment is about 540°C.

2) Rapid Cooling: Quenching in either cold water or warm water so as to obtain super saturated solid solution of second phase in Aluminium.

3) Age Hardening: Precipitation of second phase in the form of extremely fine particles either by keeping the components at room temperature (Natural Aging) or at elevated temperature of 160-180°C (Artificial Aging) for sufficient time. Aging for optimum time gives best properties. Aging for longer time may decrease mechanical properties due to overaging.

Table 1. Aluminium alloys used in heat exchanger applications

Alloy	Composition (%)	Component
1100	99.0 Al, 1.0 Fe + Si	Condenser tubes
3003 3005	1.0 – 1.5 Mn, 0.7 Fe, 0.6 Si, 0.2 – 0.6 Mg	Radiator and heater Headers, evaporator plates And fins
Proprietary variants Of 3003 & 3005		Radiator and heater tubes
Proprietary variants of 3105	0.5 Mn, 0.5 Mg, 0.6 Si, 0.7 Fe, 0.3 Cu, 0.4 Zn, 0.2 Cr, 0.1 Ti	Evaporator plates

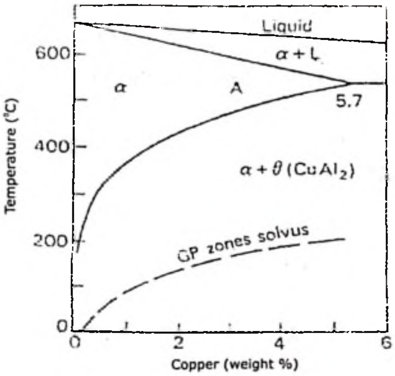

Fig.1 Binary diagram of Aluminium-Copper System

WROUGHT ALLOYS

Al-Cu-Mg Alloys (2XXX Series)

Large-scale applications of wrought aluminium alloys started in the aeronautical industry during First World War. Initially age hardenable Duralumin (Al-Cu-Mg) was most widely used aluminium alloy in the aircraft industry. Subsequently modified alloy such as 2014 (Ai-4.4Cu-0.5Mg-0.9Si-0.8Mn) were developed and well established before the advent of Second World War and are widely used in aeronautical, aerospace, defence and other engineering applications.

Alloy 2021 in as rolled plate has yield strength of 435 MPa and Tensile strength of 505 MPa, Elongation 9% with no sacrifice of weldability or toughness at low temperatures. Increased strength has been achieved by minor addition of 0.15% Cd or 0.05% Sn.

Al-Mg-Si Alloys (6XXX Series)

These alloys are widely used as medium strength structural alloys which have the additional advantage of good weldability, corrosion resistance and immunity to SCC. These alloys are used for extrusions. Mg and Si are added in balanced amount (Mg2Si 1.7: 1) or having slight excess of Silicon. Mg2Si is the precipitating phase during age hardening heat treatment. These alloys find application for architectural and decorative finishes. The alloys of this group are also used for all aluminium alloy conductors (AAAC) widely used for overhead transmission of electricity.

Al-Zn-Mg-Cu Alloys (7XXX Series)

These alloys have higher strength. 7075 is well known alloy developed in 1940 and showed a tensile Strength of 580 MPa as against strength of Duralumin of 420 MPa. However, this alloy was found to be highly susceptible to SCC in short transverse direction in the forgings. Introduction of new high purity alloys containing 0.08-0.25Zr for inhibition of recrystallisation in alloys such as 7050 (Al-20Zn-2.5Cu-0.5Mg-0.5Mn) and 7010 was made. These alloys are having reduced quench sensitivity.

Al-Li Alloys

These alloys have densities lower than 2XXX and 7XXX alloys and have 10-15% higher specific stiffness and specific strength values. Al-Li alloys show good fatigue and corrosion resistance properties. Two major alloys are 2020 (4Cu-1.1Li-0.5Mn-0.2Cd) and 2090.

NON-HEAT TREATABLE WROUGHT ALLOYS

These alloys contain mainly manganese or magnesium as major additions either singly or in combination. Approximately 95% of all aluminium flat rolled products are made from these three alloy groups. Strength is developed by strain hardening, dispersion hardening and by solid solution hardening.

3XXX series Al-Mn and Al-Mn-Mg alloys are used when moderate strength combined with high ductility and excellent corrosion resistance is required. In widely used Al-Mn (3003) alloy, tensile strength in annealed condition is 110 MPa. This alloy is commonly used for foil, cooking utensils and roofing sheet.

The addition of Mg in Al-Mn provides solid solution strengthening and dilute alloy 3105 (Al-0.55Mn-0.5Mg) is widely used in variety of strain hardened tempered. In alloy 3004 containing Mn and Mg has a Tensile strength of 180 MPa in annealed condition. This alloy is used for manufacturing of beverage cans.

Alloys containing 3-5% Mg (5XXX Series) have strength levels of 160 MPa YS. and 310 MPa T.S. for alloys 5456. Elongation is around 25%. These alloys are widely used for welded applications such as dump truck bodies, large tanks for carrying petrol, milk and grain and for fabricating pressure vessels where cryogenic storage is involved. They have good corrosion resistance and are used for hull of small boats and for the super structure of ocean going vessels. These alloys can be polished to bright surface finish particularly if made from high purity aluminium and are used for automotive trim and architectural components

Joining

Aluminium alloys can be joined by most methods used for other metals including welding, brazing, soldering, bolting, riveting and adhesive joining. Focus here will be mainly on welding and brazing.

Properties of Aluminium

Aluminium is very different from steel. It is a highly conductive metal that heats up very fast. The characteristic aluminium oxide film on its surface is a difficult barrier to penetrate during welding. In GMAW of aluminium, melt back can be a problem. A better joint fit up is required as compared to welding of steel.

Main Characteristics

(i) Low density which is almost one third of copper and iron.
(ii) Highly adherent oxide film on the surface.
(iii) High electrical conductivity.
(iv) High thermal conductivity.
(v) High specific heat.
(vi) High latent heat of fusion.
(vii) High coefficient of linear expansion.
(viii) High solubility of hydrogen in liquid metal.

Problems in Welding of Aluminium and Alloys

Following problems are faced during welding of aluminium alloys because of typical properties of this alloy.

(i) Refractory oxide film.
(ii) Porosity.
(iii) Cracking.
(iv) Loss of strength
(v) High thermal conductivity
(vi) High electrical conductivity

(i) Refractory oxide film: Aluminium readily forms an adherent oxide film. This film interferes with atomic to atomic contact between two opposite surfaces during welding. For successful welding, it is necessary to remove this film. Special fluxes are used to make the welding surfaces free of oxides in case of gas welding. Fluxes act primarily by penetrating between metal and oxide interface and floating off the oxide film. Main constituents of the fluxes are sodium and potassium chlorides. Alkali fluorides are added to increase the rate of oxide removal while lithium chloride is added to lower the melting point. Electrode coatings are broadly similar to gas welding fluxes but contain cryolites in addition to other constituents.

Flux residues are hygroscopic in nature and may absorb moisture. This moisture may be corrosive in nature to aluminium. Therefore it is necessary to remove all fluxes by thorough scouring after welding.

In GMAW, oxide is removed by the action of the arc when job makes the negative pole. Amount of energy released at the arc anode is substantially higher than released at the cathode. In GTAW, if electrode is made positive it may lead to overheating of the tungsten electrode. Therefore while DC electrode positive is used for GMAW, AC is used for GTAW.

(ii) Porosity: It is mostly due to

Table 2. Aluminium alloys for welding applications

Designation	Chemical Composition (mass %), Remainder Aluminium										Other Elements
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Zr	
R-206.0	0.10	0.10 - 5.00	4.20 - 5.00	0.20 - 0.50	0.15 - 0.35	- -	- 0.05	- 0.10	0.15 - 0.30	- -	Sn $\leq$ 0.05
R-C355.0	4.50 5.50	- 0.20	1.00 1.50	- 0.10	0.40 - 0.60	- - -	- - -	- 0.10	- 0.20	- -	-
R-A356.0	6.50 7.50	- 0.20	- 0.10	- 0.10	0.25 0.45	- -	- -	- 0.10	- 0.20	- -	-
R-357.0	6.50 - 7.50	0.15	0.05	0.03	0.45 - 0.60	- - -	- - -	0.05	0.20	- - -	- Be 0.04- 0.07
4252	8.00 11.00	- 0.80	2.00 - 3.50	0.10 - 0.50	0.10 0.50	- -	- -	- 0.20	- 0.15	- -	Cast Rod

Table 3. Physical properties of Aluminium

	Aluminium	Steel	Stainless
Density (kg/m^3)	2700	7800	78
Modulus of Elasticity (10^3 MPa)	69	200	200
Melting Point (^{0}C)	660	1530	1426
Specific Heat (J/kg ^{0}C)	940	496	490
Electrical Conductivity (% IACS)	62	10	2
Thermal Conductivity (W/m ^{0}C)	222	46	21
Coefficient of Linear Expansion (10^6 ^{0}C^{-1})	23.6	12.6	16.2

the rejection of hydrogen from the weld metal during cooling from liquid condition. Porosity is most sever in SMAW and is least with GTAW. In general more difficult is the welding position; greater is the risk of entrapment of gas. Overhead and horizontal vertical joints are particularly subject to porosity. Porosity is also more common at the start of weld run. There are various sources for hydrogen. Gas may be present in the form of moisture on the surface of aluminium. It may also be present on the cold drawn wire in the form of lubricant residue. Porosity can be reduced by storing the electrodes and welding consumables in the dry place.

Tunneling: Porosity may also form in the shape of large discontinuous cavities or long continuous holes. This may happen in GMAW under high current with spray transfer. It is overcome by the use of lower current gravitational transfer. Since porosity is common in aluminium welds, radiography standards for porosity correspond to a joint efficiency of 95%.

(iii) Cracking: Hot cracking is common in aluminium alloys. Degree of cracking rises to maximum at about 0.5% of solute and then decreases rapidly as alloy content is increased. 12% Silicon alloy is not crack sensitive. In practice hot cracking is likely to occur in 0.75% Mg & I%Si heat treatable alloy, 2% Mg alloy, Duralumin and AlMg-Si composition. Welding is done with 5% Si, 12%Si or 5% Mg alloy which brings out the weld metal out of the cracking range. Effect of dilution should be considered in choosing the filler material (Fig 1).

(iv) Cracking in the HAZ: This is also known as liquation cracking and takes place due to the presence oflow melting point constituents. It may be overcome by using a low melting point filler material or by increasing the welding speed. In high strength alloys such as Duralumin or Al-Mg-Zn alloy, cracking is observed below the solidous (200°C) as a result of formation of intergranular films at or near the solidous.

(v) Softening of Parent Metal: Work hardened metal gets annealed and strength in HAZ decreases. Age hardened metal gets overaged during welding. Effect of heat is reduced by increasing the welding speed. This leads to lesser time at high temperature in HAZ and lesser width of HAZ. In work hardened metals, strength may be partly restored by rolling or hammering. In case heat treatable metal is welded with matching electrodes, strength may be recovered by subsequent heat treatment of the

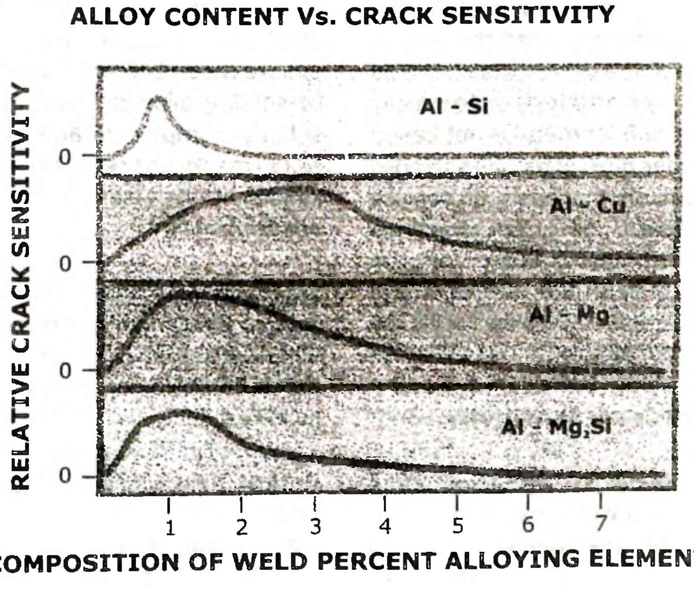

Fig. 2 Cracking sensitivity for various compositions

Table 4. Aluminium Filler alloys for general purpose GTAW & GMAW

Base metal welded to base metal	7005	6061 6063 6351	5454 5154A	5086 5083	5052	5005 5050A	3004 Alclad 3004	1100 3003 1200
1100 1200 3003	5356 †	4043	4043†	5356‡	4043†	4043†	4043†	1100‡ 1200‡
3004 Alclad 3004	5356†	4043†	5356†	5356†	5356†‡	4043†	4043†	
5005 5050A	5356†	4043§§	5356†	5356†	4043†	4043†§§		
5052	5356†	5356†‡	5356	5356†	5356§§			
5083 5086	5356†	5356†	5356†	5356†				
5154A	5356†	5356‡§	5356‡§					
5454	5356†	5356‡§	5356‡§					
6061 6063 6351	5356†	4043§						
7005	5039†							

† 5356 or 5556 may be used

‡ 4043 may be used for some applications.

§ 5154A, 5356 and 5556 may be used. In some cases they provide improved colour match after anodizing treatment; higher weld ductility; higher weld strength; improved stress-corrosion resistance.

§§ Filler metal with the same analysis as the base metal is sometimes used.

entire component for age hardening.

Selection of Filler Metal for Aluminum Welding

In welding of steel, filler metal is selected for matching strength to that of base metal. In aluminum welding, it is possible to weld many of the aluminum base metals with anyone out of number of filler metals. Several filler metals will usually meet or exceed the tensile strength of the base metal in the as welded condition. However selection of filler metal is not based on consideration of tensile strength alone but on the basis of service conditions of the welded component also. Some of the variable in selection of filler metal in aluminium welding will be considered here.

Relative Crack Sensitivity

Hot cracking in weldment may occur due to weakness in the weld and from transverse stresses across the weld. Transverse stresses are result of shrinkage during solidification of the weld. Aluminium has large coefficient of contraction/expansion. For reduction of stresses we can do the followings.

Reduction of stresses

Lower melting and solidification point - With base metal having high susceptibility to hot cracking such as 2XXX series alloys, we may choose 4XXX series filler such as 4145 that has extremely low solidification temperature. This ensure that 4145 weld metal is last to solidify allowing base metal to solidify completely and reach its maximum strength before solidifications stresses of the weld are applied to it.

Smaller freezing temperature range - By using filler metal such as 4047 which has a freezing range of about 6T, weld can be made which solidify quickly.

Critical chemistry ranges - To understand this, one can compare crack sensitivity curves for various aluminum weld composition which developed during welding of different weld metals. In 4XXX series 0.5 % to 2 % Si in filler/base metal may produces crack. Therefore if 1XXX base metal is welded with 4XXX series filler metal, dilution may lead to a weld metal composition in crack sensitivity range.

Aluminum Copper alloy are having extended range of compositions showing crack sensitivity. These alloys are having poor weldability.

Al-Mg alloys (5XXX) series have the highest strength of non heat treatable alloys. Magnesium in that weld between 0.5 to 3 % produces a weld metal composition that is crack sensitive. Al - Mg base metal with less than 2.8 % Mg can be welded with either the Al-Si (4XXX) or the Al-Mg (5 XXX) filler metal depending upon that weld performance requirements. Al-Mg base metal with more that about 2.8 % Mg typically can not be successfully welded with the Al-Si (4XXX series) filler metal because of the problem associated with excessive amounts of magnesium silicide forming in the weld metal which decrease ductility and increases crack sensitivity.

The AI-Mg-Si alloys (6 XXX) are heat treatable. These alloys contain about 10 % Mg2Si. These alloys can not be welded without filler metal. These alloys can be welded with 4XXX series or 5XXX series filler metal depending on weld performance requirements. The main consideration is to adequately dilute the Mg_2Si percentage in the base metal with sufficient filler metal to reduce weld metal crack sensitivity. Dilution with base metal in such cases is kept low.

Weld Strength

Strength of HAZ and not of weld metal decides the strength of the weldment. However the considerations in heat treatable and non heat treatable are different. In non heat treatable alloys area adjacent to weld in completely annealed. Annealing temperature is about 315-370°C and time required at this temperature for annealing is short. Weld procedures have little effect on the strength of weldment as the HAZ is the weakest and procedure only tends to improve strength of the weld.

Heat treatable alloys require longer time to reduce strength of HAZ by overaging. In these alloys, loss is both time and temperature dependent. The faster the welding processes and heat dissipation from the weld are, less in the effect of heat and higher is the as welded strength. Excessive preheating, lack of inter pass cooling and excessive heat input from slow, weaving weld passes will increases temperature and time at temperature. Use of too small a specimen to provides adequate heat sink, can create sufficient over heating.

In fillet welds strength is largely depending on the composition of filler metal. 4xxx series filler metal have lower ductility and provide less shear strength. 5XXX series filler metal have more ductility and can provide shear strength double to that of 4 xxx SERIES. Obviously more weld metal is required in a fillet when welded by 4 XXX series.

Cracking

Relative Crack Susceptibility

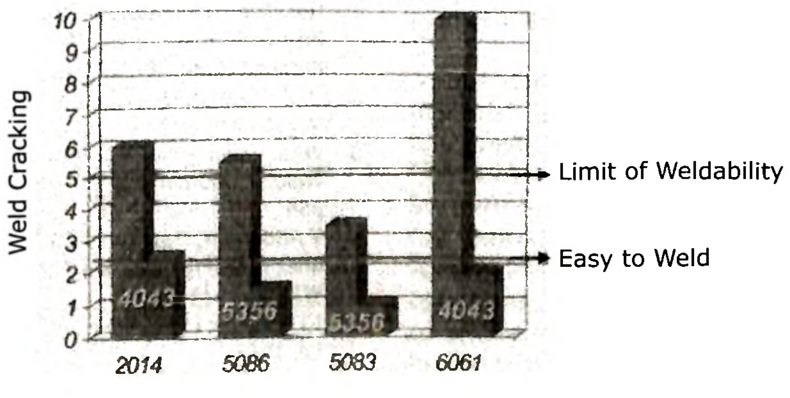

Figure 3. Compatibility of various filler and base metals

Ductility

Ductility - it can be consideration if forming is to be performed after welding or if the weld is going to be subjected to impact loading. It procedure qualification involves bend test then also ductility is important. 4 XXX have low ductility.

Corrosion Resistance

5654 filler metal was developed for welding of storage tanks to hold hydrogen peroxide. This filler metal has high purity with low copper and manganese content. Most unprotected Al base metal/filler combinations are satisfactory for general exposure. However wherever dissimilar metal combination of base and filler are used and corrosive condition are present, corrosion at the joint is possible.

SCC can occur if there is Mg segregation at grain boundaries. This condition can develop in alloys containing more than 3 % Mg and exposed to elevated temperature.

Service Temperature

When considering service at temperature more than o~ we must consider the filler metal which can operate at these temperature without any considerable effect on welded joint. Filler metal 5356, 5183, 5654 and 5556 all contain Mg in excess of 3 %, typically around 5 % and therefore not suitable for temperature service. Alloy 5554 has less than 3 % Mg and was developed for high temperature applications. Alloy 5554 is used for welding of 5454 base metal which is also used for high temp application. In some application 4XXX series filler may also be used.

Post weld heat treatment

Alloy 6061- T6 has TS of 45000 Ib/in2 before welding and 27000 Ib/in2 in as welded condition. Therefore entire component may be heat treated after welding and filler should also respond to heat treatment.

Filler 4643 was developed for welding 6xxx series of metals. This filler metal was developed by taking 4043 alloy reducing the silicon and adding 0.1 to 0.3 % Mg. Filler metal 5180 was developed for welding of 7XXX series base metal. It falls within Al-ZnMg alloy family and responds to heat treatment. Other heat treatable filler metal includes 2319,4009,4010,2060, A356, A357 355, and 357 for welding of heat treatable wrought and cast alloys.

Welding of different alloy groups

2XXX series- There alloys have high sensitivity to hot cracking and are having poor suitability for arc welding. These are generally welded with 4043 or 4145 series filler metal which have low melting point. Exception is alloys 2014, 2219 and 2519 which are easily welded with a 2319 filler metal.

3XXX series - there alloys are hardened only by arc welded with 4043 or 5356 electrode.
This series is excellent for welding and not prone to hot cracking.

4XXX series - silicon reduces meting point of aluminium and improves fluidity. This series, alloys have good weldability and are considered a non heat treatable alloy. It s principal use is as filler metal. Alloy 4047 is becoming the alloy of choice in the automobile industry as it is very fluid and good for brazing and welding.

5XXX series - has excellent weld ability with a minimum loss of strength and basically not prone to hot cracking. 5XXX series has the highest strength of non heat treatable aluminum alloys. It looses ductility when welded with 4XXX series filler due to formation ofMg_2Si.

6XXX series - heat treatable series - it is used principally in automotive, pipe, railway, structural and extruding applications. This series is some what prone to hot cracking. This can be welded with either 5XXX or 4XXX series without cracking. Adequate dilution of the bare alloys with selected filler metal is essential A4043 electrode is the most common for use with this series.

7XXX series - highest strength heat treatable alloy- it is primary used in the aircraft industry. Many of these grades especially with high copper are crack sensitive grades 7005 and 7039 are weldable with 5xxx filler metals

Main Requirements

For welding of aluminium, we should also be aware of the main requirements
(i) An intense localized heat source to take care of high thermal conductivity, specific heat and latent heat of fusion of this metal.
(ii) Ability of the process to remove the surface oxide films having high melting point (above 2000"C). These oxide films get entrapped with the molten metal leading to formation of inclusions in the weld bead.
(iii) A high welding speed to minimize distortion arising out of relatively large coefficient of thermal expansion.
(iv) A low hydrogen content of weld metal since high solubility of this gas in molten aluminium can lead to porosity in the weld bead after solidification.

Cleaning of surface - preparation for welding

In GMAW, cleanliness of aluminium is very important. Even when the aluminium is stored indoors, it is better to clean the surface of the metal within the week of it to be welded. After cleaning; component should be stored in the same area where they will be welded. The fit up requirements for aluminium are at least twice as critical as the requirements for steel. Milling is a good way to provide consistency in weld preparation.

Final determination of the most suitable filler metal can only be made after a full analysis of the performance requirements for the welded components. Filler metal selection for welding aluminium is an essential part of the development and qualification of a successful welding procedure

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