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# Effect Of Process Parameters On Mechanical Properties Of Friction Stir.Welded Joint Of Two Similar &Dissimilar Al-Alloys

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***Abstract***
Friction Stir Welding (FSW) is an advance joining process for different similar and dissimilar materials. It is commonly used for joining of Aluminum alloys. However it is necessary to overcome some challenges for its wide-spread uses. Tool design and the selection of process parameters are critical issues in the usage of this process. This study focuses on the process parameters that is required for producing effective friction stir welding of two similar aluminum alloys (AA6101T6 to AA6101T6) and dissimilar Aluminum alloys (AA6101T6 alloy to AA6351T6) . Three different tool diameters such as 20 mm, 25 mm and 30 mm with three different tool rotational speeds such as 600 rpm, 800 rpm and 1200 rpm have been used to weld the joints. The welded samples were tested for mechanical properties as well as microstructure. It was observed that 30 mm tool gives better weld quality for friction stir welding of similar aluminum alloy but 25 mm tool with 1200 rpm rotational speed gave satisfactory weld quality for friction stir welding of dissimilar aluminum alloys. It is one of the important welding process that can adopted for welding of aluminum alloys with excellent mechanical properties. The results were confirmed by further experiments.
***Keywords***— FSW, similar & dissimilar Al-Alloys mechanical properties, tensile strength, hardness, microstructure

## I. INTRODUCTION

This Friction stir welding (FSW) is a solid-state process, which means that the objects are joined without melting of base metals. It is a dynamically developing version of pressure welding process. In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged in to the joint area between two pieces of sheet or plate material [1]. The schematic representation of FSW process is shown in Fig-1 In FSW process,[2] a non consumable tool is used for joining the plates. The parts which are to be joined should be properly clamped to prevent separation. The frictional heat between the wear resistant welding tool and the work pieces causes latter to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticized material transformed to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling a solid phase bond is created between the work pieces The production of components of aluminum alloys is not very complex; but joining of these materials can sometimes cause serious problems. Lack of structural transformations in solid state and excellent thermal and electrical conductivity causes problems in fusion and resistance welding of aluminum alloys. That led to the development of friction stir welding a solid state joining technique in which the joined materials is plasticized by heat generated by friction between the surface of the plates and the contact surface of a special tool, composed of two main parts: shoulder and pin. Shoulder is responsible for the generation of heat and for containing the plasticized material in the weld zone, while pin mixes the material of the components to be welded, thus creating a joint. This allows for producing defect free welds characterized by good mechanical properties[3].

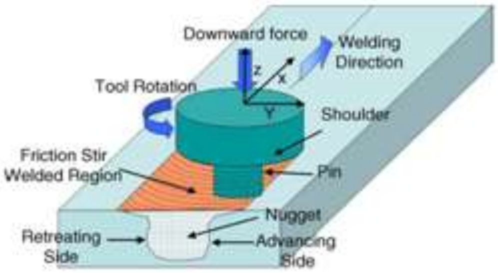

Fig. 1 Friction stir welding process [2]

K. Elangovan et al. (2008) studied the influence of tool pin profile and welding speed on the formation of friction stir processing (FSP) zone in AA2219 Aluminum alloy. Here five different tool pin profiles (straight cylindrical, frustum cylindrical, threaded cylindrical, conical and square) with three different shoulder diameters have been used to fabricate the joints at three different welding speeds. The formation of FSP zone has been analyzed microscopically. Tensile properties of joints have been evaluated and correlated with the FSP zone formation. It is found that the square pin profiled tool produces mechanically sound and metallurgic ally defect free welds compared to other tool pin profiles [4]. H. S Patil et al. (2010) had done the experimental study on the effect of welding speed and tool pin profiles on AA6082-0 Aluminum friction stir welded butt joints. They conclude that the appearance of weld is well and no defect was found. Variation of stress is function of strain. The effect of different welding speed and tool pin profile is on ultimate tensile stress and elongation. The joint fabricated using taper screw thread pin exhibits superior tensile properties [5]. Adamowski J ,and Szkodo M, (2007) studied the friction stir welds of Aluminum alloy AW6082T6. They conclude that the hardness of both the heat affected zone and the weld nugget is lower than that of the base metal. Tensile strength of FSW weld is directly proportional to welding speed. Hardness drop observed in weld region [6]. Cabibbo M., et al. (2007) studied the microstructure and mechanical properties ofAA6056 friction stir welded plate. They investigated their work by using polarized optical and transmission electron microscopy techniques. Tensile test showed yield and ultimate strength slightly lower across the weld compared to parent material. This difference causes reduction in ductility of the weld region [7]. Wang D. & Liu S. (2004) done study of friction stir welding of Aluminum .They found that the microstructure of the FSW weld consists of very fine and equiaxed grains instead of the coarse and band-like structure of the half cold-hardening Aluminum plate and the heat-affected zone is very small. Tensile strength of the weld is about 20% lower than that of the hardening Aluminum plate, but about 10% higher microhardness is demonstrated by the welds in comparison with that of the Aluminum plate in annealing condition. Both of the micro hardness and tensile strength of the FSW weld are affected by travel rate of the welding head pin. Good welds can be produced when pin and shoulder diameters of the welding head are in the proportion of 1:3 and the best visual quality [8] . Sakthivel T, et al (2008) studied the effect of welding speed on micro-structure and mechanical properties of friction–stir welded Aluminum. They concluded that the microstructure of weld nugget consists of fine equiaxed grains. These grains are more homogeneous at lower welding speed than at higher welding speed. Size of the weld zone becomes wider when decreasing the traverse speed as result of a large amount of frictional heat and easy material flow. Weld zone hardness is decreasing as compared to the parent metal but the hardness slightly increases with the increase of welding speed. The ultimate tensile strength increases when traverse speed decreases. Best mechanical properties obtained at low traverse speed due to homogeneous grains and higher heat input [9]. Yeni C, (2008) studied the post weld aging on the mechanical and micro-structural properties of friction-stir welded Aluminium alloy 7075. They found that left helical screw yields higher mechanical properties than right helical screw when tested at the same diameter. There is no porosity observed in nugget region. The post weld aging process compensates the hardness decrease observed in as-welded joints; no significant decrease in hardness is obtained throughout weld region [10]. Biswajit Parida, et al. (2014) studied the effect of Tool Geometry on Mechanical and Micro-structural properties of Friction Stir Welding of Al-alloy. They found that straight cylindrical tools shown better strength compared to tapered cylindrical tool [11]. With this motive the present work is attempt to investigate the effect of process parameters (rotational speed, welding speed and types of tool pin profile) on mechanical and micro structural properties of friction stir welded of two similar and dissimilar aluminum alloys.

## II. EXPERIMENTAL PROCEDURE

Friction stir welding set up has been made on copy a milling machine having capacity 1.5 HP made in U.S.A. The selected materials for this study were Al 6101 T6 and Al 6351 T6. The chemical compositions and mechanical properties have been given in Table 1 and 2. . The AISI D2 steel rod has been used for fabricating FSW tool in this study. The chemical composition and mechanical properties of FSW tool is shown in Table3 &4. FSW Tool design specification has been shown in table . 5.. It has excellent abrasive resistance and fatigue strength. A duplex microstructure with coarse complex carbide as shown in Fig..2 provides the steel with high wear resistance and good toughness. The fabricated friction stir welding tool has two. main parts: shoulder and round bottom cylindrical pin as shown in Fig.3. The fabricated steel FSW tool has been heat treated. In this process FSW tool was attached to the tool post and rotated tool has been plunged into the joint line between two pieces of working plate material(AA6101T6&AA6101T6) for similar FSW and(AL6101 T6& AL6351 T6 ), for dissimilar FSW which were butted together as shown in FSW set up Fig. 4 .The working plates have been clamped rigidly clamped onto a backing plate in a manner that prevents the abutting joint faces from being forced apart. The length of tool pin was slightly less than the Weld depth required weld depth required and the tool shoulder had been in intimate contact with the work piece surface during welding process. Frictional heat is generated between the wear resistant welding tool shoulder and pin, and the material of the work-pieces. This heat, along with the heat generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without reaching the melting point (hence cited a solid-state process). As the pin is moved in the direction of welding the leading face of the pin assisted by a special pin profile, forces plasticized material to the back of the pin while applying substantial pressure force to consolidate the weld metal [12] The dimension of the work piece has been kept 160 mm × 50 mm ×12 mm for each of the Al-alloy for making FSW butt joint as shown in Fig. 5. The process parameters such as tool shoulder diameter, tool rotational speed & feed rate were considered by keeping the axial force constant. Welded plates were cut from transverse direction using power saw to prepare samples for micro structural and mechanical examination. For micro structural examination samples were polished using standard metallographic procedures and then polished samples were etched with the Keller's reagent. Etched samples were then examined using scanning electron microscope (Hitachi S-3000N) made in Japan.& Field emission scanning electron microscopy (ZEISS) For tensile studies, the samples were prepared according to the ASTM E8 standards by Universal Milling machine and tests were carried out at a cross head speed of 0.5 mm/min by universal testing machine

Table 1: Chemical compositions of the working materials

| Al Alloy | Cu | Mg | Si | Fe | Mn | Al |
|---|---|---|---|---|---|---|
| 6101 T6 | 0.05 | 0.65 | 0.5 | 0.5 | 0.03 | rest |
| 6351 T6 | 0.10 | 0.80 | 0.95 | 0.60 | 0.70 | rest |

Table 2: Mechanical properties of working materials

| Al Alloy | UTS (Mpa) | YS (Mpa) | Elongation (%) | Hardness (VHN) |
|---|---|---|---|---|
| 6101T6 | 220 | 195 | 15 | 71 |
| 6351T6 | 310 | 285 | 14 | 95 |

Table3: chemical composition of FSW tool

| Constituents | C | Si | Mn | P | S | Cr | Fe |
|---|---|---|---|---|---|---|---|
| Wt % | 1.82 | 0.479 | 0.61 | 0.028 | 0.036 | 11.939 | Bal. |

Table 4: FSW tool material mechanical properties

| Properties | Values |
|---|---|
| Density | 7700 kg/m$^3$ |
| Modulus of Elasticity | 210 Gpa |
| Hardness, Brinell | 255 |
| Ultimate tensile strength | 1736 Mpa |
| 0.2% offset yield strength | 1532 Mpa |
| Poisson's ratio | 0.27-0.3 |

Table 5: Tool Design and specification

| Tool | shoulder | Probe | | |
|---|---|---|---|---|
| | Diameter (mm) | Base diameter (mm) | Top diameter (mm) | Length (mm) |
| 1 | 20 | 9 | 7 | 11.5 |
| 2 | 25 | 7 | 5 | 11.5 |
| 3 | 30 | 7 | 5 | 11.5 |

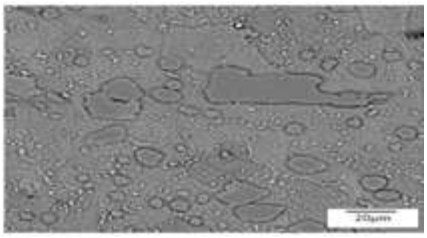

Fig. 2 Microstructures of AISI D2 tool steel


Fig. 3 FSW tools with threaded tip

Fig. 4 FSW experimental Set-up

Fig. 5 working AL-plates to be welded

## III. Results & discussion

Defect free FSW samples were made by considering the process parameters such as tool shoulder diameter, tool rotational speed and welding speed. On the basis of literature reviewed, following process parameters have been selected for study, their ranges and nomenclature used for specimens are mentioned on the Table 6 and 7

**Table 6: Selected process parameters for FSW**

| Sl. weld no. | Parent material (P1) Al 6101 T6 | Parent material (P2) Al 6351 T6 | Tool dia. (mm) | Tool rotational Speed (rpm) | Welding speed (mm/min) |
|---|---|---|---|---|---|
| 1 | Al 6101 T6 | Al 6101 T6 | 25 | 800 | 13 |
| 2 | Al 6101 T6 | Al 6101 T6 | 30 | 800 | 13 |
| 3 | Al 6101 T6 | Al 6351 T6 | 25 | 800 | 13 |
| 4 | Al 6101 T6 | Al 6351 T6 | 25 | 1200 | 12 |

tensile specimens.

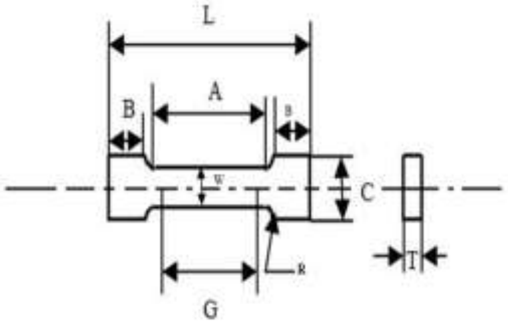


Fig. 6 Tensile test specimen diagram

G - Gauge length = 25mm
W – Width = 6 mm
T – Thickness = thickness of material = 12 mm
R – Radius of fillet = 6mm
L – Overall length = 100mm
A – Length of reduced section = 32mm
B – Length of grip section = 30mm
C – Width of grip section = 10mm

Two tensile specimens for every welded sample and the parent material were fabricated. Total twelve specimens for tensile test, coding 1a, 1b, 2a, 2b, 3a, 3b, 4a, 4b, P1andP2 were fabricated. Tensile specimens are shown in Fig. 7 the fracture occurred at the centre of marked gauge length. The tested tensile test samples have been shown in Fig 8

Fig. 7 Tensile test samples

Fig. 8 Tested tensile test samples

Table 7 Tension test results

| Specimen no. | UTS (Mpa) | Elongation (mm) | Percentage elongation (%) |
|---|---|---|---|
| 1a | 91.07 | 28.2 | 12.8 |
| 1b | 93.24 | 28.3 | 13.2 |
| 2a | 117.89 | 28.5 | 14 |
| 2b | 122.97 | 28.8 | 15.2 |
| 3a | 96.83 | 29 | 16 |
| 3b | 99.20 | 29 | 16 |
| 4a | 102.79 | 28.5 | 14 |
| 4b | 111.24 | 28 | 12 |
| P1 | 201.44 | 31.5 | 24.4 |
| P2 | 302.94 | 30 | 20 |

*3.2.1 Effect of process parameter on Ultimate tensile strength:-*

Figure 9 depicts that increase in tool rotation affect the ultimate tensile strength in similar & dissimilar weld joint. The strength of both welds joint is less than strength of parent materials. Ultimate tensile strength of the weld joint increases with rotational speed of tool. And shoulder diameter of the FSW tool. Weld no. 1&2 are similar welded joints where as weld no.3&4 are dissimilar weld joints. Ultimate Tensile strength of friction stir welding of similar aluminums alloys is more than dissimilar aluminums alloys, which are welded with same shoulder diameter, same rotational speed, same welding speed. It is because proper mixing of material at weld location is not taking place of different melting points of dissimilar aluminum alloys.

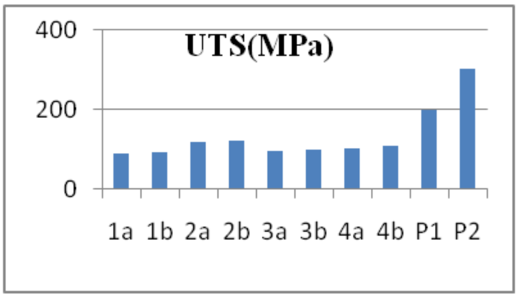


Fig. 9 Ultimate Tensile strength of parent materials and weld joints.

*3.2.2. Effect of process parameter on Elongation*:-

From Fig.10 it has been observed that as the tool rotation increases percent elongation also decreases in case of similar& dissimilar weld joints It has also been observed that percentage elongation of both the welds joint less than that of parent materials.

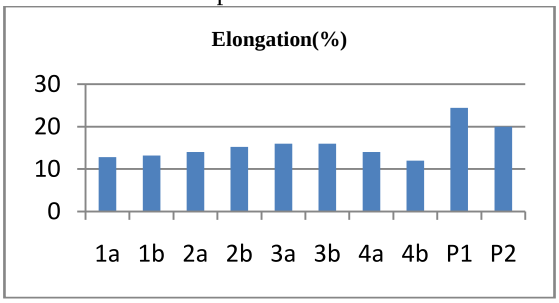


Fig 10: % Elongation of base metal and welds

## IV. Brinell Hardness test:-

Hardness number for the welding cross section evaluated by Brinell's hardness test. Figure 11 shows specimens for hardness test. The Brinell hardness number (BHN) can be calculated by dividing the load applied to the surface area of the indentation. This indentation was measured and the result was calculated as;

$$BHN = \frac{2P}{\pi D\left[D - \sqrt{D^2 - d^2}\right]}$$

Where, P= Load on the indentation tool Kg.
D= diameter of steel ball in mm

Fig. 11 Brinell hardness tested samples specimen

| Specimen no. | points | Indentation dia.(d)(mm) | Brinell hardness (BHN) |
|---|---|---|---|
| 2 | a | 4 | 47 |
| | b | 3.7 | 58 |
| | c | 3.9 | 51 |
| 3 | a | 3.9 | 51 |
| | b | 3.7 | 58 |
| | c | 3 | 95 |
| 4 | a | 4.1 | 44 |
| | b | 3.7 | 58 |
| | c | 3.1 | 88 |

Table no. 8 Result of hardness test

### *4.1 Brinell Hardness Analysis*:-

Variation of hardness on specimen 2 across various regions of welded joints is shown in figure 12& it is a similar aluminum weld. joint It has been observed that hardness of weld zone is more than that of hardness of both parent material. Variation of hardness on sample no. 3 weld joint as shown in figure 13 , It has been observed that hardness of weld zone is greater than that of parent metal 1 i.e. AA6101.. Hardness of welded portion is less than that of parent material 2 i.e.AA6513, Which is a dissimilar aluminum weld joint.. Variation of hardness on specimen 4 as shown in figure14, it has been found that Hardness of welded portion is greater than that of parent material 1 (AA6101) . Hardness of welded portion is less than that of parent material 2.(AA6513) It is also dissimilar weld. Hence it is found that hardness of weld portion affected by rotational speed and diameter of shoulder &welding speed. Fig 15 shows combined BHN value for similar and dissimilar welding of aluminum alloys. Hardness of AA6351 is more than hardness of AA6101

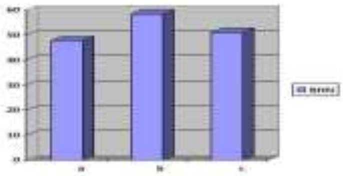

Fig.12 BHN for sample no.2

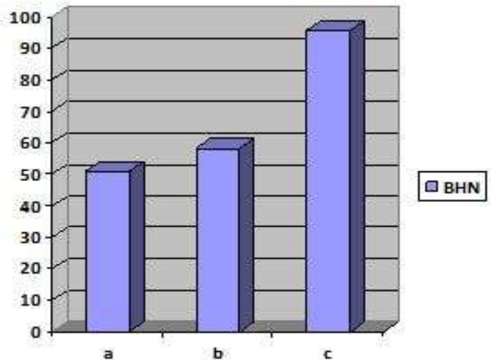


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Fig.no-13 BHN for sample no.3

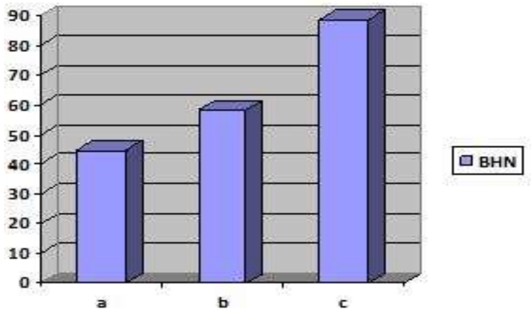


Fig no.14 BHN for sample no.4

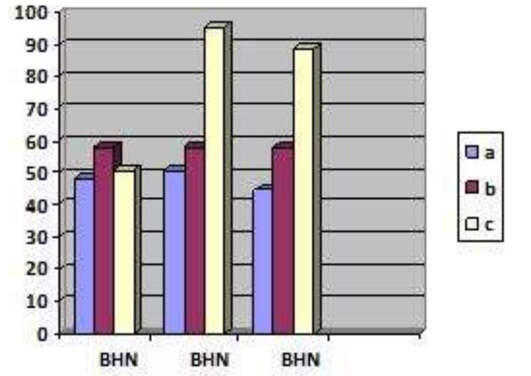


Fig no.15 ,BHN for similar and dissimilar weld jonts(2,3,4)

## V. Microstructure:-

Due to severe plastic deformation and high temperature in the stirred zone during FSW recrystallization and microstructure evolution occurs in stirred zone and precipitate dissolution and coarsening within and around the stirred zone. On the basis of microstructural characterization of grains and the precipitates, Different zones namely (a) weld nugget (WN), (b) thermo-mechanically affected zone (TMAZ), (c) heat-affected zone (HAZ) and (d) Base material (BM) have been identified. The microstructural variations in different zones have considerable effect on post weld mechanical properties.

*5.1 Microstructure for parent aluminum alloys*

Figure 16 (a) shows the microstructure of AL 6101 T6 in which particles of $Mg_2Si$ are evenly precipitated in aluminum solid solution. Some inter metallics which are undissolved also present 16(b) Figure shows the microstructure of AL 6351 T6 which is typical precipitation hardened matrix with the fine precipitation of $Cu\text{-}Al_2$. The high hardness measured shows the precipitation of the strengthening agents are complete.

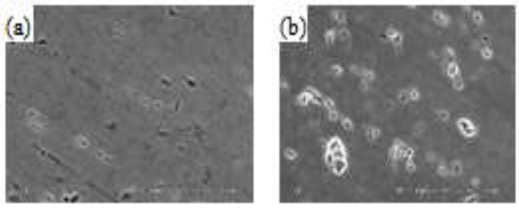


Fig. 16 Microstructure of parent material (a) Al6101T6 and (b) Al6351T6

*5.2 Microstructure studies for similar welds*

The microstructure of the different weld regions of the FSW of similar material in sample no. 2 through 800 rpm, welding speed 13 mm/min and tool diameter 30mm are shown from figure no 17(a-d) . Though the weld undergoes considerable amount of thermal cycle. Figure17 (a) microstructure of weld region shows the distribution of the precipitates is uniform throughout the weld region. Severe plastic deformation was observed and the precipitates were be destroyed and also some re-precipitation was observed. Figure17 (b) shows , formation of some oxide layer at either at the advancing side or at the retreating side of the weld sample was observed; forming some uneven boundary between the weld centre and the TMAZ and thus making some differentiation between them. A nugget region was observed near the bottom root portion of the weld centre region which is shown in figure 17 (c). The stirred zone has higher hardness compared with HAZ and TMAZ because of smaller grain size at this zone. .The HAZ formed on the both the side of the weld, i.e. advancing and retreating side of weld. The reason behind formation of the heat affected zone is temperature difference across the weld. Since the alloy plate was at room temperature before welding. When the welding was done by the rotation of tool, there was substantial increase in temperature due to the friction generated between the tool and work piece and due to the plastic deformation of work piece. Hence, grain growth was observed in the HAZ which is shown figure17 (d).

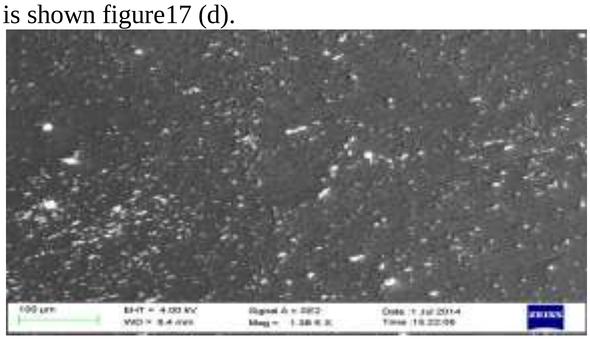

Figure 17(a) weld region

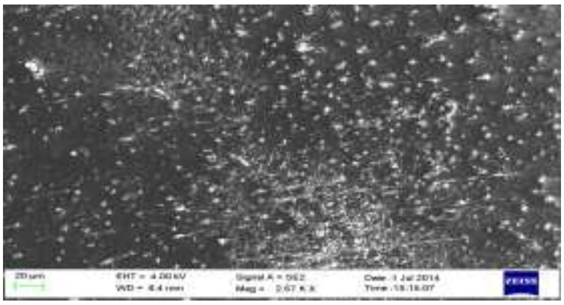

Figure 17(b) TMAZ region

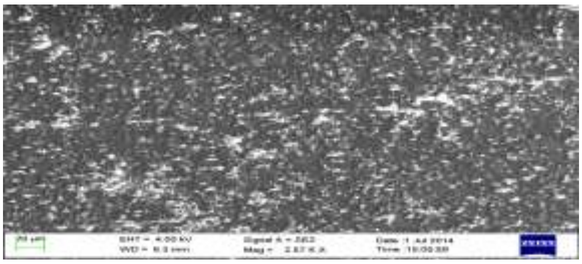

Figure17(c) Nugget region

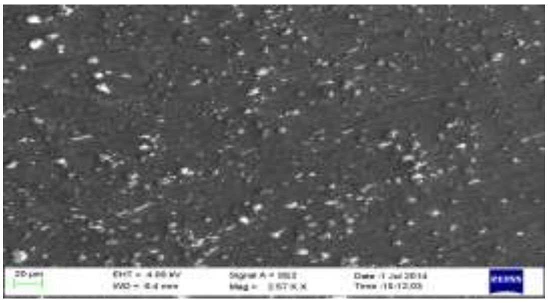

Figure 17(d) HAZ region

*5.3 Microstructure studies for dissimilar welds*

The microstructure of the different weld regions of the FSW of dissimilar material in sample no. 3 through 800 rpm, welding speed 13 mm/min and tool diameter 25mm are shown Fig18 (a-e) . The weld undergoes considerable amount of thermal cycle, There is grain refinement occurs in FSW process. Figure 18(a) shows The weld consists of uniform distribution of precipitate throughout the weld centre region. There is formation of oxide layer also between the weld centre and the TMAZ causing the formation of some uneven boundary as shown in Fig. 18(b) and Fig.18(c). At the bottom root portion of the weld centre region a nugget region is observed. which consists of banded structure as shown in Fig.18(d) .it is also known as stirred zone which has higher strength compared with the HAZ and TMAZ because of the small grain size at this zone. The lower value can be attributed to the poor fusion of the two materials. Grain growth was observed in the HAZ As shown in Fig18(e) The grains in the heat affected zone(HAZ) are severely coarsened by the FSW process. The interface between weld nugget and HAZ is a weaker region that is why joint is fractured at this region

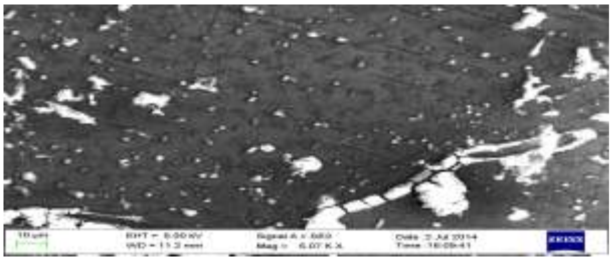

Fig.18(a) weld region

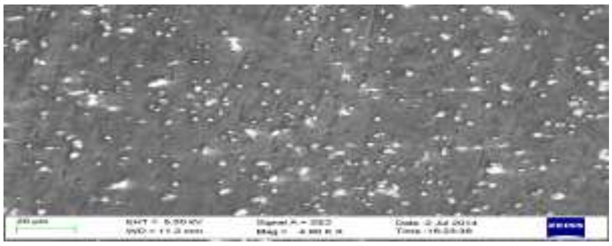

Fig.18(b) Oxide layer formation in Weld centre

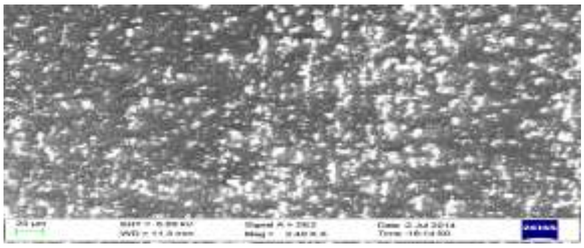

Fig.18(c) TMAZ region

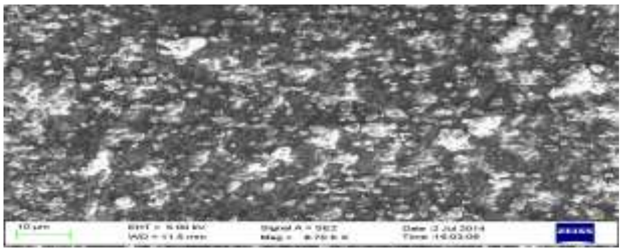

Fig.18(d) Nugget region

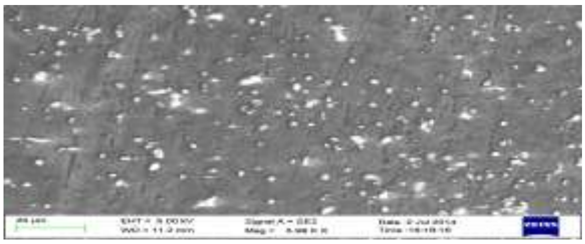

Fig.18(e) HAZ region

## VI. Conclusions

In the present study, the effect of process parameters on friction stir welding of similar aluminum alloys i.e. AA 6101 T6 to AA6101 and dissimilar aluminums alloys i.e. AA6101 to AA 6351 T6 Al alloy was studied and based on the results the following conclusions can be drawn:

- It is concluded that the rotational speed and welding speed are the main input parameter that has the highest influence on mechanical properties like tensile strength, elongation and hardness.

- As diameter of tool increases the defect at the welded region due to porosity is minimized.
- As rotational speed of tool increases quality of weld increases means defect due to porosity at the welded region is minimized.
- Process parameters and tool profile has an effect on quality of weld. As shoulder diameter and tool rotational speed increases the tensile strength of FSW weld joints of two similar and dissimilar aluminums alloys also increases.
- The Tensile strength of FSW joints is lower than the parent material strength comparing to friction stir welding of two similar and dissimilar aluminum alloys.
- Tensile strength of friction stir welding of similar aluminums alloys is more than dissimilar aluminums alloys, which are welded with same shoulder diameter, same rotational speed, same welding speed. It is because proper mixing of material at weld location is not taking place of different melting points of dissimilar aluminum alloys. It is found that hardness of weld portion affected by rotational speed and diameter of shoulder & welding speed. The hardness values of weld zone are lower than parent material which indicates the improved ductility of weld.
- From the micro-structural study it has been observed that the weld zone is stirred and having more grain refinement as compared to the HAZ zone.
- The test database developed in the present study will be useful for the design and building of aluminum ship structures fabricated by friction stir welding.
- Friction stir welding two dissimilar aluminum alloys can be easily welded and its mechanical properties are comparable to base material. The weld strength and quality of weld obtained during the experiment indicated the success of the process.

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