1

Introduction to the welding of aluminium

1.1 Introduction

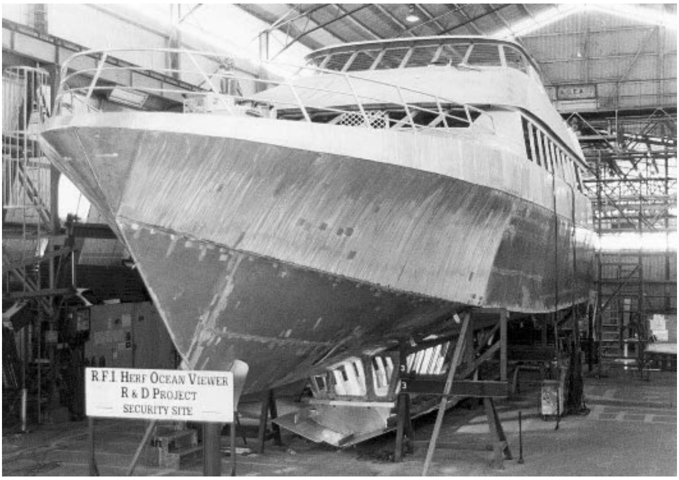
The existence of aluminium (Al) was postulated by Sir Humphrey Davy in the first decade of the nineteenth century and the metal was isolated in 1825 by Hans Christian Oersted. It remained as somewhat of a laboratory curiosity for the next 30 years when some limited commercial production began, but it was not until 1886 that the extraction of aluminium from its ore, bauxite, became a truly viable industrial process. The method of extraction was invented simultaneously by Paul Heroult in France and Charles M. Hall in the USA and this basic process is still in use today. Because of its reactive nature aluminium is not found in the metallic state in nature but is present in the earth's crust in the form of different compounds, of which there are several hundreds. The most important and prolific is bauxite. The extraction process consists of two separate stages, the first being the separation of aluminium oxide, Al_2O_3 (alumina), from the ore, the second the electrolytic reduction of the alumina at between 950 °C to 1000 °C in cryolite (Na_3AlF_6). This gives an aluminium, containing some 5–10% of impurities such as silicon (Si) and iron (Fe), which is then refined either by a further electrolytic process or by a zone-melting technique to give a metal with a purity approaching 99.9%. At the close of the twentieth century a large proportion of aluminium was obtained from recovered and remelted waste and scrap, this source alone supplying almost 2 million tonnes of aluminium alloys per annum in Europe (including the UK) alone. The resulting pure metal is relatively weak and as such is rarely used, particularly in constructional applications. To increase mechanical strength, the pure aluminium is generally *alloyed* with metals such as copper (Cu), manganese (Mn), magnesium (Mg), silicon (Si) and zinc (Zn).

One of the first alloys to be produced was aluminium–copper. It was around 1910 that the phenomenon of age or precipitation hardening in this family of alloys was discovered, with many of these early age-hardening alloys finding a ready use in the fledgling aeronautical industry. Since that time a large range of alloys has been developed with strengths which can match that of good quality carbon steel but at a third of the weight. A major impetus to the development of aluminium alloys was provided by the two World Wars, particularly the Second World War when aluminium became *the* metal in aircraft structural members and skins. It was also in this period that a major advance in the fabrication of aluminium and its alloys came about with the development of the inert gas shielded welding processes of MIG (metal inert gas) and TIG (tungsten inert gas). This enabled high-strength welds to be made by arc welding processes without the need for aggressive fluxes. After the end of the Second World War, however, there existed an industry that had gross over-capacity and that was searching for fresh markets into which its products could be sold. There was a need for cheap, affordable housing, resulting in the production of the 'prefab', a prefabricated aluminium bungalow made from the reprocessed remains of military aircraft – not quite swords into ploughshares but a close approximation! At the same time domestic utensils, road vehicles, ships and structural components were all incorporating aluminium alloys in increasing amounts.

Western Europe produces over 3 million tonnes of primary aluminium (from ore) and almost 2 million tonnes of secondary or recycled aluminium per year. It also imports around 2 million tonnes of aluminium annually, resulting in a per capita consumption of approximately 17 kg per year. Aluminium now accounts for around 80% of the weight of a typical civilian aircraft (Fig. 1.1) and 40% of the weight of certain private cars. If production figures remain constant the European automotive industry is expected to be consuming some 2 million tonnes of aluminium annually by the year 2005. It is used extensively in bulk carrier and container ship superstructures and for both hulls and superstructures in smaller craft (Fig. 1.2). The new class of high-speed ferries utilises aluminium alloys for both the super-structure and the hull. It is found in railway rolling stock, roadside furniture, pipelines and pressure vessels, buildings, civil and military bridging and in the packaging industry where over 400 000 tonnes per annum is used as foil. One use that seems difficult to rationalise in view of the general perception of aluminium as a relatively weak and soft metal is its use in armoured vehicles (Fig. 1.3) in both the hull and turret where a combination of light weight and ballistic performance makes it the ideal material for fast reconnaissance vehicles.

This wide range of uses gives some indication of the extensive number of alloys now available to the designer. It also gives an indication of the difficulties facing the welding engineer. With the ever-increasing sophistication of processes, materials and specifications the welding engineer must have a broad, comprehensive knowledge of metallurgy and welding

1.1 BAC 146 in flight. Courtesy of TWI Ltd.



1.2 A Richardson and Associates (Australia) *Ocean Viewer* all-aluminium vessel. The hull is 5 mm thick A5083. Courtesy TWI Ltd.

1.3 Warrior armoured fighting vehicle (AFV) utilising Al-Zn-Mg alloys. Courtesy of Alvis Vehicles.

processes. It is hoped that this book will go some way towards giving the practising shop-floor engineer an appreciation of the problems of welding the aluminium alloys and guidance on how these problems may be overcome. Although it is not intended to be a metallurgical textbook, some metallurgical theory is included to give an appreciation of the underlying mechanisms of, for instance, strengthening and cracking.

1.2 Characteristics of aluminium

Listed below are the main physical and chemical characteristics of aluminium, contrasted with those of steel, the metal with which the bulk of engineers are more familiar. As can be seen from this list there are a number of important differences between aluminium and steel which influence the welding behaviour:

- The difference in melting points of the two metals and their oxides. The oxides of iron all melt close to or below the melting point of the metal; aluminium oxide melts at 2060 °C, some 1400 °C *above* the melting point of aluminium. This has important implications for the welding process, as will be discussed later, since it is essential to remove and disperse this oxide film before and during welding in order to achieve the required weld quality.

- The oxide film on aluminium is durable, highly tenacious and self-healing. This gives the aluminium alloys excellent corrosion resistance, enabling them to be used in exposed applications without additional protection. This corrosion resistance can be improved further by *anodising* – the formation of an oxide film of a controlled thickness.
- The coefficient of thermal expansion of aluminium is approximately twice that of steel which can mean unacceptable buckling and distortion during welding.
- The coefficient of thermal conductivity of aluminium is six times that of steel. The result of this is that the heat source for welding aluminium needs to be far more intense and concentrated than that for steel. This is particularly so for thick sections, where the fusion welding processes can produce lack of fusion defects if heat is lost too rapidly.
- The specific heat of aluminium – the amount of heat required to raise the temperature of a substance – is twice that of steel.
- Aluminium has high electrical conductivity, only three-quarters that of copper but six times that of steel. This is a disadvantage when resistance spot welding where the heat for welding must be produced by electrical resistance.
- Aluminium does not change colour as its temperature rises, unlike steel. This can make it difficult for the welder to judge when melting is about to occur, making it imperative that adequate retraining of the welder takes place when converting from steel to aluminium welding.
- Aluminium is non-magnetic which means that arc blow is eliminated as a welding problem.
- Aluminium has a modulus of elasticity three times that of steel which means that it deflects three times as much as steel under load but can absorb more energy on impact loading.
- The fact that aluminium has a face-centred cubic crystal structure (see Fig. 2.2) means that it does not suffer from a loss of notch toughness as the temperature is reduced. In fact, some of the alloys show an improvement in tensile strength and ductility as the temperature falls, EW-5083 (Al Mg 4.5 Mn) for instance showing a 60% increase in elongation after being in service at –200 °C for a period of time. This crystal structure also means that formability is very good, enabling products to be produced by such means as extrusion, deep drawing and high energy rate forming.
- Aluminium does not change its crystal structure on heating and cooling, unlike steel which undergoes crystal transformations or *phase changes* at specific temperatures. This makes it possible to harden steel by rapid cooling but changes in the cooling rate have little or no effect on the aluminium alloys (but see precipitation hardening p 16–17).

1.3 Product forms

Aluminium is available in both wrought and cast forms. The wrought forms comprise hot and cold rolled sheet, plate, rod, wire and foil. The ductility and workability of aluminium mean that extrusion is a simple method of producing complex shapes, particularly for long, structural members such as I and H beams, angles, channels, T-sections, pipes and tubes. Forging, both hot and cold, is used extensively as a fast, economical method of producing simple shapes. Precision forging is particularly suitable for aluminium alloys, giving advantages of good surface finish, close tolerances, optimum grain flow and the elimination of machining.

The four most commonly used methods of casting are sand casting, lost wax casting, permanent steel mould casting and die-casting. The requirement for high fluidity in a casting alloy means that many are based on aluminium–silicon alloys although heat-treatable (age-hardening) alloys are often used for sand, lost wax and permanent mould castings. Lost wax and die-casting give products with smooth surfaces to close tolerances and are processes used extensively for aerospace products. A number of alloys, their product forms and applications are listed in Table 1.1.

1.4 Welding: a few definitions

Before dealing with the problems of welding aluminium alloys there are a few definitions required, not least of which is welding itself. Welding can be described as the joining of two components by a coalescence of the surfaces in contact with each other. This coalescence can be achieved by melting the two parts together – *fusion welding* – or by bringing the two parts together under pressure, perhaps with the application of heat, to form a metallic bond across the interface. This is known as *solid phase joining* and is one of the oldest of the joining techniques, blacksmith's hammer welding having been used for iron implement manufacture for some 3500 years. The more modern solid phase techniques are typified by friction welding. *Brazing*, also an ancient process, is one that involves a *braze metal* which melts at a temperature above 450 °C but below the melting temperature of the components to be joined so that there is no melting of the parent metals. *Soldering* is an almost identical process, the fundamental difference being that the melting point of the solder is *less* than 450 °C. The principal processes used for the joining of aluminium are listed in Table 1.2. Not all of these processes are covered in this book as they have a very limited application or are regarded as obsolescent.

Welding that involves the melting and fusion of the parent metals only is known as *autogenous* welding, but many processes involve the addition

Table 1.1 Typical forms and uses of aluminium alloys

Aluminium alloy Grade	Product form	Application
Pure aluminium	Foil, rolled plate, extrusions	Packaging and foil, roofing, cladding, low-strength corrosion resistant vessels and tanks
2000 series (Al-Cu)	Rolled plate and sheet, extrusions, forgings	Highly stressed parts, aerospace structural items, heavy duty forgings, heavy goods vehicle wheels, cylinder heads, pistons
3000 series (Al-Mn)	Rolled plate and sheet, extrusions, forgings	Packaging, roofing and cladding, chemical drums and tanks, process and food handling equipment
4000 series (Al-Si)	Wire, castings	Filler metals, cylinder heads, engine blocks, valve bodies, architectural purposes
5000 series (Al-Mg)	Rolled plate and sheet, extrusions, forgings, tubing and piping	Cladding, vessel hulls and superstructures, structural members, vessels and tanks, vehicles, rolling stock, architectural purposes
6000 series (Al-Si-Mg)	Rolled plate and sheet, extrusions, forgings, tubing and piping	High-strength structural members, vehicles, rolling stock, marine applications, architectural applications.
7000 series (Al-Mg-Zn)	Rolled plate and sheet, extrusions, forgings	High strength structural members, heavy section aircraft forgings, military bridging, armour plate, heavy goods vehicle and rolling stock extrusions

Table 1.2 Principal processes for the welding of aluminium

Process	Application
Fusion welding	
Tungsten inert gas	High-quality, all position welding process that utilises a non-consumable electrode; may be used with or without wire additions; may be manual, mechanised or fully automated; low deposition rate, higher with hot wire additions; straight or pulsed current.
Metallic arc inert gas shielded	High-quality, all position welding process that utilises a continuously fed wire; may be manual, mechanised or fully automated; can be high deposition rate; twin wire additions; straight or pulsed current.

Table 1.2 (cont.)

Process	Application
Manual metal arc	Limited application; uses a flux-coated consumable electrode; non- or lightly stressed joints; obsolescent.
Oxy-gas	Low-quality weld metal; unstressed joints; obsolescent.
Electron beam welding	High-quality, precision welding; aerospace/defence and electronic equipment; high capital cost; vacuum chamber required.
Laser welding	High-quality, precision welding; aerospace/defence and electronic equipment; high capital cost.
Electro-gas, electro-slag, submerged arc	Limited applications, e.g. large bus bars; porosity problems; largely obsolescent.
Welding with fusion and pressure	
Magnetically impelled arc butt welding	Butt joints in pipe; capital equipment required but lower cost than flash butt; fully automated.
Resistance and flash welding	
Spot, projection spot seam welding	Lap joints in sheet metal work, automotive, holloware, aerospace industry; high capital cost; high productivity.
Weld bonding	Combination of spot welding through an adhesively bonded lap joint; automotive industry; very good fatigue strength.
High-frequency induction seam	Butt joints; production of pipe from strip; high capital cost; high production rates.
Flash butt welding	In line and mitre butt joints in sheet, bar and hollow sections; dissimilar metal joints, e.g. Al-Cu; high capital cost; high production rates.
Stud welding	
Condenser, capacitor discharge	Stud diameters 6 mm max, e.g. insulating pins, pan handles, automotive trim, electrical contacts.
Drawn arc	Stud diameters 5–12 mm.
Solid phase bonding	
Friction welding	Butt joints in round and rectangular bar and hollow sections; flat plate and rolled section butt welds (friction stir); dissimilar metal joints; capital equipment required.
Explosive welding	Field pipeline joints; dissimilar metal joints, surfacing.
Ultrasonic welding	Lap joints in foil; thin to thick sections; Al-Cu joints for electrical terminations.
Cold pressure welding	Lap and butt joints, e.g. Al-Cu, Al-steel, Al sheet and wire.
Hot pressure welding	Roll bonded lap joints, edge to edge butt joints.

of a *filler metal* which is introduced in the form of a wire or rod and melted into the joint. Together with the melted parent metal this forms the weld metal. Definitions of the terms used to describe the various parts of a welded joint are given in Chapter 5.