Effect of Processing Parameters on Properties of Friction Stir Welded Joints of Aluminium Alloys AA7075-T_{651} and AA6061-T_6

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Abstract: In the present investigation the mechanical behaviour of AA7075T651 and AA6061T6 aluminium alloys plates joined by friction stir welding (FSW) were evaluated. The effects of weld process parameter like of tool rotation speed 650-1000 rpm and weld speed 30-40mm/min with square trapezoidal pin profile on mechanical properties were investigated. The welded joints were tested by means of by X-ray radiography, tensile, hardness and optical microscopy testing. The radiography revealed the presence of internal in FS welds and observed that increasing transverse speed increases the occurrence of weld defects. The hardness was found to be mixed effect with respect to tool rotations and transverse speed for similar FSW joints. But in dissimilar FSW joints, hardness decreases with increasing tool speed and weld speed and it was strongly affected by precipitate distribution. Difference in grain size and distribution was observed for different ranges of rotation and weld speed.

Keywords: FSW, AA7075 and AA6061, Mechanical properties, Microstructures.

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1 INTRODUCTION

Friction stir welding (FSW) is an energy efficient and environmentally friendly welding process, patented in 1991 by TWI [1]. A friction stir butt weld is produced by plunging a rotating tool into the facing surfaces of two plates. The tool consists of a shoulder and a profiled pin emerging from it. As the rotating pin moves along the weld line, the material is heated up by the frictional heat generated by the shoulder and stirred by the rotating pin in a process similar to an extrusion process. Since the temperatures are well below the melting point, problems associated with the liquid/solid phase transformation are avoided [2].

Over the last decade, frictions stir welding (FSW) has offered excellent welding quality to the joining of many alloys such as aluminium alloys [3] magnesium alloys [4], Copper alloys [5], and steel alloys [6]. It is a new and promising welding process which welds the material below its melting temperature and it has shown superior features such as excellent joint performance, mechanical properties and low energy consumption. However, many defects like porosity, kissing bond, solid inclusion and linear crack cavity or groove like defects, large mass of flash out are reported due to improper heat input during the process [7]. H. S. Patil et al., [8-10] studied effect rotation speeds, welding speeds, pin profiles on mechanical and metallurgical properties of similar and dissimilar joints of AA6082 and AA6061 alloys produced by FSW. Microstructural changes induced by the FSW process were clearly identified and resulted in a dynamically recrystallized zone, TMAZ and HAZ. A softened region has clearly occurred in the friction stir welded joints, due to dissolution of strengthening precipitates. With AA6082 on the advancing side; the corrosion rate is higher with respect to increasing welding speed of the tool while corrosion rate decreased in case of AA6061 on advancing side. Caroline et al., [11] has welded AA2014-T6 and AA7075-T6 aluminium alloys for various welding parameters. Torque, Temperature, macrograph and micro hardness were measured and concluded that torque, temperature and hardness profile depend on the amount material mixture in the stir zone. Zhikangshen et al., [12] used AA7075 plates of 2 mm thickness, for various rotational speeds and the dwell time. They investigated the microstructure and the mechanical properties of the refilled friction stir spot welding of AA7075. The keyhole of the weld was refilled successfully, the microstructure of the weld exhibits variations in the grain additionally, they observed, and defects associated to the material flow, such as hook, voids, bonding ligament and incomplete refill. Vladvoj et al., [13] presents the results of microstructure analysis, hardness measurements and tensile tests of FS-welded sheets of two aluminium alloys AA5083 and AA7075.

Better mechanical properties are obtained when harder material is placed on the advancing side and softer material in retreating side. Since tool geometry plays a vital role in dissimilar welds, different tool profiles are widely being used these days. In present study, square trapezoidal pin profile has been used to study the effect of weld process parameter on mechanical properties FSW joints on the welding of corrosion resistant AA6061 and high strength unweldable AA7075 aluminium alloys.

2 MATERIALS AND WELDING PROCEDURE

Aluminium alloys AA7075-T651 and AA6061-T6 sheet was cut on shear machine and brought to required dimensions 150 mm x 70 mm x 6.35 mm. The FSW joints were produced for similar alloys AA7075 and dissimilar alloys AA7075-AA6061. The FSW welding parameter used in this research were; tool rotation speed of 650 - 1000 rpm, transverse speed of 30 - 40mm/min. The tool tilt was maintained 00 during the experimentation and plunge depth was of 6mm throughout the weld path. Tool tip plunge feed 10 mm/min throughout the weld path. The plates welded by FSW process are fixed by a clamping fixture on a Joyti make VMC-PX20 series machine as shown in Fig. 1.

Fig. 1 Friction stirs welding on VMC machine with FSW joint

The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was used to fabricate the FSW joint. The FSW tool employed was square trapezoidal pin of H13 tool steel material with dimensions of 6mm top face and 4mm bottom face, 20mm flat shoulder diameter and 6mm pin height. The chemical composition of base material is as shown in table-1 The FSW joints were tested for various mechanical properties by using radiography, tensile testing hardness testing and microstructure analysis. Radiography inspection was performed using X-Rays as per radiography standard methods ASME Section-Article-22 at voltage-210KV and developing time/temperature-5min/200 in order to find internal defects. For tensile testing, the weld specimens were prepared as per the ASTM E8M-09 guideline to evaluate the mechanical properties; ultimate tensile strength, % elongation and joint efficiency of the FSW joints on universal testing machine. The Brinell hardness tests were also performed on weld specimens loaded at a load of 250kgf for 20sec dwell time on Brinell hardness machine and then removed. The resulting depth of impression was measured by the help of a microscope.

Table 1 Chemical composition of base materials

Chemical Composition %											
	Elements	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Zr
AA7075T$_{651}$	Required	0.4	0.5	1.2-2	0.3	2.1-2.9	0.18-0.28	-	5.1-6.1	0.2	-
	Contents	0.05	0.18	1.4	0.04	2.5	0.19	-	5.9	0.08	-
	Elements										
AA6061T$_6$	Required	0.4-0.8	0.7	0.15-0.40.	0.15	0.8-1.2	0.04-0.35	-	0.25	0.15	-
	Contents	0.62	0.45	0.2	0.13	1.05	0.09	-	0.03	0.07	-

A chart was then used to convert depth of impression to Brinell hardness number. For optical microscopy, the weld specimens were polished and etched using Keller's reagent with composition 1ml HF, 1.5 HCL, 2.5 HNO_3 9.5ml H_2O for AA6061 and 5ml HNO_3, 3ml HCL, 2ml HF and 190ml distilled water for AA7075 and then investigated microscopically with different combinations of rotational and translational speeds.

3 RESULT AND DISCUSSION

3.1 Visual and Radiography inspection of friction stirs welds:

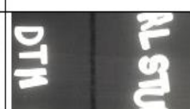
Perhaps the most straight forward and simplest inspection technique, visual inspection is an excellent means of inspecting for surface features including excess flash, galling, shoulder voids, and even weld misalignment. Visual inspection was performed on all welded samples in order to verify the presence of possible macroscopic external defects, such as surface irregularities, excessive flash, and surface-open tunnels. The lateral flash was observed in welds samples as shown in Fig. 2, resulting from the outflow of the plasticized material from underneath of the shoulder.

Fig. 2 Lateral flash in the joint FSW

Table 2 Macrographs & Radiographs of FSW at 900rpm & different weld speed

Sample	Macrographs of FSW	Radiographs of FSW	Weld Speed	Observations
A			30mm/min	Lack of penetrations, Moderate mixing
B			35mm/min	Slight sign of lack of penetrations & wormhole defect , Good mixing
C			40mm/min	Lack of penetrations, wormhole defect, Sufficient mixing

Table 3 Macrographs & Radiographs of FSW at 800rpm & different weld speed

Sample	Macrographs of FSW	Radiographs of FSW	Weld Speed	Observations
D			30mm/min	Lack of penetrations Slight signs of incomplete fusion
E			35mm/min	Lack of penetrations, crack, voids
F			40mm/min	Lack of penetrations , wormhole defect, incomplete fusion, discontinuity at the joint interface

In radiographic test it has been observed that the FSW joints shows the defects like Lack of penetrations, wormhole, voids and incomplete fusion defect. Tables 2-5 include the Macrographs of FSW, X-ray radiographs and the observations on each sample examined. The defects found are mainly lack of penetrations, wormhole or voids. It can be seen from the results table that increasing the transverse speed increases the occurrence of defects. With regard to tool rotational speed, it is evident that the extent of mixing is directly related to the medium rotational speed of 900 rpm, thus a more consolidated weld is achieved. Fig. 3 shows a graphical summary of the trends observed from the assessment of the radiographs.

Table 4 Macrographs & Radiographs of FSW at 1000rpm & different weld speed

Sample	Macrographs of FSW	Radiographs of FSW	Weld Speed	Observations
G			30mm/min	Lack of penetrations, Slight signs of incomplete fusion
H			35mm/min	Lack of penetrations, crack, incomplete fusion
I			40mm/min	Lack of penetrations, hole left

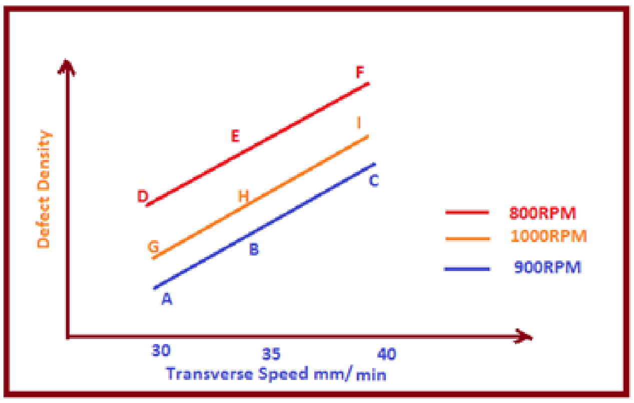
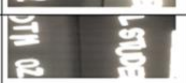


Fig. 3 Defect density Vs. Transverse Speed (mm/min)

Table 5 Macrographs & Radiographs of FSW at 650-700rpm & different weld speed

Sample	Macrographs of FSW	Radiographs of FSW	Weld Parameter	Observations
A1			700RPM, 40mm/min (AA6061 on Advancing side)	Lack of penetrations
A2			700RPM, 40mm/min (AA7075 on Advancing side)	Lack of penetrations, crack, incomplete fusion
A3			650RPM, 35mm/min (AA6061 on Advancing side)	Lack of penetrations,
A4			650RPM, 35mm/min (AA7075 on Advancing side)	Lack of penetrations, crack, wormhole defect

In dissimilar FSW joints it was observed that base metal AA6061 positioned on advancing side have fewer defects in comparison with base metal AA7075 positioned on advancing side and that gives good mixing of materials. Further, radiograph was free from mottling effect, which is very common in fusion welding of aluminium plates.

From the Figs. 4-6, it can be inferred that the tool rotation speed and welding speed are having influence on tensile properties of the FSW joints.

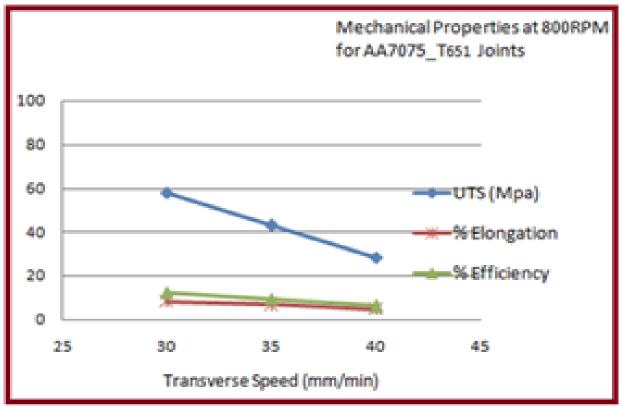


Fig. 4 Mechanical Properties of FSW Joints AA7075 at 800RPM

With constant rotational speed of 900 rpm, higher welding speed resulted in lower heat input per unit length of the weld, causes lack of stirring in the friction stir processing zone yielded poor tensile properties.

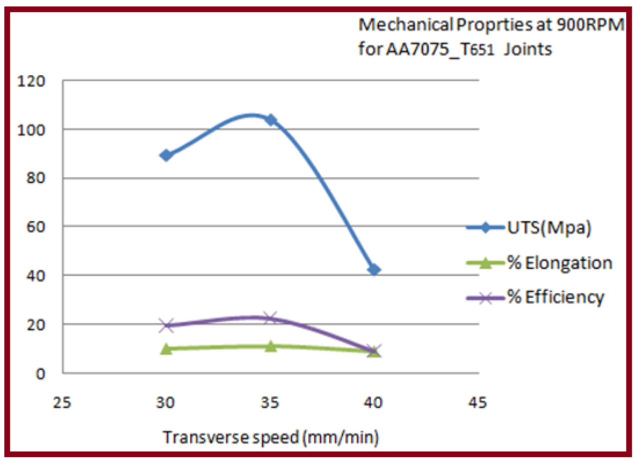


Fig. 5 Mechanical Properties of FSW Joints AA7075 at 900RPM

Lower welding speed resulted in higher temperature and slower cooling rate in the weld zone causes grain growth. Hence, the welding speed must be optimized to get friction stir processing region with fine precipitates distributed uniformly throughout the matrix.

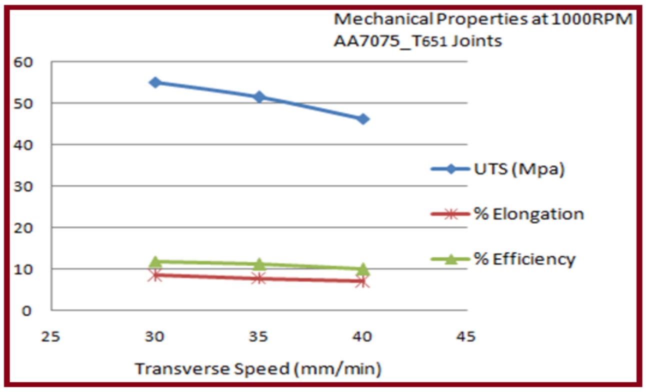


Fig. 6 Mechanical Properties of FSW Joints AA7075 at 1000RPM

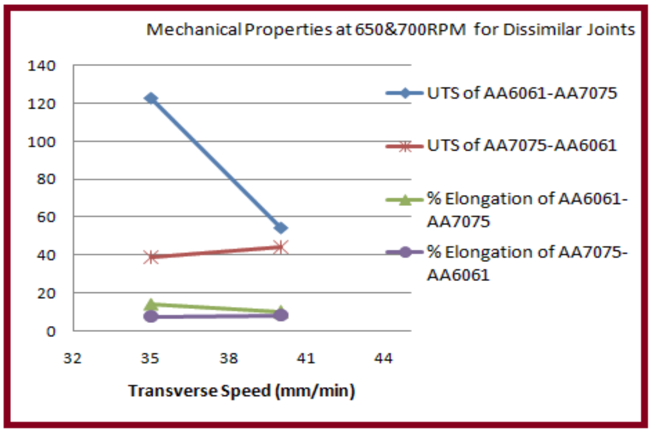


Fig. 7 Mechanical Properties of FSW Joint for Dissimilar Metals

Of the three different welding speeds, joints fabricated at a welding speed of 35mm/min exhibited good tensile properties irrespective of others welding speed. Higher tool rotational speed resulted in a higher temperature and slower cooling rate in the friction stir processing zone after welding. A higher rotational speed causes excessive release of stirred materials to the upper surface, which resultantly left voids in the friction stir processing zone. Lower heat input condition due to lower rotational speed resulted in lack of stirring. The area of the friction stir processing zone decreases with and decreasing the tool rotation speed and affect the temperature distribution in the friction stir processing zone. Hence, the tool rotation speed must be optimized to get friction stir processing zone region with fine particles uniformly distributed throughout the matrix. Of the three different tool rotational speeds, the joints fabricated at a rotational speed of 900 rpm exhibited good quality of tensile properties irrespective of other rotational speed. Irrespective of tool rotation speed and welding speed, the joints fabricated by trapezoidal tool profile at rotation speed of 900rpm and welding speed of 35mm/min exhibited good tensile properties with UTS of 104 MPa and elongation of 10.96% compared to other joints. The combined effect of higher stirring action during metal flow and an optimum rotation speed of 900rpm and welding speed of 35mm/min could be the reason for good tensile properties.

The tensile properties of the dissimilar joints obtained in the various welding conditions are shown in Fig. 7. With the AA6061 material on the advancing side, the tensile strength decreases by increasing the rotational & transverse speed of the tool (Fig. 7). The ductility is higher with decreasing the weld speed in the case of AA6061 on the advancing side, while it decreases in the case of AA7075 on the advancing side. Such dependence of the strength on the material position was previously observed. The best conditions of strengths about 122MPa UTS and 14.16 % of elongations are reached in the joints welded with AA6061 on the advancing side with weld speed of 35 mm/min.

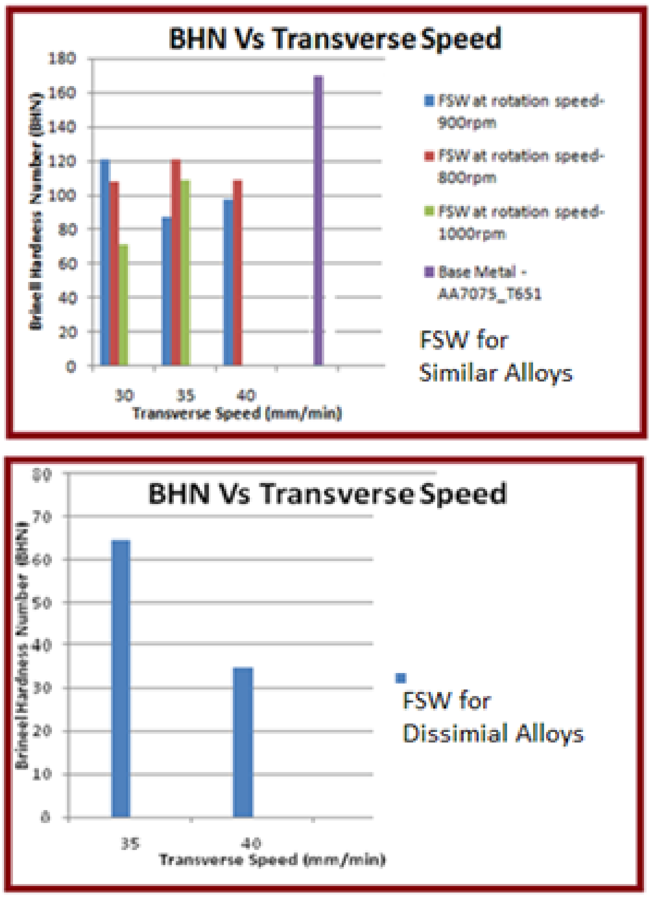


Fig. 8 Effect of transverse speed on hardness for similar and dissimilar FSW joints

3.3 Hardness of friction stirs welds:

Hardness tests were performed to determine the Brinell hardness number values of the similar alloy combination and dissimilar alloy combination. In heat treatable alloys, the precipitates only impart strength to the alloy. Dissolution of these strengthening precipitates weakens the mechanical properties of weld joints. In all the FSW joints, the temperature experienced during welding can induce an over ageing of the precipitate particle, resulting in decrease of mechanical characteristics. Actually, by inspecting hardness of FSW joints as shown in Fig. 8, the hardness values in all welded samples are reduced compared with base metal, this means that the generated heat during FSW causes softening of the welded area due to dissolution of precipitates (Fig. 9).

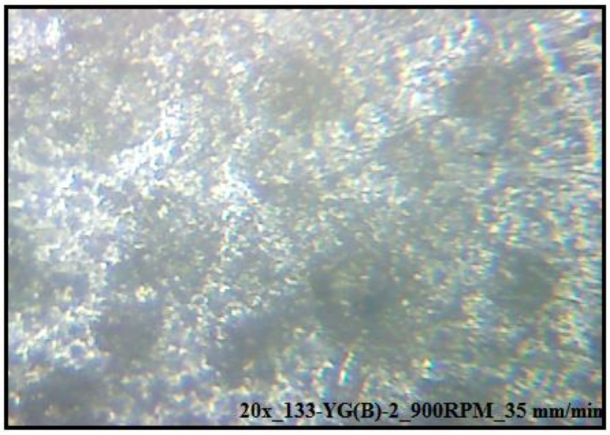


Fig. 9 Microstructure of FSW showing precipitates and voids

The maximum hardness was recorded about 121BHN for FSW compared with 170BHN for the base alloy. A hardness value has mixed result with respect to rotations speed and transverse speed for similar FSW joints. But in dissimilar FSW joints hardness value decreases with increase rotations speed and transverse speed.

3.4 Microstructure of friction stirs welds:

The microstructure appears as fine and equiaxed grains as shown in Fig. 10 in most of the welding conditions. A strong difference in grain size and distribution was observed for different ranges of rotation and transverse speed. During FSW, the tool acts as a stirrer extruding the material along the welding direction. Such complex deformation produces the vortex structure as shown in Fig. 11. By employing a trapezoidal tool, the material is forced from the plate into the weld and may travel several times depending on the rotational and welding speed. This is the reason for the different vortex structures obtained at different welding conditions.

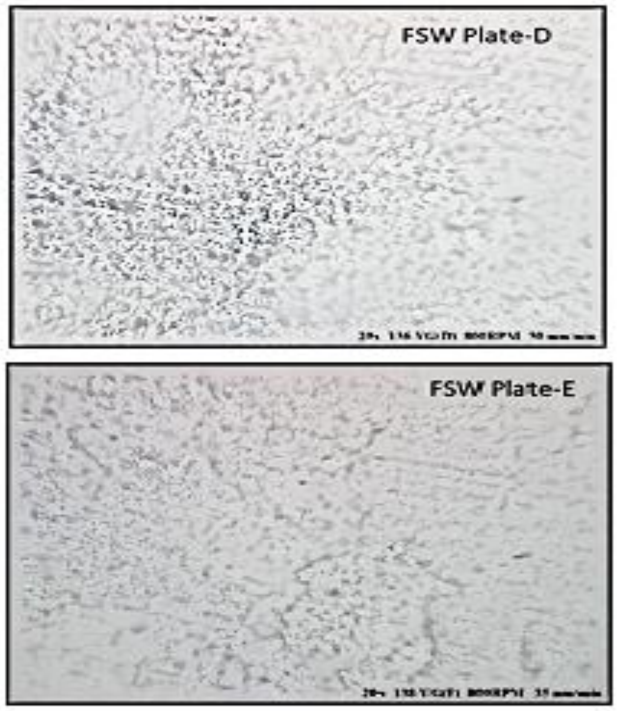


Fig. 10 Optical Micrograph of similar FSW samples

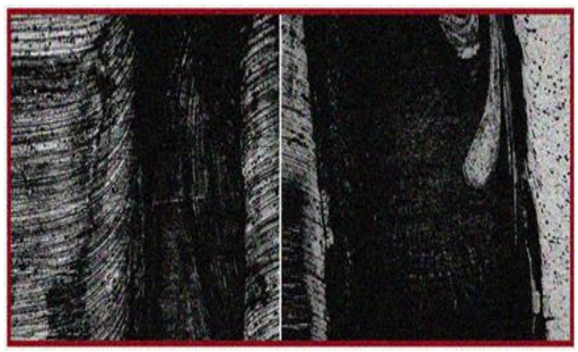


Fig. 11 Optical Micrograph of FSW showing Vortex Structure

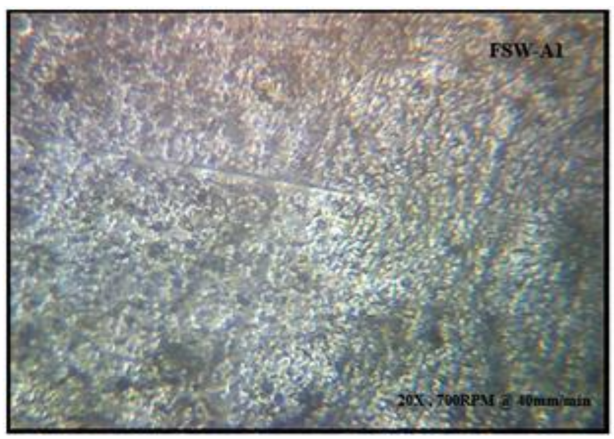


Fig. 12 Optical Micrograph of Dissimilar FSW AA6061-AA7075

A difference in grain size and distribution was observed for changing the position of alloy on advancing side of tool. The microstructure appears fine and uniform for of alloy AA6061 on advancing side of tool as shown in Fig. 12.

4 CONCLUSION

In all similar and dissimilar FSW joints lack of penetration defect was observed common in the radiograph, which could be eliminated simply by increasing the length of the pin profile. An optimum rotational speed for producing defect-free welds of aluminium AA7075T651 was found to be 900 rpm. It is also observed that increasing the transverse speed increases the occurrence of defects. In dissimilar FSW joints it has been observed that base metal 6061 positioned on advancing side gives good mixing of materials. It is observed that the occurrence of defects in dissimilar FSW joints is fewer with respect to similar FSW joints. In FSW, maximum hardness was recorded about 121BHN compared with 170BHN for the base alloy. A hardness value has mixed result with respect to rotations speed and transverse speed for similar FSW joints. But in case of dissimilar FSW joints hardness value decreases with increase rotations speed and transverse speed. Hardness was strongly affected by precipitate distribution. Difference in grain size and distribution was observed for different ranges of rotation and transverse speed. Of the three different tool rotational speeds, the joints fabricated at a rotational speed of 900 rpm exhibited good quality of tensile properties irrespective of other rotational speed.

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