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Investigation of weld defects in friction-stir welding and fusion welding of aluminium alloys

Paul Kah*, Richard Rajan, Jukka Martikainen and Raimo Suoranta

Abstract

Transportation industries are obliged to address concerns arising from greater emphasis on energy saving and ecologically sustainable products. Engineers, therefore, have a responsibility to deliver innovative solutions that will support environmental preservation and yet meet industries' requirements for greater productivity and minimised operational costs. Aluminium alloys have successfully contributed to meeting the rising demand for lightweight structures. Notable developments in aluminium welding techniques have resolved many welding related problems, although some issues remain to be addressed. The present study attempts to give an overview of the key factors related to the formation of defects in welding methods commonly used with aluminium alloys. First, a concise overview of defects found in friction-stir welding, laser beam welding and arc welding of aluminium alloys is presented. The review is used as a basis for analysis of the relationship between friction-stir welding process parameters and weld defects. Next, the formation and prevention of the main weld defects in laser beam welding, such as porosity and hot cracking, are discussed. Finally, metallurgical aspects influencing weld metal microstructure and contributing to defects are tabulated, as are defect prevention methods, for the most common flaws in arc welding of aluminium alloys.

Keywords: Defects, Friction-stir welding, Aluminium alloys, Laser beam welding, Arc welding, Process parameter effects

Review

Introduction

Aluminium alloys have been one of the primary candidates for material selection in many industries, including the commercial and military aircraft and marine sectors, for more than 80 years, mainly due to their well-known mechanical behaviour, design ease, manufacturability and the existence of established inspection techniques (Dursun and Soutis 2013). Increasing utilization of aluminium in various industrial sectors is the main driving force in the search for a viable and efficient technology for joining aluminium that does not cause deterioration in the desirable mechanical, chemical and metallurgical performance of the material.

In recent years, the growing concerns surrounding energy saving and environmental conservation have increased the demand for lightweight structures. While modern alloys such as advanced high-strength steel (AHSS) have allowed many industrial objectives to be met, for example, weight reduction while maintaining crashworthiness in vehicles, further significant reduction of weight, of the order of 30 %, is highly unlikely without the usage of multi-material structures (Sakiyama et al. 2013).

The best combinations for such multi-material structures are considered to be aluminium alloys and AHSS. However, such dissimilar materials are difficult to join by welding due to the differences in their mechanical and physical properties and due to the formation of large amounts of brittle intermetallic compounds (Ogura et al. 2012). Aluminium is unique as a weld metal when compared to ferrous alloys because aluminium lacks a solid-state phase transformation upon cooling. Therefore, only solidification determines its microstructure. However, the high temperatures found during fusion joining processes

* Correspondence: paul.kah@lut.fi
Laboratory of Welding Technology, Lappeenranta University of Technology, Lappeenranta, Finland

significantly affect the microstructure of the metals, which has a direct impact on the properties and the behaviour of the material (Courbiere 2008).

This work considers three welding methods: friction-stir welding (FSW), laser beam welding and arc welding. First, we focus on the factors contributing to the defects in FSW of aluminium alloys. As FSW is a complex hot shear and forging process, identification of the origin of defects is not straightforward. The defect population and residual stresses in the weld zone are greatly influenced by the complex plastic deformation process. Therefore, a long-standing problem has been a lack of clear information on the effects of friction-stir welding process parameters on weld defects that would enable relationships and correlations to be drawn and would assist optimisation of FSW. Relationships are identified between the plastic flow mechanism around the tool, process parameters (such as tool tilt or penetration into the joint) and FSW defects. In the second part of the paper, we focus on laser beam welds and investigate defect mechanisms in laser beam welding of aluminium. Laser beam welding is constantly evolving as laser beam power source technology advances. However, a number of problems and issues remain to be resolved. The formation and prevention of the main weld defects in laser beam welding of aluminium alloys, such as porosity and hot cracking, are discussed. The third part of the paper focuses on the weld related flaws in arc welding of aluminium alloys. Heat generated for joining can cause significant changes in material microstructure, thereby compromising the mechanical property of the base metal and causing weld distortion. For example, in fusion welding of aluminium alloys, the generated heat, which supports the joining of the metal, can lead to microsegregation of alloying elements such as copper, magnesium, silicon and manganese. Solidification cracking, weld porosity and heat-affected zone liquation cracking are some of the flaws examined.

Characteristics of friction-stir welding

Friction-stir welding (FSW) has been considered as the most significant development in metal joining of the past decade. It is regarded as a green technology because of its energy efficiency, environmentally friendly nature and versatility. FSW, a solid-state, hot-shear joining process, was developed by The Welding Institute (TWI) in 1991 (Thomas et al. 1991). The use of FSW has gained a prominent role in the production of high-integrated solid-phase welds in 2000, 5000, 6000 and 7000 Al-Li series aluminium alloys and aluminium matrix composites. Table 1 presents the advantages of FSW over traditional processes.

Process principles

The FSW process progresses sequentially through the pre-heat, initial deformation, extrusion, forging and cool-down metallurgical phases. Figure 1 shows the schematics of friction-stir welding. The welding process begins when the frictional heat developed between the shoulder and the surface of the welded material softens the material, resulting in severe plastic deformation. The material is transported from the front of the tool to the trailing edge, where it is forged into a joint (Grujicic et al. 2010; Nandan et al. 2008). Consequently, the friction-stir welding process is both a deformation and a thermal process occurring in a solid state; it utilises the frictional heat and the deformation heat source to bond the metal under the applied normal force. As can be seen in Fig. 1, the side of the plate where the direction of rotation is the same as that of the welding is the advancing side and the other side is designated the retreating side.

Generally, friction-stir welds have a somewhat different microstructure to welds from fusion welding processes, because the maximum peak temperature in the heat-affected zone is significantly less than the solidus temperature and the heat source is also rather diffused (Nandan et al. 2008). Figure 2 shows the cross section of a FSW joint, illustrating the distinct weld zones. The thermo-mechanically affected zone (TMAZ), where the grains are deformed but the original microstructures retained, lies between the heat-affected zone (HAZ) and the weld nugget (stirred zone). The process parameters greatly influence the flow of the plastically deformed

Table 1 Advantages of friction-stir welding (FSW) over traditional processes

Characteristics	Advantages
Weldability	Some aluminium alloys that are either not weldable or difficult to weld due to problems of brittle phase formation and cracking are now weldable by friction stir welding as it is a solid-state process.
Distortion	Longitudinal and transverse distortion is minimised in the FSW process due to the lower peak temperature in FSW compared to arc welding processes.
Fatigue resistance	FSW welds exhibit improved fatigue resistance during cyclic loading conditions due to the lower peak temperature and lower residual stress.
Filler material requirements	For some aluminium materials, no suitable filler material matching the strength of the base material is available for arc welding processes. FSW does not require filler material to join the metals.
Process variables	The comparatively few process parameters involved and easy controllability make FSW a relatively stable process.

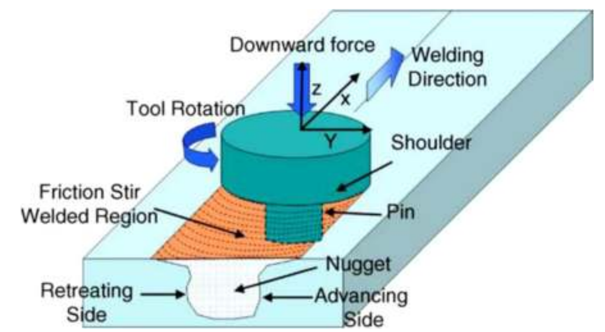

Fig. 1 Schematics of the friction-stir welding process (Mishra and Ma 2005)

material (Mishra and Ma 2005). Hence, attention should be paid to ensure suitable processing conditions, in order to avoid potential defects in the weld nugget zone (WNZ), the TMAZ or sometimes at the WNZ/TMAZ interface (Crawford et al. 2006). For example, an 'onion-ring' characteristic of the central nugget region, where the most severe deformation occurs, is a result of the way in which the material is deposited, from the front to the back, by the threaded tool.

Issues in friction-stir welding of aluminium alloys

In FSW, several thermo-dynamical process interactions occur simultaneously, including the varied rates of heating and cooling and plastic deformation, as well as the physical flow of the processed material around the tool. Throughout the thermal history of a friction-stir weld, no large-scale liquid state exists (Grujicic et al. 2010). Flaws such as porosity and hot cracking are not found in friction-stir welding as it is a solid-state joining process (Arbegast 2003). When a metal is friction stir welded, joining occurs well below the melting point, and so the parent metal does not undergo bulk melting at the joint.

In most welding processes, the materials are generally joined by reducing the resistance to deformation by supplying the required amount of energy in the form of heat. However, the heat supplied tends to create conditions that cause microstructural changes such as recrystallisation, grain orientation growth, and coarsening or dissolution of the strengthening precipitates. Such microstructural changes occur at different temperatures for different materials and are dependent upon the chemical composition of the materials involved. Therefore, depending upon the chemical composition of the material, the processing conditions can be termed either 'very hot' or 'very cold' processing (Schneider et al. 2006). Friction-stir welding is still susceptible to flaw formation because it lacks the potential for imbalances between the distinct processing zones. Defects such as non-bonding or void formation can occur at very cold welding conditions, due to insufficient material flow, and flaws such as flash formation, collapse of the nugget within the stir zone and deterioration in the strength properties of the joint can occur at very hot conditions, due to excessive material flow (Annette 2007). In addition to these flow related defects, other geometry related defects also exist, such as lack of penetration and lack of joining, which mainly occur due to operator errors.

Factors related to imbalances in the material flow associated with the position of the tool in relation to the joint are the main reasons for flaw formation in friction-stir welding. For example, incorrect setting of the tool position to the joint line can lead to a lack of joining. Depending on the distance from the tool, phenomena like dissolution and coarsening of precipitates or recovery and recrystallisation can occur to different extents (Wanjara et al. 2013; Annette 2007). Additional problems can be expected if the gap between the abutting plates is not tightly controlled. Significant reductions in fatigue strength occur with increasing gap between the plates to be welded.

Formation of an onion-ring microstructure Onion-ring structures in friction-stir welds of aluminium alloys

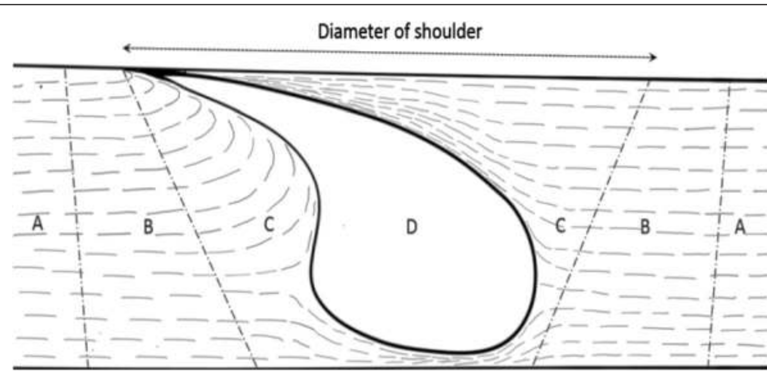

Fig. 2 Schematic of the cross section of a typical FSW weld: **a** base metal, **b** heat-affected zone, **c** thermo-mechanically affected zone, and **d** weld nugget zone (stirred zone)

can be observed as bands in the weld nuggets. Onion-ring structures have notable dark and bright bands, and the spacing between the bands is equal to the forward motion of the tool in one rotation. In an onion-ring structure, the spacing of the alternate bands increases with the increasing rotations of the tool and increasing material transport per measure of the weld length (Krishnan 2002). The rotary speed of the tool determines the amount of heat produced per unit time and the stirring and the mixing of the material around the pin (Peel et al. 2003). The rotary and traverse speeds of the tool govern the peak temperature generated during welding and the time required for welding of the material. The translation of the tool entrains the material from the advancing side, and the material is rotated around the pin and deposited on the rear of the retreating side. Material carried from the retreating side of the weld is deposited to fill in the material cavity in the wake of the pin (Krishnan 2002; Nandan et al. 2008). Thus, the FSW nugget consists of a mixture of two streams of material with different histories and mechanical properties, which often leads to an onionskin microstructure.

Increasing the process temperature significantly influences the formation and the subsequent roles that the bands play in the formation of a crack path in a weld nugget placed under cyclic loading. The differences in the size, shape and density of the intermetallic particles within the bands are the result of hotter welds. Crack initiation in the weld is affected by onionskin partial bonding defects, and the tool pitch directly influences these defects. For a constant rotational speed, softening of the weld nugget reduces as the feed rate or translational tool velocity is increased (Krishnan 2002). Hence, it is clear that the formation of an onionskin macrostructure is related to variation in the tool pitch along the weld joint. Consequently, the possibility exists for process optimization to modify the weld microstructure and improve material properties, including fracture resistance.

Formation of flash defects The material being welded experiences very hot processing conditions as the tool pin rotates at very high speeds. Therefore, excessive heat generated, thermally softens the material near the boundary of the tool-shoulder and expels large volumes of material in the form of surface flash. Excessive tool-shoulder frictional heat softening of the material is the reason for the formation of the flash, and high tool-shoulder pressure leads to the ejection of an excessive amount of flash (Bo et al. 2011). Incorrect tool pin length relative to workpiece thickness and change in penetration depth due to variation in plate thickness along the weld line or due to a bowed plate can lead to a lack of penetration. When the pin plug depth is high, the plastic material near the pin is extruded, which results in weld flash. When the pin depth is very high, extruded flash can occur at the roots of the weld, near the pin. At larger tool tilt angles, insufficient plasticised material remains to fill the cavity left in the weld nugget and weld flash appears on the retreating side (Keivani et al. 2013).

Formation of tunnel defects As mentioned earlier, if the processing conditions, i.e. weld travel speed, tool rotation, etc., fail to generate the required heat for bonding, inadequate material mixing and stirring can occur, resulting in the formation of tunnel defects (Grujicic et al. 2010). Rapid dissipation of heat from the immediate deformation zone can also lead to too cold welds. A weld produced under too cold welding conditions becomes macroscopically hard, and fracture can occur through the defect.

As the tool progresses along the weld, the plasticised material around the tool pin is transferred layer by layer. The width of the plasticised material around the pin and the material volume carried per rotation determines the restriction of the material to flow from the retreating side to the advancing side, inside the cavity. The cavity is created behind the tool pin due to the unconsumed volume of the plunged pin. In order to maintain a large heat input during friction-stir welding, the transverse speed can be reduced, thereby generating more heat and more plastic metal, which improves the flowability of the weld metal (Kumar and Satish Kailas 2008; Xiaopeng et al. 2014). Experimental results (Zhao 2014) suggest that the area in which tunnel defects can occur, increases greatly as the traverse speed increases. Increasing shoulder diameter significantly increases the heat input volume, which directly improves the flowability of the weld metal into the cavities. Therefore, optimised heat input and good flow patterns of the plastic material are necessary to avoid very cold processing conditions and thus eliminate tunnel defects. Hence, a welding tool with a relatively large shoulder can help reduce the occurrence of tunnel defects.

Formation of kissing bond defects or zigzag defects At high welding speeds or low rotary speeds, insufficient stirring of the metal can lead to partial breaking of the natural Al_2O_3 oxide layer and low heat input, which restricts the flowability of the plastic material. As a consequence, an inclusion of broken oxide particles in the form of a dark wavy zigzag line or a kissing bond defect (as shown in Fig. 3(a) and 3(b). Arrows in Fig. 3(b) highlights the defects in the weld. Fig. 3(c) and 3(d) presents the enlarged view of the defects from Fig. 3(a) and (3(b)) can occur in low heat input welds (Zhao et al. 2005).

At very high rotary speed, sufficient heat input supports proper stirring of the material with wide and diffused distribution of oxide particles. The average

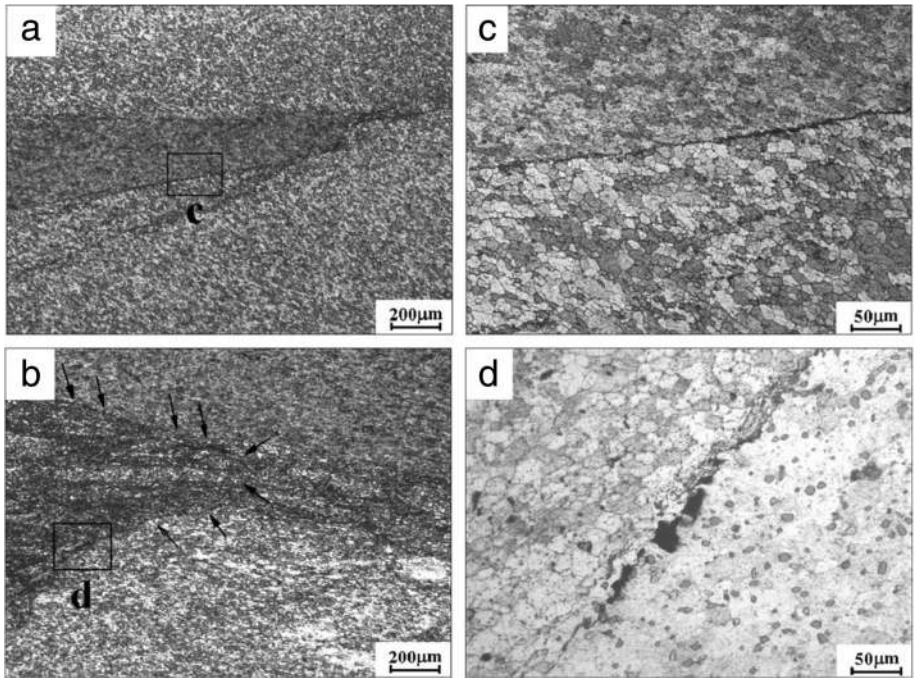

Fig. 3 Microstructure of kiss-bonding or a zigzag line defects in the weld nugget zone (Bo et al. 2011)

grain size of aluminium present in the weld nugget decreases with the increasing welding speed or decreasing rotary speed. Hence, the control of rotary speed allows significant reduction in zigzag line defects (Xiaopeng et al. 2014). It has been reported that the fatigue performance of friction-stir welded joints of 7075-T6 alloy was undermined by the presence of a zigzag line defect; a fracture initiated at the root along the zigzag line and caused failure from the weld nugget during tensile testing (Di et al. 2007). Effective selection of FSW parameters eliminates the formation of zigzag lines, contributing to improved mechanical performance.

Formation of crack-like root defects Process parameters play a key role in the formation of root defects. These defects develop because of insufficient heat input or due to incomplete breakup of surface oxide layers. When the pin plunge depth is inadequate, a groove defect can occur at the advancing side. If the pin is too short, long root grooves appear on the advancing side of the weld. Crack-like root flaws (as in Fig. 4(a) and (b)) occur due to the insufficient pin length for the thickness of the workpiece. At smaller tilt angles, insufficient downward forging of the plasticised metal leads to a root groove from a lack of penetration. Therefore, very small tool tilt angles and, correspondingly, very high tilt angles

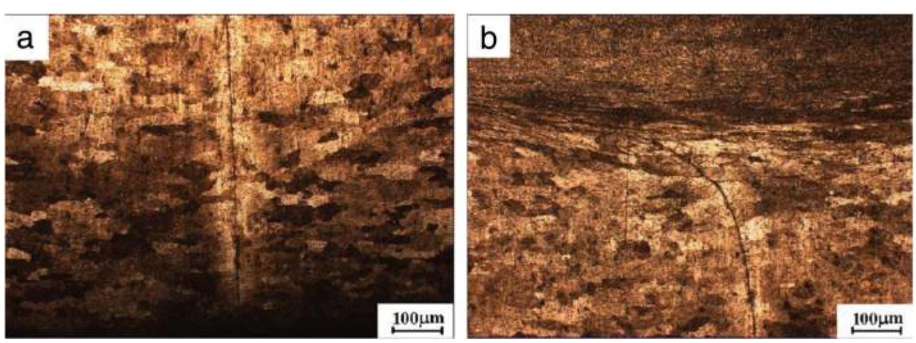

Fig. 4 (**a**) and (**b**) presents the microstructure of the crack-like root defect (Bo et al. 2011)

contribute significantly to the generation of root defects (Bo et al. 2011).

Formation of voids The presence of voids in the weld is a common defect in friction-stir welds. The fluid dynamics associated with plastic flow in the weld nugget plays a key role in the formation of such voids. Although high welding speeds promote more economical friction-stir welds and higher productivity, too high welding speeds lead to the formation of voids beneath the top surface of the weld or on the advancing side at the edge of the weld nugget. Further increase in speed leads to the formation of bigger wormhole defects (Crawford et al. 2006).

Characteristics of laser beam welding

Laser beam welding (LBW) is a promising and increasingly important joining technology for products made of aluminium alloys. Laser welding uses the radiant energy carried in a very small beam cross section of very high power density to weld the boundary surfaces of the two parts to be welded. Laser beam welding provides welds of high quality, precision and performance, and with low deformation or distortion. The tight focusability and high power density of lasers enable very good flexibility and very high welding speeds, narrow and deep welds, small heat-affected zones and good mechanical properties to be achieved. Advantageous characteristics such as reduced manpower demands, full automation and suitability for integration with robotic systems (Katayama 2005) make LBW appropriate for a wide range of applications and welding contexts.

The wavelengths of CO_2 and Nd:YAG lasers are 10.6 and 1.03–1.07 μm, respectively, and thus fall under the infrared regime. From Fig. 5, we can observe that during welding of aluminium, CO_2 lasers are reflected more than Nd:YAG lasers. CO_2 lasers generally have an efficiency of 20 %, with a very good beam quality, high precision and high welding speed (Chang et al. 2010). High surface reflectivity, high thermal conductivity and volatilisation of low boiling point constituents make LBW of aluminium quite difficult (Tu and Paleocrassas 2011). In addition, very accurate preparations of parts are required as no gap or in some cases only a minimal gap is permissible during alignment of the parts. During laser welding, the aluminium alloys are heated beyond their annealing point and the heat treatment temper is destroyed. It has been reported (Lawrence et al. 2010) that a faster cooling rate with fine sub-grain microstructure in the weld fusion zone can be obtained with laser welding and hybrid laser/arc welding processes. When comparing the weld-depth variations of CO_2 laser welding and Nd:YAG laser welding, Cao et al. (2003) found that a 4.5-kW CO_2 laser produced penetration depths of 3.5 mm in 5000 (non-heat-treatable) and 6000 (heat-treatable) series aluminium alloy. A 4-kW Nd:YAG produced weld depths of 4 mm at the same speed.

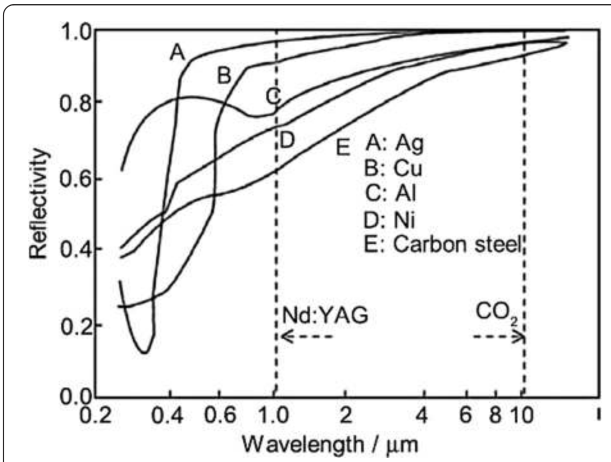

Fig. 5 Relation between metal reflectivity and wavelength (Duley 1998)

Cracks that occur during the welding of aluminium alloys result from the direct interaction of a number of complex factors, such as solidification shrinking and thermal tensions, wide solidification range, temperature and time cycle of the solidification, chemical composition of the alloy (as shown in Fig. 6) and the fastening system of the welding components (Chang et al. 2010). Studies (Hu and Richardson 2004; Cicala et al. 2005) have shown that cracking in the weld fusion zone increases with increasing weld transverse speeds. CO_2 laser, Nd:YAG laser and disk or fibre laser welding exhibit different behaviour and different plasma plume effects on weld penetration (Katayama et al. 2010). With CO_2 lasers, the plasma plume is only formed after initiation of the keyhole; this problem is not found when using Nd:YAG lasers. It has been reported that pulsed Nd:YAG laser beams on aluminium have very low levels of ionisation and only a limited loss of power through scattering from metal and oxide particles. Hence, plasma control is not required in Nd:YAG laser welding.

Weld porosity and prevention methods

A critical problem in laser beam welding of aluminium alloys is porosity, which causes stress concentration effects. The two types of porosity occur in laser welding of aluminium alloys: metallurgical porosity and keyhole porosity. Metallurgical porosity mainly occurs due to the presence of hydrogen in the weld pool. Keyhole pores are comparatively larger and irregular in shape. These porosities are mostly present in the weld centre. Keyhole porosity has mainly been observed in partial penetration welds and is rarely observed in full penetration welds (Whitaker et al. 1993; Katayama et al. 2010). Matsunawa et al. (1998) suggest that the primary cause for porosity

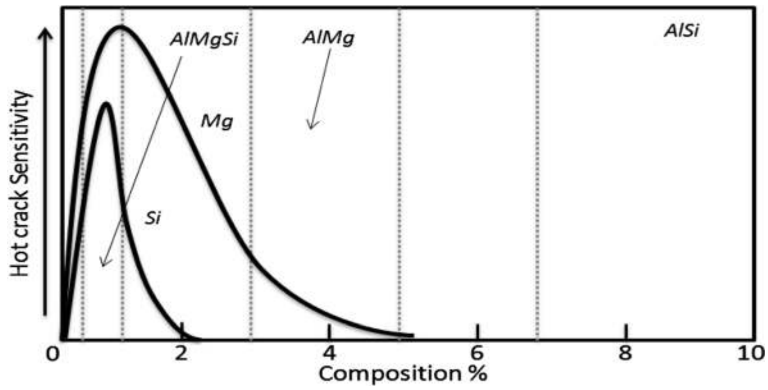

Fig. 6 Hot crack sensitivity of aluminium alloys (Dausinger et al. 2000)

is the unstable nature of the hole drilled in the liquid pool. Other observations (Katayama et al. 2010; Seto et al. 2000; Menga et al. 2014) support this hypothesis, and it has been reported that keyhole instability is the main cause of bubble initiation especially in deep penetration welding. Katayama et al. (2010) present a mechanism of porosity formation during pulsed laser welding. Seto et al. (2000) report the same information for continuous laser welding. For pulsed laser welding, it is reported that when the laser is terminated, the melt surrounding the upper part of the keyhole flows downward to fill the keyhole. Porosity is formed when the upper part of the melt rapidly solidifies, preventing the melt from flowing down to fill the keyhole. With continuous laser welding, bubbles are formed at the bottom tip of the keyhole. Some of these bubbles are able to escape the molten pool, but others are trapped at the solidifying front, resulting in the formation of porosity at the bottom of the weld seam. At low welding speeds, porosity is formed from bubbles generated at the tip of the keyhole; whereas, at high laser-power densities, porosity is formed in the middle part of the keyhole (Katayama et al. 2010). Matsunawa et al. (2000) also reported that fluctuations of the keyhole resulted in the formation of bubbles at the tip of the keyhole, which in turn formed porosities. Hydrogen porosity can be effectively reduced by increasing the welding speed so that insufficient time is available for the hydrogen to accumulate because of the rapid cooling and solidification. Using a high-power fibre laser, Katayama et al. (2009) investigated penetration and defect formation in several aluminium alloys. They found that 10-mm thick plates of AA5083 were penetrated completely with a power density of 64 MW/cm^2 and that nitrogen gas was more effective than argon at preventing porosity. Their research showed that keyhole-induced porosity can be avoided by using effective welding parameters and vacuum conditions. The results substantiated the work of Kawahito et al. (2007), who stated that processing parameters and surface conditions are responsible for porosity formation but can be effectively controlled by optimisation.

Other defects in laser beam welding

HAZ degradation is not severe in laser beam welding (LBW) of aluminium alloys as the process uses low power and low heat input. However, highly localised mechanical property variation can prove detrimental for structural materials due to localised deformation. In addition, some alloys are highly susceptible to weld metal or HAZ cracking, which is especially the case for 6xxx series alloys because of the formation of Mg–Si precipitates. Proper addition of filler wire can, however, mitigate this problem by reducing the freezing range of the weld metal and thereby minimising the tendency to solidification cracking. High-power density processes are not recommended for certain alloys, such as 6061 and some 5000, 6000 and 7000 series alloys, because the high power density can vaporise strengthening elements such as Mg and Zn. The presence of Mg is very important in 5000 series and 6000 series alloys; as is Zn in 7000 series alloys (Cross et al. 2003). Ramasamy and Albright (2000) found that vaporisation of magnesium and silicon occurred and metal hardness was reduced in welding of aluminium alloy 6111-T4 with a 2-kW Nd:YAG laser in the pulsed mode, a 3 kW continuous wave Nd:YAG laser, or a 3–5 kW CO_2 laser.

Characteristics of arc welding processes

Arc welding is a widely used joining method. Of the arc welding processes currently available, aluminium alloys are generally joined using gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). GMAW was initially developed as a high deposition, high-welding rate process facilitated by continuous wire feed and high welding currents (Regis 2008). The process is versatile because it can be applied to welding in all positions. The process can be easily automated and supports integration with robotics for large-scale production. Process control in welding of aluminium is very different from control when welding steel. Aluminium alloys have been shown to be 28 times more sensitive to variations in wire feed speed than mild steel for the same wire electrode extension (Quinn 2002). With GTAW, a number of studies have shown that the recommended operating mode for aluminium and its alloys is AC GTAW, but the effect of self-rectification in the arc requires DC component suppression and some assistance is needed to re-ignite the arc. The use of a high frequency transistor, reversing switch circuits and a conventional DC power source enables a square wave AC output. This technology was reported (Kyselica 1987) as useful for the cathodic cleaning of aluminium alloys. A flat or half-risen position is ideal for GTAW and GMAW welding processes; and overhead and cornice welding do not pose any particular problems. However, a descending weld position should be avoided so as not to weld onto the molten metal bath, which is a common cause of a lack of penetration. Failure to ensure a good electrical contact of the earth may lead to bad starts or impairment of arc stability due to the presence of alumina on the surface of the parts (Courbiere 2008). Table 2 presents some recent developments in shielding gas mixtures used in arc welding of aluminium alloys and key gas characteristics.

Arc welding cracks and prevention methods

The heat generated for joining the metals can cause significant changes in the material microstructure, thereby compromising the mechanical properties of the base metal and causing weld distortion. Hot cracking, a high-temperature cracking mechanism, is the main cause for almost all cracks in aluminium welds. Hot cracking is also known as solidification cracking, hot fissuring and liquation cracking. Solidification cracking, weld porosity and heat-affected liquation cracking are some of the specific flaws found in fusion welding of aluminium alloys (Leonard and Lockyer 2003). In fusion welding of aluminium alloys, the middle portion of aluminium welds remain in quasi-steady state condition but at the terminating end (weld crater), intense variations occur from time to time in energy, mass and momentum transfer. This results in unsteady temperature and fluid flow fields (Saunders 1997; Dickerson 1998). As the supply of heat input is cut-off, cracks develop due to the lack of metal ductility and due to tensile stress (Guo et al. 2009). High heat conductivity of aluminium alloys allow solidification of weld pools at a faster rate, resulting in crack formation in weld craters. High thermal expansion combined with a brittle structure just below the solidification temperature results in aluminium alloys being sensitive to solidification cracking (Runnerstam and Persson 1995). Solidification cracking is intergranular i.e. along the grain boundaries of the weld metal. Lack of low-melting-point eutectic present at grain boundaries prevents solidification cracks from occurring in pure aluminium. In solute-rich aluminium alloys, crack sensitivity is very low since eutectic is abundant that it backfills and heals incipient cracks. However, at certain compositional limits, the amount of eutectic liquid is large enough to form continuous films at grain boundaries. This combined with high shrinkage leads to solidification cracking. Most aluminium-based filler materials with 4 to 5 wt.% Mg or Si are successfully able to prevent the solidification cracking during welding. Kerr and Katoh (1987) observed a linear increase in crack length for a corresponding increase of augmented strain or heat input. According to the studies of Pereira et al. (1994), the shape of the weld pool has considerable influence on the formation of solidification cracking, and the development of fine grain structures will tend to reduce the solidification cracking tendency. Based on simulation of liquation cracking in a 7017 aluminium alloy (Lu et al. 1996), it was noted that the applied stress level and the temperature at which the stress is applied determine the development of liquation cracking. An increase in the cooling rate may reduce cracking. In welded structures of aluminium alloys, hot cracking occurs as a result of inappropriate filler material, excessive base alloy dilution of weld metal and improper joint design (Guo et al. 2009). The generated heat, which supports the melting and joining of the metal, can lead to micro-segregation of alloying elements such as copper, magnesium, silicon and manganese (Chong et al. 2003). Susceptibility to

Table 2 Special shielding gas mixtures used in arc welding of aluminium and key gas characteristics (based on (Regis 2008))

Shielding gas mixtures	Resultant positive weld features	Gas characteristics
Argon and helium (80 %)	Improvements in bead profile and fusion	Argon—low cost and better protection as its density is higher than air.
Argon and chlorine	Significant reduction in porosity & improved process tolerance	Chlorine—extreme toxicity limits its suitability for many applications.
Argon and Freon	Improved arc stability and weld bead geometry	Argon/Freon mixtures—non-toxic so Freon can substitute chlorine yet obtain similar effects to argon/chlorine mixtures.
Helium	Greater penetration	Helium—welding Al leads to high levels of ozone. Small amounts of nitric oxide can control ozone formation.

Table 3 Common problems encountered in fusion welding of aluminium alloys, metallurgical aspects and prevention strategies (based on (Kou 2003))

Difficulties encountered	Type of alloy	Metallurgical aspects promoting the defect	Microstructure	Solutions
Solidification cracking	Higher strength alloys (e.g. 2014, 6061, 7075)	◦ Solidification temperature range ◦ Grain structure ◦ Primary solidification phase ◦ Quantity of eutectic liquid at the end stage of solidification	◦ Coarse columnar dendritic structure—higher susceptibility ◦ Fine equiaxed dendritic structure with abundant eutectic liquid—lower susceptibility	♦ Appropriate dilution ratio ♦ Appropriate control of minor alloying elements ♦ Grain refinement—using agents ♦ Magnetic arc oscillations ♦ Reduce strains—preheating ♦ Improve weld bead shape
Loss of strength in HAZ	Work hardened materials and heat-treatable alloys	◦ Increase in heat input/unit length—increases the size of HAZ and retention time above effective recrystallisation temperature	◦ Deformed grains (due to work hardening) that tend to recrystallise (forming strain free, soft grains)—softens the HAZ	♦ Reduce heat input—weld process like EBW or GTAW
Liquation cracking	Higher-strength alloys	◦ Wide PMZ—high thermal conductivity and wide freezing temp range ◦ Large solidification shrinkage ◦ Large thermal contraction	◦ Grain boundary (GB) liquid—weakens the PMZ	♦ Appropriate filler material ♦ Reducing heat input—multipass welding, etc. ♦ Decrease in degree of restraint ♦ Oscillating arc method

porosity and fusion defects has limited the use of arc welding of aluminium to applications where weld quality is not of paramount importance (Table 3).

Conclusions

Aluminium alloys are most attractive solutions for many industrial sectors, including the aerospace, marine and other transportation industries, where demand for lightweight structures exists. FSW avoids problems related to melting, formation of cast microstructure and solidification of weld shrink zone that are associated with conventional fusion welding. Weld defects found in friction-stir welds are quite different from conventional welding flaws. FSW defects include an onionskin microstructure, tunnel voids, porosity, defective tightness, excessive flash, 'kissing-bond' defects and crack-like root flaws. In order to avoid such defects, the thermo-physical and mechanical properties of the welded material should be identified and the processing temperature and processing rates manipulated accordingly. Tool rotary speed and tool traverse speed govern the peak temperature generated during FSW and the time required to weld the material. The way in which temperature affects material properties varies significantly for different aluminium alloys. Hence, friction-stir welding parameters suitable for processing one series of aluminium alloys differ considerably from those suitable for other series alloys.

Innovations in power source technology for laser beam welding are expanding the range of suitable applications. The availability of higher power lasers and higher power densities has enabled the formation of stable keyholes and improved beam qualities and have mitigated problems related to high surface reflectivity and high thermal conductivity. As a result of these developments, both CO_2 and Nd:YAG lasers can now be used for a wide variety of aluminium alloys. Shorter wavelengths mean a slight advantage in welding speeds for Nd:YAG lasers compared to similar power CO_2 lasers. Two types of porosity occur in laser welding of aluminium alloys: metallurgical porosity and keyhole porosity. Keyhole instability is the main cause of bubble initiation especially in deep penetration welding; however, this can be reduced by using effective welding parameters and vacuum conditions. Metallurgical porosity mainly occurs due to the presence of hydrogen in the weld pool; therefore, to reduce hydrogen porosity, increased weld speed should be used, which results in insufficient time for hydrogen to accumulate due to rapid cooling and solidification.

Arc welding is a widely used joining method for aluminium alloys. Intense variations of energy, mass and momentum transfer occur from time to time at the terminating end of the weld, resulting in unsteady temperature and fluid flow fields. The lack of metal ductility and tensile stress promote crack formation. Utilization of an appropriate dilution ratio and control of minor alloying elements, grain refinement and magnetic arc oscillations can minimise its occurrence. At certain compositional limits, the amount of eutectic liquid is large enough to form continuous films at grain boundaries. This combined with high shrinkage leads to solidification cracking. In solute-rich aluminium alloys, crack sensitivity is very low since eutectic is abundant that it backfills and heals incipient cracks.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
All authors have prepared, analysed and approved the final manuscript.

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