# Causes of common problems encountered during welding of aluminium

This chapter presents metallurgical aspects related with welding of aluminium alloys. Causes of common problems encountered during welding of aluminium alloys have been described. The mechanism of solidification cracking and its control has been elaborated in detail.

**Keywords:** Aluminium welding, heat treatable aluminium alloy, precipitation hardening, problems in aluminium welding, inclusion, gas and shrinkage porosity, solidification cracking, controlling solidification cracks

## 38.1 Need of aluminium welding

Welding of the aluminium is considered to be slightly difficult than the steel due to high thermal & electrical conductivity, high thermal expansion coefficient, refractory aluminium oxide ($Al_2O_3$) formation tendency, and low stiffness. However, increase in applications of aluminium alloys in all sectors of industry is a driving force for technologists to develop viable and efficient technologies for joining of aluminium without much adverse effect on their mechanical, chemical and metallurgical performances desired for longer life. The performance of weld joints of an aluminium alloys to a great extent is determined by its composition, alloy temper condition and method of manufacturing besides welding related parameters. All the three aspects are usually included in aluminium alloy specification. Aluminium alloy may be produced either only by cast or by casting and subsequent forming process (which are called wrought alloys). Welding of wrought aluminium alloys is more common and therefore in this chapter discussions are related to wrought aluminium alloys. Depending upon the composition, aluminium alloy are classified from 1XXX through 9XXX series. Some of aluminum alloys (1XXX, 3XXX, 4XXX and 5XXX) non-heat treatable and others (2XXX, 6XXX and 7XXX series) are heat treatable.

### 38.1.1 Strengthening of Non-heat treatable aluminium alloys and welding

The strength of the non-heat treatable aluminium alloys is mostly dictated by solid solution strengthening and dispersion hardening effects of alloying elements such as silicon, iron, manganese and magnesium. Magnesium is the most effective alloying element in solution strengthening therefore 5XXX series aluminium alloys have relatively high strength even in annealed condition. Most of the non heat treatable aluminium alloys are work hardenable. Heating of these alloys during welding (due to weld thermal cycle) lowers prior work hardening effect and improves the ductility which in turn can lead to loss of strength of HAZ. Moreover, high strength solid solution alloys of 5XXX series such as Al-Mg and Al-Mg-Mn are found suitable for welded construction structures as they offer largely uniform mechanical properties of the various zones of a welded joint.

### 38.1.2 Strengthening of heat treatable aluminium alloys and welding

The most of heat treatable aluminium alloys (2XXX, 6XXX and 7XXX series) are strengthened by solid solution formation, work hardening and precipitation strengthening depending upon the alloy condition and manufacturing history. Strength of these alloys in annealed condition is either similar or slightly better as compared to non-heat treatable alloys mainly due to presence of alloying elements such as copper, magnesium, zinc and silicon. Generally, heat treatable aluminium alloys are precipitation hardened. The precipitation hardening involves solutionizing followed by quenching and aging either at room temperature (natural aging) or elevated temperature (artificial aging).

Three most common precipitation hardenable aluminium alloys namely Al-Cu (2XXX series), Al-Mg-Si (6XXX series) and Al-Zn-Mg (7XXX series) are primarily hardened by forming phases namely $Al_2Cu$, $Mg_2Si$ and $Zn_2Mg$ respectively besides many complex intermetallic compounds developed during aging process. Therefore, presence and loss of these precipitates significantly affects the mechanical performance (hardness, tensile strength and % elongation) of weld joints of these alloys. However, the existence of theses hardening precipitates is influenced by weld thermal cycle experienced by base metal and weld metal during welding. In general, all factors decreasing the heat input (either due to low welding current, increase in welding speed or use of low heat input welding processes such as electron beam, pulse TIG) would reduce the width of heat affected zone associate adverse effects such as the possibility of partial melting of low melting point phases (eutectic) present at grain boundary, over-aging, grain growth, reversion or dissolution of precipitates or a combination few or all.

$$\text{Al–Cu–Mg (e.g., 2024):} \quad SS \rightarrow GP \rightarrow S' (Al_2CuMg) \rightarrow S (Al_2CuMg)$$
$$\text{Al–Mg–Si (e.g., 6061):} \quad SS \rightarrow GP \rightarrow \beta' (Mg_2Si) \rightarrow \beta (Mg_2Si)$$
$$\text{Al–Zn–Mg (e.g., 7005):} \quad SS \rightarrow GP \rightarrow \eta' (Zn_2Mg) \rightarrow \eta (Zn_2Mg)$$

In the solution heat treated condition, heat treatable alloys exhibit lower cracking tendency than in the aged condition mainly due to more uniform microstructure and lesser restraint imposed by base metal. Welding of heat treatable aluminium alloy in aged condition leads to reversion (loss/dissolution of precipitates) and over-aging (coarsening of precipitates by consuming fine precipitates) effect which in turn softens the HAZ to some extent. However, under influence welding thermal cycle, alloying elements are dissolved during heating and form heterogeneous solid solution and subsequently rapid cooling results in super-saturation of these elements in aluminium matrix. Thus, solutionizing and quenching influence the heat affected zone. Thereafter, aging of some of the alloys like Al-Zn-Mg occurs slowly even at room temperature which in turn help to attain strength almost similar to that of base metal while other heat treatable alloy like Al-Cu and Al-Mg-Si alloys don’t show appreciable age hardening at room temperature. Hence, Al-Zn-Mg alloys are preferred when post weld heat treatment is neither possible nor feasible.

## 38.2 Weldability of aluminum alloys

Weldability of aluminium alloys like any other metal system must be assessed in light of purpose (application of weld joint considering service conditions), welding procedure being used and welding conditions in which welding need to be performed. Weldability of aluminium may be very poor when joined by shielded metal arc welding or gas welding but the same may be very good when joint is made using tungsten inert gas or gas metal arc welding process. Similarly other aspects of welding procedure such as edge preparation, welding parameters, preheat and post weld heat treatment etc. can significantly dictate the weldability of aluminium owing to their ability to affect the soundness of weld joints and mechanical performance. Thus, all the factors governing the soundness of the aluminium weld, the mechanical and metallurgical features determine the weldability of aluminium alloy system. In general, aluminium is considered to be of comparatively lower weldability than steels due to various reasons a) high affinity of aluminium towards atmospheric gases, b) high thermal expansion coefficient, c) high thermal and electrical conductivity, d) poor rigidity and e) high solidification temperature range. These characteristics of aluminium alloys in general make them sensitive from defect formation point of view during welding. The extent of undesirable affect of above characteristics on performance of the weld joints is generally reduced using two approaches a) effective protection of the weld pool contamination from atmospheric gases using proper shielding method and b) reducing influence of weld thermal cycling using higher energy density welding processes. Former approach mainly deals with using various environments (vacuum, Ar, He, or their mixtures with hydrogen and oxygen) to shield the weld pool from ambient gases while later one has led to the development of newer welding processes such as laser, pulse variants of TIG and MIG, friction stir welding etc.

## 38.3 Typical welding problems in aluminum alloys

### 38.3.1 Porosity

Porosity in aluminum weld joints can be of two types a) hydrogen induced porosity and b) inter-dendritic shrinkage porosity and both are caused by entirely different factors (Fig. 38.1). Former one is caused by the presence of hydrogen in the weld owing to unfavorable welding conditions such as improper cleaning, moisture in electrode, shielding gases and oxide layer, presence of hydro-carbons in form of oil, paint, grease etc. In presence of hydrogen porosity in the weld metal mainly occurs due to high difference in solubility of hydrogen in liquid and solid state of aluminum alloy. During solidification of the weld metal, the excess hydrogen is rejected at the advancing solid-liquid interface in the weld which in turn leads to the development of hydrogen induced porosity especially under high solidification rate conditions as high cooling rate experienced by the weld pool increases tendency of entrapment of hydrogen. Excessive hydrogen porosity can severely reduce strength, ductility and fatigue resistance of aluminum welds due to two reasons a) reduction in effective load resisting cross-sectional area of the weld joints and b) loss of metallic continuity owing to the presence of gas pockets which in turn increases the stress concentration at the weld pores. It also reduces the life of aluminum welds. Therefore, to control hydrogen induced porosity in aluminium following approaches can be used a) proper cleaning of surfaces, baking of the electrodes to drive off moisture and remove the impurities from weld surface b) addition of freon to the shielding gas, c) churning the weld pool during weld solidification using suitable electro-magnetic fields.

Inter-dendritic porosity in weld mainly occurs due to poor fluidity of molten weld metal and rapid solidification. Preheating of plates and increasing heat input (using high current and low welding speed) help in reducing the inter-dendritic porosity.

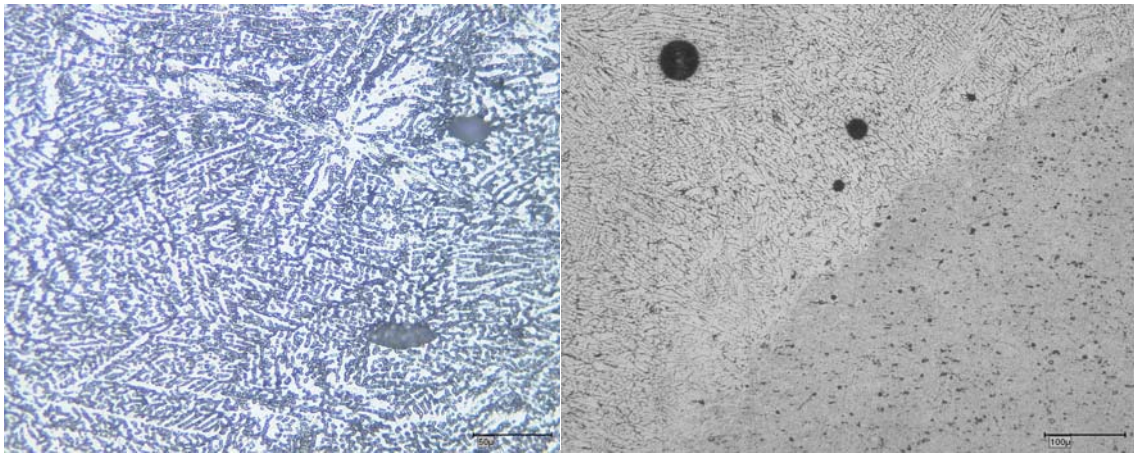


Fig. 38.1 Micrographs showing a) dendritic and b) gas porosity in aluminium welds (100X)

### 38.3.2 Inclusion

In general, presence of any foreign constituent (one which is not desired) in the weld can be considered as inclusion and these may be in the form of gases, thin films and solid particles. High affinity of aluminium with atmospheric gases increases the tendency of formation of oxides and nitrides (having density similar to that of aluminium) especially when a) protection of weld pool is not enough, b) proper cleaning of filler and base metal has not been done, c) shielding gases are not pure enough and therefore making oxygen and hydrogen available to molten weld pool during welding, d) gases are present in dissolved state in aluminium itself and tungsten inclusion while using GTA welding. Mostly, inclusion of oxides and nitrides of aluminium are found in weld joints in case of un-favourable welding conditions. Presence of these inclusions disrupts the metallic continuity in the weld therefore these provide site for stress concentration and become a source of weakness leading to the deterioration in mechanical and corrosion performance of the weld joints (Fig. 38.2). Ductility, notch toughness and fatigue resistance of the weld joints are very adversely affected by the presence of the inclusion. To reduce the formation of inclusion in weld it is important to give proper attention to a) avoid sources of atmospheric gases, b) developing proper welding procedure specification (selection of proper electrode, welding parameters, shielding gases and manipulation of during welding), and c) manipulation of GTAW torch properly so as to avoid the formation of tungsten inclusion.

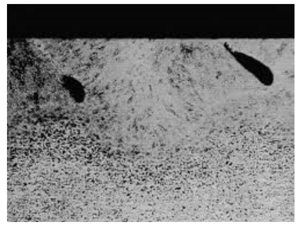


Fig. 38.2 Inclusions and other impurities in weld joints

### 38.3.3 Solidification cracking

This is an inter-dendritic type of cracking mostly along observed along the weld centerline in very last stage of solidification primarily due to two factors a) development of tensile residual stresses and b) presence of low melting point phases in inter-dendritic regions of solidifying weld is called solidification cracking (Fig. 38.3).

The solidification cracking mainly occurs when residual tensile stress developed in weld (owing to contraction of base metal and weld metal) goes beyond the strength of solidifying weld metal. Moreover, the contribution of solidification shrinkage of weld metal in development of the tensile residual stress is generally marginal. All the factors namely thermal expansion coefficient of weld and base metal, melting point, weld bead profile, type of weld, degree of constraint, thickness of work piece etc. affecting the contraction of the weld will govern the residual stresses and so solidification cracking tendency. The presence of tensile or shear stress is mandatory for cracking means no residual tensile stress no cracking. Residual stresses in weld joint can not be eliminated but can be minimized by developing proper welding procedure.

Increase in degree of restraint during welding in general increases solidification cracking tendency due to increased residual tensile stresses. Similarly, concave fillet weld bead profile results higher solidification cracking tendency than those of convex weld bead profile. In same line, other related materials characteristics of base metal such as increase in thickness of plate, high thermal expansion of coefficient and wider solidification temperature in general increases the residual stresses and so solidification cracking tendency.

Apart from the residual tensile stresses, strength and ductility of weld metal in terminal stage of solidification also predominantly determine the solidification cracking tendency. In general, all the factors such as composition of the weld metal, microstructure, segregation tendency, wider solidification temperature range and higher fluidity of low melting point phases (owing to reduction in surface tension and viscosity) of molten weld metal increase the solidification cracking.

Fig. 38.3 Solidification cracking in aluminium weld

#### 38.3.3.1 Composition of aluminum alloy

Presence of all alloying element (silicon, copper, magnesium, zinc) in such a quantity that increases the solidification temperature range tends to increase the solidification cracking tendency. In general, addition of these elements in aluminum first widens the solidification temperature range then after reaching maximum it decreases gradually as evident from the Fig. 38.4. It can be observed that addition of these elements at certain level results in maximum range of solidification temperature and that corresponds to highest solidification cracking tendency. It can be noticed from the Fig. 38.4 that solidification cracking is lower with both very low and high concentration of alloying element owing to varying amount of low melting point eutectic and other phases. A very limited amount of low melting point phases obviously increases resistance to solidification cracking due to high strength of solidified weld metal in terminal stage of solidification while in case of aluminium alloy (such as eutectic or near to the eutectic composition) or those with high concentration of alloying elements having large amount of low melting point phases to facilitate healing of cracks by the backfill of incipient cracks which in turn decreases the solidification cracking tendency.

Therefore, selection of filler metal for welding of aluminum alloys is done in such a way that for given dilution level, concentration of alloying element in weld metal corresponds to minimum solidification temperature so as to reduce the solidification cracking possibility. In general, application of Al-5%Mg and Al-(5-12%) Si fillers are commonly used to avoid solidification cracking during welding of aluminum alloys.

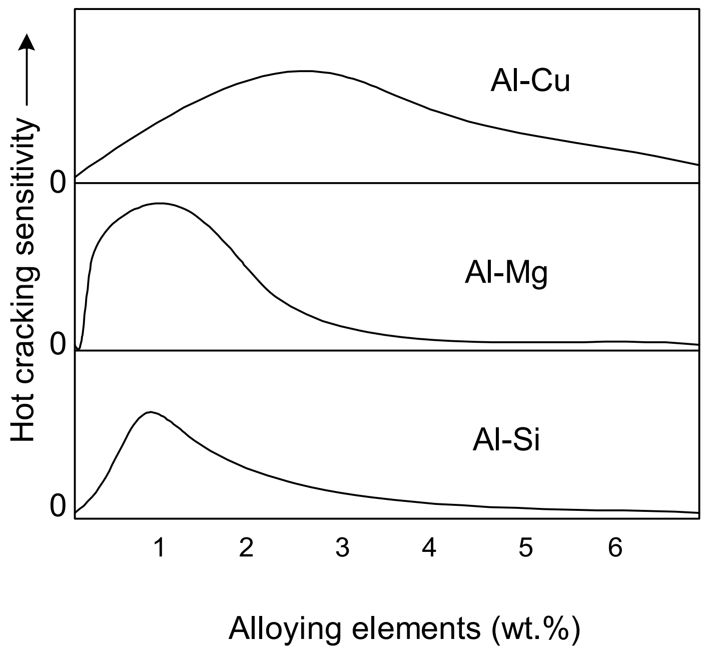
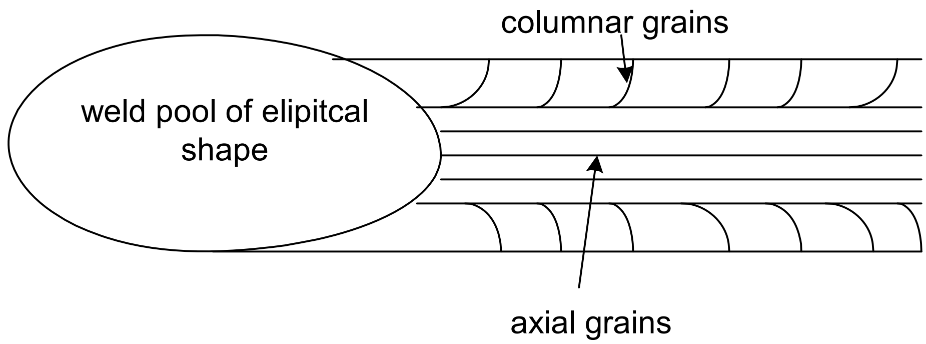
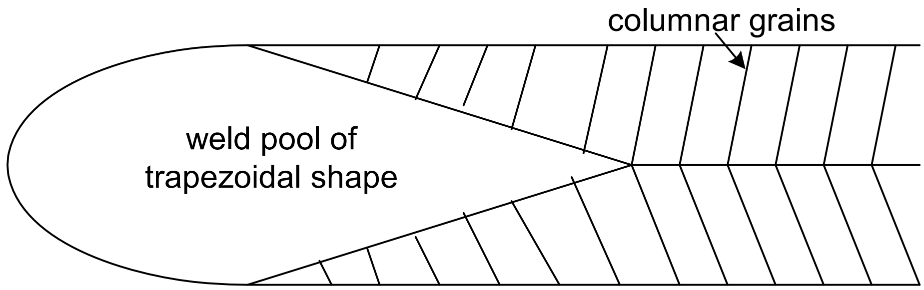



Fig. 38.4 Influence alloying elements on solidification cracking tendency

The influence of microstructure of weld metal on solidification cracking depends on the way it affects the segregation tendency owing to variation in size and orientation of grains. In general, fine grain structure results is large grain boundary area and hence more uniform distribution of low melting point phases and reduced segregation of alloying element. Further, fine equiaxed grain structure provides better heeling of incipient crack through back fill by liquid metal available at last to solidify due to improved fluidity of melt through the micro-channel present between already solidified metal. Conversely for a given solidification cracking sensitive alloy composition coarse columnar grain structure having abutting orientation encourages the cracking tendency as compared to fine equiaxed and axially grain (Fig. 38.5). Moreover, the morphology of low melting point phases as governed by their surface tension and viscosity in liquid state near last stage of solidification also affects the solidification cracking sensitivity. In general, low melting point phases having low surface tension and viscosity (so high fluidity) solidify in form of thin films and layer in inter-dendritic regions which are considered to be more crack sensitive than those of globular morphology formed in case of high surface tension and viscous low melting point phases.




a)




b)

Fig. 38.5 Schematic diagram showing influence of welding speed on weld pool and grain structure of weld a) low speed and b) high speed

**38.3.3.2 Control of solidification cracking**

- Changing composition of the weld metal so as to reduce the solidification temperature range and increase the amount of low melting point eutectic phases and phase mixtures to facilitate heating of incipient cracks.
- Refinement of the grain structure: The microstructure of weld metal can be controlled in many ways such as addition of grain refiner, use of external electromagnetic or mechanical forces and selection of proper welding parameters such as heat input (VI) and welding speed or use pulse current for welding. Addition of grain refiner (Ti, B, Zr etc) in aluminium weld metal so as to facilitate the development of fine and equiaxed grain structure and reduce columnar grain structure. Similarly, low heat input leads to development of fine equiaxed grains and low welding speed produces curved grain associated with pear drop shaped weld pool. Mechanical vibrations and electro-magnetic stirring of weld pool also help to refine the grain structure avoid the abutting columnar grains (Fig. 38.5 b).

- Reducing tensile residual stresses developing in weld joints using any of the approaches such as controlling weld bead geometry, selection of weld joint design, welding procedure and low strength filler can help in reducing the solidification cracking.

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