# Effect of tool Geometry and process parameters on microstructure and mechanical properties of Dissimilar Friction stir welding of AA6061-AA5052

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***ABSTRACT***

**Friction stir welding (FSW) is a solid state welding technology specially used for joining similar and dissimilar non-ferrous alloys like aluminium & magnesium alloys. FSW have numerous advantages over conventional welding methods like environment friendliness, energy efficiency, low distortion of material, lower loss of alloying elements, high strength of joint and versatility. In the current research, FSW of AA 6061 and AA5052 was carried out using two different tool geometries and by varying process parameters like tool rotational speed and traverse speed to establish its influence on the microstructure variation and mechanical properties of the welded joints. Metallographic observations of joints were carried out using optical and scanning electron microscopy. Hardness profile and residual stress were investigated. The welded joints were tested for tensile properties and impact toughness. It was confirmed that tool geometry and process parameters plays an important role in formation of defect free weld joint. Optical and scanning electron microscopy revealed that the elongated pancake microstructure of the base material (BM) was altered into a dynamically recrystallized microstructure of submicron grain size in the weld nugget. Strengthening precipitates, present in AA6061- T6 before welding, were found to be dissolved completely in the nugget zone (NZ), whereas overageing with much larger precipitates were observed in heat-affected zone (HAZ). Results of microhardness and tensile tests confirmed that the HAZ is the weakest region of the weld. The welded sheet exhibited reduced strength and ductility as compared to the BM. Impact energy of weld was lower than parent material. Compressive residual stresses were noticed in the weld nugget.**

**Keywords: Dissimilar welding, Severe Plastic Deformation, Friction Stir welding, Micro hardness, Impact Toughness**

## I. INTRODUCTION

Light metals with high strength are the immediate and future requirements for aerospace, defense as well as automotive industries. Aluminum and its alloys, specially precipitation hardenable, have become increasingly popular in structural parts because of their properties like high strength to weight ratio, superior corrosion resistance, good thermal and electrical conductivity, acceptable weldability, recyclable and non-magnetic nature [1]. Aluminum alloys are extensively used in the manufacture of aircraft structures and other structural applications in defence and automobiles [2]. Despite the fact that most of metals are joined by using fusion welding method, alloys of aluminium, titanium, and magnesium cannot be joined that much easily. Fusion welded joints of these alloys generally suffer from problems like welding cracks, voids, distortion, residual stresses, composition variation and dilution of alloying elements, which are not desirable for practical applications. Dissimilar joining process is even more tedious than similar welding process, owing to variation in chemical composition and mechanical properties of the base materials [3]. As fusion welding of dissimilar aluminium is complex, Friction Stir Welding (FSW) process is extensively used for welding of dissimilar materials. Since, FSW is solid state welding process; formation of brittle secondary phase is suppressed.

Friction stir welding (FSW) invented by The Welding Institute (TWI) in 1991, has revealed great potential in joining materials that are conventionally thought to be unweldable or hard to weld [4]. This process improves mechanical properties as well as produces weldment free from porosity. Less amount of heat generation, extensive plastic flow of material, mechanical mixing, large forging pressure, proscribed flow of material, very fine grain size and random misorientation of grain boundaries in the stirred region are the unique features of FSW. It has been reported that joints produced by FSW can achieve 80 to 100% strength when compared to the base material [5].

FSW process uses a non-consumable rotating tool having a specially designed pin and a shoulder. The tool is inserted into the abutting edges of sheets or plates to be joined and it traverses along the line of joint under axial load. The friction between the tool and the workpiece generates heat and this localized heating softens the material around the pin. Combined effect of tool rotation and translation leads to movement of material from the front to the back of the pin and significant forging force consolidates the weld metal. The welding of the material is facilitated by severe plastic deformation in the solid state without fusion or filler materials. FSW joints typically consist of four different microstructural regions. They are (a) unaffected base metal; (b) heat affected zone (HAZ); (c) thermo mechanically affected zone (TMAZ); and (d) stirred or nugget zone [6-7].

Many researchers have investigated the effect of tool Geometry and process parameters on microstructure and mechanical properties of similar and dissimilar Friction stir welding of aluminium alloys. Zhaohua Zhang et al. [8] had studied effect of the rotational speed and dwell time on microstructure and mechanical properties and reported that these parameters have large impact on hardness and tensile strength. H.J. Liu et al. [9] had examined effect of welding speed on microstructure and mechanical properties of friction stir welded AA6061 and found that the tensile strength of the defect-free joint increases with the welding speed and tensile fracture location is in the HAZ adjacent to the TMAZ on the AS Jian He al. [10] had investigated effect of tool rotational speed on microstructure and residual stresses on friction stir welded AA6061 alloy and reported that tool rotational speed is most important parameter in deciding mechanical properties of welded joints. Friction stir welding of dissimilar aluminium alloys had been investigated by numerous researchers and many of them have reported that mechanical properties of joints welded by FSW are better compared to fusion welded joints [11-13]. EBSD study on microstructure and texture of friction stir welded AA5052-O and AA6061-T6 dissimilar joint was done by Bin Wang et al [14] and reported texture evolution during welding.

Here, an attempt is made to study effect of tool geometry, rotational and traverse speed on microstructure and mechanical properties of dissimilar friction stir welded of AA6061-T6 and AA5052-O.

## II. EXPERIMENTAL DISCRIPTION

Rolled, homogenized Plates of AA 6061-T6 and AA5052-O with elemental composition (Table 1), and mechanical properties (Table 2) were used in this experiment, whose composition was confirmed by ICP OES (inductively coupled plasma optical emission spectroscopy). Samples of dimension 200mm x 70mm x 3mm were cut using power shearing machine. Friction stir welding was performed on Semi-automatic Vertical Milling Machine. A specially designed and fabricated FSW fixture was used for clamping. Process parameters, Rotational speed and traverse speed, were varied using two different tool geometries. The FSW experimental setup is as shown in Fig 1.

TABLE 1 CHEMICAL COMPOSITION OF AL 6061-T6 AND AL5052 ALUMINIUM ALLOYS.

| Material | %Si | %Mg | %Cu | %Mn | %Fe | %Cr | %Ti | %Zn | %Al |
|---|---|---|---|---|---|---|---|---|---|
| Al6061-T6 | 0.61 | 0.98 | 0.21 | 0.05 | 0.68 | 0.17 | 0.068 | 0.025 | 97.18 |
| Al5052-O | 0.12 | 2.23 | 0.01 | 0.01 | 0.23 | 0.18 | 0.016 | 0.011 | 97.19 |

TABLE 2 MECHANICAL PROPERTIES OF AL 6061-T6 AND AL5052ALUMINIUM ALLOYS.

| Material | Hardness (HV0.1) | YS (Mpa) | UTS (Mpa) | Elongation (%) |
|---|---|---|---|---|
| Al6061-T6 | 101 | 263 | 298 | 11 |
| Al5052 | 62 | 198 | 232 | 10 |

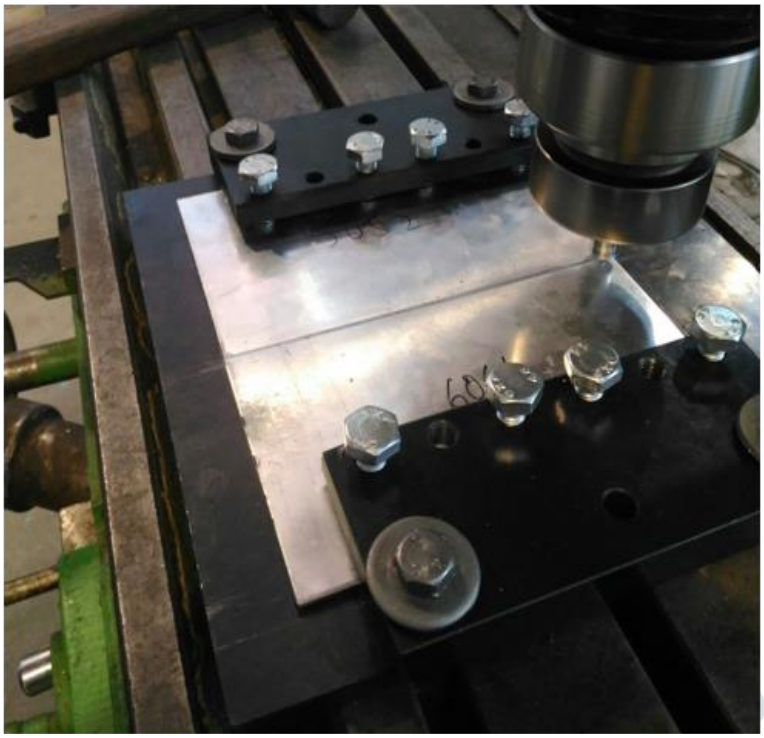

Fig. 1 Experimental Setup for Friction Stir Welding

H13 was selected as the tool material for FSW process. Hardening treatment i.e. oil quenching was carried on tool after machining in order to rise hardness of tool. Two tool geometries were selected for this experimentation. One tool was having Cylindrical taper pin profile and another tool was having flat Rectangular pin profile. The diameter of the shoulder 12 and the length of the pin was 2.5 mm from the surface of the shoulder, for both the tools. Tool tilt angle was kept 3°. Dissimilar FSW joints are produced from aluminum alloys 6061-T6 and 5052-O with rolled plate dimensions that were nominally 200 x 70 x 3 mm. Butt welds of 180 mm length was made using different process parameters as shown in table 3. For microstructural analysis, mirror polished, welded and as received samples, were etched to reveal microstructure. These samples were first polished (emery paper 200-1500) to the higher degree of polishing needed for such Aluminium alloy. Then the samples were lapped by using diamond paste. The black residue formed during lapping was removed by running water, then dried and washed with cotton. The samples were etched using Keller's reagent containing 2ml HF + 3ml HCl + 5ml $HNO_3$ + 190ml $H_2O$. The prepared samples were analyzed by using image analyzer.

Microhardness of the processed samples were taken on microhardness tester with a load of 100g and 10s dwell time. The hardness indentation was taken for every 3mm intervals so as to get the exact hardness. Tensile test and impact test of samples were taken according to ASTM standard. Tensile test was carried out in transverse direction. Residual stresses were measured by X-ray diffraction technique.

TABLE 3: PARAMETER VARIATION DURING FSW EXPERIMENTATION.

| Experiment | Pin Profile | Rotating Speed (RPM) | Feed rate (mm/min) |
|---|---|---|---|
| 1 | Simple Cylindrical | 700 | 36 |
| 2 | Simple Cylindrical | | 72 |
| 3 | Simple Cylindrical | | 120 |
| 4 | Simple Cylindrical | 1050 | 36 |
| 5 | Simple Cylindrical | | 72 |
| 6 | Simple Cylindrical | | 120 |
| 7 | Simple Cylindrical | 1400 | 36 |
| 8 | Simple Cylindrical | | 72 |
| 9 | Simple Cylindrical | | 120 |
| 10 | Square | 700 | 36 |
| 11 | Square | | 72 |
| 12 | Square | | 120 |
| 13 | Square | 1050 | 36 |
| 14 | Square | | 72 |
| 15 | Square | | 120 |
| 16 | Square | 1400 | 36 |
| 17 | Square | | 72 |
| 18 | Square | | 120 |

## III. RESULTS AND DISCUSSION

### Surface appearance:

All welded specimens were first examined by visual inspection of weld face surface. Fig. 2 shows the surface appearance of the welded plate. Uniform semicircular surface ripples in weld track can be seen. These surface ripples, which have onion rings pattern, were caused by the final sweep of the trailing edge of the constantly rotating tool shoulder. The presence of such ripples indicates strong stirring and mixing of the material at the interface of abutting joint, i.e. at weld centerline. It was observed that, welds exhibited very smooth surface morphologies and large defects were absent for the joints welded by simple cylindrical tool for all welding conditions. However, joints produced with tool having square pin profile did not show smooth surface morphologies. This may be due to pulsating stirring action of square pin profile.

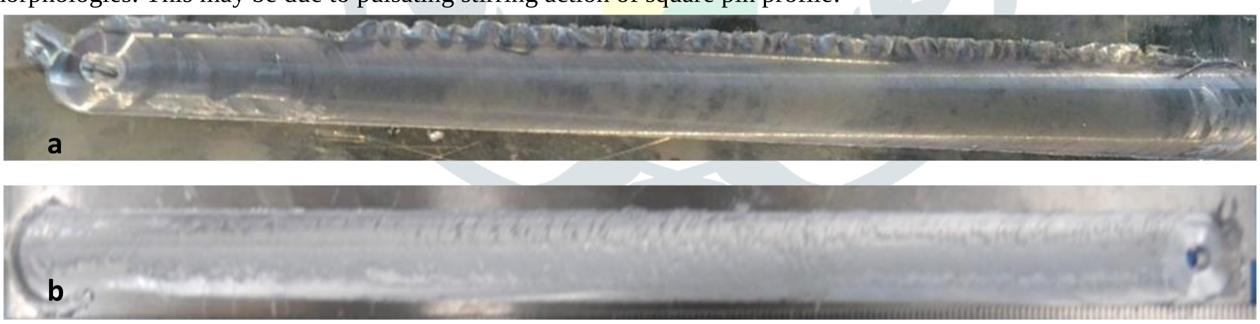


Fig 2. Surface appearances of the welded plates by a) Simple Cylindrical tool b) Square tool

### Microstructural Investigations:

It was observed that tool geometry plays an important role in microstructural modification during FSW process. For the tool with simple cylindrical pin profile, the material sticks to the tool at lower rotational speeds and hence tunnel defect was observed throughout the NZ. At higher RPM, material becomes more soft and flows easily hence defect free NZ was fabricated. In case of, tool with square pin profile material flow is much easier because of pulsating stirring action and hence defect free NZ can be obtained at lower RPM compared to simple cylindrical pin geometry. It was observed that, tool rotational speed (RPM) has major impact on heat generation and subsequently on microstructure and mechanical properties of dissimilar FSW joints, compared to that of tool traverse speed (mm/min).

The microstructure of parent AA6061-T6 and AA5052-O is shown in Fig 3(a) and (b) respectively. Rolled, homogenized and aged to condition T6 (solution heat treated, stress relieved then artificially aged) AA 6061 as well as AA5052 shows elongated pancake like microstructure. Fig.4 shows optical microstructures of nugget (a) and thermomechanically affected (b) zones of dissimilar joint of AA6061-AA5052 at 1050 rpm and 72 mm/min traverse speed using square pin tool. Fine recrystallized grains were observed at nugget zone without any precipitates. Average grain size at advancing and retreating was in submicron. The formation of complex intercalation structures consisting of swirl-like features and dissimilar lamellae during the intermixing occur in FSW of dissimilar materials [15]. A considerable amount of intermixing among the two alloys was observed in the microstructure. It was observed that because of pulsating stir action produced by Square pin tool, grain structure obtained is much finer compared to that of simple cylindrical pin tool. Continuous dissimilar lamella were observed in case of cylindrical tool where as discontinuous dissimilar lamella were found in thermomechanically affected zones of joints welded by square pin tool.

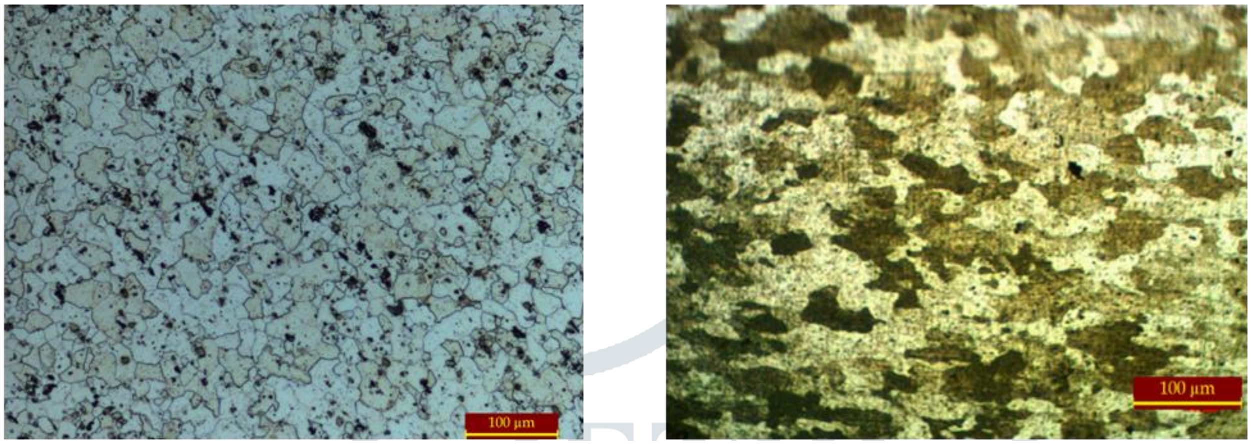


Fig 3. Microstructure of parent AA6061-T6 (a) and AA5052-O (b)

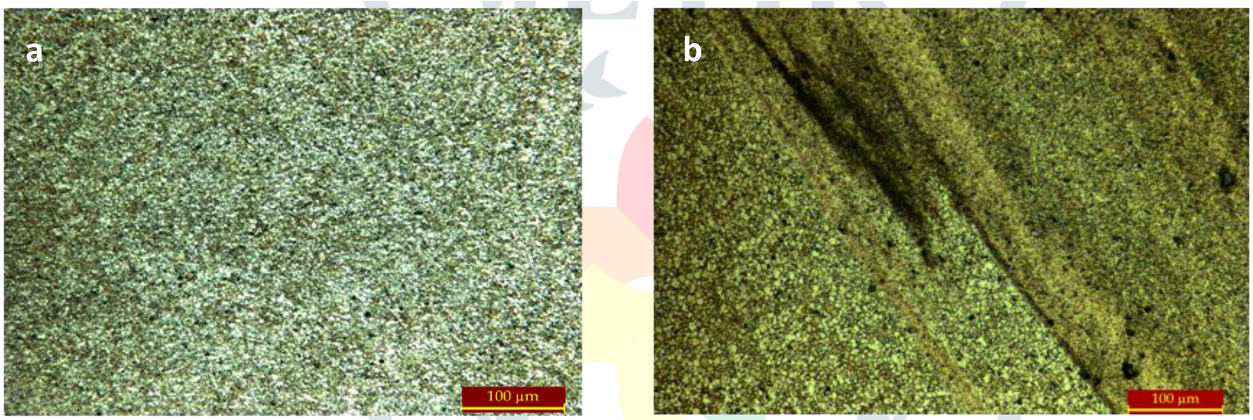


Fig 4. Optical microstructures of nugget (a) and thermomechanically affected (b) zones of dissimilar joint of AA6061-AA5052 at 1050 rpm and 72 mm/min traverse speed using square pin tool.

## Tensile Properties:

Tensile test was carried out for as received and welded samples with various process parameters with ASTM E8 standard. The samples were cut by Wire EDM machine. Tensile test was performed on UTM machine of capacity 100 tonnes. It was observed that, tensile strength (UTS) of all the processed samples decreased. Reduction in tensile strength can be attributed to dissolution of all the precipitates in the processed zone. It was observed that Tool geometry, Rotational speed and Traverse speed are very important parameters of friction stir welding process. Amongst these, tool geometry is found to be most influential parameter. Square tool geometry shows better UTS values compared to simple cylindrical tool as shown in Fig. 5.

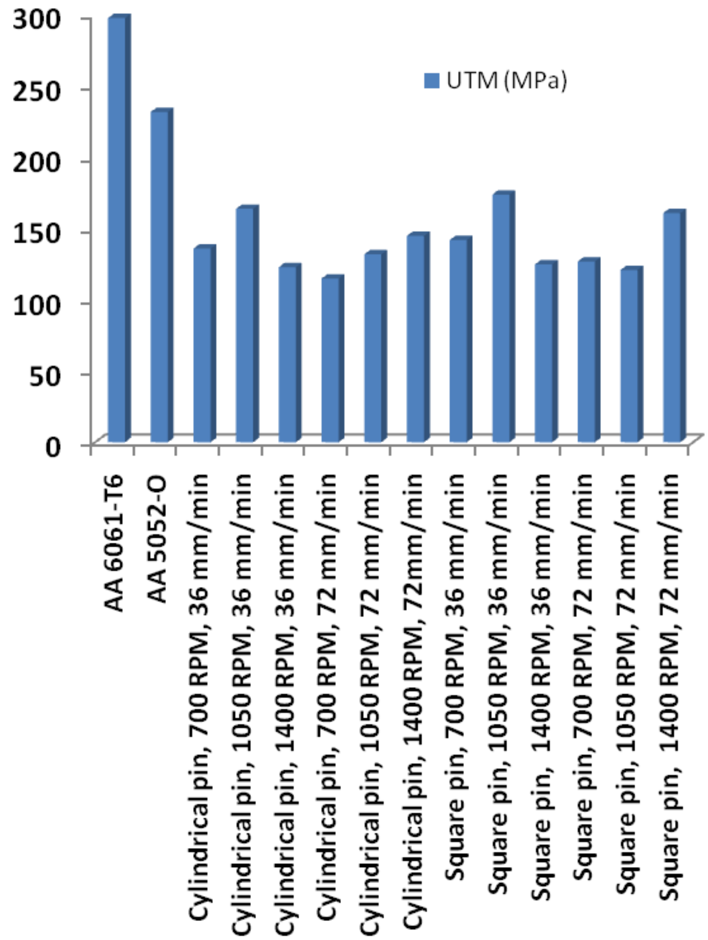


Fig 5: Effect of process parameters and tool geometry on ultimate tensile strength of dissimilar weld AA6061-T6- AA5052-O.

## Hardness Traverse:

Microhardness profile in the cross sectional plane of the friction stir welded dissimilar AA6061-AA5052 at 1050 rpm and 72 mm/min traverse speed with two different tool geometries is shown in Fig. 6. It can be observed that microhardness values are nearly constant in the nugget and the neighbouring HAZ. The retreating side (AA 5052 side) showed slightly wider softened region than the advancing side (AA 6061 side). In general hardness depends on the precipitate distribution rather than grain size for precipitation hardenable alloys. Hardness values of welded joints by two different tool geometries are observed to be nearly equal and showing same trend.

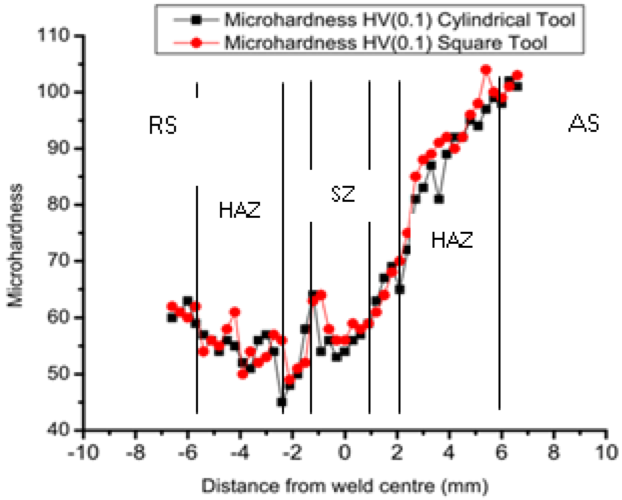


Fig 6: Microhardness traverse in the cross sectional plane of the friction stir welded dissimilar AA6061-AA5052 at 1050 rpm and 72 mm/min traverse speed with two different tool geometries

## Impact Toughness:

Impact energies at diverse welding conditions dissimilar welding of AA6061-AA5052 is shown in Fig.7. It shows that the impact energies diminished in friction stir welded material respect to the corresponding base metals. Impact energy was higher for square pin tool with 1050 RPM rotational speed and 36mm/min traverse speed than other welding conditions. This significant decrease in impact energy may be due to the defects generated during FSW process. Defects present at joint of samples causes decrease in impact energy. It can be observed that the changes in energy absorbed are sensitive to changes in pin profiles as well as changes in rotation speeds.

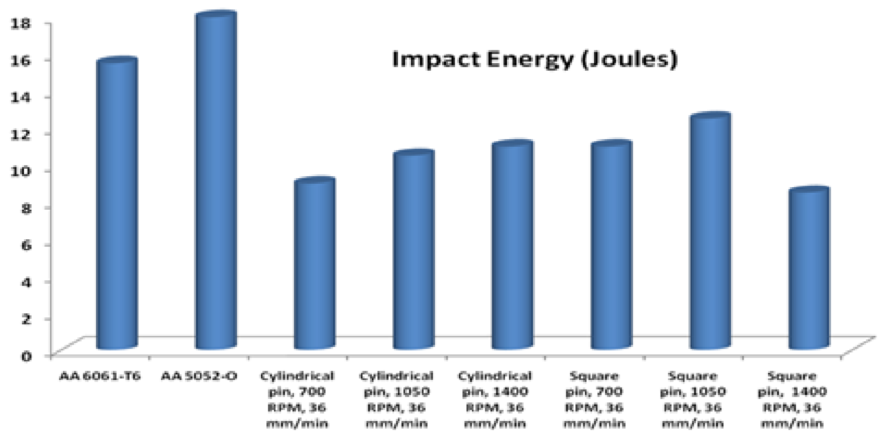


Fig 7: Impact energy at different welding conditions for dissimilar welding of AA6061-AA5052

## Residual stresses:

Residual stress distribution in transverse direction for joint made at 1050 rpm and 36 mm/min traverse speed using cylindrical and square tool for material AA6061-AA5052 is shown in Fig.8. Residual stress distribution was measured intervals of 1 mm from weld center. Compressive residual stresses were observed in the weld nugget and tensile residual stresses were noticed away from nugget zone. It is also revealed that maximum tensile stress was located 5 mm away from the weld centerline at advancing side. Unevenness in residual stress profile can be seen within the weld zone with stress being higher on the advancing side, which could be related to higher thermal gradients on the advancing side. It was also evident that cylindrical pin tool profile has better residual stress profile compared with square pin tool.

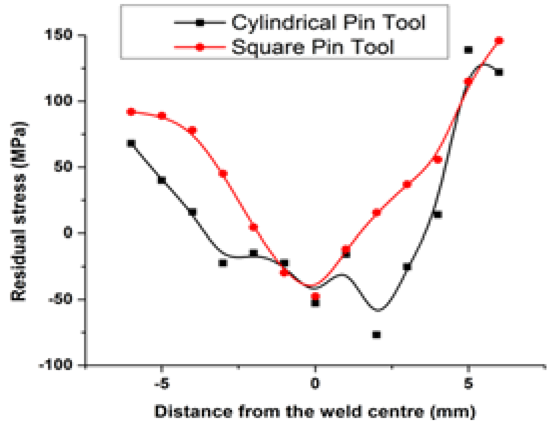


Fig. 8: Residual stress distribution in transverse direction two different tool geometries at 1050 RPM and 36mm/min traverse speed

## IV. CONCLUSION:

On the basis of experimental results for dissimilar friction stir welding of AA6061-T6- AA5052-O, following conclusions can be drawn.

- Dissimilar materials joint of AA6061-AA5052 made with square pin tool at rotational speed 1050 rpm and travel speed 36 mm/min shows maximum ultimate tensile strength.
- Tunnel defect was mostly found in the joints made with simple cylindrical pin tool while square pin tool resulted in hole defect at lower rotational speed and higher traverse speed.
- Friction stir welding resulted in a various different microstructural zones like stirred (Nugget) zone, TMAZ and HAZ. Very fine and equiaxed grains were observed in nugget zone because of the dynamic recrystallization. It was noticed that minimum average grain size at stirred zone was 3.7µm due to severe plastic deformation.
- Impact energy of welds was lower than parent materials. Maximum impact energy was observed with optimum process parameters having no defects in the joint. Low impact energy can be attributed to the defects present at joint.
- Hardness values at the stirred zone was found to be lower than parent material. This may be due to dissolution of precipitates and formation of super saturated solution.
- Compressive residual stresses were noticed in the weld nugget and tensile residual stresses were noticed in the HAZ.
- Overall, it can be depicted that, square tool produces better microstructure and mechanical properties compared to cylindrical tool because of pulsating stirring action.

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