



A Review on Friction Stir Welding of Aluminium Metal Matrix Composites

¹Saksham Dhanjal, ²Gaurav Dhuria

¹Under-Graduate Student, ²Faculty,

Department of Mechanical Engineering, DAVIET, Jalandhar, India

Abstract: Friction Stir Welding is an emerging solid state joining process. Aluminium based composites that are extensively used in Aerospace and Defence sector are suitable to be joined by FSW that are otherwise very tough to weld by fusion welding techniques. In this review article, the various process parameters, microstructure evaluation, fracture and fatigue behavior of the welds obtained by Friction Stir Welding of Aluminium metal matrix composites (AMMC) has been discussed.

Keywords: Friction Stir Welding, Aluminium metal matrix composite, microstructure evaluation, mechanical properties, fracture and fatigue behaviour.

I. Introduction

Composites are materials that are composed of discrete constituents i.e. reinforcement distributed in a continuous phase called matrix. Aluminium metal matrix composite, comprising of aluminium or its alloy as matrix material and reinforcements like SiC, Al₂O₃ are some of the most common members of composite family. High specific strength and stiffness compared to their parent matrix material are some of the advantages of Aluminium metal matrix composites[1]. Due to their better properties and light weight, these are extensively used in aerospace and defence industry [2]. But the welding of these composites is still a concern. When subjected to fusion welding techniques, difficulties like high thermal expansion and conductance, high solubility of the gases in the molten state, solidification shrinkages and oxide inclusions are encountered[1]. Apart from this, in composites the reinforcement particles add up further difficulties such as thermal stresses due to different thermal coefficients of the metal matrix and reinforcement particles[1]. When the material is melted, the aluminium reacts with reinforcement particles which produces an undesirable phase which produces a strength depleted zone in weld zone[2].

The discussion so far leads to a conclusion that there must be a solid state joining process to weld these composites. Friction Stir Welding is an emerging and promising solution for this problem. FSW was invented and patented by TWI of Great Britain in 1991[2]. In FSW, a non consumable rotating tool having a pin and a large diameter shoulder is plunged in the abutting surfaces of the plates to be joined and is transverse along the weld line. The frictional heating produced by the tool softens the material in the weld zone and the subsequent stirring of material by the rotating pin produces a weld[1]. The material moves from the front of the tool pin to the back of the tool pin during the welding operation. The side of the joint where the tool rotation is same as the transversing direction is the advancing side of the joint and the side where the motion due to rotation opposes the translational movement is called the retreating side of the joint[3]. A schematic diagram of Friction Stir Welding process is shown in the fig.1

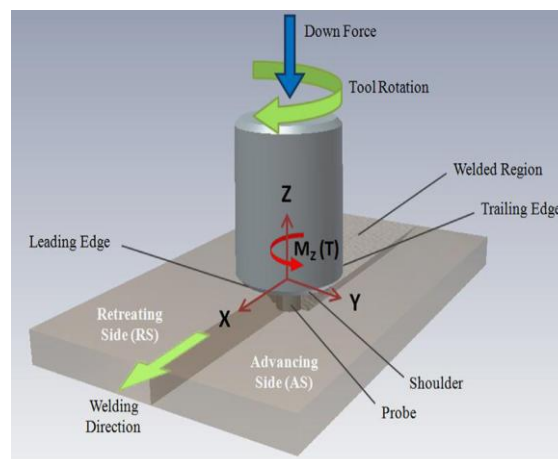


Fig. 1 Friction Stir Welding process [2]

II. Process Parameters

Like any other process, in FSW the output is controlled by several input process parameters. The different process parameters in FSW of AMMC's are discussed in following discussion.

A. Tool material and profile

The tool design plays an significant role in FSW. The tool performs mainly two functions. First one is to generate heat and second one to stir the material to produce the weld [4]. A large part of frictional heating is caused due to tool shoulder[4],as well as due to friction of rotating pin and plastic deformation of the material. The mechanical stirring is done by the rotating pin plunged in the abutting plates.

Threaded tool profiles ([5],[6],[7],[8],[2]) have been commonly used for FSW of Aluminium matrix composites. Threaded profile produces a pulsating stirring in the softened material which in turn produces smaller grains and finer structure resulting in a joint with higher strength.[9]

The tool used in FSW of composites should be hard and highly wear resistant as there are abrasive particles in form of reinforcement present in the composite workpiece. Ferro-Titanit tool ([1],[5],[10]) and H13 tool steel [6] have been used for FSW of Aluminium matrix composites. Liua *et al.* [8] have reported the use of WC/Cobalt hard alloy.

III. Welding Parameters

Quality of weld and joint strength is affected by several parameters. Tool rotational speed and tool transverse speed have been widely reported as parameters of vital interest. A higher rotational speed generates more heat and results in more intense stirring of the weld material [4]. However an increased weld transverse speed results in lowered heating value due to fresher and colder material coming in contact with tool at a faster rate. Tool tilt angle w.r.t the work surface is another important parameter. A tilt angle towards trailing direction ensures that the material displaced by the pin is held efficiently by the shoulder and the material goes from the front of the pin to back of the pin smoothly[4].Plunge depth of pin in the plates also affects joint quality. If the plunge depth is too less, the shoulder will not come in contact with the work plate surface and a surface groove is formed. On the other hand, if the plunge depth is more, excessive flash will occur resulting in thinning of the plates in the region beneath shoulder.[4]

IV. Microstructural Evolution

As there is intense plastic deformation of material in FSW, recrystallization and microstructure evolution occurs in the stirred zone. Three different zones are produced i.e. Nugget Zone (NZ), Thermo-Mechanically Affected Zone (TMAZ) and Heat affected Zone (HAZ).These three zones in FSPed Al 7075-T651 alloy are shown in fig.2

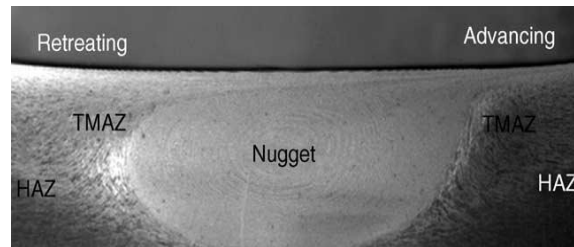


Fig. 2 showing NZ,TMAZ and HAZ(Al 7075-T651)[4]

Nugget zone is commonly referred as weld nugget or stirred zone. Between the nugget zone and base material lies the thermomechanically affected zone[11,12].This zone is affected by temperature as well as extent of plastic deformation. Next to TMAZ is the heat affected zone which is created by thermal effects only. This zone shares same grain size as base material.[4]Studies have shown the presence of finer reinforcement particles in the nugget zone with respect to the particles present in the base material([1],[5],[13],[14]). Minak *et al.*[13] using EDS and SEM proved the presence of finer Al_2O_3 particles in nugget zone Fig. 3. Breaking effect of the tool on the particles during FSW leads to refinement of reinforcement particles. The sharp edges of the reinforcement particles are rounded off by the tool and bigger particles are cracked to smaller size [5] and due to abrasive action of tool on the reinforcement particles [1]. Maximum reduction in the alumina particles was found near the end of the tool pin due to the stress gradient induced by the tool.[13]. Uzun[15] reported presence of segregated SiC particles in banded microstructure of the nugget zone in FSW of Al 2124/SiCp. Alternate regions of more and less SiC particle density were discovered. However Feng *et al.* [5] reported that SiC particles were not segregated in onion ring structure found in the nugget zone of AA2009/15%SiCp composite and proposed that the SiC distribution is enhanced due to the intense stirring and material mixing. Evolution of fine and equiaxed grains in the nugget zone due to dynamic recrystallization was reported by Feng *et al.* [5].

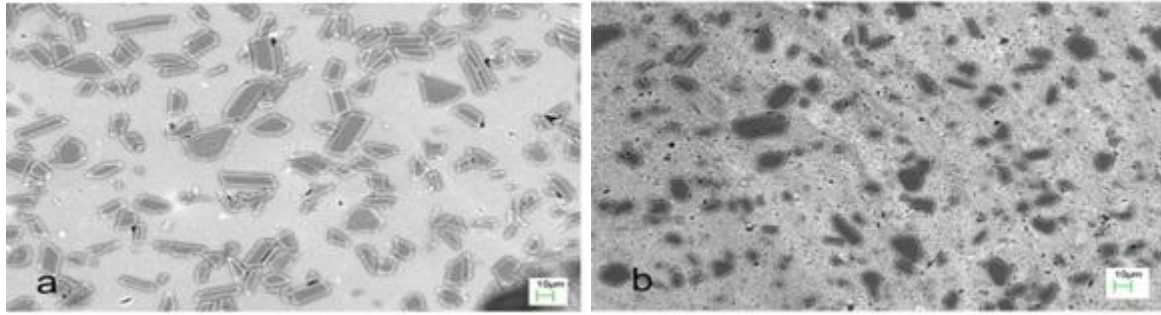


Fig. 3 SCM micrograph of (a)base material and (b) stirred zone of Al6061/22%vol. Al_2O_3 composite[13] Marzoli *et al.* [14] reported that the alumina particles hinder the material flow of aluminium matrix in nugget zone which is the reason of partial completion of the recrystallization in the nugget zone. Small round particles were found in the nugget which were rounded off by alumina particles which gets abraded by the tool during FSW. Like fusion welding, no agglomeration of reinforcement particles was found and welds were free of porosity [14]. Pirondi and Collini[10] also identified three distinct zones i.e. NZ, TMAZ and HAZ. Onion ring structure was found in nugget zone which is produced due to the spiral flow of the trailing side of the tool. Reinforcement particles were found clustered and fragmented in the nugget zone. As compared to particle size(10 μm to 20 μm), grain size of aluminium matrix was comparatively more (50 μm).

V. Weld Properties

Due to the intense plastic deformation arising from mechanical stirring of the material, microstructural changes occur that affect the mechanical properties like hardness, tensile strength and fatigue behavior of the weld joint. In this section, these properties of the welds obtained by FSW on composites are discussed.

A. Hardness

Studies show that there can be an increase([5],[13]) or decrease [7] in the hardness of the base material and the stirred zone. Minak *et al.* [13] performed FSW on Al6061/22%vol. Al_2O_3 and proposed that process parameters have significant effect on the hardness obtained post welding. But hardness increased after the welding as compared to base material. This is because of the grain refinement of the aluminium matrix. This increase in hardness was accompanied with very fine reinforcement particles which were result of breakage induced from the rotating tool. The hardness increased from 66HV of base material to 94HV in transition zone and 100HV in stirred zone. However Ceschini *et al.* [7] reported a reduction in hardness in weld zone as compared to base material in FSW of AA6061/20%vol. Al_2O_3 . This decrease has been attributed to over-aging effect induced due to the heat produced by friction during welding. There was further reduction in hardness from the surface which is in contact with tool and on the opposite side of the plate. The high hardness in the surface contacting tool is due to the lower matrix grain size which is in accordance with equation of Hall-Petch [16]. Microhardness profile on cross-section of the weld joint is shown in fig.4. Feng *et al.*[5] examined the effect of microstructural evolution on the mechanical properties of FSWelded AA2009/SiCp composite and reported an increase in hardness in the nugget zone. The increase in hardness was attributed to being a result of partial dissolution of the coarse precipitates and re-precipitation during process of natural aging during FSW. The reinforcement particles and matrix grains both undergo refinement which is also a reason of increased hardness. It was also proposed that after T4 treatment, the hardness values across the weld were similar but the hardness in nugget zone was somewhat lesser than the HAZ and TMAZ zone due to formation of a Cu_2FeAl_6 .

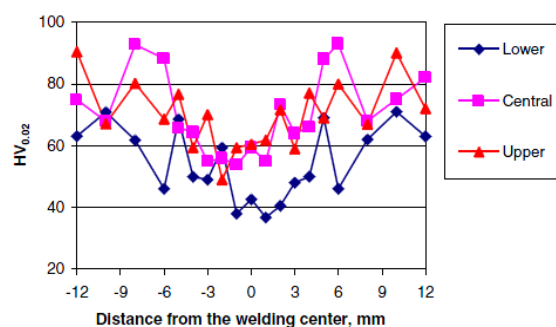


Fig.4 Microhardness profile on weld cross-section of AA6061/20%vol. Al_2O_3 composite.[7]

B. Tensile strength

Tensile Strength is a very important performance parameter of Weld joints. A maximum tensile strength with 99% efficiency was obtained at 880RPM and 260mm/min in FSW of AA6061/22vol.% Al_2O_3 by Minak *et al.*

[13]. In their studies, under any parameter set, the efficiency was higher than 90% and the results obtained by FSW were better than reported by fusion welding techniques. However, Ceschini *et al.*[7] reported that the ultimate and proof strength of the material decreases by 28% and 43% respectively as compared to base material in FSW of AA6061/20vol./Al₂O_{3p} whereas the elongation at fracture increases by 64%. The joint efficiency measured was 72% of the base material tensile strength and 52% of the proof strength of the base material. Reduction of proof strength than tensile strength was attributed to the overaging effect of the matrix due to coarsening of the intermetallic precipitates in the welding zone. The abraded reinforcement particles by the tool was attributed as the reason for increase in elongation because finer reinforcement particles exhibit a more ductile behavior. Similar results have also been reported by some other researchers ([17],[18]). Feng *et al.*[5] reports an increase in tensile and yield strength, as shown in fig.4, in FSW of AA2009/SiCp composite as compared to as extruded composite. This improvement was attributed to precipitate strengthening which is a result of welding process. Apart from this, the homogeneous distribution of the fine particles of the SiC also contributed towards the increase in the strength. A comparison of strength of the base material and FSWed material is shown in fig.5.

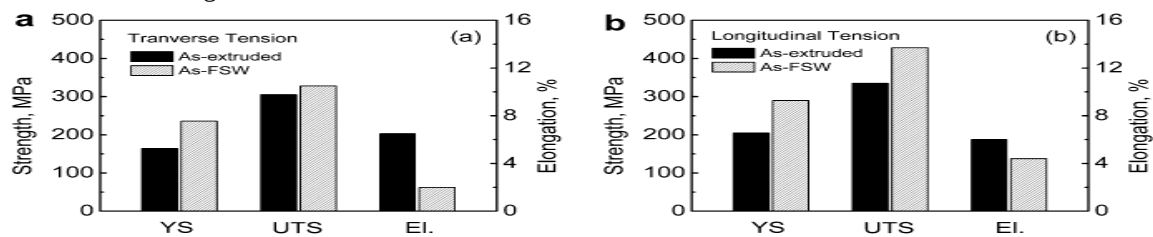


Fig.5 Comparison of strengths of base composite and FSWed AA2009/SiCp composite.(a)Transverse Tension, (b)Longitudinal Tension [5].

C. Fracture and Fatigue Behaviour

In many applications such as road vehicles and aerospace components, fatigue properties of weld joints are very critical. Therefore to successfully implement FSW to composites, fatigue behavior needs to be clearly understood. Since more research is done on analyzing microstructure, mechanical properties of the FSW welds of composites, some researchers have also analysed the fatigue behavior of the FSWed composite joints. Ceschini *et al.* [7] reported a lower low cycle fatigue life of welded composite than the base material in FSWed AA6061/20% Al₂O₃ composite. They concluded that loss of fatigue life is due to the overaging effects induced due to heating of the matrix during welding operation. Reinforcement particle cracking, Interfacial de-cohesion in the matrix and the reinforcement particles and Coalescence of voids in the matrix have been reported as three primary mechanisms of fractures in composites ([19],[20]).

VI. Dissimilar FSW of Aluminium alloy and Metal Matrix composites

Due to higher processing cost of metal matrix composites compared to monolithic alloys, they should be used only where there is effective utilization of their unique properties and elsewhere monolithic aluminium alloys can be used. So there arises a need to effectively join MMC and aluminium alloys. But fusion welding techniques cannot solve the problem due to segregation of reinforcement in the melting zone[21]. But FSW can be applied because it do not involve fusion of the materials. Some research work has been done on this issue which is briefly discussed in this section. Shrifitabar and Nami[21] studies the microstructure of the AA 2024 and Al/Mg₂Si composite and reported that both of materials retain their identities and are not blended at all locations. The joints with single weld pass are free from defects but welds with double pass have some defects which is the result of different flow abilities of the both materials. This fact is also concluded by Wert [22]. They also concluded that at very high temperature during the FSW, eutectic phase is formed in the AA 2024 alloy.

VII. Conclusion

In this review article, the process parameters, microstructure evolution and weld properties like hardness, tensile strength and fracture and fatigue behaviour of FSWed AMMC's have been discussed. From the discussion, following conclusions can be drawn:

1. Unlike fusion welding, FSW has been successfully employed to join Aluminium matrix composites.
2. Tool profile and material are very critical parameters. From the literature available, it can be concluded that threaded tool profile is used in most studies as it gives better mixing of softened material. Also, due to the presence of abrasives as reinforcement in composites, highly wear resistant tool materials are required for efficient operation.
3. Welding parameters such as tool rotational and transverse speed, tilt angle and plunge depth have a significant effect on the different weld properties such as hardness, tensile strength and fatigue behaviour.

4. Intense stirring of the material refines both the matrix grains and reinforcement particles which ultimately decides the weld properties.

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