REVIEW PAPER ON FRICTION STIR WELDING OF VARIOUS MATERIALS AND ALUMINIUM MATRIX COMPOSITES.

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Abstract:

Objective: The comprehensive body of knowledge that has built up with respect to the friction stir welding (FSW) of aluminum alloys since the technique was invented in 1991 is reviewed on this paper. **Methods/Analysis**: The Friction Stir Welding of aluminum alloys with various other alloys and aluminium matrix composites are reviewed on this paper. The basic principles of FSW are described, followed by process parameters study which affects the weld strength. **Findings:** The microstructure and the likelihood of defects also reviewed. Tensile strength properties attained with different process parameters are discussed. **Conclusion:** It is demonstrated that FSW of aluminum and other material is becoming an emerging technology with numerous commercial applications.

Keywords: Aluminum Alloys, Tool design, Tool Wear, Friction-Stir Welding, Microstructure, Tensile Strength, and AMC.

I. INTRODUCTION

Friction Stir Welding (FSW) was invented at The Welding Institute (TWI) of the United Kingdom (Cambridge) in 1991 as a solid state joining technique and was initially applied to Aluminum Alloys (Dawes C and Thomas W, TWI Bull, 1995; Thomas W M, *et al.*, 1991). Friction Stir Welding is a solid state joining process combining deformation heating and mechanical work to obtain high quality, defect free joints. Friction Stir Welding is especially well suited to joining Aluminum Alloys in a large range of plate thickness and has particular advantages over fusion welding when joining of highly alloyed Aluminum is considered.[1]. The heat input into the material and the resulting welding temperature can be controlled by adapting process parameters like the down-force, rotational speed or welding speed as shown in Fig. 1.1

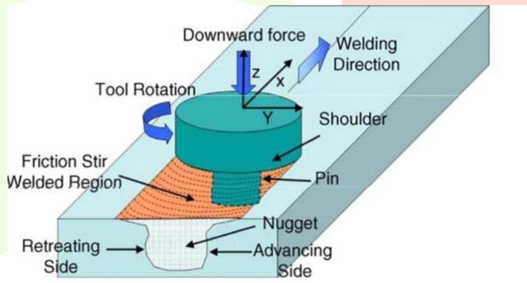

Fig. 1.1 Principle drawing of the FSW process for joints with indication of the main parameters

A method of solid state joining on a work piece offers a tool pin of material harder than the base metal’s continuous surface which causes relative cyclic movement between the pin and the base metal. The frictional heat is generated as the pin stirs the work piece so as to create a plasticized region in the metal around the probe, stopping the relative cyclic movement, and allowing the plasticized material to solidify around the probe.[2]

The peak welding temperature can be limited to 80% of the melting temperature of the base metal (BM). Therefore, this process can be considered as a hot working process. As FSW has been widely used to join aluminium alloys, it may be developed as a viable route to join AMCs especially for high strength non-weldable series (AA2xxx, AA6xxx, and AA7xxx), which are susceptible to solidification cracking in the weld zone and liquation cracking in the heat affected zone (HAZ) [14]. Dissimilar joints of AMCs or with different metals can be manufactured by using FSW without concerns for composition compatibility, which is an important consideration in fusion welding to avoid solidification cracking [10].

FSW is an ideal process for producing low cost and high performance joints. The practical approach of FSW is to use a non-consumable rotating tool consisting of two parts including a shoulder and a pin. During FSW the pin is inserted into the faying surface of the plates and then moved horizontally in the direction of the joint line. The surface of the tool has dual actions for heat generation and mechanical sweeping of softened metal. The heat input through the frictional action between the tool and work piece leads to softening of the area around the pin. Meanwhile, the softened materials are swept in the form of severe plastic deformation from the advancing side (AS) to the retreating side (RS) to form a solid state joint. The advancing and retreating sides of the plates to be joined are defined by the direction of tool rotation (clockwise or anti-clockwise) and the traverse movement of the tool. Plate side is defined as advancing if the tool movement is in the same direction of the tool rotation, whilst it is retreating if the tool moves in the opposite direction (see Fig. 1).

Different types of joint like butt, lap, and T-joints can be welded successfully by FSW [8, 10, and 15].

Moreover, FSW is considered as a green and environmentally friendly welding technology because of low energy consumption, no gas emission, and no need for consumable material such as electrodes, filler metals, and shielding gases (normally present in fusion welding processes). A survey carried out by the American Welding Society (AWS) in 2002 showed that $34.4 billion per year is spent on arc welding including the use of consumables, repair, and energy consumption in the USA. The adoption of FSW has increased rapidly and 10% of joining processes have reportedly been replaced by FSW [16].

1.1 Principle of Operation

A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and subsequently traversed along the joint line. the FSW tool rotates in the counterclockwise direction and travels into the plunge (or left to right).The advancing side is on the right, where the tool rotation direction is the same as the tool travel direction (opposite the direction of metal flow), and the retreating side is on the left, where the tool rotation is opposite to the tool travel direction (parallel to the direction of metal flow) The tool serves three primary functions, that is, heating of the work piece, movement of material to produce the joint, and containment of the hot metal beneath the tool shoulder [1].

II. SUMMARY

2.1 Overview of MMC

In recent years, MMCs have attracted considerable attention for critical applications in industrial sectors such as spacecraft structures, deck panels, and automotive and railway brake discs. The global demand for MMCs is expected to increase from about 5496 tons to nearly 8000 tons in the period from 2012 to 2019, and it is continuously rising [17].

Light metals like aluminium, magnesium, and titanium alloys are considered as ideal base matrices to produce MMCs reinforced by car- bide, nitride, boride, and oxide in the form of particles, whiskers, and fibres [18] [19]. MMCs can possess unique properties including good thermal conductivity, low coefficient of thermal expansion, low specific density, high specific stiffness, good dimensional stability, and excellent strength to weight ratio depending on the type of reinforcements used [20–22].

As a result of these desirable properties, MMCs have been used to withstand excessive Environmental condition of substantial changes in temperature. For example, the International Space Station is exposed to varying temperatures from +125 °C to −125 °C as it orbits around the earth [23].

As a versatile material, AMCs may be selected as an alternative to high strength aluminium alloys in aeroengines and aerospace structures like fins, wings, and fuselage. In 2001 NASA used composite aluminium Al–Li 2195 rather than aluminium alloy Al 2219 for the external fuel tank of space shuttles leading to a reduction of weight by 3400 kg. This saving in weight increases the cargo capacity of space shuttles and enables it to transport more than one component in a single flight to the International Space Station [24]. Also, the use B/Al in truss and frame of aero planes saved 45% weight from an all aluminium design. Another application of AMCs is a 3.6 m antenna for Hubble Space Tele- scope manufactured from Gr/Al (P100/6061 Al). It offers high stiffness, superb electrical conductivity, and low coefficient of thermal expansion [23]. In addition, AMCs have found a wide range of applications in military sector such as armour, due to the combined static strength and high ballistic performance [10]

2.2 Weldability Of Aluminium Alloys And Amc's:

The strength of pure aluminium is inadequate for structural applications. Therefore, to eliminate this limitation it is alloyed with other metals like copper, manganese, magnesium, zinc, and silicon. Different mechanical properties can be achieved by controlling the amount of alloying elements and heat treatments. Aluminium and its alloys are often considered as formable and ductile due to their face-centered cubic crystal structure and are available in wrought and cast forms. The former can be produced, typically, by semi-continuous direct chill casting followed by rolling (hot or cold), extrusion, and forging, whilst the latter can be made from sand casting, lost wax casting, permanent steel mould casting, and die-casting. Wrought aluminium is classified into two types depending on the main alloying elements. Non heat treatable weldable aluminium alloys including AA1xxx, AA3xxx, and AA5xxx series are strengthened by cold working, whereas AA2xxx, AA6xxx and AA7xxx series are heat treatable, non-weldable alloys that can be strengthened by precipitation hardening [25,26].

In general, welding of aluminum and its alloys needs considerable attention. Problems may occur including the loss of strength and defect formation when fusion welding processes are used. Trapped porosity may also appear in the cross section, due to the dissolution of shielding gases (oxygen, nitrogen and hydrogen) or moisture in the electrode and flux in molten metal. Furthermore, lack of fusion occurs in part due to the high melting temperature up to 2060 °C of stable aluminium oxide on the surface. Centre-line or solidification cracking is also a serious problem in fusion welding of aluminium alloys. This failure occurs as a result of stresses induced by metal contraction in cooling and the often large difference between the liquidus temperature and eutectic or final solidification temperature. The variations in heating and cooling cycle in the HAZ normally result in lowered the strength of joint in heat treatable alloys [25, 27].

In addition to the aforementioned problems accompanied by welding of aluminium and its alloys, other difficulties come into view when AMCs are welded by fusion welding processes including:

(a) incomplete mixing between filler and BM, (b) the formation of excess eutectic, (c) the presence of large size porosity of more than 100 μm in the fusion zone, and (d) reaction between molten metal's and reinforcements resulting in undesirable phases such as Al_4C_3 [10]. A study was reported by Storjohann et al. [28] to compare three types of fusion welding (GTA, LBW, and EBW) with heat inputs of 165, 108, and 5.9 J/mm, respectively, with solid state welding (FSW) to fabricate similar AMC joints for AA6061/Al_2O_3/20p (20% volume of Al_2O_3 particles) and AA2124/SiC/20w (20% Volume of SiC whiskers). They found that in all fusion welding processes Al_2O_3 particles completely dissolved in molten aluminium leading to the reduction in the strength of joints. In the case of SiC whiskers, the formation of Al_4C_3 and precipitation of a Si-rich phase occurred as a result of fast reaction between the reinforcement and molten metal. In contrast, a good joint was achieved by FSW and there was no significant change in reinforcement volume fraction for both AMC joints. Therefore, the findings of this study gave a clear indication of the suitability of FSW to weld different types of AMCs.

2.3 Microstructure Of Fsw Joints In Amc's:

The heat generated through the rotation of FSW tool ideally reaches approximately 0.8 of the melting temperature of the joined AMCs. This leads to reinforcement redistribution and refinement, re-crystallization, and grain growth in the NZ. The microstructure of the AMC shows that the reinforcement materials are clustered and distributed heterogeneously in the matrix as a result of production processes (casting or powder metallurgy). The inhomogeneous distributions of reinforcement materials in the microstructure of the BM can affect the isotropy of mechanical properties. It is accepted that the stirring action during FSW causes a break up of clustered reinforcement and homogenous distribution in the weld zone due to the mixing of material and severe plastic deformation [29, 30]. In contrast, Periyasamy et reported that the NZ of AA6061/SiC/10p joints fabricated at a heat input below 1039 J/mm consisted of coarsely clustered SiC particles.

Meanwhile, the size of Al_2O_3 and SiC particles decreases obviously as compared to the original material and the particle edges can be rounded or blunted in the NZ. As a result, the aspect ratio of the particles decreases noticeably. This phenomenon may be explained by the abrasion and stirring effect between particles and tool pin circumference, shoulder surface during welding process [28, 29]. Ceschini et al. [30] pointed out that finer particles were formed closer to the shoulder of the tool than the tip of the pin. However, if the size of original reinforcement is small it is not exposed to the refinement process. For example, Storjohann et al. [28] reported that no change was noticed in the size of SiCw reinforcement with a diameter of 1–2 μm and length of 5–7 μm. Instead the whiskers were reoriented. Whilst 20 μm Al_2O_3 particles were subjected to refinement during FSW

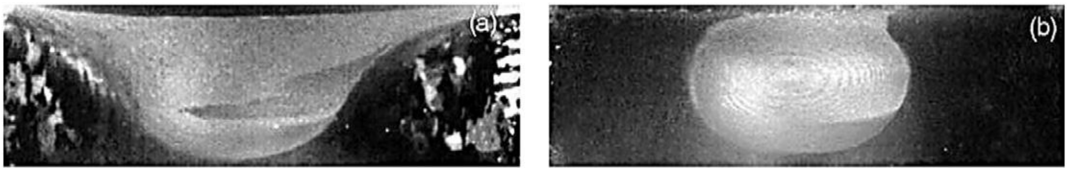

Fig 2.1 Nugget shape — (a) basin, (b) elliptical [10].

The NZ may be characterized by equiaxed grains much smaller than those in the BM. This indicated that new grains nucleated in the NZ during FSW as a result of dynamic re-crystallization. Feng et al. [32] reported that an obvious reduction in grain size of the NZ reached to about 5 μm in FSW of 8 mm thickness AA2009/SiC/15p plate. Grain growth occurs after PWHT to a T4 condition which leads to a grain size of 8 μm. Similar observations were made by Wang et al. [33]. They reported that the reduction of grain size from 10 μm to 6 μm taking place in the NZ of FSW 6 mm thick AA2009/SiC/15p plate. They believe that the high energy point on SiCp broken surface is the main location of the nucleation and growth of nano-size grains to decrease the aluminium matrix/rein- forcement interface free energy. However, the growth of new grains in T4 PWHT was restricted by the presence of SiC particles. In addition, Periyasamy et al. [26] indicated that a fine grain structure, fine eutectic, and the elimination of dendritic structure in the NZ were achieved at high heat input through the increase of tool rotation speed. On the other hand, faster cooling rate due to low heat input leads to the formation of coarse grains because of incomplete recrystallization in the NZ of AA6061/SiC/10p FSW joint.

In summary, the evaluation of microstructure of AMCs welded by FSW showed an improvement in reinforcement distribution and refined particles due to the stirring action in FSW. Also the formation of new grains with equiaxed dimensions occurs as a result of dynamic re-crystallization process.

2.4 Tensile Strength Of AMC JOINTS:

The tensile strength of AMC joints fabricated by FSW was compared to that of the BM. The efficiency of joint produced by FSW is higher than that fabricated by conventional welding methods. Many factors influence the tensile strength of AMC joint including tool design, welding parameters, PWHT, and the formation of intermetallic compound.

2.5 Effect Of Tool Design:

The shape of tool shoulder and pin plays a significant role in the tensile strength of FSW joints. Vijay and Murugan [30] investigated the effect of different pin shapes (square, hexagonal, and octagon) in tapered and un-tapered profile on the tensile properties of FSW Al/TiB_2/10. The joint efficiency fabricated by un-tapered square pin exhibits a maxi- mum tensile strength which reaches 99.47% of that of the BM in comparison to other profiles. This is attributed to the high ratios of static volume to dynamic volume of plasticized material, measured as 1.56 for square pin, 1.21 and 1.11 for hexagon and octagon profiles, respectively. This result was confirmed in a later study by Hassan et al. [31]. They used un-tapered (square, hexagonal, and octagon) pin profiles to join hybrid AMC (Al–4%Mg, 1% SiCp and 1% graphite particles). Wang et al. [32] found that the use of conical threaded pin at high traverse speed at 800 mm/min rather than a flat cylinder in joining AA2009/ SiC/17p led to an increase of the joint efficiency to 97% due to the improvement of the flowability of softened material. In a study reported by Yigezu et al. [19] in FSW 5 mm thick Al–12%Si/TiC/10 plates, three shoulder diameters (18, 20, and 22 mm) and threaded cylinder pin were used as FSW tool. They reported that the tensile strength of the weld joints varied from 124 MPa to 172 MPa depending on the tool type and process parameters. A 20 mm shoulder diameter is preferable for obtaining the maximum ultimate tensile strength (UTS). More recently, Kumar et al. [17] investigated the tensile strength of 5 mm rolled Al–4.5%Cu/TiC/10. In order to reveal the effect of three shoulder surface geometries on mechanical properties, full flat surface, 1 mm flat surface, and 2 mm flat surface shoulder with a 7° concave angle were used in FSW. Among the three surface shoulders, the second shoulder configuration resulted in the highest tensile strength. They concluded that the higher heat input as a result of higher contact area between the second shoulder surface and the work piece led to sufficient mixing in the stir-ring zone, as compared with the other two tool profiles.

2.6 Effect of welding parameters:

In FSW process, the welding parameters including tool rotation speed (ω, rpm), traverse speed (V, mm/min) and axial force (F, kN) affect the amount of friction heat generation and mixing process. There- fore, optimum welding parameters must be selected in order to produce the best joint strength. The efficiency of AMC weld joints is generally in the range from 60% to 97% of those of the BM. It is accepted that the UTS of FSW joints of AMCs increases by increasing the rotation speed until a specific limit [27]. The maximum strength was achieved by using a rotation speed ranging from 1000 to 1200 rpm depending on the types of AMC. This leads to the conclusion that there is insufficient heat input in welding joint if the rotation speed is below 1000 rpm, whilst excessive heat input is produced for the weld joint if the rotation speed is more than 1200 rpm. Either case of insufficient or excessive heat input produces inadequate mixing of soft metal. On the contrary, both Yigezu et al. [16] and Kumar et al. [18] reported that the tensile strength decreases linearly when the tool rotational speed increases in FSW rolled Al–12%Si/TiC/10 and rolled Al–4.5%Cu/TiC/10, respectively.

In addition to the tool rotation speed, another important parameter is the traverse speed of the tool along the weld line. A suitable traverse tool stirs the material efficiently from the AS to the RS. Three possible behaviours for the effects of the traverse speed on the tensile strength of AMC joints are discussed below.

Firstly, an unsteady behaviour of the traverse speed on the tensile strength for different types of AMC has been noted. For example, researches [20] on AA6061 composite aluminium as base matrices showed that the relation between the UTS and the traverse speed is not directly proportional. As traverse speed increases the tensile strength increases and reaches a maximum value before it decreases. They assert that the amount of heat input due to friction action between the tool and BM is mainly affected by tool rotation speed. On the other hand, the cooling rate is determined by the traverse speed. Therefore, at lower traverse speed an increase in frictional heat generation and slow cooling rate is accompanied by coarse grains (grain growth). Tunnel defects may occur due to excessive stirring resulting from slow traverse speed. In contrast, at higher traverse speeds insufficient heat input is generated into the joint, which leads to inadequate stirring action of softened material from the AS to the RS also causing tunnel defects. Therefore, reduced tensile strength can be resulted from both low and high traverse speeds.

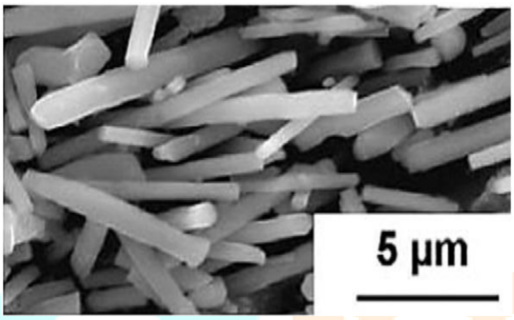

Fig. 2.2 Reorientation of reinforcement in FSW AA2124/SiC/20w [28]

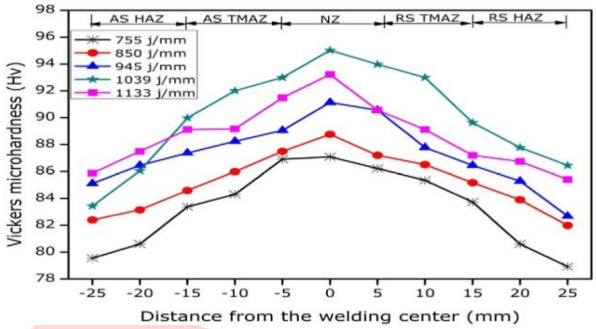

Fig. 2.3 Microhardness profile across the weld region of AA6061/SiC/10p at different heat inputs

Secondly, a linear behavior of traverse speed on the tensile strength for AA2009/SiC/17p was reported by Wang et al. [29]. The maximum joint efficiency was achieved to reach 97% of the BM at a higher traverse speed of 800 mm/min. They pointed out that at lower traverse speed failure of the joint happened in the HAZ which was characterized by lowered hardness due to dissolution and precipitates growth. This led to the reduction in tensile strength. On the other hand, as the traverse speed was increased the clusters were partially dissolved in the matrix in the HAZ owing to high cooling rate. Thus an increase in joint efficiency was achieved as a result of the increase of HAZ hardness and shift in fracture location from HAZ to NZ.

Thirdly, as reported by other researchers [24], the increase of the traverse speed slightly decreases the tensile strength of the joint (inversely proportional) for AMCs AA2124/SiC/25p, Al–4.5%Cu/TiC/10, and Al–12%Si/TiC/10, respectively. The best welding speeds are 40 mm/min for AA2124 and 20 mm/min for the other two AMCs. However, they mentioned that the influence of traverse speed on UTS is less obvious than the tool rotation speed and tool design.

Applied axial force is another important parameter in FSW. The heat generated by friction between the BM and tool depends on the friction coefficient which is specified by the applied force. Higher heat input is generated by a larger amount of applied force which causes sufficient flow. Defect free joint can be achieved if a sufficient axial force which is higher than the flow stress of the BM is applied. Thus higher tensile strength can be obtained when an adequate force is selected. In spite of the importance of the applied force on the amount of heat generation and the retention of the plasticized metal, few researchers have taken into account the effect of this parameter as one of the key welding variables on tensile strength.

Dinaharan and Murugan [21] reported that the maximum tensile strength of joint was obtained at 6 KN axial force when joining in-situ composite AA6061/ZrB_2. Further increment in hydrostatic pressure leads to a reduction in the tensile strength. The appearance of micro voids in the joint at lower force and excessive flash at larger force causes a reduction in the cross section of the joint and hence leads to a reduction in tensile strength of joint. Similarly, Murugan and Kumar [23] indicated that for the FSW joints of AA6061/AlNp tunnel defects appeared in the cross section of joint due to the lack of heat generation when using lower axial forces. Therefore, a reduction in tensile strength happened when the applied force was lower than 5 kN On the other hand, if the applied force was more than 5 kN it led to thinning of the NZ and formation of worm hole, and therefore reduced the joint efficiency. A similar findings was reported by Kalaiselvan and Murugan [21] in FSW joints of AA6061/B4C with a different optimum axial force at 10 KN in their study.

In conclusion, welding parameters including tool rotation speed, traverse speed, and axial force affect significantly the UTS of AMC joints. Rotation speed has the greatest effect on joint efficiency, whilst traverse speed and axial force affect the tensile strength of AMC joints to a varying degree [33]. There is no general trend that can be related to welding parameters for all types of AMCs. Therefore, each material needs its own study to achieve its maximum tensile strength for the FSW joint.

2.7 Tool Wear in FSW of AMCs:

Wear of FSW tool is a critical issue particularly for AMC materials, which occurs as a result of friction, rotation, and movement of FSW tool along the base material. According to Rai et al. [7], plastic deformation, abrasion, diffusion, and reaction between the environment and the tool material are the major wear mechanisms that happen in FSW tools. Mishra and Ma [10] reported that FSW of soft metals such as aluminium and magnesium did not exhibit significant wear of the tool. However, tool life issue becomes more significant when hard metals of high melting temperature or MMCs are welded by FSW. This phenomenon is characterized by the deformation and reduction in the pin diameter.

The appearance of hard reinforcement particles in AMCs makes abrasion a dominating factor for tool wear in FSW. Prado et al. [12,13] studied the effect of welding parameters including rotation speed between 500 and 2000 rpm and traverse speed between 1 and 9 mm/s on threaded 1/4–20/01 AISI oil-hardened steel tool wear. Similar joints for AA6061/Al_2O_3/20p and monolithic aluminium AA6061-T6, were used in their studies. They pointed out that no wear was observed in the tool when welding a monolithic aluminium alloy, whilst severe wear started in joining AA6061/Al_2O_3/20p when reaching its maximum value at 1000 rpm then gradually becoming constant after a period of time (self-optimized tool shape). And thus the turbulent flow (vortex flow) of worn tool is less than the unworn tool due to the eroded threads. The rate of tool wear at various welds lengths and the relationship between weld speed and tool wear rate. However, from microstructure evaluation it was found that sound joint could be produced continuously by using tools with self-optimized shapes.

III. CONCLUSION:

FSW is the best process to welding of different alloys of aluminum for long lengths with an excellent quality. Considerable effort is being made to weld higher temperature materials such as alloys of magnesium, titanium and steels by using FSW. Extensive efforts are also required for joining of dissimilar aluminum alloy with various variables under consideration.

The mechanical properties of AMCs joined by FSW are largely dependent on the combined effect of both the composition of AMCs and the FSW processing conditions. Therefore, the mechanical performance of FSW joints should be evaluated accordingly. Early researches showed that FSW is a potential welding process to achieve defect free joints of AMCs. There is a clear need for more efforts to understand the effect of FSW on these materials in adequate depth to meet design and production requirements. For instance, there is a need for systematic studies which take into account the effects of reinforcement percentage and types of reinforcement on joint efficiency. More work is needed to understand the performance of FSW joint of such as AA2124 and AA6092 as base matrices for AMCs with different reinforcement percentages. Also there is a need for joining AMCs to other materials rather than monolithic aluminium alloys such as magnesium alloys, a new candidate material for aerospace application.

Furthermore, welding parameters such as tool rotation speed, traverse speed, and axial force have a significant effect on the amount of heat generation and strength of FSW joints. Macrostructural evaluation showed the formation of tunnel defects due to inappropriate flow of plasticized metal. Micro structural evaluation of FSW joints clearly shows the formation of new fine grains and refinement of reinforcement particles in the weld zone with different amount of heat input by controlling the welding parameters. However, there is no general trend between welding parameters and mechanical properties for different types of AMCs. Further work needs to be carried out to define the welding window of each composite metal for optimized mechanical properties. Also there is very limited data on fatigue strength and fracture toughness of friction stir welded AMCs. More effort is needed to study these properties in more depth to establish the full potential of FSW joints of AMCs.

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