Problems in Welding of High Strength Aluminium Alloys

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Pure aluminium has very low strength, yet many of its alloys are stronger than ordinary structural steels. Some aluminium alloys especially those in the 5XXX and 7XXX series (e.g., 5083, 7020, and 7039) are so strong that they could be used in armour structures.

The 5XXX series alloys are nonheat-treatable Al-Mg alloys. Mg is the most effective alloying addition for solid solution strengthening, so Al-Mg alloys of 5XXX series have relatively high strength in the annealed condition. In addition, they can be further strengthened by cold work.

The 7XXX series alloys are heat-treatable Al-Zn-Mg or Al-Zn-Mg-Cu alloys. They develop their strength by solution heat treatment followed by ageing. In contrast to the 5XXX series alloys, the 7XXX series alloys do not respond favourably to cold work, because they are strengthened almost exclusively by GP zone formation and precipitates which nucleate from the GP zones. Introducing many new dislocations by cold work after solution treatment and quenching does not greatly accelerate formation of precipitates.

Aluminium alloys can be joined by most fusion and solid-state welding processes as well as by brazing and soldering, but this article is concerned with inert gas tungsten arc welding (GTAW or TIG) and inert gas metal arc welding (GMAW or MIG) only, because they are the two most commonly used welding processes. The following three problems associated with welding of high strength aluminium alloys are discussed:

- Porosity;
- Hot cracking;
- Stress corrosion cracking (SCC).
Porosity is a common problem in welding of all types of aluminium alloys. Hot cracking and SCC may appear in welded joints of 7XXX series alloys but usually do not occur in 5XXX series alloys.

1. Porosity in Weld

Although porosity is almost unavoidable in gas-shielded welding processes (either TIG or MIG), it usually does not pose any serious problem in welding of steels. However, porosity is the major cause for rejection of aluminium welds by various non-destructive testing codes. This highlights the need to understand mechanisms of porosity formation in aluminium welds and methods of reducing the porosity level.

The main source of porosity is hydrogen contamination. Solubility of hydrogen in superheated liquid aluminium is very high but is drastically reduced in solidified aluminium. Therefore, when solidification takes place in the welding pool, the excessive hydrogen will form “bubbles” gradually, and the “bubbles” will be trapped in the weld to become porosity if they cannot escape to air before the solidification is complete. In steel welds, porosity is less a problem for two reasons: First, when steel solidifies, hydrogen solubility also reduces a lot, but the reduction is not so drastic as in process of aluminium solidification; Second, the solidification temperature range of steel is roughly two times greater than aluminium, and the thermal conductivity of steel is only about one-quarter that of aluminium, so solidification takes place much more slowly in steel than in aluminium, making it considerably easier for the “bubbles” in the welding pool of steel to escape.

Hydrogen can enter the arc column of welds deposited by TIG and MIG from a variety of sources such as:

(1) Hydrogen within the filler metal and parent metal;
(2) Hydrogen-containing contamination (e.g., oil, greases and solvents) or hydrated oxide films on the surfaces of the filler wire and parent metal;
(3) Moisture in the shielding gas.
The greatest single source of porosity is the surface contamination of the filler wire, and the resulting porosity is greater in MIG than in TIG due to the high ratio of surface area to volume of the filler metal required for MIG.

One of the most effective methods to reduce porosity is to control the weld bead shape. Narrow and deep welds tend to trap porosity since individual pores must rise a long distance to escape to the surface. Compared with downhill welding, uphill welding provides a shorter vertical path for hydrogen bubbles to escape before weld solidification is complete and thus produces fewer surface and internal pores.

The oxide films on aluminium alloys thicken with time, so prolonged storage after cleaning and before welding increases the porosity level and should be avoided. Welding using small current and short arc length helps to reduce porosity level.

Turbulent convective fluid flow by electromagnetic stirring during solidification has been shown to produce a substantial reduction in porosity and grain size in aluminium alloys deposited by the TIG process.

Radiography indicates only the macro-porosity as discrete pores. In general, there is 5 to 10 times more micro-porosity than macro-porosity, and both the macro- and micro-porosity affect the mechanical properties of the weld metal. The micro-porosity as well as the macro-porosity can be revealed clearly under the optical microscope by metallographic examination and measured quantitatively using an image analyser connected to the microscope.

2. **Hot Cracking**

Hot cracking is a potential problem in TIG or MIG welding of some 7XXX series aluminium alloys. As the name indicates, this kind of cracking occurs while the metal is still hot. It usually occurs in the fusion zone during solidification, so it is also called solidification cracking.

Hot cracking may also occur in HAZs if some grains there are partially melted during welding. The partial melting may take place at grain boundaries which have low melting
points due to chemical segregation. Hot cracking in HAZs is often referred to as *liquation cracking*, since it occurs at liquated grain boundaries only.

It is generally accepted that hot cracking occurs during the final stage of solidification and is associated with the existence of small amounts of segregate-rich low melting point liquid separating solid grains. Cracking occurs when the stresses developed across the adjacent grains exceed the strength of the almost solidified weld metal. Such stresses can be induced by *solidification shrinkage* of the weld metal and *thermal contraction* of the workplace, which are both significant with aluminium alloys. When hot cracks occur at the early stage of solidification, they may be easily refilled by the remaining low melting point liquid. However, this “healing” process becomes more and more difficult as the remaining volume of liquid decreases and the paths between grains become more restricted.

There are two possible ways to overcome the hot cracking problem:

- Reducing the thermal contraction stresses;
- Adjusting chemical composition of weld metal.

The severity of thermal contraction stresses increases with both the degree of constraint and the thickness of the workpiece. Unfortunately, aluminium armour plates are usually very thick. However, the degree of constraint can be reduced by optimising the welding sequence, and thermal contraction of weld metals can be lowered by using relatively small welding current.

The hot cracking susceptibility of high strength 7XXX series aluminium alloys, as in other alloys, is strongly affected by the chemical composition of the weld metal. For example, crack susceptibility increases with increasing Cu content when Cu content is below 3% and reduces with increasing Cu content when Cu content is above 3%. The resistance to cracking is enhanced by the addition of grain refining agents such as Zr in the alloy. Hot cracking can be avoided by using proper filler wires and dilution ratios to control the weld metal composition.
3. **Stress Corrosion Cracking**

It was reported in The Straits Times of 22 Feb. 1993 that almost half of Thailand’s Stingray battle tank developed faults or cracks after a few years’ service. The armour of the battle tank is made of a high strength aluminium alloy. The likely cause for the structural defects is Stress Corrosion Cracking (SCC).

For SCC to occur, three conditions must be met:

- Susceptible microstructures;
- Corrosive environments (which do not necessarily cause general chemical corrosion);
- Tensile stresses.

The 7XXX series aluminium alloys are more susceptible to SCC than the 5XXX series aluminium alloys. Medium-strength, low copper, and copper free 7XXX alloys have been developed for a variety of engineering properties. Most 7XXX series aluminium alloys have excellent SCC resistance in the longitudinal direction and good SCC resistance in the transverse direction but relatively poor resistance in the short-transverse direction (i.e., thickness direction).

Because of the orientation dependence of SCC in aluminium alloys, stresses in the most susceptible direction (usually, the short-transverse direction) must be avoided or minimised. In addition to operating stresses, SCC can result from residual forming or welding stresses, stresses introduced by machining operations, and stresses from misfit of parts being assembled. It is these residual stresses, rather than operating stresses, that are most often responsible for SCC failure, because they may be overlooked during the design process.

The welding residual stresses in the short-transverse direction may be very high for T welded joints or corner joints, but it is possible to limit the stresses to low levels through the use of soft weld overlays or by proper welded-joint design or choice of welding parameters. Reducing stresses in the short-transverse direction to a minimum greatly reduces the likelihood of SCC failure in susceptible alloys.
Heat treatment or tempering affects corrosion resistance and mechanical strength by controlling the distribution of alloying elements between solid solution and insoluble precipitates. To minimise SCC susceptibility, over-ageing treatments (T7) may be utilised at some sacrifice of tensile strength. However, tempering or heating during welding may be undesirable and reduce SCC resistance of the welded joints. For example, in alloy 7017 (Zn5.01-Mg2.44-Cu0.12-Zr0.13-Mn0.29-Si0.11), white zones due to MIG welding were found to be more susceptible to SCC than the parent material in T651 temper. For heat treatable 7XXX series, thermal treatment after welding is sometimes used to obtain maximum corrosion resistance.