Investigation on microstructure and mechanical properties of Friction Stir Welded AA6061-4.5Cu-10SiC composite

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Abstract. The application of Metal Matrix Composites (MMCs) is restricted by the availability of properly developed fabrication methods. The main challenge here is the fabrication and welding of MMCs in a cost effective way. In the present study, synthesis of AA6061-4.5%Cu-10%SiC composite was done by stir casting method. The joining of MMCs was performed by Friction Stir Welding (FSW) using a combination of square and threaded profile pin tool (CSTPP). Further, the welded composite was evaluated for microstructure and joint properties. The microstructural characterization showed uniform distribution of refined fine grains and numerous small particles at nugget zone. The hardness at the stir zone is higher than that of the base material. The tensile test revealed 96% joint efficiency in transverse direction.

Keywords: Friction Stir Welding, Metal Matrix Composite, nugget zone, Microstructure, hardness.

1. Introduction
Metal Matrix Composites have transpired to be a more futuristic metal in the engineering field due to its superior mechanical properties, alterable thermal and electrical properties. These materials possess significant advantages in terms of strength to weight ratio, stiffness and wear resistance [1, 4]. However, in the past, applications of such materials were limited due to high cost of production and difficulty in welding of composites. Recent advancements in the synthesis of composites and novel techniques in the area of welding have played significant role in the use of such materials. Joining of metal matrix composites is achieved by two ways, either fusion welding or solid state welding. Fusion welding has exhibited several problems like settling of heavier particles in the bottom of the weld pool, formation of intermetallic compounds between the matrix and the reinforcement, solidification shrinkage, voids, cracks, less penetration depth, hot cracking, work hardening effect, precipitation distortion in the joint etc. [5, 7]. Such defects will deteriorate the mechanical strength of the joint. These problems can be eliminated by using solid state welding techniques.
Friction stir welding (FSW) is a solid state welding, and it was invented by ‘The Welding Institute’ at UK in 1991 [8]. The joint is accomplished by a non-consumable rotating tool inserted into the abutting material, until the tool shoulder touches the surface of the joint and moved along the direction of the joint. The stirring action of the tool at the joint interface produces frictional heat and deforms the material [9, 10]. The temperature attained during friction stir welding in the weld zone is less than the melting point temperature of the base material [11]. Due to the stirring action of the tool, material starts to deform and move from advancing side to retreating side and deposited at the back of the tool wake produced by the forward movement of the tool, hence joint is formed. The strength of the joint is based on the process parameters. The process parameters which influence the quality of the joints are rotational speed, welding speed, thrust force, tool geometry and features, material of the tool, hardness of the tool etc [11, 1, 12, 13]. The material flow is mainly dependent on the shape of the tool profile which affects the quality of weld [12, 14]. The threaded pin has swept volume to static volume ratio equal to 1.01, which provides an improved mixing action [1]. Further, the threaded pin assists for a plastically deformed work piece material to be fully delivered around the pin from the upper part of the joint to the lower part and vice versa [15]. The FSW tool with a square pin has greater swept volume to static volume ratio. Therefore, square pin produces a pulsating effect, which enables reduction in grain size [13]. From the literature report, it was observed that no work has been reported on FSW of composite using combination of square and threaded (CSTPP) profile tool. Hence, the present study is focusing on the effect of rotational speed, welding speed and CSTPP on ultimate tensile strength.

2. Experimental Work

2.1. Preparation of metal matrix composite
AA6061-4.5%Cu-10SiC composite was prepared by stir casting process. The weighed quantity of AA6061-4.5wt.% Cu ingot matrix was cleaned with acetone to remove the impurities from the surfaces. The matrix was melted at a temperature of 800°C using graphite crucible with motorized stirring system. The chemical composition of the matrix is shown in the Table 1. About 21 gram of scum powder is added to 3 kilogram of the molten alloy. The dross is removed from the surface of the melt using a refractory skimmer. The dissolved gases were removed by addition of Hexachloroethane tablets to molten metal. After degassing the surface of the molten metal cleaning is performed again. The vortex was created with the help of a rotating mechanical stirrer. The speed of rotation was maintained at 600 rpm. The 10 wt% SiC particles was pre-heated and introduced into the melt by churning action of the stirrer. Pre-heating of SiC particles enhances wettability between molten aluminum alloy and reinforced powder by maintaining temperature of the melt, removing surface impurities and gases associated with powder agglomeration. To obtain a uniform pattern of stirring, an impeller is used in the melt. It produces great amount of turbulence in the flow pattern and induces better mixing of the SiC particles into the matrix. After the complete addition of SiC particles, the stirring is continued for 5 minutes. The stirrer is then withdrawn from the melt. The composite melt was then solidified in a metal casting mould.

| Table.1. Chemical composition of the AA6061-4.5% Cu matrix |
|----------------|----------------|----------------|----------------|----------------|
| Copper (wt.)   | Magnesium (wt.)| Silicon (wt.)  | Iron (wt.)     | Manganese (wt.)|
| 4.5            | 0.8 – 1.2      | 0.4 – 0.8      | 0.7            | 0.15           |
| Aluminum (wt.) | 37.7           | 6.9            | 0.11           | Remaining      |

2.2. Friction Stir Welding of Composites
The cast composites are machined to required size of 100x50x6mm to carry out friction stir welding. The mechanical property of the cast composite is shown in Table 2. Butt joint configuration was selected to carry out FSW. After cleaning through acetone, the samples were clamped on the fixture to secure the plate together. Friction stir welding setup is shown in Figure 1. The welding tool is made of M2 steel which is hardened to 53HRC. The tool consists of square profile at the shoulder side and
thread profile (M6x1p) at the pin free end as shown in Figure 2. The FSW process involves mainly 3 stages, a) Plunging: inserting the tool into the workpiece; b) Stirring: plastically deform the material and move the material from the leading edge to the trailing edge of the tool (extrusion and forging); c) Retraction: removing the tool from welded composite. The process parameters used to weld the composite are shown in Table 3. The advancing side refers to the side where material movement direction of welding tool movement is in same direction. In the case of retreating side it is quite opposite.

Table 2. Mechanical Properties of Composite

| Composite          | Vickers Hardness (Hv) | Ultimate Tensile stress (N/mm²) | Percentage Elongation |
|--------------------|-----------------------|--------------------------------|-----------------------|
| AA6061-4.5%Cu-10%SiC| 105±2                 | 254±3.5                        | 6.5% ± 0.1            |

3. Results and discussion

3.1 Microstructure of composite

AA6061 and 4.5(wt.) Cu alloy matrix reinforced with 10% (wt.) SiC composite was successfully synthesized by stir casting process. The Metallurgical characterizations are investigated through SEM images. Figure 3 (a) presents the SEM image of the composite, exhibiting typical dendritic structure. The average grain size of composite is 63.5 ± 4μm. The composite revealed equilibrium phases precipitated in grain boundaries and SiC particles appeared at the interior of the grain boundary. Figure 3 (b) indicates the honeycomb structure in the grain boundary. A reasonable dispersal of SiC particles was observed in the matrix. A common defect which has been observed in the composite, in the past, is the agglomeration of hard particles, which usually leads to reduction of toughness of the composite [6]. However, such sort of defect was not observed in the cast composite. Figure 4 (a-f) shows the EDX mapping of composite. In the image Si and Cu rich regions were observed in Figure 4 b). It is also observed that there is no evidence of cracks. This may be due to proper selection of process parameters [17]. There is a good bonding between the matrix and reinforcement leading to effective load transfer from the matrix to the reinforcement particles.
3.2 Microstructure of Friction stir welded composite

AA6061-4.5% Cu-10%SiC composite was successfully friction stir welded using CSTPP tool. The stirring action of the tool at the weld center produces plastic deformation resulting in fine grains. The weld zone reflected significantly altered microstructure as compared to that of the base material. Figure 5 shows the advancing side of SEM image of the friction stir welded composite with rotational speed of 710 rpm and welding speed of 50 mm/min. Based on the microstructure developed at the weld region of the composite, it can be divided into four zones: Nugget Zone (NZ), Thermomechanically affected zone (TMAZ), Heat affected zone (HAZ) and Base Material (BM) [3, 13]. The change in the microstructure mainly depends on the frictional heat generated and plastic deformation due to stirring of the tool [13]. Stirring action of the tool causes high strain in the weld zone which arises in rearrangement of SiC particles and precipitates, from agglomerated at the grain boundary in the base material to homogeneous distribution in the NZ of welded specimen. The smaller and equiaxed grains observed in the NZ, resulted from the mechanism of constant dynamic recrystallization [16, 18]. There is a reduction in size of SiC particles and precipitates due to collision of hard particles with each other and abrasive action of the tool [13, 16]. In the region of TMAZ, highly elongated grains distributed along the flow line [13, 19] have been observed. This is due to combined action of plastic deformation and heat [20] which results in insufficient strain to form recrystallization [21]. In HAZ, material experiences only heat and no influence of plastic deformation.
Intern, the increase in temperature leads to grain growth and increase in grain size. In BM, since there is no influence of both plastic deformation and heat, the grain size remains unchanged.

Figure 6 shows the SEM image of composite friction stir welded using CSTPP with rotational speed of 710 rpm and welding speed of 50 mm/min. Figure 6 (a) represents the micro structure formed at retreating side of the welded zone. Figures 6 (b-d) represent the grain distribution at the top, middle region of square pin, middle region of threaded pin and bottom of the NZ. The variation in the grain size at the NZ is due to inhomogeneous distribution of peak temperature from top to bottom of the NZ. The top of the NZ experiences higher centrifugal force compared to bottom NZ. During recrystallization a small extrusion crushing force will be acting on metals per unit area, resulting in larger crystal nucleus. Meanwhile, the shoulder acting as heat source produces higher temperature at the top of NZ, requiring longer cooling time due to which grain growth takes place. On the other hand, the penetration depth of the pin is less than the thickness of the weld to avoid plunging of the pin into backing plate. As a result, at the bottom of the NZ, due to lack of stirring and forging, there will be insufficient plasticization and flow of the material. At the root of the weld, base plate acts as heat sink and the heat is transferred from the top by heat conduction. The extrusion forming in the bottom is not fulfilled under maximum temperature. Therefore, extrusion at the root of the weld happens due to plastic deformation of the materials around. The entire phenomenon is responsible for the formation of fine grains at the bottom of the NZ. This is in agreement with the findings of [18].

Figure 6 SEM micro images of friction stir welded AA6061-4.5(wt%)Cu-10(wt%) SiC composite joint fabricated using CSTPP tool with rotational speed of 710 rpm and welding speed of 50 mm/min, showing grain size distribution at a) Retreating side of TMAZ b) Top of the NZ, c) Middle of the square region NZ, d) Middle of the Threaded region NZ, e) bottom of the NZ and f) Advancing side of TMAZ

3.3 Mechanical properties of friction stir welded composites

3.3.1 Hardness distribution at weld region

The hardness of the composite joint welded by friction stir welding process using CSTPP tool, is a function of grain size, dislocation density, hard reinforcing particles, and welding process parameters. Figure 7 shows the hardness distribution obtained across the transverse cross-section of a composite joint welded at different rotational speed and welding speed. However, the hardness distribution along the weld zone is W-shaped [23]. All the composite joints showed higher hardness value at NZ as compared to base material. Finer grain sizes result in higher hardness according to Hall-Petch theory [24]. Usually, hard particles in metal matrix have double effect on the hardness. One arises from its
hard nature and second one relates to the role of SiC particles in grain boundary pinning [25]. Numerous small SiC particles were produced by striking of hard particles to each other and abrasive action of the tool. Therefore, NZ was filled by more number of smaller particles distributed homogeneously which will contribute to increased hardness [3]. Decrease in hardness was observed as the distance increases from the center, on both sides of NZ. Lower hardness value has been observed between the base composite and NZ, known as Heat affected Zone (HAZ). This is mainly due to grain softening induced by the thermal effect during stirring of the material by the tool. From Figure 7, it is observed that as the welding speed increases, the hardness increases. The welding speed decides the time of exposure of frictional heat between the tool and the base material interface per unit length. The more the time of frictional heat exposure, the more is the heat supplied and eventually affects the grain growth [26]. The increase in the hardness is due to decrease in the quantity of heat supplied which leads to formation of fine grains. The highest hardness was obtained for rotational speed of 1000 rpm and welding speed of 80 mm/min, which is higher than the hardness obtained for rotational speed of 710 rpm and welding speed of 80 mm/min. Increase in the tool rotational speed leads to increase in heat generation and also proper stirring of the materials at NZ [26]. Lower rotational speed results in lower heat condition and lower stirring effect which leads to improper consolidation of material at weld zone. Hence, improved hardness has been obtained for higher rotational speed of 1000 rpm and welding speed of 80 mm/min. The lower hardness is obtained for a rotational speed of 1400 rpm and welding speed of 50 mm/min. Higher tool rotational speed of 1400 rpm and lower welding speed of 50 mm/min results in higher heat generation than the required heat and also excessive stirring of material. This softens the material and creates turbulence in material flow. The higher heat results in growth of grain which leads to decreased hardness [9].

![Figure 7 Hardness distribution across NZ of composite FS welded at different rotational speed and welding speed (R- Retreating side and A- Advancing side)](image)

3.2.2 Joint strength of welded composite
Table 4 presents the ultimate tensile stress, percentage elongation and joint efficiency of friction stir welded composite. The process parameters such as rotational speed and welding speed have shown direct influence on the joint efficiency. The rotational speed has impact on generation of frictional heat, stirring and proper mixing of the material at weld zone. The welding speed moves the tool in the direction of weld and transfers the soft material from the front to the back of the tool. The improper selection of process parameters leads to the formation of defect in the weld zone and results in formation of initial cracks. The joint efficiency of 96 % has been obtained for a tool rotational speed...
of 1000 rpm and welding speed of 80 mm/min. The joint efficiency increases with increasing rotational speed from 710 rpm to 1000 rpm and decreases with further increase in rotational speed of 1400 rpm. It was found that the rotational speed is more significant factor than the other process parameters [1]. The lower rotational speed produces less heat generation, leading to reduction in heat transfer to the weld region. Lesser heat leads to improper material flow and less plasticized material in the NZ. Therefore lesser tensile strength obtained at lower rotational speed [12]. When rotational speed is very high, heat generated is also more, which results in more plasticized material and the stirring effect creates turbulence in the material flow. The combined effect of these led to the growth of grain. Hence, lower tensile stress is obtained at higher rotational speed [12].

Table 4 Tensile test results of the FS welded joint

| Rotational Speed (rpm) | Welding Speed (mm/min) | Yield Strength (N/mm²) | Ultimate Tensile Strength (N/mm²) | Elongation % | Joint efficiency (%) |
|------------------------|------------------------|------------------------|----------------------------------|--------------|----------------------|
| 710                    | 50                     | 115±2                  | 175±2                            | 5.7±0.1      | 69                   |
| 710                    | 63                     | 136±2                  | 192±2                            | 5.5±0.1      | 76                   |
| 710                    | 80                     | 149±2                  | 204±3                            | 5.2±0.1      | 80                   |
| 1000                   | 50                     | 144±3                  | 206±3                            | 5.1±0.1      | 81                   |
| 1000                   | 63                     | 173±2                  | 223±2                            | 4.6±0.2      | 88                   |
| 1000                   | 80                     | 197±2                  | 243±3                            | 4.3±0.1      | 96                   |
| 1400                   | 50                     | 119±3                  | 167±3                            | 6±0.1        | 66                   |
| 1400                   | 63                     | 136±2                  | 183±2                            | 5.8±0.1      | 72                   |
| 1400                   | 80                     | 159±2                  | 204±2                            | 5.4±0.1      | 80                   |

The fracture visible in the Figure 8 (a)-(c) display the ductile fracture. The fracture surface exhibited tear ridges and dimples in turn confirming the ductile fracture. At the bottom of dimples, SiC particles were observed. The particles inside dimples suggest that the voids are initiated at particle matrix interface. In addition, the dendritic nodules of the fracture surface show that fracture propagates through interdendritic separation. Figure 8 (b) represents the fracture surface of the friction stir welded composite in the direction of weld, for rotational speed of 1000 rpm and welding speed of 80 mm/min. All the joints were failed on the advancing side where lowest hardness value was recorded. Figure 8 (c) represents the fracture surface of friction stir welded composite at rotational speed of 1000 rpm and welding speed of 80 mm/min in the direction of weld (along). There is a large difference in the appearance of fracture surfaces, in the across and along directions of welded specimens. Across the direction weld samples have exhibited larger dimples. The fractured specimens of composites in the direction of weld have exhibited ductile fracture with dispersed shallow dimples of fine and round equiaxed dimples and SiC particles being detected in the dimples and tearing ridges [16]. This is due to fine equiaxed grain structure.

4. Conclusions
The AA6061-4.5%Cu-10SiC composite were successfully synthesized by stir casting process. The influence of tool rotational speed and welding speed on microstructure, hardness and tensile strength of FS Welded composite is investigated. Wide defect free ranges were obtained for a CSTPP tool. The microstructural behavior of the weld zone exhibited homogeneous distribution of fine recrystallized grains with numerous small SiC particles and precipitates being found at the NZ due to stirring action of the tool and collision of hard particles to each other. At nugget zone, slightly larger grain size was obtained as compared to bottom of the NZ. Elongated grains were observed at TMAZ. The NZ hardness was higher than that of base material due to grain refinement and small hard particles. Joint
efficiency of 96% was obtained for a rotational speed of 1000 rpm and welding speed of 80 mm/min. For across the weld samples, larger dimples were observed. The fractured specimens of composites in the direction of weld exhibited dispersed shallow dimples of fine and round equiaxed dimples, with SiC particles being detected in the dimples and tearing edges.

![Figure 8 SEM image of the fracture surfaces. (a) Base composite, (b) friction stir welded composite across the direction of weld, tool rotational speed of 1000 rpm and welding speed of 80 mm/min. (c) friction stir welded composite in the direction of weld tool rotational speed of 1000 rpm and welding speed of 80 mm/min.](image-url)

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