Comparative Study of Friction Stir Welding and MIG Welding For Aluminium 6066

[1]Harmeet Singh, [2]Harish Kumar, [3]Chander Shakher, [4]Gaurav Jain
[1,2,3,4]Rayat institute of Engineering and IT, Rail Majra, (Saheed Bhagat Singh Nagar), Punjab India

Abstract
Aluminium 6066 alloy is a widely used alloy in aircraft and aerospace structures, boat and ship building, architectural fabrication, pipe and tubing, cycle frames and components etc. The joining of aluminium has to be done in a way that minimum residual stresses are produced by the joining process. Two different welding processes i.e. a conventional Metal Inert Gas (MIG) welding and an innovative solid state welding process known as Friction Stir Welding (FSW) have been compared for making a butt weld joint of aluminium 6066. An experimental investigation has been carried out on microstructure, hardness distribution and tensile properties of butt weld joints of aluminium 6066 alloy. Results from the scanning electron microscope have shown that the heat affected zone of friction stir weld is narrower than MIG weld due to the lower temperature involved in the process. Microstructure study has revealed that friction stir weld has equiaxed granular structure whereas MIG weld has dendritic structure. Hardness distribution results have shown a general decay of mechanical properties of MIG welded joint as compared to the friction stir welded joint mainly due to high temperature encountered in the process. Hence from the industrial perspectives, FSW process is very competitive as it saves energy, results in higher tensile strength of the weld and no fusion related problems.

Keywords
Steel Structure; Welded Joint; Residual Stress; X-ray Diffraction

I. Indroduction

A. Friction Welding

Friction welding is a solid state welding process where no actual melting of the parent metal takes place. The basic principle of friction welding is that one of the part being welded is rotated while the other is kept stationary. The two parts are then brought together by an axially applied force. Rubbing the two surfaces together produces sufficient heat such that local plastic zones are formed and axially applied load causes the plasticized metal to be extruded from the joint, carrying with it any contaminants and oxides etc. Thus the two automatically cleaned surfaces are brought together under pressure and an inter-metallic bond is formed. Heat input is low and it is confined to the interface only, at the same time weld area is heated up sufficiently to cause grain refinement and hence improving the ductility of the weld. Thus it is a rapid, easily controlled and mechanized process extensively used in the automotive industry for welding of items such as differential casings, half shafts and bi-metallic valves etc.

One distinct characteristic of friction welding is its ability to weld alloys and combination of alloys previously regarded as unweldable.

B. Types of Friction Welding

The following are the different methods or types of friction welding:

- Conventional or continuous friction welding
- Inertia/Spin/Rotational welding
- Orbital friction welding
- Linear vibration welding
- Friction Stir welding

1. Conventional / Continuous Friction Welding

This is the original method of friction welding. In this process mechanical energy is converted to heat energy by rotating one work piece while pressing it against a stationary work piece. After a specific period of time rotation is suddenly stopped and the pressure is increased and held for another specified time producing a weld. This method of welding is also referred to as the continuous drive friction welding.

2. Inertia / Spin / Rotational Welding

This system consists of two chucks for holding the parts to be welded, one of which is fixed and the other rotating. Before welding one of the work pieces is attached to the rotating chuck along with a flywheel of a given weight. The piece is then spun up to a high rate of rotation to store the required energy in the flywheel. Once spinning at the proper speed, the motor is switched off and the parts are forced together under pressure. The force is kept on the parts to be welded after the spinning stops to allow the weld to set.

3. Orbital Friction Welding

This method overcomes some of the major limitations of the other friction welding techniques viz. its application to circular or nearly circular components and difficulty in attaining angular alignment and non uniform pattern of heat generation over the interface. Here one part is stationary and the other moves in a circular path with an orbit radius ‘e’ without rotating about its own axis. The two parts are pressed together and when sufficient heat has been generated all that is done is to reduce the orbit radius ‘e’ to zero, i.e. to bring the moving part to the centre of the stationary one to achieve perfect alignment.

4. Linear Vibration Welding

In Linear vibration welding the parts are placed in contact and put under pressure. An external vibration force is then applied to slip the pieces relative to each other, perpendicular to the pressure being applied. The parts are vibrated through a relatively small displacement known as the amplitude, typically between 1.0 to 1.8 mm, for a frequency of vibration of 200 Hz (high frequency), or 2–4 mm at 100 Hz (low frequency), in the plane of the joint. In this way the temperature of parts rises due to relative motion. When the temperature of layers rises to the required degree, the vibration is stopped and axial pressure is increased. This technique is widely used in the automotive industry, among others. A minor modification is angular friction welding, which vibrates the material by torquing them through a small angle.

5. Friction Stir Welding

Friction-stir welding (FSW) is a solid-state joining process (meaning the metal is not melted during the process) and is used

ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

for applications where the original metal characteristics must remain unchanged as far as possible. This process is primarily used on aluminium, and most often on large pieces which cannot be easily heat treated post weld to recover temper characteristics. It was invented and experimentally proven by Wayne Thomas and a team of his colleagues at The Welding Institute UK in December 1991.

(i). Advantages of Friction Stir Welding

The solid-state nature of FSW immediately leads to several advantages over fusion welding methods since any problems associated with cooling from the liquid phase are completely avoided. Issues such as porosity, solute redistribution, solidification cracking and liquation cracking are simply not there in FSW. In general, FSW has been found to produce a low concentration of defects and is very tolerant to variations in parameters and materials. A number of potential advantages of FSW over conventional fusion-welding processes have been identified as:

- Good mechanical properties in the as welded condition
- Improved safety due to the absence of toxic fumes or the spatter of molten material.
- No consumables - A threaded pin made of conventional tool steel, e.g. hardened H13, can weld over 1000m of aluminium, and no filler or gas shield is required for aluminium.
- Easily automated on simple milling machines - lower setup costs and less training required.
- Can operate in all positions (horizontal, vertical, etc.), as there is no weld pool.
- Generally good weld appearance and minimal thickness under/over-matching, thus reducing the need for expensive machining after welding.
- Low environmental impact.

(ii). Disadvantages

Nevertheless, FSW is associated with a number of unique defects. Insufficient weld temperatures, due to low rotational speeds or high traverse speeds, for example, mean that the weld material is unable to accommodate the extensive deformation during welding. This may result in long, tunnel-like defects running along the weld which may occur on the surface or subsurface. Low temperatures may also limit the forging action of the tool and so reduce the continuity of the bond between the material from each side of the weld. The light contact between the material has given rise to the name 'kissing-bond'. This defect is particularly worrying since it is very difficult to detect using non-destructive methods such as X-ray or ultrasonic testing. If the pin is not long enough or the tool rises out of the plate then the interface at the bottom of the weld may not be disrupted and forged by the tool, resulting in a lack-of-penetration defect. This is essentially a notch in the material which can be a potent source of fatigue cracks. Some disadvantages of the process have been identified as:

- Exit hole left when tool is withdrawn.
- Large down forces required with heavy-duty clamping necessary to hold the plates together.
- Less flexible than manual and arc processes (difficulties with thickness variations and non-linear welds).
- Often slower traverse rate than some fusion welding techniques although this may be offset if fewer welding passes are required.

C. Metal Inert Gas Welding

- Gas metal arc welding (GMAW), sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) is a welding process in which an electric arc forms between a consumable wire electrode and the work piece metal(s), which heats the work piece metal(s), causing them to melt, and join. Along with the wire electrode, a shielding gas feeds through the welding gun, which shields the process from contaminants in the air. The process can be semi-automatic. A constant voltage, current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used. There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray, and pulsed-spray, each of which has distinct properties and corresponding advantages and limitations.
- Originally developed for welding aluminum and other non-ferrous materials in the 1940s, GMAW was soon applied to steels because it provided faster welding time compared to other welding processes. The cost of inert gas limited its use in steels until several years later, when the use of semi-inert gases such as carbon dioxide became common. Further developments during the 1950s and 1960s gave the process more versatility and as a result, it became a highly used industrial process. Today, GMAW is the most common industrial welding process, preferred for its versatility, speed and the relative ease of adapting the process to robotic automation. Unlike welding processes that do not employ a shielding gas, such as shielded metal arc welding, it is rarely used outdoors or in other areas of air volatility.

II. Study of Literature

- H. S. Patil and S. N. Soman [2010] Friction stir welding (FSW) is a novel solid state welding process for joining metallic alloys and has emerged as an alternative technology used in high strength alloys that are difficult to join with conventional techniques. The FSW process parameters such as rotational speed, welding speed, axial force and attack angle play vital roles in the analysis of weld quality. The aim of this research study was to investigate the effects of different welding speeds and tool pin profiles on the weld quality of AA6082-O aluminium. This material has gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to-weight ratio. Tri-flutes and taper screw thread pin were used as tool pin profiles in this research. The appearance of the weld was well and no obvious defect was found using these tools. Consequently, the obtained results explained the variation of stress as a function of strain and the effect of different welding speed and pin profiles on yield strength ultimate tensile strength and elongation. The friction stir welded plates of AA6082-O by using the taper screw thread pin profile reached the ultimate tensile strength of 92.30% of the base metal ultimate strength and % elongation of 27.58%.
- Biswajit Parida et al. [2011] This study was on the development of friction stir welding (FSW) of commercial grade Al-alloy to study the mechanical and micro structural properties. The research included experiments related to the effect of FSW optimum process parameter on weld ability of Al alloy. The paper was subdivided in to two different sections: 1. Study of Mechanical properties and 2. Study of micro-structural properties. Section1 described the tensile strength of welded sample and distribution of micro hardness in different zones of FSW weld specimen and section2 contained the microstructure characterization of different zones of friction stir welds.

- Wichai Pumchan [2011] Influence of the friction stir welding on the microstructure and hardness of aluminium 6063 and 7075 was invesMIGated. The parameters which influence on welding were rotational speed of 2000 rpm, welding speed of 50-200 mm/min and tilt angle pin tool of 2° . As the result found maximum tensile strength is 105 MPa for welding speeds to 100 mm/min. For the hardness test results showed that the highest measured hardness is 152 HV at weld centre was welding speed 50 mm/min. The microstructures in welding area have structure of aluminium 7075 which expected to affect the high tensile strength and hardness testing.
- D.Muruganandam et al. [2011] Friction stir welding was performed for four different tool rotation Speeds namely 600, 800, 1000 and 1200. Defects were analyzed using radiography. It was found that defect concentration was maximum for the 600 RPM tool rotation. It was a little lesser for the 800 RPM parameter and even lesser for the 1000 RPM speed rotation. Minimum defects were observed for the highest tool rotation speed, namely 1200 RPM. An analysis of defects is given in this paper. Tensile Test values and bend test values were also reported.
- Damjan Klobcar et al. [2012] A study was made of the weld ability of 4-mm-thick aluminium-alloy 5083 plates using friction-stir welding. A plan of experiments was prepared based on the abilities of a universal milling machine, where the tool-rotation speed varied from 200 rev/min to 1250 rev/min, the welding speed from 71 mm/min to 450 mm/min and the tool tilt angle was held constant at 2°. The factors feed per revolution (FPR) and revolutions per feed (RPF) were introduced to get a better insight into the friction-stirring process. Samples for microstructure analyses, Vickers micro-hardness measurements and special miniature tensile-testing samples were prepared. The microstructure was prepared for observation on a light microscope under a polarised light source. A set of optimal welding parameters was determined at a FPR of 0.35 mm/rev, at which quality welds could be made with a minimal increase in the weld hardness and an up to 15 % drop in the tensile strength.
- L. Karthikeyan et al. [2012] Aluminium AA 2011 and AA 6063 alloys are commonly used in various aerospace and marine applications. However welding of these alloys by conventional techniques is difficult. Friction stir welding (FSW) is a recent welding technique which has gained importance in welding dissimilar aluminium alloys. In this article aluminium alloys AA 2011 and AA 6063 were friction stir lap welded and their tensile and micro structural properties were evaluated. On evaluation it was found that sound weld joints could be produced using FSW. Moreover it was observed that welding strength improved with increased tool rotation speed. Optimum tool rotational speed for defect free nugget zone was found to be 1400 rpm and tool feed was found to be 60 mm/min.

A. Summary
Till date no. of investigations has been done on friction stir welding and other conventional welding methods. Various materials are welded using these welding methods. There are no. of factors which affect the material properties after welding viz. material flow behaviour during welding, welding parameters, heat generation during welding etc. These parameters play vital role in present time were safety, strength and quality being the priorities. Investigation done by various researchers will help in predicting strength degradation of aluminium alloy welded through friction stir welding. Literature review has also outlined best methods that can be used to evaluate mechanical or physical properties after welding.

B. Need and Significance of the Proposed Work
Aluminium-6066 is used in aircraft and aerospace structures, ship and boat building, architectural fabrication, window and door frames, pipe and tubing, and aluminium furniture, cycle frames etc. For the high end applications like aerospace, aircraft, ship and boat building etc. safety and reliability is a crucial point of view. One most important factor in the welding of aluminium is the stresses induced during welding need to be addressed. Many welding techniques have been used for welding aluminium like friction welding, friction stir welding, arc welding, spot welding, tungsten inert gas welding, metal inert gas welding etc. Out of these friction stir welding is gaining popularity in comparison to the MIG welding. Mechanical properties as well as microstructure need to be carefully evaluated as a little alteration of these properties may lead to premature failure of welded structures. MIG welding has been chosen for comparison since it is the most widely used process.

C. Experimental Setup
Setup can broadly be classified into following categories:
- Preparation of Specimen for welding
- Welding operations

Preparation of Specimen for Welding First of all specimen of 4× (150×70×6) of Al-6066 were prepared by friction stir welding as well as for MIG welding. After welding is done different samples were taken for different types of testing.
The testing setup basically consists of following main element:
- Tensile testing on Universal testing machine
- Hardness testing on Vickers hardness testing machine
- Microstructure evolution on Scanning electron microscope machine

1. Tensile testing
For tensile testing the samples are prepared as shown in fig. 1 and its testing is done on Universal testing machine as shown in fig. 2.

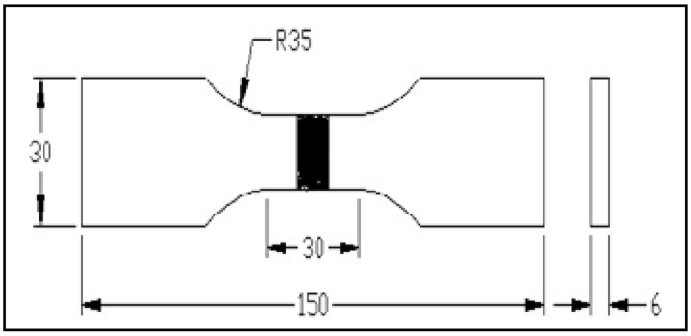

Fig. 1: Tensile Test Specimen

In the tensile testing following parameters are measured:
1. 0.4 % proof stress: It is the maximum stress that is required to cause a permanent extension of to 0.3 % of gauge length .
2. Tensile strength: It is calculated by dividing the maximum load which a specimen is subjected during the test by the original area of cross-section of sample.
3. Percentage elongation: It is the ratio of increase in gauge length of specimen to the original gauge length expresses

 ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

as a percentage.

Fig. 2: Tensile Testing on UTM

2. Hardness Testing

Hardness is measured at different locations using Vickers hardness testing machine. For hardness testing 500 gf load was used for 15 seconds. Hardness points are taken in perpendicular direction from the weld at -5,-10,-15,-30, 0, 5,10,15,30 mm respectively. Their distribution is shown in fig. 4.4. Vickers hardness at a point is measured by the equation as given by ISO 6507-1:2005:

$$HV = \frac{0.1891F}{d^2}$$

Where F is the force applied in Newton and d is the average length of the diagonal left by the indenter in millimetres.

3. Microstructure Evolution

For SEM analysis spots considered were weld nugget, TMAZ, HAZ, and base metal. (TMAZ only for FSW). Micro structural changes were examined with scanning electron microscope (SEM) operating at 15kv. For the microstructure images the cross-section of the different spots was polished and then etched with Keller's reagent. Keller's reagent consists of composition as shown in Table 1:

Table 1: Keller's Reagent Composition

Element	Composition
Distilled water	95ml
Nitric acid (hno_3)	2.5ml
Hydrochloric acid (hcl)	1.5ml
Hafnium (hf)	1ml

IV. Results and Discussion

In this chapter various results obtained from tensile testing, hardness testing, SEM microstructure for FSW and MIG welding is compared with the base metal as follows:

A. Tensile Testing

Results of tensile testing are tabulated in Table 2

Table 2: Tensile Testing Results

SPECIMEN / TESTING	0.4% Proof Stress (MPa)	Tensile Strength (MPa)	Percentage Elongation (%age)
Base Metal	160	195	14
FS Welded	107	139	7.19
MIG Welded	103	131	6.12

1. Proof Stress

Aluminium 6066 lower than the parent metal but are better than conventional welding methods i.e. MIG welding. For both FSW and MIG joint the fracture location was in weld region. It is found that, in FSW the fracture location is between weld nugget and the thermo mechanically affected zone (TMAZ) on the advancing side because of the weaker bond region between TMAZ and weld nugget as nugget region has equiaxed grains while the TMAZ region has coarse grains. The joint efficiency which is the ratio of tensile strength of welded joint to the tensile strength of base metal is near about 70% for friction stir welding as compared to 67% in MIG welding. Degradation of 0.4% proof stress and percentage elongation is 33% and 48% respectively for FSW. For MIG welding degradation of 0.4% proof stress and percentage elongation is 36% and 56% respectively.

B. Hardness Testing (Hv)

The Vickers hardness profile of the welded plates was measured at mid thickness on a cross -section perpendicular to the welding direction using Vickers hardness tester with 500 gf load for 15 seconds Hardness points are taken at the nugget, TMAZ(for FSW), HAZ and base metal at a perpendicular direction from the weld at 0, -5,-10,-15,-30,5,10,15,30 mm respectively their distribution is shown in fig. 4.1. The Vickers hardness of the base metal was 80 Hv. The hardness of MIG joint in the weld metal region was 39 Hv. This shows that the hardness is reduced in MIG joint due to higher heat input and use of lower hardness $AlSi_5$ filler metal.

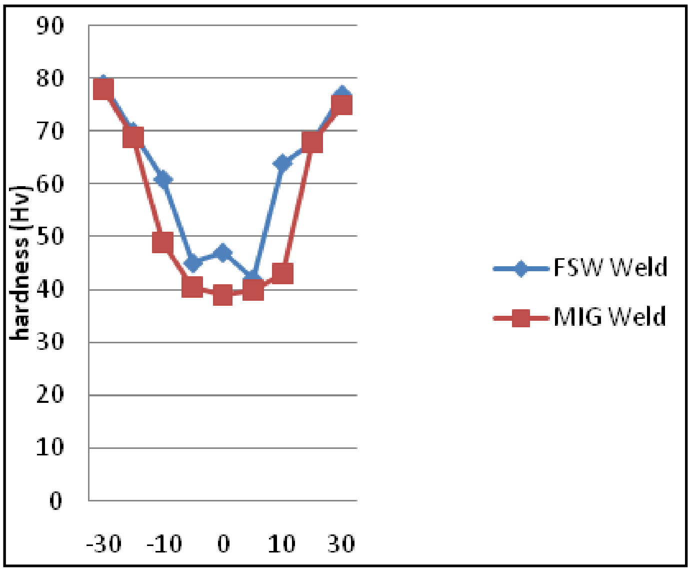

Fig. 3: Hardness Profile (Hv) FSW v/s MIG

The Vickers hardness of FSW joint in the weld region is 47 Hv. In FSW joint lowest hardness is observed on the advancing side which 42 Hv. The hardness is lower than the base metal due to dissolution of strengthening precipitates during the weld thermal cycle. However, FSW showed higher hardness compared to MIG joint due to shear stresses induced by tool motion which lead to generation of very fine grain structure, which allows a partial recovery of hardness in the weld nugget. In case of MIG welding, very high arc temperature increases the peak temperature of the molten weld pool causing a slow cooling rate. This slow cooling rate, in turn, causes relatively wider dendritic spacing in the fusion zone.

C. Microstructure

Fig. 4 shows the microstructure of base metal which has a uniform structure with uniformly distributed very fine strengthening precipitates. Fig. 6 and 7 shows the weld nugget zone and heat affected zone of FSW (a) and MIG (b) respectively. The weld zone of FSW joint contains equiaxed grains and it is due to the dynamic recraystallisation during FSW process. The fusion zone (weld nugget) of MIG joint contains dendritic structure and it may be due to fast heating of base metal. Strength of base metal is due to alloying elements such as silicon and magnesium. These elements combine to form strengthening precipitates β”- Mg5Si6. These precipitates are stable at temperatures below 200oC. In MIG HAZ and Weld nugget strengthening precipitates are lower than the base metal due to higher temperatures. In FSW temperatures are

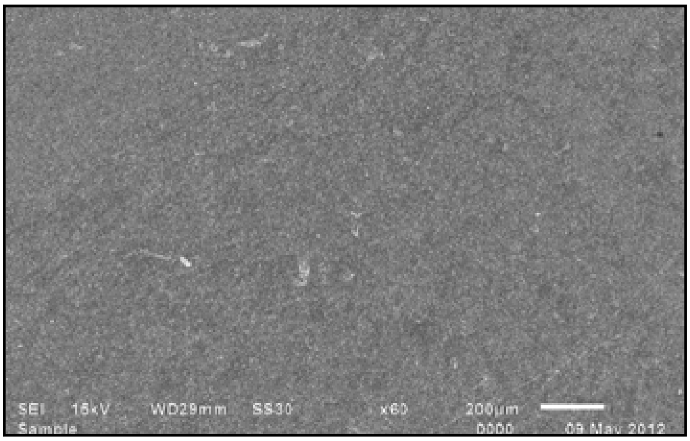

Fig. 5: SEM image of Base Metal

over 200-250°C and β” is easily dissolved. In weld nugget temperatures are higher therefore Mg_2Si precipitates goes into the solution. During cooling, precipitation time is limited due to which only a small fraction of β’ precipitates are formed. The nugget hardness recovery is due to recrystalization of very fine grain structure and by natural aging. In FSW, friction heat softens the welded material at a temperature less than its melting point. The softened material underneath the shoulder is also subjected to extrusion by the rotating tool. It is expected that this process will inherently produce a weld with relatively few residual stress and distortion.

When aluminium alloys are welded using non-heat treatable AlSi filler metal to avoid solidification cracking problem, the weld material is composed of fewer strengthening precipitates compared to base metal. In fusion welding even though, large amount of silicon is available in base and filler metal (the available magnesium which is present in base metal alone) for precipitation reaction in the weld pool its content is very low. Hence, the weld region of 6066, when welded with AlSi5 filler metal usually contains lower amount of strengthening precipitates compared to the base metal region. Therefore the precipitate strengthening of Mg_2Si precipitates is weak in MIG joints. On the other hand, the weld region of FSW joint contains the alloying elements similar to the base metal.

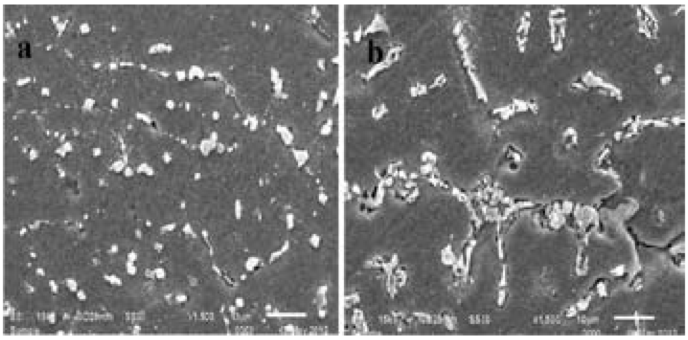

Fig. 6: SEM images of weld nugget: a) FSW, b) MIG

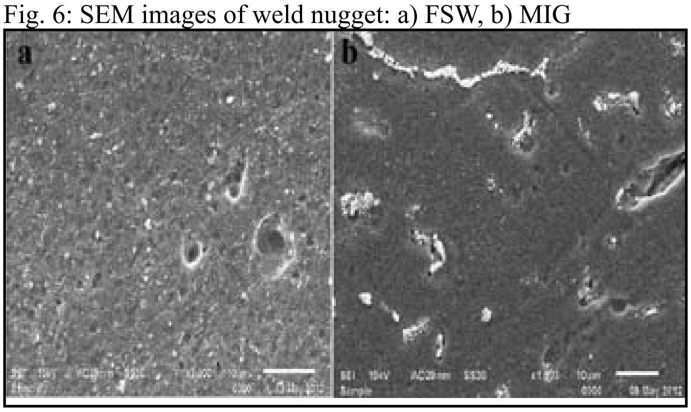

Fig. 7: SEM images of HAZ: a) FSW b) MIG

The friction-stir process produced precipitate differing from those in the base material, which has a high density of needle shaped precipitates with a low density of b8 precipitates. Between 12.5 and 10 mm from the weld center the density of needle shaped precipitates decreases. All precipitates are dissolved within a region of 8.5mm from the weld, all these combindly results in softening of weld.

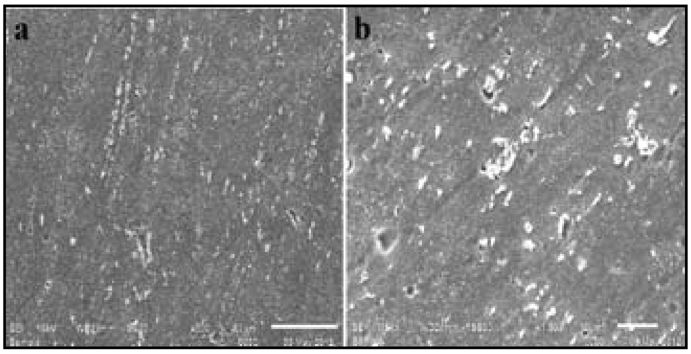

Fig. 8: SEM images of TMAZ of FSW at (a) 500X (b) 1500X

Fig. 8 shows the images for thermo-mechanically affected zone for FSW whose properties lies in between those of base metal and heat affected zone. It is a zone which has recovered grains.

V. Conclusion

On the basis of experimental investigation carried out on FSW and MIG welded joints of AA 6066, the following conclusions are drawn:

- The formation of fine, equiaxed grains and uniformly distributed very fine strengthening precipitates in the weld region is the reason for superior tensile properties of FSW joints as compared to MIG joints.
- Tensile test results shows that FSW joints have higher

ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

strength and higher ductility compared to MIG joints. The joint efficiency which is the ratio of tensile strength of welded joint to the tensile strength of base metal is 3% more in FS welding in comparison to MIG welding.

- Hardness tests confirm the general decay of mechanical properties induced by higher temperature experienced by material in case of MIG joint.
- Hardness tests performed in case of FSW joint shows great differences among four different zones: nugget zone, TMAZ, HAZ (Heat affected zone) and base metal. The first two zones are characteristized by a general drop of mechanical properties, even though nugget zone showed a slight recovery due to fine grain structure.

From industrial perspectives, FSW is very competitive because it saves energy due to less heat input, prevents joints from fusion related defects, is cost effective and has better strength than MIG joint.

References

[1] H. S. Patil, S. N. Soman,"Experimental study on the effect of welding speed and tool pin profiles on AA6082-O aluminium friction stir welded butt joints", International Journal of Engineering, Science and Technology Vol. 2, No. 5, pp 268-275, 2010.

[2] Biswajit Parida, Sukhomay Pal, Pankaj Biswas, M M Mohapatra, Sujoy Tikader,"Mechanical and Micro-structural Study of Friction Stir Welding of Al-alloy", International Journal of Applied Research In Mechanical Engineering (IJARME), Vol. 1, Issue-2, 2011.

[3] Wichai Pumchan,"The Influences of the Friction Stir Welding on the Microstructure and Hardness of Aluminium 6063 and 7075", International Conference on Advanced Materials Engineering, Vol. 15, 2011.

[4] D.Muruganandam, K.S.Sreenivasan, S.Ravi Kumar, "Study of process parameters in friction stir welding of dissimilar aluminium alloys", Proceedings of the 2011 International Conference on Industrial Engineering and Operations Management Kuala Lumpur, Malaysia, 2011.

[5] Damjan Klobcar, Ladislav Kosec, Adam Pietras, Anton Smolej,"Friction-stir welding of aluminium alloy 5083, Materials and technology", Vol. 46, Issue 5, pp. 483–488, 2012.

[6] L. Karthikeyan, M. Puviyarasan S. Sharath Kumar B. Balamugundan,"Experimental studies on friction stir welding of aa2011 and aa6063 aluminium alloys", IJAET Vol. 3, Issue 4. pp. 144-145, 2012.

Harmeet Singh is working as Assistant Professor in RIET, Railmajra, Punjab, India.

Harish Kumar is working as Associate Professor in RIET, Railmajra, Punjab, India.