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# EFFECT OF TOOL ROTATIONAL SPEED ON MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF FRICTION STIR WELDED ALUMINUM MMCS

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## ABSTRACT

Metal matrix composites (MMCs) are very attractive materials, due to their high stiffness, high temperature stability, and superior wear resistance compared to the unreinforced alloys. In particular, the discontinuously SiCp reinforced aluminium based composites, due to their lower cost and the possibility to be processed by conventional metal working processing such as extrusion, forging, rolling are excellent candidates for structural components in the aerospace and automotive industries. Despite the intense effort put into the development of high performance composites, relatively little work has been directed towards joining these materials. The main hurdle in joining especially Al-(SiC) MMC is related to the mismatch in melting points, thermal coefficient, thermal conductivity between the reinforcement and the matrix alloy, and also interfacial chemical reactions between the reinforcements and the molten matrix alloy, and the inhomogeneous reinforcement distribution after welding. In recent years a new solid-state joining technique, the Friction Stir Welding (FSW) process, has been successfully applied to several Al alloys, leading to joint properties in some cases higher than that of the base material. The main objective of the present work is to study the effect of tool rotational speed on the formation of microstructure in friction stir processed zone(FSP), thermo mechanically affected zone and heat affected zone of friction stir welded Aluminum - 10% SiCp reinforced metal matrix composites. The tensile properties of the joint were evaluated and they are related with microstructure and tool rotational speed of the process. The microstructure characterization of the FSP zone shows evidence of a substantial grain refinement of the aluminium alloy matrix due to dynamic recrystallization induced by the plastic deformation and frictional heating during welding. A maximum weld joint efficiency of around 68.34% was yielded by the joint fabricated at a tool rotational speed of 1100 rpm.

**Keywords:** *Friction Stir Welding, MMCs, Tensile Properties and Microstructure.*

## 1. Introduction

Friction Stir Welding (FSW) was developed and patented by The Welding Institute (TWI) in 1991[1]. Friction Stir Welding is a solid-state welding technology that has proven to be very effective for joining non-ferrous materials such as aluminum alloys, copper, and magnesium [2–3]. The process is typically solid state, meaning that the process operates below the solidus temperature of the metals being joined and no melting occurs during the process. Which facilitates welds that are high in quality, strong, and inexpensive since the absence of oxidation and porosity. FSW is being successfully applied to the aerospace, automobile, and shipbuilding industries [4]. The previous papers related to FSW of metal matrix composite(MMCs) many have focused on microstructure observations of the welds. The weld nugget exhibits the relatively homogeneous SiCp distributions but has fine particle density bands. In addition, the nugget contains some porosity around the coarse SiCp and cracking of some coarse SiCp. The TMAZ, which is adjacent to the weld nugget, has been plastically deformed and thermally affected [5]. The weldability of A359/SiC/10p AlSiC MMC. Statistical experiments were performed to identify the significant variables and their effects on the hardness, tensile and bending strength, ductility and microstructure of the weld [6]. The abrasive effect of the tool pin on the ceramic reinforcement led to reduction of the particles size, but no reduction in the particles shape-factor. The hardness in the nugget was compared with base metal and it was found that it was slightly increased in TMAZ [7]. Homogeneous distribution of SiCp as well as spherodization of silicon needles and their spreading through the matrix were the dominant

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reasons for property improvement in the stir zone. Band-like arrangement of SiCp and silicon needles leads to an increase in the hardness of the transitional zone in comparison with the base composite [8]. The formation of onion rings in friction stir welds of 6061Al alloys by using different FSW parameters. Onion rings found in the welded zone is a direct evidence of characteristic material transport phenomena occurring during FSW. It was suggested that the friction stir welding process can be thought to be simply extruding one layer of semicylinder in one rotation of the tool and a cross-sectional slice through such a set of semicylinder results in the familiar onion ring structure [9-11]. This paper reveals the effect of tool rotational speed on the formation of microstructure in friction stir processed zone, thermo mechanically affected zone and heat affected zone of friction stir welded AA6061-10%SiCp MMCs. The tensile properties of the joint were evaluated and they are related with microstructure and tool rotational speed of the process.

## 2. Experimental Work

The base material used in this study was 6 mm thick rolled plate of AA6061. The chemical composition and mechanical properties of base material are presented in tables 1 & 2, respectively. Trial experiments were carried out to find the working limits of welding parameters. Friction stir welding of AA6061-10%SiCp MMCs is carried out with rotational speeds ranging from 600 to 1300 rpm and welding speeds at 0.37 to 1.25 mm/sec. It has been observed that 800 to 1200 rpm and 0.75mm/sec showed improvement in weld quality. In all the trials, the axial load was kept constant at 6 KN.

**Table 1: Chemical Composition of Base Metals (AA6061)**

| Al | Mg | Si | Cu | Cr | Fe | Mn | Ti | Zn |
|---|---|---|---|---|---|---|---|---|
| 97.9 | 0.92 | 0.5 | 0.228 | 0.219 | 0.139 | 0.053 | 0.002 | 0.002 |

**Table 2: Mechanical Properties of the Base Metal**

| Metal | YS ( MPa) | UTS (MPa) | % Elon. | Hardness Hv |
|---|---|---|---|---|
| AA6061-10%SiCp | 200 | 278 | 6.5 | 92 |

A high speed steel (HSS) tool with a shoulder of 18 mm diameter and a threaded pin of 6 mm diameter, 5.7 mm long and 1 mm pitch was used for welding as shown in Fig 1.

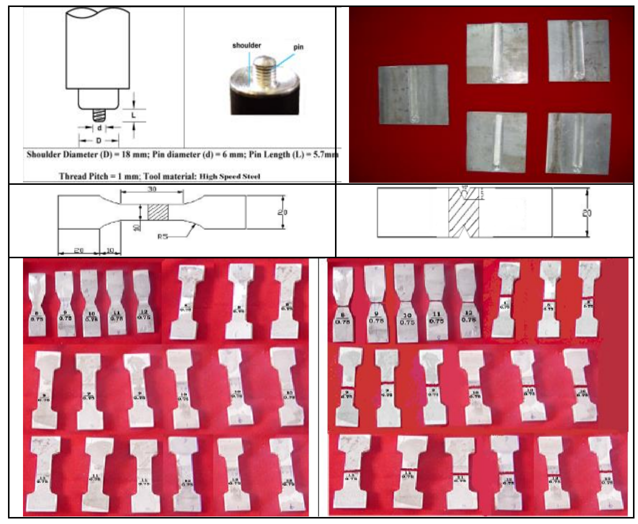



**Fig. 1 FSW Tool, Joints Photos, Dimensions of Notch and Smooth Tensile Specimens, Tensile Specimens (Before and After Tensile Test)**

Only single passes were done during friction stir welding process. The processed material was then subjected to tensile and microhardness tests. The specimens for tensile tests were cut in the longitudinal direction parallel to the welding direction. Two different tensile specimens were prepared to evaluate the transverse tensile properties. The smooth (unnotched) tensile specimens were made ready to evaluate tensile strength, elongation and reduction in crossectional area. Notched specimens were evaluated for notch tensile strength and notch strength ratio of the joints. Tensile testing was carried out using a 100 KN, electromechanical controlled UTM. The welded joints were sliced using power hacksaw and then machined to the required dimensions to prepare tensile and microstructure specimens. The specimens were polished using different grades of emery papers. Final polishing was done using the diamond compound (1μm particle size) in the disc-polishing machine. Specimens were etched with kellers reagent to reveal the microstructure. Micro structural analysis was carried out using a light optical microscope (VERSAMET-3) incorporated with an image analyzing software (Clemex-Vision). Vickers microhardness was measured with 0.5 kgf load and a dwell period of 15s.

## 3. Results and Discussion

### 3.1 Tensile properties

Fig.2 shows the tensile strength, % of

elongation, reduction in cross sectional area, notch tensile strength, NSR and joint efficiency of the weldment, AA6061-10%SiCp MMCs joints welded at a tool rotational speed from 800 to 1200 rpm.

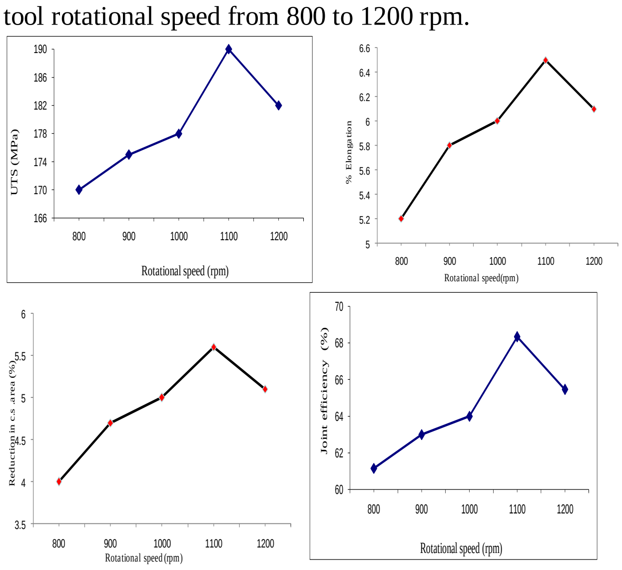



**Fig. 2 Effect of Tool Rotational Speed on Tensile Properties**

At each condition three specimens are tested and average of the results of three specimens is presented in Fig. 2. It can be inferred that at a tool rotational speed from 800 to 1200 rpm it is found that the UTS and joint efficiency keeps on increasing till 1100 rpm and the values of 190 and 68.34 it is found to be uniform flow of the plasticized metal, since with increase in tool rotational speed there is a reduction of value 182 and 65.46. Due to the UTS, the joint gets fractured in and around the HAZ and TMAZ weld region, and there by the efficiency is 68.34% due to the softening of this region. The softening of this zone is directly related to the modification of precipitates. In this region, the elevated temperatures generated during the FSW process zones and coarsen strengthening precipitates, creating a local strength minima in the region [4].

### 3.2 Macrostructure

From Fig. 3 shows the macrostructure of the defect-free joints can be obtained using 1100 rpm, because of the sufficient tool rotational speed (heat input) can improve the flow of the plastic materials. The pin hole can be found in the joint welded by the tool rotational speed from 800 to 1200 rpm, even though the specimens were taken from good appearance welded. The pin hole is formed because of the plastic material cannot flow (insufficient coalescence of transferred material) during welding process[9-13]. Consequently, the tunnel defects occur in the middle portion of the weld, this is due to insufficient or low heat generation of the metal.

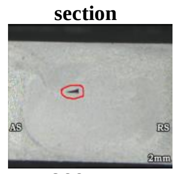
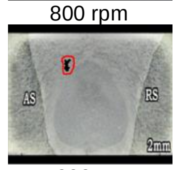
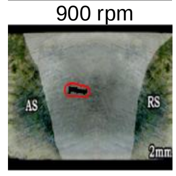
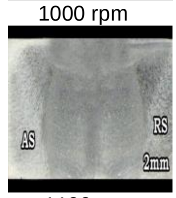
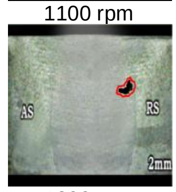
| Macrostructure of Weld cross-section | Tensile specimen | Observations |
|---|---|---|
|  800 rpm |  | Pin hole at the middle portion of the FSPZ & TMAZ in AS. Due to insufficient material flow(low tool rotational speed) |
|  900 rpm |  | Pin hole at the top portion of the FSPZ & HAZ in AS. Due to insufficient material flow(low tool rotational speed) |
|  1000 rpm |  | Pin hole at the middle portion of the FSPZ & TMAZ in AS. Due to insufficient material flow(low tool rotational speed) |
|  1100 rpm |  | No defect. Due to sufficient material flow(optimum tool rotational speed) |
|  1200 rpm |  | Pin hole at the side portion of the TMAZ & HAZ in RS. Due to excessive material flow(high tool rotational speed) |

**Fig. 3 Effect of Tool Rotational Speed on Macrostructure of Al 6061-10% SiCp MMCs (Welding Speed=0.75 mm/sec & Axial Force=6 KN)**

When the tool rotational speed is increased further at 1200 rpm, there is a defect in the weld, because of excessive coalescence of transferred metal and excessive heat generation of the metal. The weld produced at a tool rotational speed of 1100 rpm shows no defects due to the sufficient heat generation and proper plastic flow of the metal.

### 3.3 Microhardness

The microhardness of the welded specimen along its FSP, TMAZ, HAZ are measured by varying the tool rotational speed from 800 to 1200 rpm and is presented in Fig.4. It also shows that the hardness is maximum at the stir zone and hardness reduces, uniformly in the advancing and retreating side. This is due to the variation in the tool rotational speed (temperature) over the base metal and also the material flow behavior of FSW process.

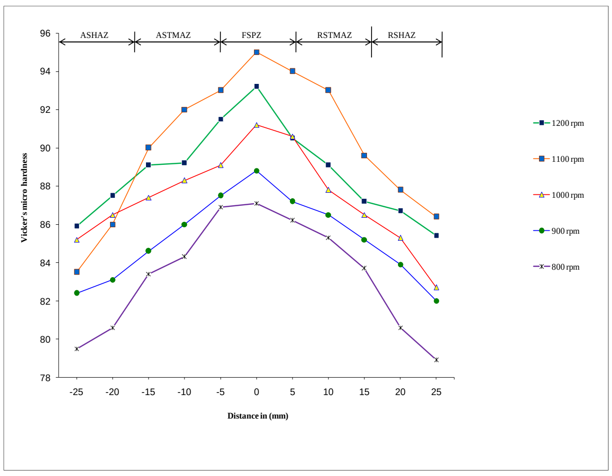



**Fig. 4 Microhardness Profile Across the FSW Region**

Fig. 4 shows gradually increases towards the stir zone, from 800 to 1200 rpm. From the graph inferred that HAZ and TMAZ of hardness values are less compared with FSPZ.

This is one of the reasons for FSW zone of Al alloy, higher hardness value compare to the base metal has been noticed [14-16]. In FSP zone of AA6061-10%SiCp higher hardness value compare to the base metal has been noticed. This is one of the reasons for superior tensile properties of the joints.

### 3.4 Microstructure

The Fig. 5 shows the dendrite microstructure of the BM is composed of a primary phase (block color stands for Al base metal) and Al-SiCp in eutectic structure (grey tiny dots are mainly SiCp).

In the BM, the SiC particles, which are shaped as plate and spherical-like, are distributed partially in the primary a phase and formed eutectic structure [5].

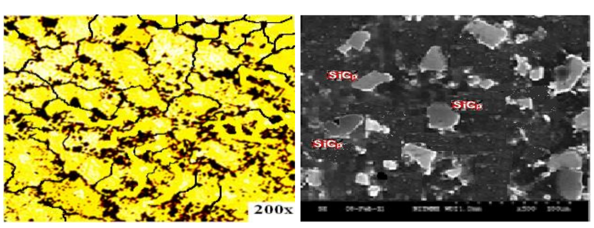



**Fig. 5 Micro and SEM images of Base Metal**

Fig.5 shows the optical microstructures of interface, SZ, TMAZ, HAZ of Al6061- 10% SiCp joints. During friction stir welding the transition regions are formed between the SZ and unaffected BM. FSW produces a fine recrystallized grain structure in the stir zone of aluminium alloys [17–18]. From fig.6 shows the very fine dynamically recrystallized structure of tool rotational speed 1100 rpm in the SZ rather than at lower (800 rpm) and higher tool rotational speed (1200 rpm). The SZ has a very homogeneous microstructure than that of the BM. The stir zone has fine recrystallized grain structures, and the eutectic SiCp was uniformly dispersed in the stir zone. The number of finer SiC particles, which is formed by stirring of the tool probe, increases during the FSW.

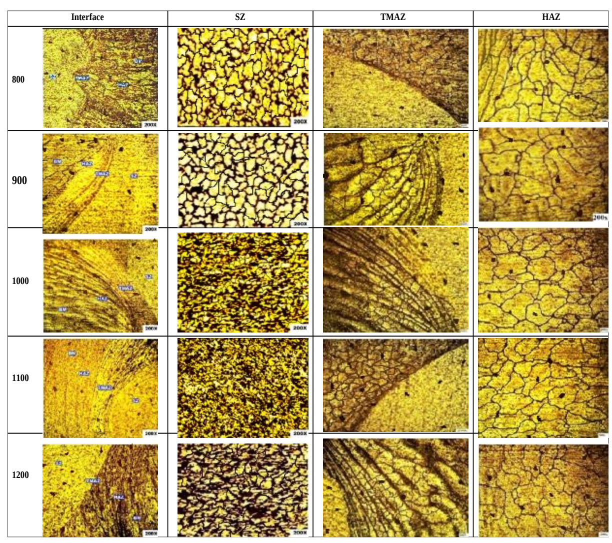



**Fig. 6 Microstructure of Interface, SZ , TMAZ and HAZ of Al6061-10% SiCp MMCs**

Fig.7 shows SEM images of the various tool rotational speed of the SZ. From fig.7 shows the 1100 rpm, the SiC particles are homogeneously dispersed in the SZ and the plate-like particles disappear. The plate-like SiCp may be broken into slightly finer particles by the stirring of the welding tool. Finer SiC particles are distributed more in the SZ than in the other regions, though the size of the SiC particles in the base metal is entirely different from the other regions. The size of the SiC particles decreases with increasing tool rotational speed. Based on these results, it is considered that the size of the SiC particles should be affected by the temperature. The SiC particles will be finer and more granular due to the solid collisions at the lower temperature as a result of the more difficult plastic deformation. The directions of the SiC particles in the stir zone were different for each region [19-21].

### 3.5 Fracture surface

The displayed fractographs invariably consist of dimples failed in a ductile manner under the action of tensile.

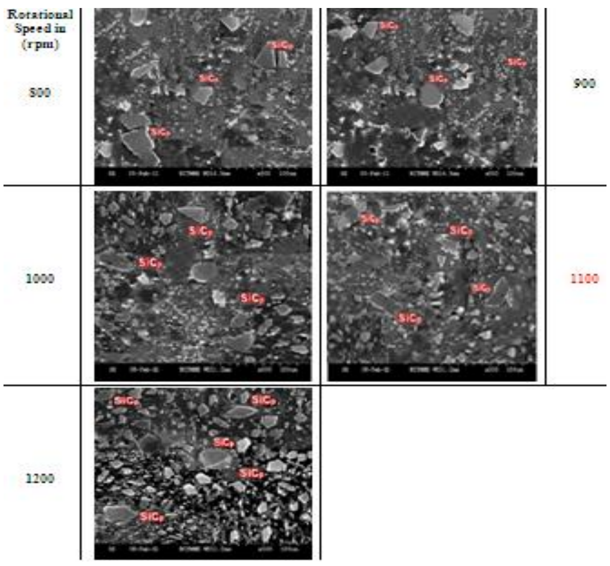



**Fig. 7 SEM Structure of Al6061-10% SiCp MMCs**

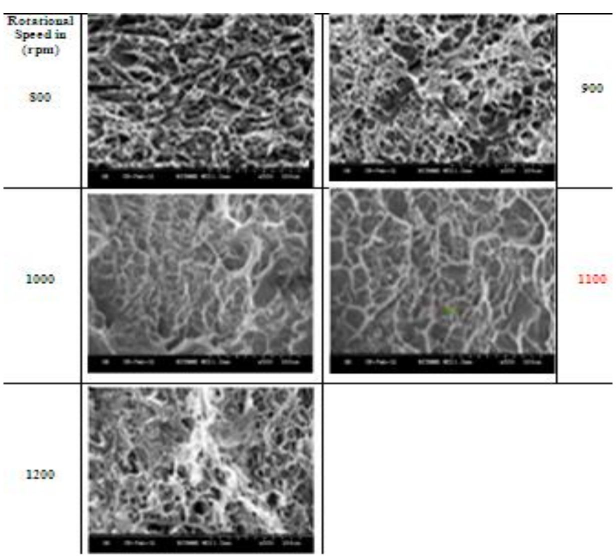



**Fig. 8 SEM Fractographs of Tensile Specimens**

### 3.5 Fracture surface

The displayed fractographs invariably consist of dimples failed in a ductile manner under the action of tensile loading. An appreciable difference exists in the size of the dimples with respect to the welding conditions (different tool rotational speeds) and heat input of the welding processes [22–23]. Very fine dimples are seen in Fig.8 (1100rpm). Since fine dimples are a characteristics feature of ductility compared to all other joints. The dimple size exhibits a directly proportional to relationship with strength and ductility. If the dimple size is finer, then the strength and ductility of the joint is higher. Lot of cracks are present with river line patterns, very few dimples are present. Overall it is brittle fracture. The tool rotational speed of 1100rpm shows very fine and more number of dimples and compared with remaining tool rotational speed.

## 4. Conclusions

The effect of tool rotational speed on the microstructure and tensile properties of friction welded AA6061-10%SiCp MMCs has been analyzed. From this investigation, the following important conclusions can be derived.

i. The five tools rotational speed welded joint, the joints fabricated by 1100 rpm exhibited higher UTS, efficiency and defect free welds.
ii. In this tool rotational speed, the microstructure shows very fine grains are observed in the SZ of the all joints and also the SiCp are distributed uniformly from the SEM analysis.
iii. The microstructure of TMAZ and HAZ region, the grains are coarser in the size compare to SZ in the joints.
iv. Hardness is higher in the stir region compared to the TMAZ, HAZ and base metal regions irrespective of tool rotational speeds.

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