# A Comparative Study of Mechanical Properties and Microstructures of FSW joints with Conventional welded joints

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***Abstract***— *Energy savings and environmental preservation are important issues for us to resolve. Since reducing the weight of vehicles is one of the efficient measures, the use of the combination of steel and aluminium alloy has been increasing in fabricating vehicles. Under this situation, many trials to weld steel to aluminium alloy have been conducted. However, sound joints have not been produced so far, because hard and brittle intermetallic compounds were formed at the weld whenever steel was welded to aluminium by fusion welding. In gas welding process the metals get heated and due to the heating of the metal the strength of the metal decreases and also the microstructure of the metal changes. But in friction stir welding the metal gets less heated compared to the gas welding process. Due to the less heat absorbed by the metal the strength and microstructure changes comparatively less than the gas welding process. So comparatively friction stir welding gives accurate microstructure and tensile strength than the gas welding process. In the present work we tried to compare the micro structure, micro hardness and tensile strength of two Friction Stir welded joint with the gas welded joint.*

***Keywords***— *Friction Stir Welding (FSW), Al alloys, mechanical properties, microstructure.*

## I. INTRODUCTION

FSW/FSP is emerging as a very effective solid-state joining/processing technique. In a relatively short duration after invention, quite a few successful applications of FSW have been demonstrated. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminium alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. The difficulty of making high-strength, fatigue and fracture resistant welds in aerospace aluminium alloys, such as highly alloyed 2XXX and 7XXX series, has long inhibited the wide use of welding for joining aerospace structures.

These aluminium alloys are generally classified as non-weldable because of the poor solidification microstructure and porosity in the fusion zone. Also, the loss in mechanical properties as compared to the base material is very significant.

These factors make the joining of these alloys by conventional welding processes unattractive. Some aluminium alloys can be resistance welded, but the surface preparation is expensive, with surface oxide being a major problem. Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminium alloys. The basic concept of FSW is remarkably simple. 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 traversed along the line of joint (Fig. 1). The tool serves two primary functions: (a) heating of work piece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the work piece and plastic deformation of work piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of

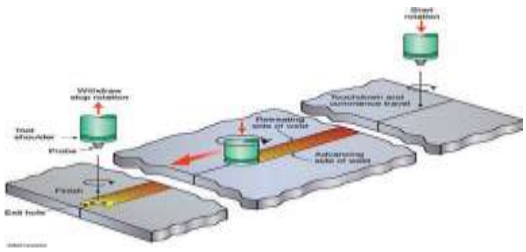

**Figure 1 Schematic drawing of friction stir welding**

Friction stir welding (FSW) is a relatively new solid-state joining process. This joining technique is energy efficient, environment friendly, and versatile. In particular, it can be used to join high-strength aerospace aluminium alloys and other metallic alloys that are hard to weld by conventional fusion welding. FSW is considered to be the most significant development in metal joining in a decade. Recently, friction stir processing (FSP) was developed for micro structural modification of metallic materials. This project focuses on process parameters that in required for producing effective friction stir welding joint. The objective of this work was to investigate the mechanical and metallurgical properties in order to demonstrate the feasibility of friction stir welding (FSW) for joining of 6063Aluminum Alloy. Four rotational speeds, 710, 1000 r.p.m and three traverse speeds 28, and 40 mm/min were applied. Metallographic examinations of friction stir welded plates were carried out using optical and scanning electron microscopy. Hardness profiles of welded joints were measured using Vickers hardness testing. The hardness profile at transfer cross sections showed marked decrease in hardness values depending on welding conditions and position of hardness measurements. The FSW welds exhibited higher joint efficiencies relative to conventional welding techniques.

## II. Material Selection

6063 is an aluminium alloy, with magnesium and silicon as the alloying elements. The standard controlling its composition is maintained by The Aluminium Association. It has generally good mechanical properties and is heat treatable and weldable. It is similar to the British aluminium alloy HE9. 6063 is mostly used in extruded shapes for architecture, particularly window frames, door frames, roofs, and sign frames. It is typically produced with very smooth surfaces fit for anodizing. 6063 is used for architectural fabrication, window and door frames, pipe and tubing, and aluminium furniture.

6063 is highly weldable, using tungsten inert gas welding. Typically, after welding, the properties near the weld are those of 6063-0, a loss of strength of up to 30%. The material can be re-heat-treated to restore a higher temper for the whole piece.


**Figure 2 Al Alloy**

The material used in this study (6063 Al alloy) , was received from Misr Aluminium Company in the form of long plates 5mmX50 mm cross section.

Tables 1, 2 and 3 show the chemical composition, mechanical and physical properties of 6063 Al

**Table 1 CHEMICAL COMPOSITION OF A6063 T1**

| **Alloy** | Si | Fe | Cu | Mg | Zn | Cr | Ti | Al | Approx melting Range |
|---|---|---|---|---|---|---|---|---|---|
| **6063 T1** | 0.25 | 0.35 | 0.1 | 0.5 | 0.1 | 0.1 | 0.1 | 98 | 582-658 $^0$C |

**Table 2 MECHANICAL PROPERTIES OF A6063 T1**

| **Alloy** | Ultimate Tensile MPA | Tensile yield MPA | E1 % | Vicker's hardness |
|---|---|---|---|---|
| **A6063** | 115 | 60 | 12 | 80 HV |

**Table 3 PHYSICAL PROPERTIES OF A6063 T1**

| **Alloy** | Coefficient of Thermal Expansion | Thermal Conductivity W/M$^0$K at (25$^0$C) | Density kg/m$^3$ | Elastic Modulus GPA |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| | µm/mm$^{0}$C | | | |
| **A6063** | 23.4 | 193 | 2.7x10$^{3}$ | 69 |

No heat treatment processes were done. Welding specimens were machined to the following dimensions (75 *150 *5 mm.) . A standard vertical milling machine was specially prepared to conduct the experiments. A special tool was designed to be adopted in the vertical milling machine head. A conical head tool with a shoulder was used A special fixture setup was designed and fabricated to clamp the two specimens to be welded. The setup proved to be rigid and reliable.

**Tool design**

A non-consumable cone steel probe was designed to be the stir welding tool .The design and fabrication of stir welding tool was done based on the general descriptions given elsewhere Tool probe was machined from W100T low alloy steel in the as annealed condition. After that, the probe was subjected to astonishing temperature (840ºC) and then oil quenched followed by tempering to achieve 59HRC. These dimensions obey the recommendations of TWI 2000 b,c related to the tool pin design. In the present study the tool diameter was 34 mm with a re-entrant angle of 1.5 degree at the trailing edge shoulder and the tapered tool pin diameter was 7.5mm at the tool pin tip (See Fig 2)

**Welding Procedure:**

The welding process was achieved using a modified head in the vertical milling machine. The plate has been welded along the plate rolling direction. The two pieces to be welded are brought into contact placed on a steel back plate and tightly clamped with holding fixtures to the traverse table of conventional milling machine. Fig.3. shows the setup of the FSW process. The welding tool was rotated in the clockwise direction and the specimens which were tightly fixed at the backing plate were travelled. After that, the rotating tool pin was traversed with constant rotational and traverse speeds.

To minimize the stresses on the tool pin, a small diameter hole was drilled in the abutting face of the weld seem at the welding start point. Firstly the rotating tool pin was inserted in the pilot and exerted compression to penetrate until the probe shoulder makes complete contact with upper side of the two mating surfaces. The tool pin rotates for a few seconds without traversing movement to generate enough frictional heat to plasticize the material under the probe shoulder.

After that, the rotating tool pin starts the traverse motion with a constant speed FSW has many welding parameters, such as tool (including shoulder and screw- like probe ) materials and design, tool rotation speed, traverse speed(welding speed) and angle of the tool, e.t.c. In this work FSW process was conducted with two variables; rotational speed(rpm) of the tool pin and traverse speed (mm/min) of the machine table. The rotational speed was chosen as : 710, 1000 rpm while the traverse speeds were 28,40 mm/min.

**Figure 3 FSW Tools**

**Figure 4 Friction Stir Welding Process**

**Testing:**

To prepare the welding zone for metallographic examinations, the samples were ground and fine polished to the mirror surface and then washed, cleaned and dried. Vickers hardness profile near the weld zone was measured on a cross section and perpendicular to the welding direction with a 100kgf load for 10s.The readings were plotted as a function of distance from welding center.

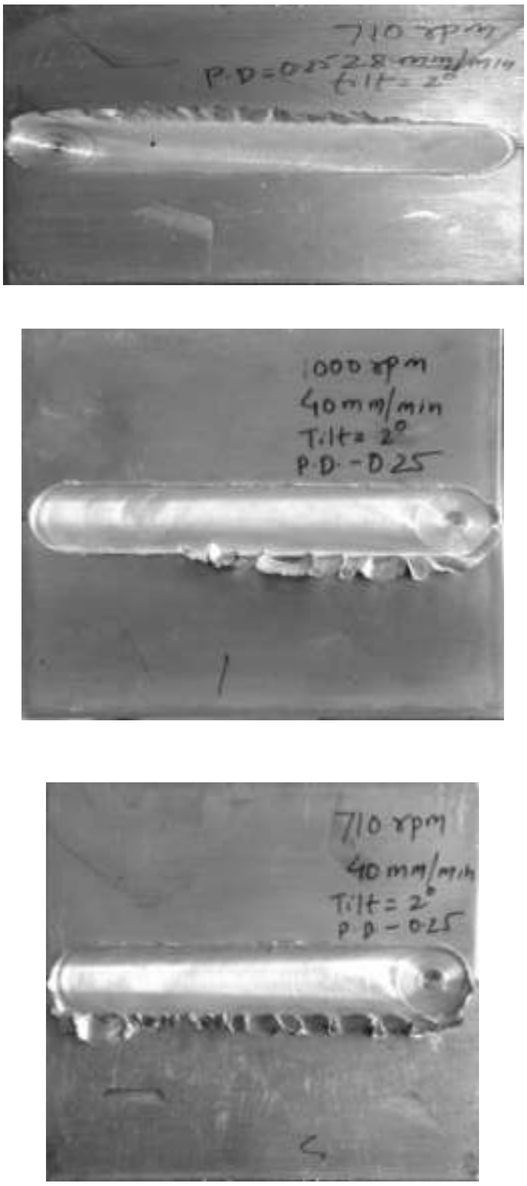


**Figure 5 Welded pieces 1, 2 & 3**

The welded samples were cut to be ready for testing on tension with standard dimensions.

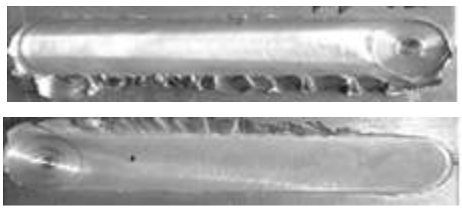

**Figure 6 Lateral finish in the joints**

Tensile tests were carried out at room temperature using an Instron–type computerized testing machine with cross-head speed of 1.9 x10-2 mm/s. To determine the tensile strength of stir zone, tensile test specimens were sectioned in the longitudinal direction to the weld line by an electro discharge machining( EDM.). The specimens were machined and ground, then cleaned with methanol and dried in a furnace to avoid inclusions in welding zone. The specimens were prepared to be tested on hardness, tension, and subjected to optical and scanning electron microscopy (SEM). Micro structural changes from the weld zone to the unaffected base metal were examined with optical microscope and SEM (Scanning Electron Microscope). The light optical microscope was used to examine the welded specimens delineated the salient micro structural features in the welded parts and to compare grain structure. Eching with keller's reagent was done, then optical microscope was used. Figures 2 and 3 represent typical examples of the difference between various welding regions due to respectively. Scanning electron micro scopes [ISM-T330A] was used for examining the welded samples and study the micro structural features of the polished samples All of the weld metallography was performed on a plane perpendicular to the welding direction at the weld centreline. Some tests were done to inspect the defects in welding zone.

**Micro Structural Observations:**

The friction stir welds of A6063 alloy 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. On the other hand, Biallas et al. suggested that the formation of onion rings was attributed to the reflection of material flow approximately at the imaginary walls of the groove that would be formed in the case of regular milling of the metal. The induced circular movement leads to circles that decrease in radii and form the tube system. In this case, it is believed that there should be thorough mixing of material in the nugget region.

Although microstructural examinations revealed an abrupt variation in grain size and/or precipitate density at these rings. It is noted that the understanding of formation of onion rings is far from complete and an insight into the mechanism of onion ring formation would shed light on the overall material flow occurring during FSW.

The contribution of intense plastic deformation and high-temperature exposure within the stirred zone during FSW/FSP results in recrystallization and development of texture within the stirred zone and precipitate dissolution and coarsening within and around the stirred zone. Based on micro structural characterization of grains and precipitates, three distinct zones, stirred (nugget) zone, thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ). The micro structural changes in various zones have significant effect on post weld mechanical properties. Therefore, the micro structural evolution during FSW/FSP has been studied by a number of investigators.

**Figure 7 AE 1000X Sample 1**

**Figure 8 AE HAZ 1000X Sample 1**

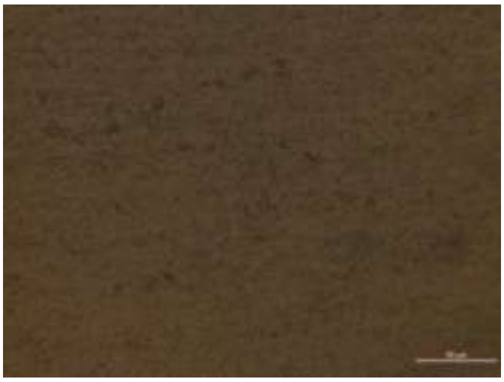

**Figure 9 AE WZ 500X Sample 1**

**Figure 10 Optical Microscope & its lens**

The hardness measurements shown in Figs. represent the hardness profiles for specimens at different rotational speed, and different traverse speeds. The hardness profiles were taken at three different locations across the weld nugget, i.e. near the weld-face, at midway through the weld nugget, and near to the root of the FSW joint. The mean values were plotted against the distance from welding centerline. In general, the hardness decreases from the base metal towards the weld centerline. This typical profile is as for some of friction stir welded aluminum alloys [6, 7] On the other hand, it decreases from the weld root towards the weld face. However, the hardness profile shows a more or less saddle pattern near the weld centerline especially near the weld face.

Such softening phenomenon has been attributed to the dynamic recovery and dynamic re-crystallization processes during FSW of aluminium alloys. The decrease in hardness from base metal to the centreline of weld nugget at constant rotational speed could be attributed to the higher degree of softening in the weld nugget.

Microstructure of the different welding zone regions respectively. Fig. exhibited three distinct micro structural zones; (a) base metal ,(b) heat affected zone HAZ,(c) and (d)weld nugget. The plastic deformation at weld interface occurred at a wide range of strain rate and temperature depending on the location; the distance from weld centerline. Therefore, at weld nugget two competing mechanisms may acted simultaneously, namely strain hardening and softening mechanisms and the observed structure may be the resultant of a repeated cycles of deformation and re-crystallization. A significant micro structural change of the investigated alloy was the recrystallization process of the weld joint.

**Figure 11 Vicker's hardness machine & Vicker's hardness values**

## III. RESULTS AND DISCUSSION

The weld root surface of all investigated weldments showed visually and ultrasonically a well joined sound flat surface. The increase in stir-probe rotational speed enhanced the weld soundness which may be a result of softening process associated with dynamic recovery and recrystallization process at the weld at the nugget.

**Mechanical Properties**

Hardness measurements across the centerline of stir welded specimens showed markedly low hardness values at weld center line (Fig). The graphs represent the typical behavior as of some FSW of aluminum alloys Such softening phenomenon can be attributed to the dynamic recovery and dynamic re-crystallization process during FSW of aluminum alloys .It could be concluded that when rotational speed is more than 1000 rpm there exists an adversely affects on the softening process. This could be attributed to the higher degree of strain hardening in weld nugget. On the other hand, the degree of recrystallization increases with the increase in both rotational and traverse speeds. This explanation was reached also by many researchers

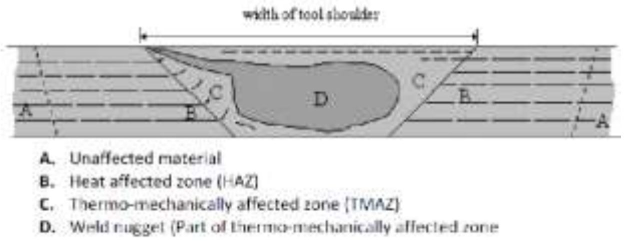


**Figure 12 Microstructure Classification**

All welded specimens were first subjected to visual inspection of weld face surface. Macroscopic examination of transverse and longitudinal cross section- showed defect free sound weldments, produced under all applied experimental conditions. Uniform semicircular surface ripples in weld track were observed. These surface ripples, which have onion rings configuration, were caused by the final sweep of the trailing edge of the continuously rotating tool shoulder. A similar observations were made by many researchers. There are surface ripples in the weld track.

After this experimentation, various points are come out from the operation of FSW and testing of welded joints.

The weld root surface of all investigated weldments showed visually and a well joined sound flat surface. The increase in stir-probe rotational speed enhanced the weld soundness which may be a result of softening process associated with dynamic recovery and recrystallization process at the weld at the nugget.

The pin diameter and shoulder diameter are increased with the increase in thickness of the plates or specimen undergoing the process of FSW. The speed of the tool is one more important parameter to be selected for the process. It is selected as per the thickness of the plates and diameter of the tool. Also suitable higher speed helps to generate higher temperature which is important requirement for the FSW process.

Also for the effective welding process the suitable higher temperature should be created during the process, so that weld quality is to be increased. The higher speed of the tool give more better quality of the weld aesthetically. As the temperature reaches to its high range the quality of weld increased i.e. quality of weld directly proportional to the temperature created during the process. As the tool pin length is more plunge depth of tool in to the work piece is more. It will take more area of swirling action of material which results in the better mixing of material to each other and weld become stronger. So that when the thickness of the plate increases the tool diameter and length of the tool get increases simultaneously. But it should not exceed the thickness of the plate.

The clamp and support arrangement acts as a heat sink that dissipates heat. The clamped side may become more hardness value and lower tensile strength. No cracks and bloe holes were observed at WN or at HEZ in all the samples because of less melting in metals and no gases used or released to trap into. As no sudden cooling in metals less chances of cracks observed.

Heat effected zones were clearly observed at the joints as the heat generated at the joints Elongated grain sizes were observed joints. They were more in sample1, next at sample 3 and lastly at sample2.because the A6063T1 is reasonably tempered metal and because of the heating and slow cooling of the metal grain size increased.

In Tensile test , it is more for sample 1, then in sample 3 and minimum in sample 2 because the ductility increases with the increase in cooling time and peak temperature generated. Higher tool speeds and high feed rates increases the peak temperature generated.

**Testing Of FSW Joint:**

When the FSW joints are tested under the microscopes we get results in various views like weld penetration, cracks or blow holes if present in the weld, heat affected zone, effect of welding on grain structure of the material. The metallurgical testing of the joints has been done in accredited lab to find out desired results. Also the results of tensile test carried out each of the joints shown in the above figures are tabulated in the following tables.

**Hardness Measurements at the Cross Section of the Weld**

The hardness measurements shown in Figs. represent the hardness profiles for specimens at different rotational speed, and different traverse speeds. The hardness profiles were taken at three different locations across the weld nugget, i.e. near the weld-face, at midway through the weld nugget, and near to the root of the FSW joint. The mean values were plotted against the distance from welding centerline.

In general, the hardness decreases from the base metal towards the weld centerline. This typical profile is as for some of friction stir welded aluminum alloys [6, 7, 8, 32, and 33] On the other hand, it decreases from the weld root towards the weld face. However, the hardness profile shows a more or less saddle pattern near the weld centerline especially near the weld face. Such softening phenomenon has been attributed to the dynamic recovery and dynamic re-crystallization processes during FSW of aluminum alloys. The decrease in hardness from base metal to the centerline of weld nugget at constant rotational speed could be attributed to the higher degree of softening in the weld nugget.

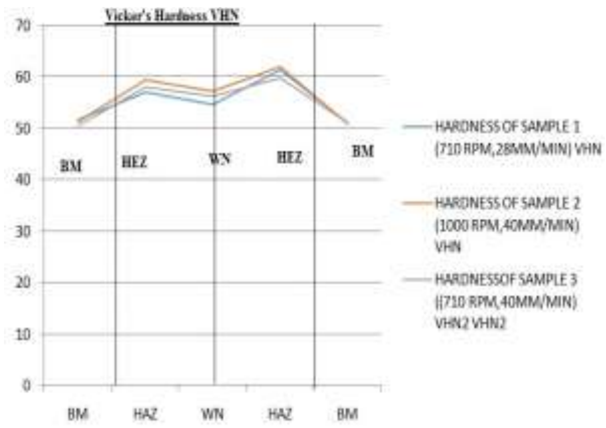


**Figure 13 Micro Hardness for Samples**

**Table 4 Micro Hardness for Samples**

| | S1 | S2 | S3 |
|---|---|---|---|
| BM | 51.61 | 51.31 | 50.59 |
| HAZ | 57.01 | 59.61 | 58.1 |
| WN | 54.68 | 57.31 | 56.3 |
| HAZ | 61.51 | 62.11 | 59.8 |
| BM | 51.09 | 51 | 51.2 |

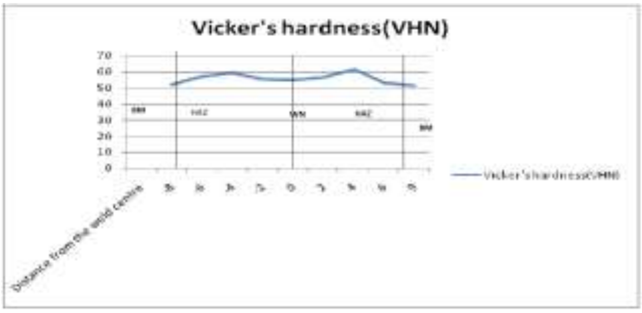


**Figure 14 Microhardness at various zones for Sample 1**

**Table 5 Microhardness at various zones for Sample 1**

| Distance from the weld centre | Vicker's hardness(VHN) |
|---|---|
| -8 | 51.61 |
| -6 | 57.01 |
| -4 | 59.08 |
| -2 | 55.03 |
| 0 | 54.68 |
| 2 | 56.02 |
| 4 | 61.51 |
| 6 | 53.01 |
| 9 | 51.09 |

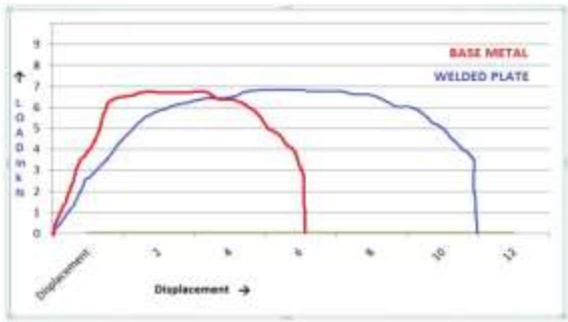


**Figure 15 Tensile Test for Base Metal & Welded plate**

The FSW process parameters were optimized with respect to mechanical and metallurgical properties of the weldments. In addition, tool pin profile has also influenced the weld quality. From this research work, it is inferred that the rotational speed of 710 rpm, traverse speed of 28mm/min is the most efficient among Friction Stir Welds when micro hardness is comparatively high in 1000 rpm and 40 mm/min. micro structure disturbance is minimum in sample1 (710 rpm ,28mm/min) because of the low temperature generation when compared to the (1000 rpm, 40mm/min) sample2 and (710 rpm, 28 mm/min) sample1.

Micro hardness is more for sample2(1000 rpm,40mm/min) with a value 0f 62.11 VHN because of the high welding temperature generated at the welding joint.

The FSW of 6063 Al alloy has been proved to be efficient and the weldments found defect free and the machine used and the designed tool proved to be reliable.

No cracks and blow holes were observed at WN or at HEZ in all the samples because of less melting in metals and no gases used or released to trap into. As no sudden cooling in metals less chances of cracks observed. Heat effected zones were clearly observed at the joints as the heat generated at the joints Elongated grain sizes were observed joints. They were more in sample1, next at sample 3 and lastly at sample2.because the A6063T1 is reasonably tempered metal and because of the heating and slow cooling of the metal grain size increased. The FSW welds exhibit high ductility of stir zone depending on the welding conditions.

In Tensile test , it is more for sample 1, then in sample 3 and minimum in sample 2 because the ductility increases with the increase in cooling time and peak temperature generated. Higher tool speeds and high feed rates increase the peak temperature generated.

When tensile strength is compared, displacement is more at the base metal because of its softness. It is been observed that The displacement is becoming less when we move from base metal to heat effected zone and heat effected zone to weld zone. It is because of the temperness or hardness generated at the heat effected zone and weld zone

When the gas welded joint is tested under UTM, it is found that ,it cannot be compared with the friction stir joints because of the high temperature generation. The extremely high temperature generated at the joints the hardness of the joint remarkably increased . Based on the results found in gas welding joints it is been concluded that the Friction Stir Processing is needed at gas welding joints and project can be taken into further step.

**Conclusions and Future Work**

In the light of the present experimental results the following conclusions could be drawn. From this research work, it is inferred that the rotational speed of 710 rpm, traverse speed of 28mm/min is the most efficient among Friction Stir Welds when micro hardness is comparatively high in 1000 rpm and 40 mm/min. micro structure disturbance is minimum in sample1 (710 rpm ,28mm/min) because of the low temperature generation when compared to the (1000 rpm, 40mm/min) sample2 and (710 rpm, 28 mm/min) sample1. Micro hardness is more for sample2 (1000 rpm,40mm/min) with a value of 62.11 VHN because of the high welding temperature generated at the welding joint. The weld soundness was improved by increasing the rotational speeds.

The FSW of 6063 Al alloy has been proved to be efficient and the weldments found defect free and the machine used and the designed tool proved to be reliable.

Dynamic re-crystal1ization in the DRZ can be considered a continuous dynamic recrystallization (CDR) on the basis of dynamic recovery. Sub grain growth associated with absorption of dislocations into the boundaries is the CDR mechanisms.

Friction stir welds exhibited more joint efficiency relative to base metal hardness depending on welding conditions and measurements location although the observed tensile strength of F.S.W welded 6063 Al was much higher than that reported after welding of the same material with other weld processes.

No cracks and blow holes were observed at WN or at HEZ in all the samples because of less melting in metals and no gases used or released to trap into. As no sudden cooling in metals less chances of cracks observed.

Heat effected zones were clearly observed at the joints as the heat generated at the joints Elongated grain sizes were observed joints. They were more in sample1, next at sample 3 and lastly at sample2.because the A6063T1 is reasonably tempered metal and because of the heating and slow cooling of the metal grain size increased. The FSW welds exhibit high ductility of stir zone depending on the welding conditions.

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## Acknowledgements:


The authors would like to express deep sense of gratitude to the Head of the Dept.(Mech) of IIT Kharagpur and IIIT Nuziveedu & Acharya Nagarjuna University, Guntur for their support and guidelines which are very helpful in improving the quality and presentation of this paper.


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