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## Aluminum Alloys: Fundamentals of Welding Metallurgy

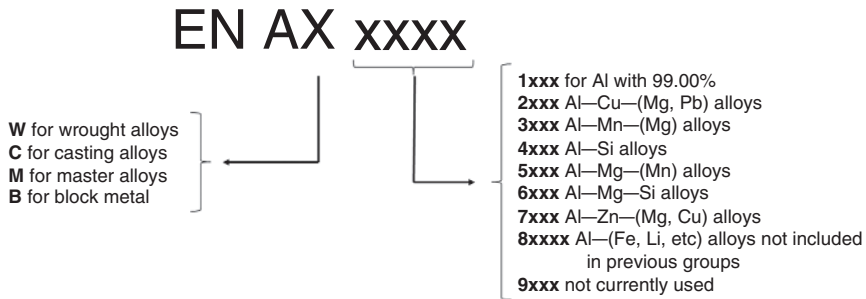
### 1.1 Introduction

Aluminum (Al) alloys have been used traditionally for structural parts of aircrafts. At the beginning of the twenty-first century, the leading aircraft companies started to use composite materials due to their advantages such as low weight. Nonetheless, the usage of Al in structural parts still continues due to better recyclability of these materials and satisfying the weight reduction of the structure [1]. Al is a light alloy with a density of  $2.7 \text{ g/cm}^3$ , is nonmagnetic, has an FCC crystal structure, has high formability and low-temperature toughness, and has a relatively high corrosion resistance depending on the alloying elements [2]. Al alloys are also easily processible with casting, machining, and extrusion. Some Al alloys capable of precipitation hardening have strengths comparable to steels [2]. In contrast to carbon and low-alloy steels, Al does not possess any polymorph; therefore, only the solidification behavior determines the properties of the weld zone in the fusion welding [3]. Cooling of the solidified weld zone does not have a prominent effect on the microstructure of the weld due to absence of any polymorph transformation in Al alloys.

Al alloys are classified based on their mechanical properties, manufacturing process, and alloying elements. Wrought Al alloys are determined by the degree of cold work and chemical composition. Cast Al alloys are determined by the casting process and chemical composition. Other mechanisms such as precipitation hardening and solid-solution hardening may also contribute to the strength of Al alloys [2]. The alloying elements that promote precipitation hardening in Al are Cu, Cu—Mg, Cu—Li, Cu—Si, Zn, Zn—Mg, Zn—Mg—Cu, and Li—Cu—Mg [2]. The alloying elements that promote solid-solution hardening are Mn, Si, Zn, Mg, and Cu [2].

The designation system for wrought Al alloys in the European standard system is a four-digit numeric. Figure 1.1 shows the designation system according to the European standard. There is also a supplementary designation system whose basis is a chemical symbol. The applications of some Al alloys are provided in Table 1.1.

Along with austenitic stainless steel and Ni alloys, Al alloys are good candidates for the construction of LNG cargo containment, as Al possesses a high toughness due to its FCC structure [11]. The usage of Al alloys as structural materials requires their joining in various joint designs. Mechanical joining methods such as riveting have been used in lap configuration, which adds to the weight of the



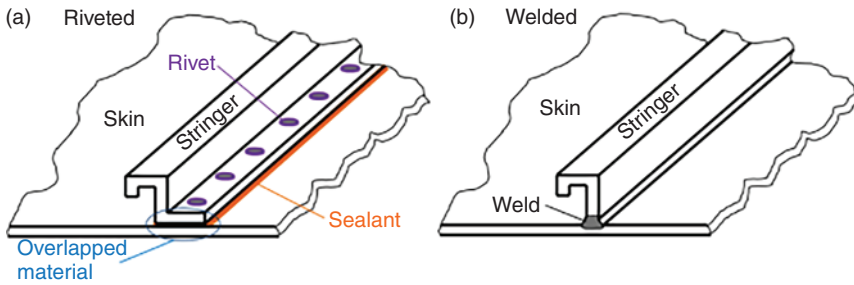
**Figure 1.1** Designation system for wrought aluminum alloys according to the European standard.

**Table 1.1** The applications of some Al alloys.

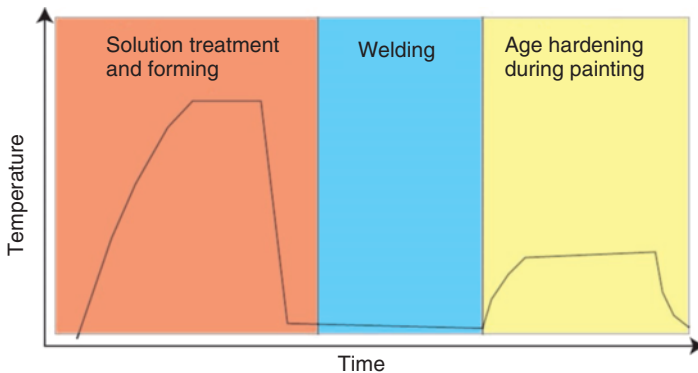
| Alloy  | Application  |
|--------|--|
| AA2xxx | Propellant cabin of launch vehicles [4]  |
| AA5xxx | Shipbuilding [5]   |
| AA6xxx | Car body [6], battery tray [7]   |
| AA7xxx | Bicycle frame [8], panel structure of launcher [9], underframe in high-speed trains [10] |

structure. An example is the stringer–skin connection used in the fuselage of the aircraft (Figure 1.2a), where additional adhesive is used to seal the joint. Welding technologies help to reduce the weight by eliminating the overlap region and the sealant and while maintaining the same performance (Figure 1.2b) [12]. In Tee-joining, the high heat conductivity of Al causes a high thermal gradient to form between the weld pool and base material. Lap joining also adds to the weight of the structure and hence is used for thin sheets less than 1 mm, where welding processes such as resistance welding are to be used. Regarding the weld design, fillet welds are usually avoided in the structural parts under fatigue due to crack initiation from the root of the weld [13]. The joint design also affects the residual stress during welding. For instance, the Tee-joints cause a higher residual stress during welding than lap joints due to higher heat sink effect in the Tee-joints, which causes a higher cooling rate [14].

The Al alloys that are heat-treatable (HTA) need to undergo specific sequences during forming and assembling to obtain desired mechanical properties. For example, in the car body, the Al sheets are welded in a solution-treated or hot-formed state. The final aging treatment, which is connected to the paint bake cycle, is performed after welding [15]. Figure 1.3 shows the schematic workflow of Al alloy used in the car body. Hot forming of Al alloy is performed in the solid-solution state, which is quenched subsequently to preserve the solid-solution state. The joining methods are performed after this stage, and then a paint bake cycle is carried out to regain the strength through aging treatment.



**Figure 1.2** Joining of a stringer-skin aluminum part used in the fuselage of the aircraft made by (a) riveting and (b) welding. Source: Ref. [12]/with permission of Elsevier.



**Figure 1.3** The forming, solution treatment, welding, and age hardening while paint baking of Al alloys used in the car body.

There are some challenges during welding of Al alloys, and understanding their mechanisms helps to avoid them and hence obtain the optimum performance of the welded structure. Some issues that exist during welding steel are not present during welding Al due to its physical properties. For instance, Al is a nonmagnetic material and therefore the problems of arc blowing will not occur during arc welding processes. Instead, other issues are pronounced during welding Al. The thermal conductivity of Al is six times that of steel and therefore the welding processes with high power density need to be used for Al. Though the melting point of Al is low, due to high specific heat of Al the heat sources need to have high intensity. Due to the high heat conductivity of Al, the use of welding processes with low heat intensity for wrought alloys and precipitation-hardened alloys produces a wide heat-affected zone (HAZ) with lower strength (due to softening) and distortion. In precipitation-hardened alloys, it is also probable that the precipitates in the HAZ dissolve and reprecipitate, which leads to brittleness [2]. The thermal expansion coefficient of Al is twice that of steel. This along with its low Young's modulus causes a high distortion, especially in thin structures, making it difficult to maintain the tolerances [16]. To keep the distortion within the limits of tolerance,

the components need to be tightly clamped and often tack-welded. The welding sequence also needs to be planned carefully [2].

A significant difference between steel and Al arises from metallurgical aspects. Structural steels encounter phase transformation during cooling; the most important one is the austenite to ferrite transformation. While the strength of structural steels increases in the HAZ during welding, Al alloys lose their strength in the HAZ. A higher number of issues exist while welding Al alloys that are heat-treatable, which means their strength is increased by precipitation. Other Al alloys get their strength by other mechanisms such as solution hardening and work hardening. Three main series of heat-treatable Al alloys are introduced in the following.

### 1.1.1 Aluminum–Copper Alloys

Al–Cu alloys known as 2xxx family are mainly used in the structure of the airframes and possess high fatigue strength. The precipitation hardening is the main mechanism of strengthening in these alloys. From the supersaturated state, a series of phases form by the increase in temperature:



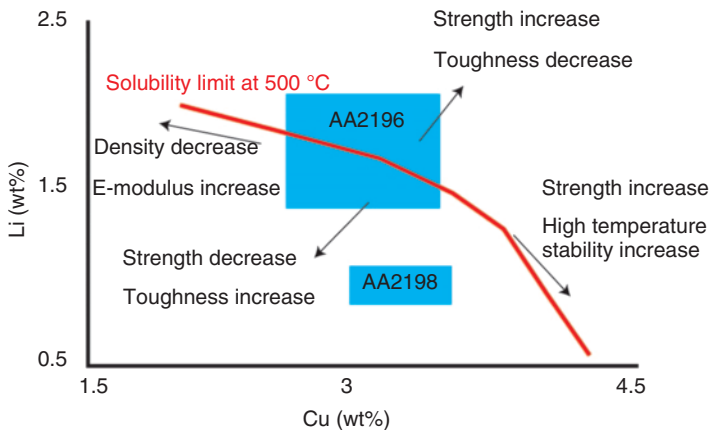
GP phases are coherent phases and differ in the size and the lattice strain they induce.  $\theta'$  and  $\theta$  are semi-coherent and incoherent, respectively, the latter being the equilibrium phase, whose contribution to the strength is the lowest compared to the other phases.

### 1.1.2 Aluminum–Zinc–Magnesium Alloys

$\text{MgZn}_2$  is the main precipitate in this group of Al alloy. These Al alloys are less sensitive to quenching, and thus a supersaturated condition can be obtained even after air cooling. Natural aging can occur in these alloys after a couple of months to recover their initial hardness, making these alloys to have a self-hardening effect [17]. So, these alloys do not need a post-weld heat treatment (PWHT) to recover their hardness. However, these alloys are susceptible to solidification cracking (SC) in the fusion zone (FZ) and liquidation cracking in HAZ. Evaporation of Mg and Zn due to their low boiling point can cause pore formation during welding [18].

### 1.1.3 Aluminum–Magnesium–Silicium

The strength in the HAZ of these alloys is only partially restored by subsequent aging, as explained in Figure 1.28. The degree of strength lost in the HAZ depends on the heat and the time it receives this heat. It means that the welding process and its parameters determine the degree of strength lost in the HAZ. A lower heat input favors a narrower HAZ region that is less softened.



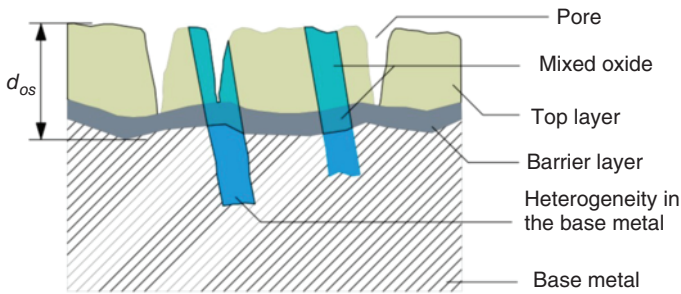
**Figure 1.4** Schematic representation of mechanical properties of Al–Li–Cu alloys in relation to Cu and Li content. Source: Adapted from [19].

### 1.1.4 Aluminum–Lithium Alloys

These alloys, as special Al alloys, are used in the aircraft industry. Lithium has a low density and a high solubility in Al and hence offers a great potential to be used in the structure of airplanes. 1% lithium decreases the density of Al by 3% and increases the elastic modulus by 6% [19]. Some Al–Li alloys belong to Al–Cu–Li alloys such as AA2196 (found as extruded parts) and AA2198 (found as sheets and plates) [19]. The mechanical properties of these alloys primarily depend on the content of copper and lithium, as shown in Figure 1.4 [20]. The red line shows the solubility limit at 500 °C. The increase in Cu leads to an increase in  $\text{Al}_2\text{CuLi}$  precipitation hardening phases, which increase the strength. An increase in Li promotes the formation of  $\text{Al}_3\text{Li}$  precipitates and lowers the density. In addition to precipitates, the dispersoids may also exist. Dispersoids, in contrast to precipitates, are formed above the solubility limit temperature, and hence they cannot be altered by heat treatment of the solid alloy. Manganese is an element that forms incoherent dispersoids and increases the toughness and fatigue strength [19]. In Al–Mg–Li alloys, the main precipitate is  $\text{Al}_3\text{Li}$ . Al–Li alloys are prone to pore formation during welding, which downgrades their weldability [21].

## 1.2 Weldability

Welding of Al affects the mechanical properties due to the change in the microstructure during solidification as well as the heat effects in the solid state. The surface tension and the viscosity of the Al melt are low [22]. This increases the risk of melt burn through and spatter during welding Al. The physical, chemical, and metallurgical properties of Al alloys influence their behavior during the welding processes. Despite having a low melting temperature (up to 650 °C), a high thermal conductivity of Al ( $\lambda = 120 - 240 \text{ W/m K}$ ) necessitates a high heat intensity for welding.



**Figure 1.5** Structure of the Al oxide layer in wet air. Source: Adapted from [19].

The thermal conductivity of Al decreases with increasing temperature. Some Al alloys, despite having excellent properties, exhibit low joint efficiency by welding and hence their usage is less favored than other Al alloys that have lower mechanical properties but exhibit better joint efficiency. Some features of Al make it different from steels in terms of weldability. The first feature is the oxide of Al alloy. The special characteristics of Al oxide necessitate some considerations to obtain weldability. The presence of hydrogen is another factor that causes weldability challenges. This is very different from steel in which hydrogen causes completely different problems in welding. Hot cracking is another problem that occurs in the FZ during the final stage of solidification. A similar phenomenon named liquation cracking occurs adjacent to the FZ in partially melted zone (PMZ), which degrades the mechanical properties. The mechanisms of all these phenomena are explained in detail for Al alloys, whose understanding helps to avoid them during welding and improve the weldability.

### 1.2.1 Aluminum Oxide

The oxide of aluminum ( $\text{Al}_2\text{O}_3$ ) is very dense, tough, and thermally stable and has a high melting temperature ( $T_m = 2050^\circ\text{C}$ ). It is also nonconductive to the electricity. The oxide layer consists of a narrow barrier layer and a thick layer, which have a certain porosity. The presence of alloying elements promotes the formation of complex oxides as well as the change in the thickness of the oxide layer. This oxide layer can trap hydrogen, which changes the characteristics of the oxide layer [19]. The scheme of the oxide layer on the surface of Al in the wet air is shown in Figure 1.5.

The oxide layer can cause an incomplete bonding by inhibiting a metallurgical bonding during welding if it is not removed away by proper methods. In arc welding processes this is done by cleaning effect of the arc in reverse polarity, during which the workpiece is in the positive pole. The oxide layer also influences the plasma spectra and its electronic temperature during arc or laser welding processes [23]. In the absence of the oxide film, the elements are more easily heated to the ionization temperature. Also, the electronic temperature of the plasma is higher, which is due to the absorption of the heat by the oxide film. This causes the depth and the width of the weld to be lower in the presence of the oxide film [23].

Due to its higher melting temperature, the oxide is not melted during welding Al and covers the Al surface with a firm shell, which interferes with the formation of the weld pool [24]. Due to its detrimental effect, the oxide layer has to be removed before welding.

### 1.2.2 Hydrogen and Pore Formation

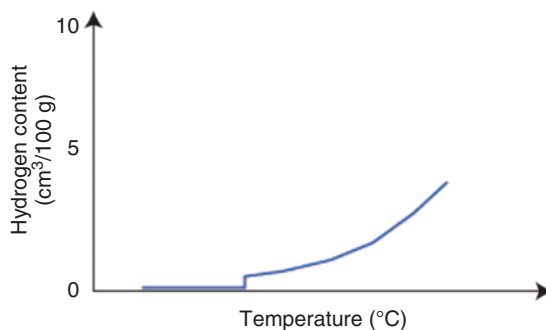
Hydrogen is the main gas that forms pores during welding Al alloys. The elements of nitrogen and oxygen do not cause pore formation, as they have a high affinity to make stable nitrides and oxides and therefore are not available in the form of gas. Hydrogen is soluble to a high extent in molten Al, whose solubility decreases abruptly after solidification (Figure 1.6). After solidification, the excess amount of hydrogen, which is not soluble in the solid state, will exit and stay in the melt as pores. This problem is exacerbated when the cooling rate is rapid. By increasing the welding speed, the gas escape is hindered and the pores will become higher in quantity. The position of the welding is also determinant in pore formation. The gas can leave the melt pool easily when welding is performed in the flat position. In the overhead position, there is no escape path for the gas bubbles, and therefore, this position of welding should be avoided for welding Al. One source of hydrogen is humidity, by which the water reacts with Al in the arc space and consequently hydrogen is released according to:

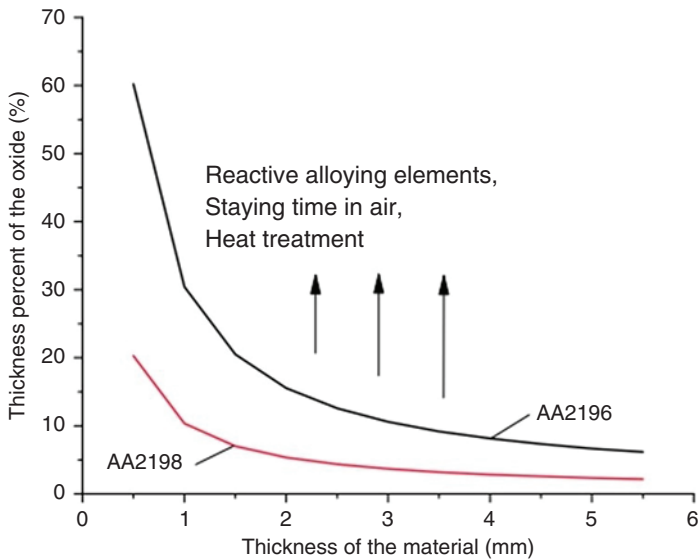


The sources of hydrogen are the humidity in the protecting gas, the humidity entered from the atmosphere, and the residues on the surface of the workpiece or the filler, such as paint, oil, and hydroxides.

Another source of hydrogen is the oxide layer of the Al. The pores that result from the oxide layer of the base material appear as uniform coarse pores over the weld length. The pores that result from the hydrogen of the oxide layer of the filler material appear as uniform fine pores [19]. The thicker the oxide layer, the higher the amount of hydrogen. The thickness of the oxide layer, as mentioned before, depends on the alloying elements or, in other words, the type of Al alloy. For example, AA2198 possesses a thinner oxide layer than AA2196. Another factor that determines the amount of hydrogen from the oxide layer is the thickness of the Al

**Figure 1.6** Solubility of hydrogen in aluminum at various temperatures.

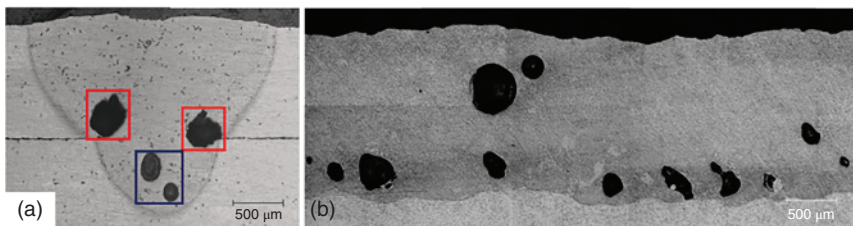




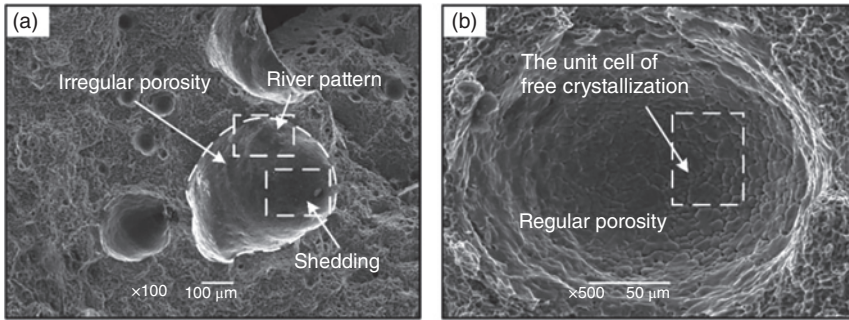
**Figure 1.7** Relation between the portion of the oxide layer and the thickness of the sheet for two Al alloys. Source: Adapted from [19].

sheet [19]. By increasing the thickness of the Al sheet, the ratio of the oxide/total mass of Al decreases, which in return lowers the amount of hydrogen introduced. The portion of the oxide layer decreases exponentially with thickness, as shown schematically in Figure 1.7. The annealing temperature and time can also increase the thickness of the oxide layer.

The oxide layer can also produce pores in another way. During laser welding of Al, the high temperature inside the keyhole vaporizes the oxide layer at the interface, which appears as pores (red squares in Figure 1.8) [25]. These pores are distinguished by the pores caused by the keyhole instability, which form at the bottom of the weld (blue squares in Figure 1.8). The mechanism of pore formation by keyhole is explained in detail in Chapter 3. Also, the mechanism that controls these kinds of pores will be discussed. As an example, introducing a gap between



**Figure 1.8** Pores caused by oxide layer (inside the red squares) during laser welding of a 6061 alloy. (a) Cross section view and (b) longitudinal view. Source: Ref. [25]/with permission of Elsevier.



**Figure 1.9** SEM image of (a) technical or keyhole-induced pore and (b) metallurgical pore. Source: Ref. [27]/Taylor & Francis.

the plates provides a vent to relieve the pressure, causing a more stable keyhole [25]. This leads to less pore formation and a stronger weld.

Based on these, the surface of Al needs to be cleaned before welding either by mechanical or chemical methods [19]. The degree of removal of the surface oxide depends on the thickness of the oxide layer. Considering that the thickness of the oxide is not uniform (see Figure 1.5), the removal of the surface should make sure that the oxide layer is removed completely. The mechanical methods of removing the oxide layer, especially the milling processes, are the most proper ones. Though in these methods the surface becomes wavy, it is free of adhered deposits, which appear after chemical methods [2]. One example of the chemical cleaning method is soaking in 20% sodium hydroxide solution and subsequent soaking in dilute nitric acid to neutralize the residual alkali before welding [26]. Due to the rapid formation of the oxide layer, even in the vacuum, the welding process should be carried out right after the surface treatment.

In fusion welding processes wherein a keyhole exists, such as laser beam welding, another kind of pores can form during welding. The source of these pores is not hydrogen, but the metallic vapor and the shielding gas entrapped by the keyhole collapse. When the melt pool solidifies rapidly, these entrapped vapors and gases do not have enough time to escape from the melt pool, forming a keyhole-induced pore [26]. A scanning electron microscopy (SEM) image of this hole is provided in Figure 1.9a. These pores have irregular shapes with step-like inner walls and traces of solidification contraction [26]. The pores that are caused by hydrogen or by metal vapor produced by the burning of the metal elements are referred to as metallurgical pores [27]. The metallurgical pores have regular shapes, and the inner interface is smooth due to free crystallization cell boundary on the wall of the pore. The internal pressure of accumulated hydrogen inside the pore in the solidification stage initiates after nucleation of the pore and then the continuous diffusion of hydrogen into it [27]. The pores formed by keyhole collapse in the unstable welding pool are also referred to as the technical pores, which are irregular and large [27]. These pores can be reduced by controlling the process parameters. The pores caused by hydrogen are smaller in size than the ones induced by instability of the keyhole [28]. The details of the formation of the technical pores are addressed in Chapter 3.