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PROCESS POSSIBILITY OF WELDING THIN ALUMINIUM ALLOYS

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ABSTRACT

The manufacturing industry continues to be challenged by low weight and cost requirements, increase of energy efficiency, improvements of performance and reducing deleterious environmental effects. Aluminium has become an important part of the manufacturing process of automobile, aircraft, shipbuilding and engineering industries. This paper is based on a literature review of thin sheet weldabilities and welding processes possibilities. There are difficulties existing during the welding of thin aluminium alloys specifically associated with heat input which affects weld quality, leading to porosity, cracking, burn-through and distortion defects. Approaches to mitigate these problems have been adopted, such as careful clamping of the workpiece, improved preparation of joints for tight fit–up, advanced control of heat input, and others. Commonly-used welding processes like Gas Metal Arc Welding, Gas Tungsten Arc Welding, Plasma Arc Welding, Laser Beam Welding and Friction Stir Welding show good potential for use in welding of thin aluminium alloys.

Keywords: Thin sheet aluminium alloys, Porosity, Hot cracking, Burn through, Distortion.

1. INTRODUCTION

Manufacturers are continuously searching for opportunities to improve efficiency, and the increased use of aluminium components is an area of considerable interest. Aluminium alloys exhibit many desirable properties: they are light, ductile, readily worked, and have good thermal and electrical properties. Aluminium also has a tenacious oxide film on the surface that gives good corrosion resistance (Kita-Shinagawa and Shinagawa-ku, 2011). While aluminium is a highly effective material, certain particular problems are faced during welding processes. This paper will review welding of thin sheet aluminium alloys (by definition, thin sheets having a thickness of 4 mm or less (Greenwood and Earnshaw, 1984) and a density of less than 5g/cm^3), with the main objective being to discuss the relative possibility of welding these alloys. Presented first is a concise analysis of key problems that currently effects weld joints. This is followed by presentation of the welding processes for welding aluminium. With a view to outlining the means to ensure maximum affectivity and efficiency, this study pays particular attention to the selection of an appropriate welding process, and to the procedure and technique needed to ensure good weld quality. Aluminium is an active material and reacts with oxygen in the air to produce a thin hard film of aluminium oxide on the surface. The melting point of aluminium oxide is approximately 20520C. This aluminium oxide film, particularly as it becomes thicker, absorbs moisture from the air. Moisture is a source of hydrogen, which is the cause of porosity in aluminium welds (Cary and Helzer, 2004). Aluminium alloys are used in many applications in which strength/weight ratio is attractive, such as the automotive, aviation, ship-building, bridge building and other engineering industries (Kita-Shinagawa and Shinagawa-ku, 2011). The two main classes of aluminium alloys are cast aluminium alloys and wrought aluminium alloys. Each class is divided into series based on the major alloying element in the alloy. For the most common applications, the more interesting group is wrought aluminium alloys, as they possess higher strength than cast aluminium alloys (Praveen and Yarlagadda, 2005).

When welding thin sheet aluminium alloys, a number of key problems have to be taken into account, which will be outlined briefly in this introduction. A foremost objective is to avoid burn-through and distortions, because the material heats up very quickly. During welding of thin sheets, an important consideration, therefore, is utilization of the lowest possible heat input and minimization of the size of the heat affected zone (HAZ).

Aluminium doesn’t change colour when welded or heated. The welding parameters must be controlled and adjusted to ensure the right amount of energy which gives an appropriate shape of weld pool (Mike and Jim, 2009).

Another important consideration is that welding thin sheet requires tight fit-up, otherwise a hole is created that encourages burn-through. Furthermore, the gap resulting from poor fit-up cannot absorb heat. Tight fit-up reduces the potential for movement, as the gap closes during welding, and also minimizes welding volume. Utilization of small wire diameters means less heat is required, which, in turn, heats the metal less. It also allows for more control over the weld bead. Wire melting with lower temperature and use of a slower wire-feed speed results in a high quality weld of thin sheet (Mike and Jim, 2009).

Conventional arc welding processes create uncontrollable heat, which leads to a large number of problems in thin sheet welding, including burn-through or melt-through, distortion, porosity, buckling, and warping and twisting of the welded sheet (Rakesh et al., 2009b). To summarize, main problems of welding thin sheet are to avoid burn-through, porosity, hot-cracking and distortion (Benachour et al., 2011).

2. WELD DEFECTS OF THIN ALUMINIUM ALLOYS SHEETS

2.1 Distortion

Distortion can be defined as “the non-uniform expansion and contraction of weld metal and adjacent base metal during heating and cooling cycle of the welding process” (Cary and Helzer, 2004). Many factors can cause distortion, but the major ones in aluminium alloy welding are mechanical force and thermal rise. The possibility to avoid distortion during arc welding is limited (Mathers, 2002). The principles of controlling welding distortion of thin sheets and producing good quality welding are follows: (Tsai et al., 1999). Using of appropriate design practices. Design considerations include choosing appropriate welding joints, good welding preparation such as accurate spacing, and balancing the welding sequence. Control of the welding variables, such as reducing fillet weld size, using high-speed welding, using low heat-input welding processes and using a back-step technique.

Focus on welding quality control programs, which include personnel training.

Figure 1 shows the most common distortions; longitudinal shrinkage, transverse shrinkage and angular distortion. Longitudinal shrinkage is shrinkage stress which results in shortening of the member along the principle axis of the weld joint. Transverse shrinkage is shrinkage stress which results in shortening of the member across the toes of the welding joint. Angular distortion is shrinkage stress which results in rotation of one member with respect to an adjacent member. Bowing is shrinkage due to symmetric shortening. Buckling is the same as bowing but the defect is a more localised deformation, as seen on larger structures or thinner, less restrained sections (Pritchard and Laub, 1991).

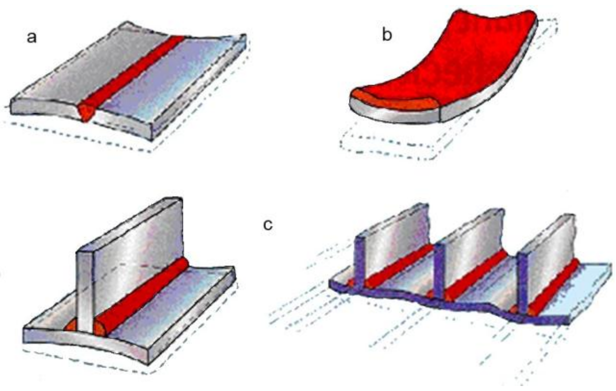

Figure 1 Transverse (a), longitudinal (b) and angular (c) distortion (Courtesy of TWI Ltd).

2.2 Burn-through

Burn-through is caused by using too large heat input in the weld zone or too deep penetration. There are many ways to prevent this problem, such as reducing the heat input, balancing the travel speed, and using a narrow focusing arc under a protective inert gas barrier. The problem can also be addressed by using a smaller wire size with lower current and high welding speed (Kobelco, 1983). Aluminium alloys are more likely than steel to generate bubbles of hydrogen, because of the discharge of a large amount of dissolved hydrogen during solidification of the molten metal. The bubbles of hydrogen create a large amount of burn-through in the weld metal (Kita-Shinagawa and Shinagawa-ku, 2011). Figure 2 illustrates burn-through resulting from too high amperage (Craig, 2001).

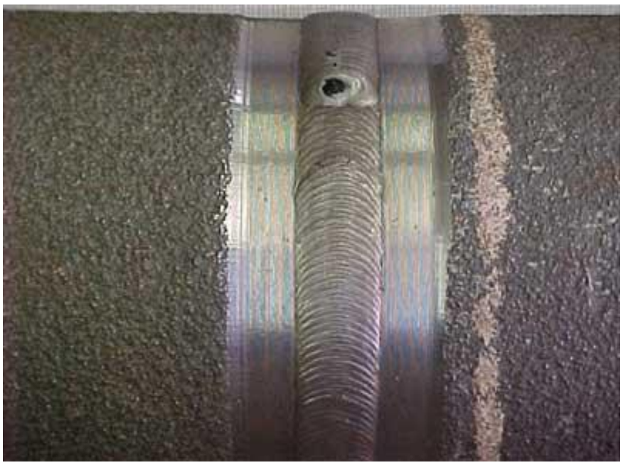

Figure 2 Burn-through as a result of too high amperage (Craig, 2001).

2.3 Heat input

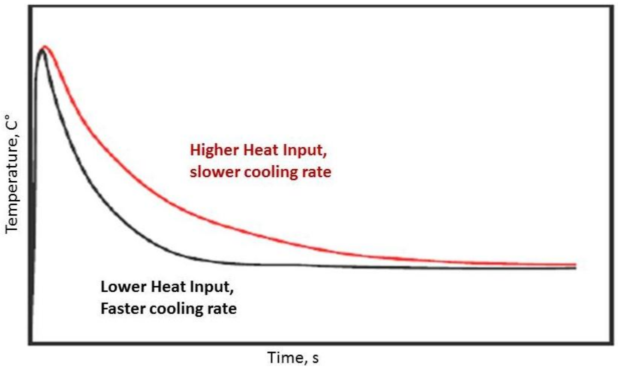

Figure 3 Heat input influences cooling rate (Funderburk, 1999).

During GMAW operation, power is transferred per unit time and energy density to the electrode, which creates melting between the arc and base metal. In general, the heat input is an important characteristic because it influences the cooling rate, which affects the mechanical properties and metallurgical structure of the HAZ. Figure 3 presents the influence of heat input on the cooling rate: when the heat input increases, the cooling rate, which is related to the base metal thickness, decreases. Also the heat input decreases when the cooling rate increases. These two variables interact with other factors, such as material thickness, specific heat, density, and thermal conductivity (Majumder, 2011). Many factors can cause high heat input, such as higher voltage, higher current, and lower travel speed. These factors can lead to wrapping or burn-through, especially in thin sheet material. Generally, aluminium alloys require a fast travel speed to reduce the energy feed into the workpiece (Funderburk, 1999).

2.4 Porosity

One characteristic influencing welding of aluminium alloys is hydrogen solubility. The hydrogen solubility of molten aluminium increases highly and forms solid to melting point and liquid state to melting point and continually increases as the temperature increases. During the welding, some small amount of hydrogen dissolves into liquid, which may cause porosity (Gilbert and Elwin, 2004).

A major cause of porosity with aluminium welding is absorption of hydrogen in the weld pool, which forms gas pores in the solidifying weld metal. The two mechanisms which cause porosity during laser welding are: higher temperature dissociating moisture from the work piece surface, and gas entrapment by the turbulent welding pool and keyhole (Weston et al., 2003). GMAW process resulted in more porosity, as wire is contaminated by hydrogen. The FSW process is more advantageous because it is a solid-state welding process with no melting, has low distortion, requires no edge preparations, displays no porosity, utilizes no weld consumable, such as shield gas or filler metal, and exhibits some tolerance to the presence of an oxide layer (Pritchard and Laub, 1991; Badheka et al., 2010). Figure 4 shows the porosity that can occur in aluminium welding.

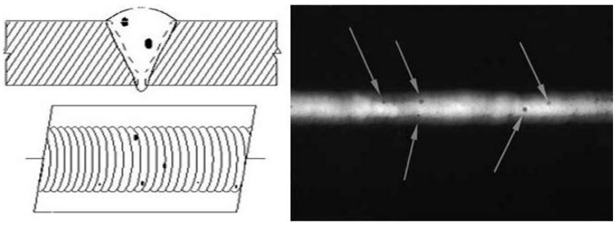

Figure 4 Porosity occurs in aluminium alloy (NDT Resource Center, 2012).

2.5 Hot-cracking

Hot cracking is a welding problem that does not occur in pure metals but may be found in certain alloy systems. Solidification cracking happens due to thermal expansion and contraction during welding. The fundamental mechanism is the same in all of the alloy systems and is a function of how metal alloy systems solidify. The partial melted zone is the region outside the fusion zone where grain-boundary liquation occurs during welding due to heating above the eutectic temperature. Figure 5 illustrates the crack types including longitudinal and crater, which are most commonly found in aluminium alloys (Pritchard and Laub, 1991). Crater cracks occur in the end crater of a weld run due to incorrect welding technique and can be found either at the stop or start of the weld run. Longitudinal or centreline cracking runs on the top surface of the weld and usually runs parallel to or along the centre line of the weld, sometimes changing directions diagonally (Kim et al., 2010).

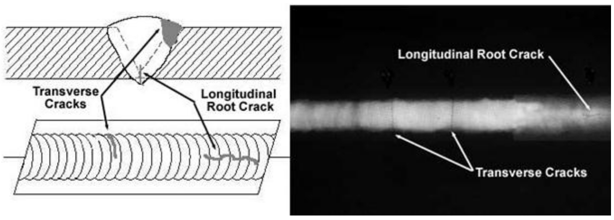

Figure 5 Cracking types usually found in welding of aluminium alloys (NDT Resource Center, 2012).

Consideration of the base alloy is important when making attempts to reduce or avoid cracking. When using base alloys that have low crack sensitivity, a filler alloy of similar chemistry should always be used. When welding base alloys with high crack sensitivity, a filler alloy with low sensitivity is required (Pritchard and Laub, 1991).

3. CATEGORISATION OF ALUMINIUM ALLOYS

As mentioned, aluminium alloys are divided into two categories: casting compositions and wrought compositions. The differentiation for each category is based on the primary mechanism of properties and application ranges. The weldability of aluminium depends on the chemical composition of the alloy. Many alloys of aluminium have been developed and it is important to know which alloys can be welded easily (Praveen and Yarlagadda, 2005).

It is important to understand the differences between the alloys available and their different performance and weldability characteristic. It is also an important to understand their identification system (Pritchard and Laub, 1991). Figure 6 illustrates the grouping of aluminium in alloying elements. There are eight series of wrought aluminium alloys; the system is based on the four-digit wrought aluminium alloys identification system. The first digit indicates the principal alloying element which has been added to the aluminium, and is often used to describe the aluminium alloy series, for example 1000 series, up to 8000 series. The first step to successful aluminium welding is to be familiar with the many luminium alloys, their characteristics, and the aluminium identification system (Praveen and Yarlagadda, 2005; Mathers, 2002).

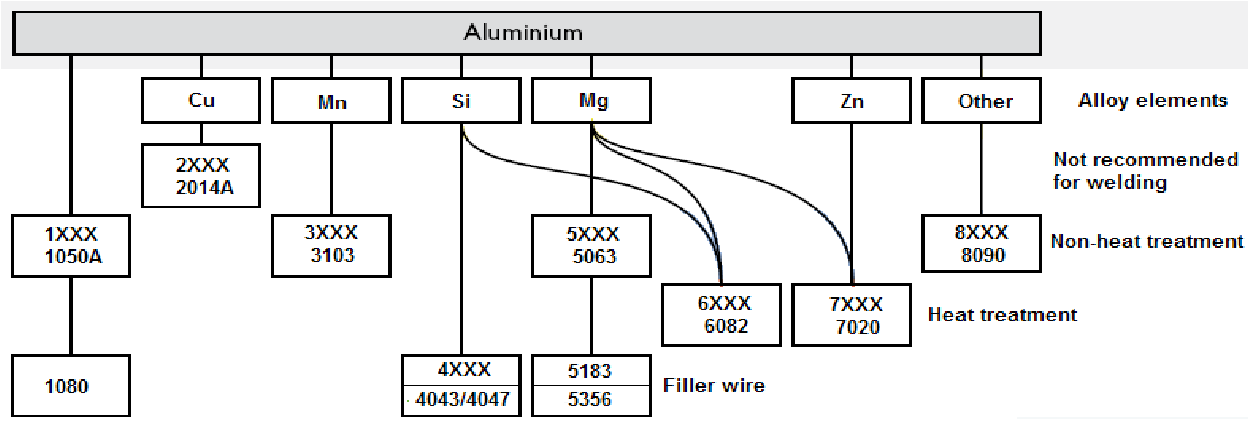

Figure 6 Chart of aluminium alloys replotted from (AFROX, 2012).

Welding aluminium alloys using traditional fusion processes is often problematic. While the large majority of alloys have reasonable to optimal weldability (1XXX, 3XXX, 4XXX, 5XXX, and 6XXX), other alloys have metallurgical drawbacks, such as 2XXX, and 7XXX. Recently, the weldability of the 7XXX series has been re-evaluated since the use of FSW mitigates some of the undesired effects (Volpone and Mueller, 2008).

4. MODERN WELDING TECHNOLOGY

The unique combination of light weight and relatively high strength makes aluminium the second most popular metal that is welded. Cleanliness is important when aluminium is to be welded. The proper cleaning procedure is therefore important and this must be following up during the production (Matheisen and Chr, 1995). Shielding gases have an effect on the arc stability of the metal transfer mode, weld bead shape and melting rate, but the shielding gas must be carefully selected based on the process and base metal to be welded (Cary and Helzer, 2004). In general, the shielding gases chosen depend on the specific application. Helium is not widely used as it has high ionization potential, which produces higher arc voltages when compared to argon for same current. The increased heat input affects depth of penetration and its wider, less constricted arc column increases weld bead width. Therefore, Helium is not the best choice for welding of thin aluminium sheets. Argon is the most commonly used shielding gas for welding aluminium alloys, because of its good arc starting characteristics and cleaning action (Kita-Shinagawa and Shinagawa-ku, 2011).

Modern welding technology has developed greatly in recent years, new processes have been invented, and alternative welding processes such as hybrid welding generated. Welding power sources have continued to become smaller, more efficient, lighter and more controllable (Cary and Helzer, 2004). Currently, a number of welding processes have the ability to weld thin aluminium alloys; GMAW, GTAW, PAW, LBW and FSW. There are differences in the output of the processes, and process choice is related to the application and demands of the customer.

4.1 Gas Metal Arc Welding Process

The GMAW process is an arc welding process that uses a continuously fed wire both as the electrode and as a filler metal, the arc and weld pool being protected by an inert gas shield. This process has the advantages of a high welding speed, small heat affected zone, excellent oxide film removal during welding, and an all-positional welding capability (Cary and Helzer, 2004). The GMAW process typically has an arc travel speed of 300-380 mm/min and weld metal deposit varies from 1.2 kg/h when welding out of position to 5.5 kg/h in a flat position (Radhakmishnan, 2005).

GMAW is the most commonly used arc welding process for thin aluminium sheet because of improvements in the reliability and performance of the welding equipment, especially AC and DC power sources (Kita-Shinagawa and Shinagawa-ku, 2011). The GMAW process is flexible and capable of operating at a wide range of current levels. It is a good process for joining 2 mm or less sheet metal and also offers the advantage of high welding speed with versatility and the ability to get high quality welds (Kita-Shinagawa and Shinagawa-ku, 2011). The most suitable GMAW processes for high quality welding of thin sheet aluminium alloys are for example AC Pulse GMAW (AC P-GMAW) and Cold Metal Transfer GMAW (CMT GMAW) (Mandal, 2001). Other advanced GMAW welding processes can also be used.

4.1.1 AC P-GMAW Process

AC P-GMAW is which repeats Direct Current Electrode positive and Direct Current Electrode Negative in a cycle based on the Electrode Negative (EN) ratio. This welding system is more suitable with thin material, because the heat input is lower than DC pulse GMAW. The electrode polarity for welding with solid wires can be electrode positive or "reverse" polarity. Electrode Positive (EP) directs more heat into the base metal than electrode negative ("straight" polarity) (So et al., 2010).

Research has been done on microstructure, weld bead geometry, dilution and mechanical properties of AC P-GMAW welds (Rakesh et al., 2009a). The properties of butt and overlap weld joints of thin sheet 1 mm of 6082 aluminium alloys, producing by using AC P-GMAW, with high speed video camera operating at 2250 frames per second in both polarities EN and EP. The polarity was set to control the melting coefficient of the melting rate per unit current, also heat input and penetration depth. The polarity was changed at different time intervals from EP to EN to avoid spatter emitted from an open arc. The main principle of the system is use of the EN ratio to control the weld penetration. During AC P-GMAW the current is mainly dependent on the wire feed rate; a feed rate increase for a given wire feed reduces the current and hence the penetration (Wesley, 2010). Low penetration is a required characteristic of thin sheet welding. Therefore, the depth of penetration can be controlled by changing the EN ratio, and increasing the EN ratio results in shallow penetration. Therefore the results are an excellent of thin sheet welding (Rakesh et al., 2009a and 2009b).

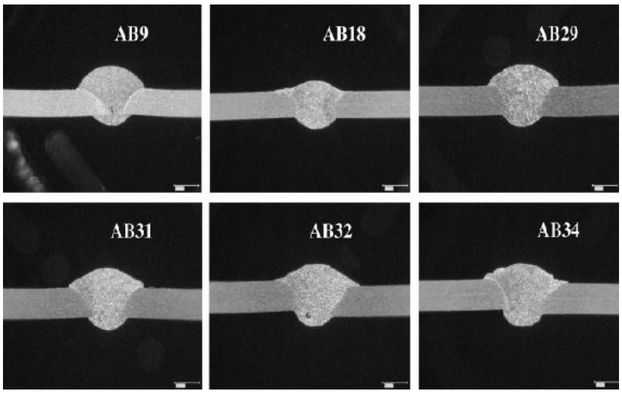

Figure 7 Macro photographs of butt-joints produced under different conditions (Rakesh et al., 2009a).

Porosity quantification was studied in (Chen and Wang, 2008) using material pulse image analyzing software. It was found that AC P-GMAW is good not only for reducing the heat input, but also for controlling the porosity. The porosity (%) was found to be in a range of 0-5.82 %, with pore size in the range of 0–30 μm. Welding porosity was less than 1% and was attributed to change of the electrode polarity causing easy escape of absorbed gases. Generally, the AC P-GMAW process is more suitable for thin metal welding, because the system has adjusting unit for changing the polarity at different intervals for EP and EN, which avoids spatter emitted from the open arc. Utilization of the AC P-GMAW process allows use of a low frequency pulse of 0.5–20 Hz, which enables improved bead shape (Rakesh et al., 2009a).

Table 1 shows the parameters using during the AC P-GMAW process studied in (Rakesh et al., 2009a). The same parameters were used for the welds shown in Figure 7 and 8.

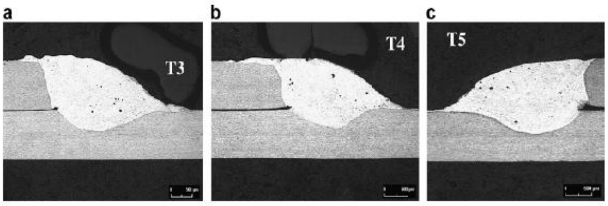

Figure 8 Macro photographs of lap joints produced under different conditions T3 (a), T4 (b), T5 (c) (Rakesh et al., 2009a).

The figures show that good weld joints and good gap bridging capacity can be achieved. Therefore using AC P-GMAW process has an advantage during welding of thin sheets of aluminum alloys (Rakesh et al., 2009a).

4.1.2 Cold Metal Transfer

CMT is a short-circuit GMAW process in which droplets detach from the wire in digital process-control. The principle CMT is that the motions of the wire have been integrated into the welding process and into the overall control of the process. The CMT process has a very low short-circuit current, and thus, low heat input. The current is kept low by controlling of short-circuit, resulting in virtually spatter free transfer. CMT is used in applications that benefit from low voltage and amperage and reduced thermal input. Consequently, there are advantages when utilizing the process in the welding of thin sheet aluminium alloys.

Table 1 Welding parameters used in AC P-GMAW (Rakesh et al., 2009a).

Weld description	Average current (A)	Average voltage (V)	EN ratio	Frequency f (Hz)	Welding speed (V) (mm/min)	Heat input (E) (J/mm)
AB9	52	20.0	28.91	57	1900	32.61
AB18	59	13.0	18.83	83	2500	21.53
AB29	48	15.3	19.03	63	1700	25.91
AB31	61	16.2	19.76	91	2500	23.47
AB32	65	14.6	17.82	86	2400	23.87
AB34	58	14.4	10.62	69	2000	24.83
T3	74	14.4	13.46	81	2400	26.66
T4	64	14.1	15.84	78	2000	26.94
T5	59	16.2	6.01	71	1800	31.94

Figure 9 illustrates a high quality weld of 1 mm thick $AlMg_3$ sheet welded with the CMT process. New technology from Fronius has made it possible to use CMT to produce high quality welds with aluminium alloys (Fronius Int, 2004). There are other advanced processes as well, such as Miller Electric's Regulated Metal Deposition (RMD) or Lincoln Electric's Surface Tension Transfer (STT) process.

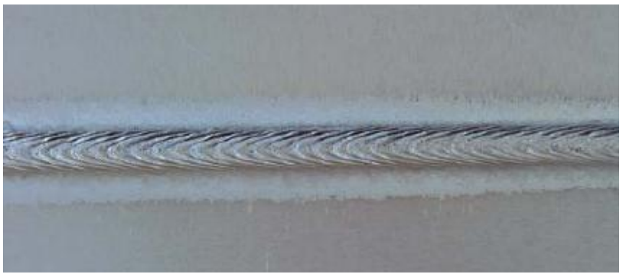

Figure 9 Fillet weld on a 1 mm thick $AlMg_3$ sheet, CMT welded at a welding speed of 20 mm/min (Fronius Int, 2004).

4.1.3 DC P-GMAW Process

Weld microstructure, dilution rate and mechanical properties of the butt, weld bead geometry and overlap weld joints of 1 mm thick 6082 aluminium alloy sheet were reviewed. Weld joints were made by direct current-pulsed GMAW (DC P-GMAW). The welding results demonstrated high process stability for welding thin sheets of aluminium. Weld bead geometry parameters such as weld size, throat and weld convexity increases with the increase in heat input. The dilution in case of lap joints (10–25%) was less than that of butt joints (60–80%). Mechanical properties of the welds are poor as the tensile strength of 6082 alloy welds was around 150 MPa, and the percent elongation was about 1.3%, and it was primarily due to high porosity. Porosity (%) in weld joints was found in the range of 0.33–11.59%. The porosity is one of the most important problems with DC P-GMAW welds. However there is a lot of developments in this field and the problem might be overcome soon (Mike, 1974).

4.2 Gas Tungsten Arc Welding Process

The GTAW process is an arc welding process which produces coalescence of metal by heating the metal with an arc between a tungsten (non-consumable) electrode and the workpiece (Sathiya et al., 2012). Shielding gas is obtained from a gas or gas mixture (Cary and Helzer, 2004). The GTAW is limited to an arc travel speed of 1500 mm/min and metal deposit rate of 1 kg/h; the arc voltage may range from 10-15 V with current of 50-350 A (Radhakmishnan, 2005). The GTAW process is especially useful for joining aluminium and magnesium, which form refractory oxides, and for reactive metals, such as titanium and zirconium, which can become brittle if exposed to air while molten. With thin aluminium alloy sheets, the GTAW process can weld in all positions, although better results are obtained in the flat position (Cary and Helzer, 2004).

The GTAW process can produce high quality welding of aluminium alloys with sheets of thicknesses between 0.5 mm and 5 mm. Stability gives flexibility in arc control and creates a way of preventing burn-through and wrap, which might be expected during the welding of thin sheets. The system provides a narrow and focused arc, and when the welding starts, the arc initiates almost instantaneously (Cary and Helzer, 2004).

Control of the frequency is the major variable used to prevent the burn-through or warping which usually happens when using the GTAW process. The frequency, or Hz, is the number of times the arc switches between EP and EN in one second. Increasing the frequency, "constricting the nozzle," gives a narrow shape to the arc cone, increasing the arc force. This stabilization gives an excellent directional control over the arc and reduces arc wandering. When making frequency adjustments during welding of thin sheet, the best output frequency is 80 to 120 Hz; this frequency creates a narrow arc cone, which gives a flexible arc, helping to prevent burn-through and wrap (Jiang et al., 2008). Figure 10 shows a high quality GTAW butt-weld, without weld-pool backing support, on 0.8 mm $AlMg_3$ sheet.

Figure 10 Butt-weld, without weld-pool backing support, on 0.8 mm $AlMg_3$ sheet with GTAW process (Jiang et al., 2008).

The aluminium oxide layer which forms on the surface needs to be removed during welding; when using AC GTAW, the electrode positive EP portion of the AC cycle, in which electricity flows from the work to the tungsten, "blasts off" the surface oxide. The negative EN portion of the cycle does not do any actual welding; only directing the heat from the tungsten into the metal (Jiang et al., 2008).

4.3 Plasma Arc Welding Process

The PAW process is a process which produces coalescence of metals by heating them with a constricted arc between an electrode and the work-piece (transferred arc) or the electrode and constricting nozzle (non-transferred arc) (Cary and Helzer, 2004). New PAW welding techniques have been developed, such as Micro-plasma Arc Welding (MPAW), Fine Plasma Arc Welding and Variable Polarity Plasma Arc Welding (VPPAW). The main concept of VPPAW with aluminium is a variant of plasma arc welding with a square-waved alternating current. The power sources used allow the amplitude and duration of the negative half-cycle and the positive half-cycle to be varied independently. This system was developed for welding of aluminium alloys. The welding quality of VPPAW is better than ordinary gas shielded welding. VPPAW plays an important role in the automotive and automotive remanufacturing industries. MPAW is traditionally used for welding thin sheets (down to 0.1 mm thickness) and wire and mesh sections. The needle-like stiff arc minimizes arc wander and distortion. This process can be operated at very low welding currents from 0.1 A to 20 A (Kumar et al., 2009).

4.3.1 Double Sided Arc Welding

Double Sided Arc Welding (DSAW) system was designed and constructed with five main components; a variable polarity power supply and plasma arc welding console, a PAW torch, a GTAW torch, a welding table traversing mechanism for holding and moving the weld specimens between the two fixed torches at the desired welding speed (Kwon and Wekman, 2008).

Weldability of thin sheet using a PAW process with a DSAW process has been investigated (Gilbert and Elwin, 2004) and it was found that the concept is suitable for the production of high quality welds, when welding AA5182-O with a sheet thickness of 1.2 mm, in a butt-joint, using square wave AC, welding speed of 40 to 3600 mm/min, and power welding of 2.1 kW. Increased productivity of thin sheet (1.2 mm or similar) aluminum welding was reported (Kwon and Wekman, 2008). Figure 11 presents a schematic diagram of the DSAW process and specimen clamps.

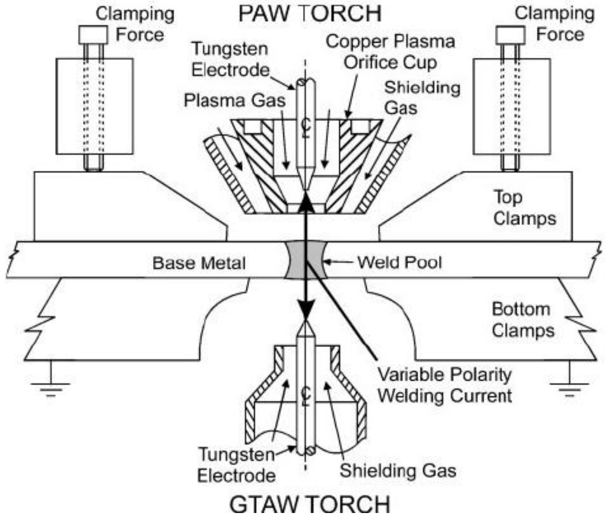

Figure 11 Schematic diagram of DSAW process and specimen clamps (Kwon and Wekman, 2008).

Research on a DSAW process system with 3.4 kW welding power and welding speed of 1800 to 4200 mm/min has been reported. At the slowest welding speed, blowhole defects were observed periodically along the DSAW weld beads when the energy input per unit length was too large (Kwon and Wekman, 2008).

4.4 Laser Beam Welding Process

LBW is a welding process that uses the heat generated by a high power coherent monochromatic light beam which can be focused to a small spot, producing a very high energy density (Cary and Helzer, 2004). The laser beam is produced by simulating emission of electromagnetic in specific solid or gaseous material. The power density of laser welding (109–1011 W·m^2) is significantly higher than other arc welding processes (106–108 W·m^2) (Cary and Helzer, 2004). LBW has limitations which are related to the low energy density; the low level energy will not permit vaporisation and the formation of liquid cylindrical volume (Radhakmishnan, 2005).

There are two basic types of lasers used in thin materials welding of aluminium alloys. The most common type is solid state lasers, which use a solid medium. The other type is gas lasers, which normally use a mixture of helium and nitrogen (Cary and Helzer, 2004).

The major parameters of laser beam welding are power density of the laser, beam diameter, beam absorptivity, and traverse speed. Other parameters such as weld design, shielding gas, gap size for butt welds, and depth of focus with respect to the substrate also play important roles in laser beam welding of thin aluminium alloys (Dickeron, 1993).

The depth of penetration with laser welding is directly related to the power density of the laser beam and is a function of incident beam power and beam diameter. The laser beam diameter parameter is the most important parameter to consider for welding thin sheet materials of Al-alloys, because it determines the power density. It is, however, very difficult to measure for high-power laser beams. The laser beam absorptivity efficiency depends on the absorption of light energy by the workpiece (Dickeron, 1993).

The characteristics of laser butt welding of 2 mm thick non-heat-treatable AA5052-H12 and 3 mm thick heat-treatable AA6061-T6 aluminum alloys have been investigated (El-Batahgy and Kutsuna, 2009). Previous study had indicated porosity, excessive material loss, and solidification cracking as the most common problems encountered in laser welding of aluminum alloys. It was reported that solidification cracking could be avoided through two different approaches. The first one is based on the addition of filler metal, as reported in other research work (Arata et al., 1987). The second approach utilized autogenously welding using a back strip from the same base metal. The second approach is more suitable with thin aluminium alloys and is applicable in normal production situations. The porosity was prevented by efficient cleaning of the base metal before welding and optimization of the flow rate of the argon shielding gas (El-Batahgy and Kutsuna, 2009).

It has been reported that an Nd:YAG laser with a characteristic wavelength of 1.06 µm provides better coupling with aluminium than a CO_2 laser with a characteristic wavelength of 10.6 µm. It is important to consider the effect of the defocusing distance when welding thin sheet aluminum alloys, because increasing or decreasing it causes a sharp decrease in the laser beam power density at the top surface of the specimen (El-Batahgy and Kutsuna, 2009). Defocusing is also an important consideration during changes in welding focus, because it is difficult to maintain control over the plate's flatness and its position with respect to the laser head. Good quality welds are attained when the weld is made under low pressure or high vacuum conditions, or under a negative pressure welding condition with a Tornado gas nozzle whose effect is to reduce porosity (Tu and Paleocrassas, 2010).

4.5 Friction Stir Welding Process

The FSW process uses a non-consumable rotating tool and solid state welding process and joins material by heating it into a plasticized state. The rotating tool generates heat through friction with the base material. This action allows material to be mixed and a joint is formed upon cooling. Friction stir welding is a low temperature solid state process (Cary and Helzer, 2004; Saeid et al., 2011; Rodrigues et al., 2009). The basic principles of FSW are shown in Figure 12.

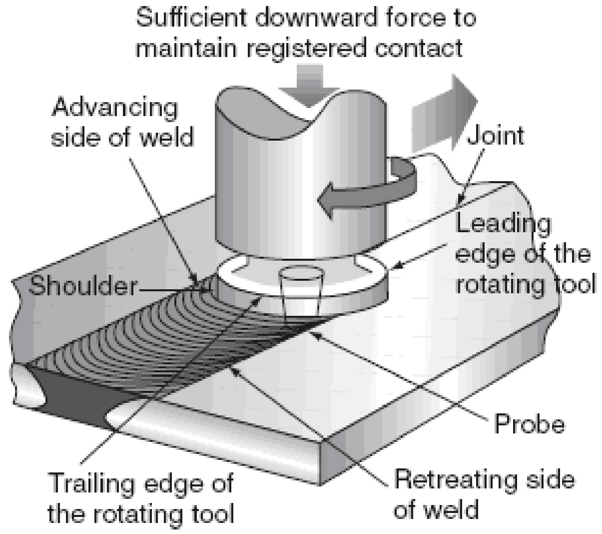

Figure 12 Principle of the friction stir welding process (Courtesy of TWI Ltd).

Friction stir welding is more suitable for joining semi-finished products of thickness 0.30 to 35 mm (on the side weld, butt-joint and lap-joint). FSW technology is mainly used for joining material that cannot be easily joined with arc welding processes, such as GMAW and GTAW (Volpone and Mueller, 2008; Kumar et al., 2011).

Microstructure analyses of thin sheet FSW welds (Rodrigues et al., 2009) have shown that the materials were successfully joined without porosity and with no defect in both the weld top and root surface, as shown in Figure 13. Images a and b are of welds produced with tool 1 (conical shoulder) using "hot welding" with a welding speed of 180 mm/min (v), rotation speed of 1800 rpm (ω) and tool angle of 2.5°, and images c and d are of welds produced with tool 2 (scrolled shoulder) using "cold welding" with a welding speed of 320 mm/min, rotation speed of 1120 rpm and tool angle of 0°. The Hot Welding (HW) method resulted in a smooth surface compared to the Cold Welding (CW) method (Rodrigues et al., 2009).

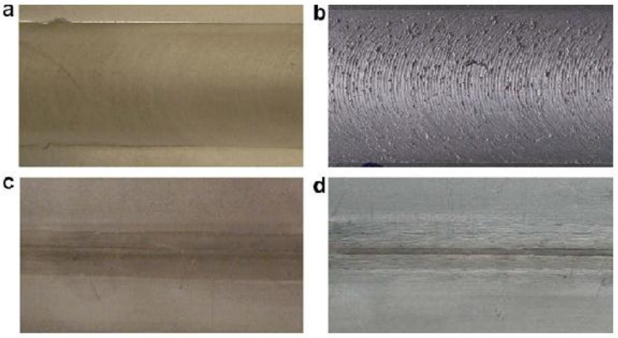

Figure 13 Crown (a) and route (b) views of the welds HW and CW (c, d) (Rodrigues et al., 2009).

Research in (Mroczka and Pietras, 2009) investigated welding of 1 mm thick sheet (6082-T6) with different parameters and setup. FSW obtained good quality welds of 6082-T6 aluminum alloys at 710 rpm and with welding speed of 244–900 mm/min. The welds were without porosity and defect-free. Micro-hardness measured across the welds was found to have a distinct drop in the heat affected region (about 12–14 mm from the welding line).

The FSW process has many advantages compared to other processes such as fusion welding (GMAW, GTAW) because the FSW process minimizes cracking and porosity problems and reduces welding costs. The system does not use filler wire, no gas shield is necessary for welding aluminium, and no welder certificate is required. The FSW process successfully welded, with a high quality result, 1 mm thick aluminium alloys such as AA6061-T4, AA5182-H111, AA6016-T4 and 6082-T6 (Loureiro et al., 2007).

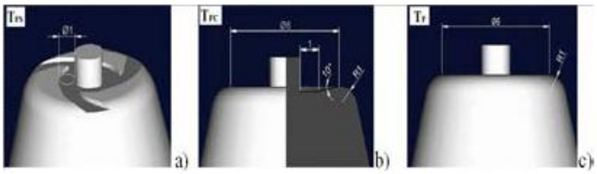

Figure 14 Tools used and their main dimensions fillet + scroll tool (a), fillet + cavity tool (b) and flat fillet tool (c) (De-Giorggi et al., 2009).

When welding thin sheet aluminum alloys using the FSW process it is very important to consider tool geometry. Fatigue performance is an important property to be examined. In (De-Giorggi et al., 2009), an AA6082-T6 sheet was successfully joined using the FSW technique with three different types of shoulder geometry. The shoulder geometries studied were:

shoulder with a scroll (T_{FS}), shoulder with a shallow cavity (T_{FC}), and flat shoulder (T_F). Figure 14 presents the tools with their dimensions. The most important task of the shoulders is to apply confining pressure to the plasticized material (De-Giorggi et al., 2009).

The (T_{FC}) tool produced a small amount of lash and the crown was not smooth (slight thermal cycle). The bead obtained by the (T_{FC}) tool is characterized by a smooth surface and few flashes. The T_F tool produced smooth crowns and a few flashes (higher thermal input) in the joint region. The process parameters (plunge depth, tilt angle, spindle speed, and feed rate) and the heat power depend on the contact surface between the tool and the sheets, the material flow under the tool, and the shoulder pressure on the workpiece. Higher heat input causes a higher peak temperature in the thermal cycle, which produces a higher residual stress field. The results showed no porosity and no defects in both the top and root weld surfaces for all three welding conditions. Figure 15 shows the influence of shoulder geometry on the top weld surface (De-Giorggi et al., 2009).

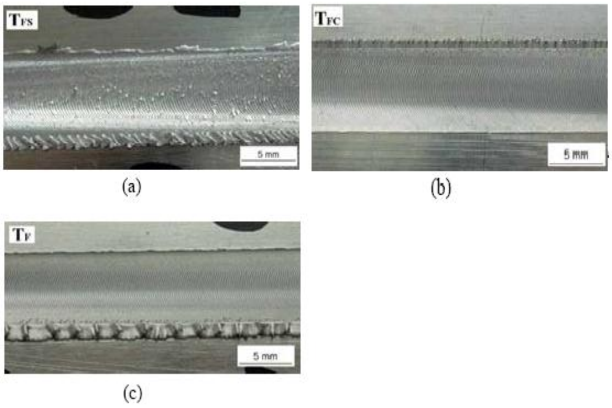

Figure 15 Top weld surface obtained by with studied tools: fillet (a) + scroll tool; fillet + cavity tool (b); fillet tool (c) (De-Giorggi et al., 2009).

5. CONCLUSION

Material and welding technologies for industrial use are continually evolving. Efforts to reduce weight and cost, increase energy efficiency, improve performance and reduce environmental effects continue to provide challenges to the use of thin aluminium alloys. Based on this study, the following conclusions can be made:

The AC P-GMAW process prevents the occurrence of problems with porosity, burn through, hot-cracking, and distortions, because the system allows the polarity to be changed at different intervals to adjust EP and EN. The system permits use of a low frequency pulse of (0.5 – 20 Hz), and the ability to adjust the EN ratio means the depth of penetrations can be controlled.

The CMT GMAW process prevents the occurrence of problems with porosity, burn through, hot-cracking, and distortion, because the system has digital process-control which is controlling heat-input and welding speed limit. Using digital process control, the system provides control of the motion of the wire and detects the short circuit which retracts the wire and helps detach the droplet.

Using the GTAW process with AC High Frequency power sources and pure argon as a shielding gas produces high quality welds of thin aluminium alloys. Using GTAW and an AC inverter with square wave technology provides a narrow and focused arc, and the arc is initiated almost instantaneously. The GTAW and an AC inverter with square wave provide a stabilisation which creates way to prevent burn through, porosity, hot-cracking and distortion. The system also allows adjustments to increase the frequency of the constriction of the nozzle such that a narrow shape of the arc cone and increasing arc is achieved.

Utilization of the PAW process with the DSAW method is a suitable approach to produce high quality welds with thin sheet aluminium alloys because of the high energy and the high welding speeds possible. The VPPAW with square wave AC direct current, welding speed of 240 to 360 mm/min and power welding of 2.1 kW provides to produce high quality weld with thin sheet aluminium alloys. The GTAW and PAW processes are more suitable with thinner materials, especially electronic industry products or products requiring high quality aluminium alloy welds.

LBW produces high quality welds of thin sheet aluminium alloys, when the focusing length is set such that an appropriate power density is produced. The condition of under pressure, high vacuum or negative pressure welding with a Tornado gas nozzle gives high quality welding of thin sheets of aluminium alloys.

It is important to consider the effect of the defocusing distance when welding thin sheet aluminum alloys, because increasing or decreasing it causes a sharp decrease in the laser beam power density at the top surface of the specimen.

The FSW process produces high quality thin sheet welding. Important parameters are the rotational speed, tool geometry and tool shoulder. The hot weld FSW method results in a smooth surface during welding of thin sheets.

The FSW process has advantages in the welding of aluminium alloys, compared to traditional fusion welding, because of its low operational cost, high speed, good productivity and low numbers of defects.

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