CHAPTER 5

INVESTIGATIONS ON METALLURGICAL ASPECTS OF FRICTION STIR WELDED AA6061/AlB₂, AA6061/TiB₂, AND AA6061/SiC COMPOSITE PLATES

The present chapter investigates the metallurgical properties of friction stir welded AA6061/AlB₂, AA6061/TiB₂, and AA6061/SiC composite plates. The relationships between process parameters and macro and microstructures of the AMC welds are attained. The computation of the impact of the separate welding variables and their imperative interaction impacts on metallurgical properties is conducted depends upon the experimental results. The graphical plots are illustrated after the computation of the macro and microstructures for the direct and interaction impacts of the process parameters. The micrograph images are recorded using the PC data acquisition system that imparts the welding variables effects on the microstructures, percentage of ductility and ultimate tensile strength of the AMC weldments for depth insight.

5.1 AA6061/AlB₂

5.1.1 Macro and Microstructures

In the present study, boron was fabricated by adding B₂O₃ particles into the molten AA6061 matrix. In general, chemical reactions take place at the interface of molten aluminium alloy, AA6061 and B₂O₃, due to huge gap
in Gibbs-free energy between Al$_2$O$_3$ (lower) and B$_2$O$_3$ (higher) (Nafisi & Ghomashch 2007). This chemical reaction leads to the formation of boron and Al$_2$O$_3$ into molten state to produce aluminium boride. The reaction of AA6061 with B$_2$O$_3$ takes the following steps.

\[ 2\text{Al} + \text{B}_2\text{O}_3 \rightarrow \alpha - \text{Al}_2\text{O}_3 + 2[\text{B}] \]  
\[ (5.1) \]

In general, solubility of boron (Figure 5.1) in aluminium is low and thus can be increased by increasing the temperature (Hoseini & Meratian 2005). According to Al-B binary phase as shown in Figure 5.1, possible chemical reactions takes place during synthesis are given as follows in equation (5.2) (Sava et al. 2012):

\[ 2[\text{B}] + \text{Al} \rightarrow \text{AlB}_2 \]  
\[ (5.2) \]

Figure 5.1 Al – B phase diagram (Hoseini & Meratian 2005)

Figure 5.2 shows the resulting microstructures of AlB$_2$ reinforcement particles in the aluminium alloy matrix.
The FSW welded joints typically consists of three regions based on their grain size distribution: 1. Heat affected zone (HAZ) 2. Thermo-mechanical affected zone (TMAZ) and 3. Stir zone (SZ) (Khodaverdizadeh et al. 2013) as shown in Figure 5.3.

During friction stir welding of AMC, the base aluminium metal undergoes severe plastic deformation because of heat generated. Plastic deformation off metal leads to the formation of grains in the weldment. The formation of fine grains is known as dynamic recrystallization. The grain size is proportional to the heat generated at the interface and it is a key factor in determining the grain density. Higher heat inputs associated with decrease in welding speed/travelling speed or increase in rotational speed of tool produces grain growth predominantly. Subsequently, coarsens the recrystallized grains. The presence of boron particulates in the Al matrix constricts the movement of growth of grain boundary by setting up a barrier.
The effect of limiting the growth of grain boundary is called as pinching effect (El-Rayes Magdy & El-Danaf Ehaba 2012). Further, the reinforced boron particles can break the grains formed. According to Barmouz et al. (2011), a large number of broken and disoriented grains were created during plastic deformation. The presence of boron particulates in Al matrix increases the nucleation sites for recrystallization. Finer the grains better the microstructures observed in weldments.

![Figure 5.3 Typical weld regions of FSW joints](image)

**Figure 5.3 Typical weld regions of FSW joints**

Formation of reinforced particle-rich and particle free regions within the SZ of specimen was observed during FSW of AA7075/SiC by Bahrami et al. (2011). From the Figure 5.4, it is clearly observed grain size in particle rich regions is smaller than the grain size in particle free regions. The average grain size in the welded zone is about 3 µm.

With parameter setting of rotational speed to 1000 rpm and travelling speed of 20 mm/min, the influence of reinforcement particles in stir zone microstructures were studied.
Figure 5.4 Microstructures of AlB₂ reinforced Al composite weldments

Larger grain sizes were observed due to the higher heat inputs generated. AlB₂ particulate in some regions breaks the grains and limits the grain boundary movement. Figure 5.5 shows the SEM images of FSW composites of hot rolled Al – 5 wt%. B. Multilayer structures can be observed in the composites. Boron particle agglomerations in aluminium composites are shaped in ribbons. The agglomerations are the result of insufficient penetration of boron particles in the base aluminium metal. From the XRD investigations (Figure 5.6), phases of composites under setting of rotational speed of 800 rpm and travelling speed of 50 mm/min were observed. The results show the presence of Al, AlB₂ and B in the composites. A slight amount of Fe was observed and this is due to the contamination of FSW tool with the base metal while welding.

Kontoyannis & Vagenas (2013) research concludes that there is a greater advantage in analyzing peak heights of density when compared to integrated intensities when percentage of each phase is calculated. The peak heights of composition intensity were taken as reference for analysis. During
FSW process, some parts of boron reacted with the aluminium forming intermetallics in SZ due to excessive heat generated. The lamellar AlB$_2$ particles in aluminium are about 5 µm in length. The lighter and darker regions in the Figure 5.6 represent aluminium and AlB$_2$ particles respectively. The density of pores is very low in the welded zone and has negligible effect on strength. Finally, weldment shows the good interface bonding AlB$_2$ and Al matrix.

![SEM micrographs at the weld nugget zone of AMC plates](image)

**Figure 5.5 SEM micrographs at the weld nugget zone of AMC plates**

The XRD pattern of AA6061/AlB$_2$ composite plates is shown in Figure 5.7. The pattern clearly indicates that the constituent phases of the friction stir welded sample contain only Al, AlB$_2$, and B phases. The results revealed that the FSW stirring action on the AMC’s does not produce any secondary phases other than AlB$_2$ phase in parent aluminium matrix alloy.
Figure 5.6 SEM image on the surface of AA6061/AlB$_2$ composite

Figure 5.7 XRD pattern in welded zone
5.2 AA6061/TiB₂

5.2.1 Macro and Microstructures

The different regions of the low heat input joints are examined for microstructures using scanning electron micrographs (Figures 5.11 to 5.13). From the observations with low heat input, the lower level of particle breaking up is seen from the micrographs. At the intermediate heat input (30.50 kJ/mm), the various regions of the specimen (FS welded Al MMC) are taken microstructures using optical micrographs (Figures 5.8 to 5.9).

The smaller size grains are seen through micrographs while providing the increased heat input. The maximum broken particulate agglomerations are seen in the joint regions. The partial broken of the bigger size TiB₂ agglomerations are observed in the TMAZ. The separation of the TiB₂ particulate agglomerations in the heat affected zone of the joint is inadequate due to generation of the frictional heat. The observations of FS welded MMC are observed with maximum particle breaking from micrographs using various functions such as tool rotational speed and the welding speed. Higher downward force is provided the scattering of the TiB₂ agglomeration in the welded joint interface which is seen in Figure 5.12.

Even distribution of the particulate across the different regions of the weld interface such as thermo-mechanically affected, weld nugget and heat affected zones is achieved with higher heat inputs during the welding technique. Partially broken up TiB₂ particulate agglomerations are observed in the TMAZ and HAZ except weld nugget of the specimen.
Figure 5.8 Microstructures of base metal region of AMC

Figure 5.9 Microstructures of weld nugget of friction stir welded AA6061/10% TiB$_2$ composite

Friction stirring of the weld tool is provided the fine distribution of the agglomerates in the weld region. The partial broken up agglomeration is
observed in the HAZ and TMAZ which is influenced by the friction stirring process. The large size grains and unbroken particulate agglomerations are seen in the HAZ of the microstructure.

The microhardness review is carried out on the optimized weld joint (Figure 5.12) which portrays the lower hardness in the HAZ. The annealing impact occurs at weld region due to heat generated by tool rotation at the stage of FSW process. The different region of the optimized joint interface (joined at optimum condition for maximum UTS) is observed for obtaining the microstructures.

Figure 5.10 SEM image of base metal region
Figure 5.11 SEM image of heat affected zone (HAZ)

Figure 5.12 SEM image of weld nugget (uniform distribution of reinforcement particles are clearly seen due to FSW stirring action)
Finely broken TiB$_2$ particulates are shown in the weld nugget through microstructures (Figure 5.13). It is inferred from the investigation that the stirring action of the tool is influenced the particulates distribution during FSW process. The TMAZ and weld nugget micrographs are compared and it is inferred that unbroken particulate agglomerates and a little larger size particulates are seen in the TMAZ. Aforesaid is occurred due to the less stirring impact in the TMAZ in FSW process. Heat affected zone of the weld interface is seen with undisturbed particulate agglomerates.

5.3 AA6061/SiC

5.3.1 Macro and Microstructures

The macro and microstructures of the friction stir welded AA6061/10%SiC composite joints are clearly examined in this section. The
micrographic images of joints revealed that the distribution of grains in the aluminium matrix is uniform. The composites that are fabricated by stir casting method seem to be efficient in elimination of any induced cracks in the composite material.

Figure 5.14 Microstructures of FS welded AA6061/10% SiC composite at welding speed of 60 mm/min (a) TMAZ – advancing side (b) TMAZ – retreating side (HAZ) (c) stir zone
The macro and microstructural images of the friction stir welded composites are shown in Figure 5.14. The microstructures of FS welded joints are classified into four regions: (1) Base Material (BM) region; (2) Heat Affected Zone (HAZ); (3) Thermo-Mechanically Affected Zone (TMAZ); and (4) Weld Nugget Zone (NZ). The Thermo-Mechanically Affected Zone (TMAZ), which lies in between the Heat Affected Zone (HAZ) and the Weld Nugget Zone (NZ). The TMAZ has undergone severe plastic deformation in the advancing side of welding direction. The grains of both aluminium matrix alloy and reinforcement particles in TMAZ are rotated by 90° when compared to the grain distribution in other zones of the welded composite joints. The reinforced SiC particle alignment for some extent is observed in the TMAZ region other than NZ. The reinforcement particles does not show any significant changes in the heat affected zone (HAZ) located between TMAZ and base composite region on both advancing and retreating sides.

The grains at the weld nugget experience a consistent plasticized metal flow within the retreating and advancing sides. The formation of onion rings is found to be very apparent owing to the fact that the cylindrical sheets of material extruded during each rotation of the FSW tool and cutting through each section tends to form geometrical patterns. The common type of defects observed in FS welded joints is warm holes, piping, and tunnel defects. The presence of silicon carbide particles in al matrix restricts the material free flow of al matrix and thus avoids the formation of defects. The presence of onion rings in weld nugget is mainly associated with FSW composite joints and the same pattern is less seen in FSW metal joints. FSW process rearranges the particles distribution in al matrix and this is due to excessive stirring and deformation. The FSW tool stirring action refines and breaks the reinforcement particle grains in the weld nugget. Smaller and finer grains are produced due to plastic deformation. The pattern of micrographic images in weld nugget is significantly varies from other weld regions.
The changes observed in microstructures of composite weld joints mainly because of the frictional heat generated and plastic deformation by FSW tool (Kalaselvan & Murugan 2013). High stresses caused by the FSW tool stirring action breaks and rearranges the SiC reinforcement particles and precipitates at the weld nugget. SiC particle agglomerations observed along the grain boundary in aluminium matrix alloy. Dynamic recrystallization tends to produce smaller and finer grains in the weld nugget (Feng et al. 2008). The highly elongated grains are observed in the thermo-mechanically affected zone (Li & Liu 2013, Khodaverdizadeh et al. 2012). This elongated grain structures are the resultant of insufficient recrystallization (heat and plastic deformation) (Xu et al. 2012, Sarkari Khorrami et al. 2012). The particles in heat affected zone experiences only frictional heat and not underwent plastic deformation.
5.3.2 Effect of Tool Rotational Speed

5.3.2.1 Macrostructures

The macrostructures of the FSW aluminium alloy and MMC joints are observed and tabulated for the impact of the tool rotational speed. The material flow is occurred at the tool pin due to the heat generation through the stirring action during FSW process. For the various levels of tool rotational speeds, the macrographs of the weld nugget zone of AA6061 are shown in Figure 6.8. From these various tool rotational speeds, a defect free weld is produced at a tool rotational speed of 800 rpm. The improper stirring action and intermittent metal flow around the tool pin is occurred at the lesser speed (<800 rpm) due to inadequate plasticization of the parent material under the tool shoulder. The turbulent metal flow around the tool pin is occurred at the
higher speed (<800 rpm) due to excess plasticization of the parent material under the tool shoulder (Lim et al 2004). The defective welds are produced at higher and lower rotational speed of the tool (<800 rpm and >800 rpm).

The common defects produced from the fusion welding of MMCs are porosity, segregation, catastrophic failure at the interface and hot cracks, deleterious reaction, etc., which are deteriorating the joint properties and the weld quality. This solidification related defects are not occurred at the FSW process and materials are welded in the solid state itself as a result of the heat generation using the friction and metal flow through the stirring action. Yet, the defects of FSW joints are kissing bond, pin hole, piping defect, cracks, tunnel defect, and Zig-Zag line, etc., as a result of improper flow of material and inadequate consolidation of the material in the weld nugget zone. The inadequate plunging of the welding tool at the time of FSW process is produced un-welded butt surface below the stir region which is known as kissing bond (Rajakumar et al. 2011).

The mechanism of the kissing bond is associated with the inadequate breakup of the oxide layer with the inadequate stretch of the contacting surfaces in the region of the welding pin. The inadequate breakup of the oxide layer during friction stir welding process is occurred due to lessened heat input. There is a maximum probability that the adequate breakup of the oxide layer is not attained in the root weld of the specimen. The insufficient stirring is produced the continuous oxide film on the initial butt surfaces. It is welded without the metallic bond among the oxide free surfaces in the weld root. Consequently, kissing bond is produced due to a continuous oxide film and fracture is occurred in a zig-zag line (Diwan & Ravinder 2006).
5.3.2.2 Microstructures

The interface of the stir zone and TMAZ for all the specimens is failed during the tensile test. The evaluation of the failures is identified through the microstructures at the stir zone and TMAZ (AS and RS). An intermetallic phase of the aluminium matrix and elongated grains are seen in the microstructure of the parent material.

The Figure 5.15 is shown the optical micrographs of the nugget zone of the all the joints. The elimination of the all traces of dendritic solidification microstructure is observed along the nugget regions and fine precipitates. SiC particles are evenly distributed in the weld nugget due to the stirring process of the tool and vigorously recrystallized circumstance of the metal at the time of FSW process. This fact is recorded by other researchers also (Barcellona et al. 2006, Lim et al. 2004).

It is seen from the micrographs that there is a notable difference in the grain size at the weld zone relating to the various welding circumstances. Fine grains are seen with the welds) at different tool rotational speeds (800 rpm, 1100 rpm and 1500 rpm) which are shown in the Figure 5.14. The tool rotational speed is directly proportional connection with the heat input is observed from the figure.

5.3.3 Effect of Welding Speed

5.3.3.1 Macrostructures

The friction stir welded joint cross sections analyzed at various magnifications (10x, 20x, 50x and 100x), using a Olympus optical microscope, and the macro- graphic images are shown in Figure 5.14.
The macrostructures of the different weld zones include base metal, thermo-mechanical nugget regions of AA6061/10%SiC AMC’s for five levels of welding speeds are discussed. Among all the five welding speeds used to weld the composites, defect free welds are obtained for the welding speed of 90 mm/min. Low welding speeds results in insufficient metal flow due to less plasticization of the weld nugget by FSW tool. Higher welding speeds, more than optimal range (90 mm/min), tends to cause the turbulent flow of material around the FSW tool pin in the weld direction due to excessive plasticization of weld nugget region material (Rajakumar et al. 2011). Both these two welding speed conditions prove to be ineffective for producing defect free welds.

5.3.3.2 Microstructures

The microstructural images taken at the different weld zones of all the welded composite joints are shown in Figure 5.14. From the micrographic images, it is found that there is a significant variation in the size and distribution of grains of the stir zone, TMAZ, and HAZ when compared to the base metal AA6061/SiC composite microstructures. The coarse and randomly distributed grains of the composite are changed to homogenously alignment of fine grains in the stir zone due to the FSW tool stirring action. The weld joint contains more number of smaller and finer grains at the weld nugget for welding speed of 90 mm/min. An AA6061/10%SiC AMC’s joint welded at the welding speed of 75 mm/min consists of larger number of finer grains than the any other welding speed parameter setting joints. This may be attributed to the increased microhardness value of the welded joints.

The applied heat input to unit area is inversely related to the welding speed. Higher welding speeds tend to supply low heat inputs. Lower welding speeds, i.e., low distance per unit area supplies more amount of heat to the given region. Low welding speeds tends to produce excessive stirring
action on the specimen surface and results in formation of defects in the weld nugget (Rajakumar et al. 2011). Moreover, low welding speeds (higher heat inputs) generates maximum value of temperatures and slower cooling rates. This condition leads to the formation of coarser and randomly placed grains in the stir zone, which resultant in declined value of the hardness in the weld joint. With the increases heat input, there is proportionate decrease in tensile strength value because of turbulence of plasticized material at the weld nugget, and thus broken SiC particles are clustered to form reinforcement particle segregations. By considering all these effects of coarse grains, higher stirring action, low microhardness deteriorates the effective value of tensile strength of the welded joint.