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# Investigation on Tool Material, Profile, and Pre/Post Treatments Used in Friction Stir Welding

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***Abstract:*** *The aim of this research paper is to focus on different tool material, profiles and pre/post treatments used in friction stir welding. Tool materials used in this study are hot die steel, AISI H 13 tool steel, tool steel, hard material cemented carbide, hot working alloy steel, high speed steel, high carbon high chromium steel, die steel, high carbon steel, tempered high carbon steel, quenched and tempered steel, TiAIN - coated HSS-Steel tool, and tungsten carbide. Different profile and dimensions tools are viewed. The review is done along with the pre/post treatments. These treatments are ARB (Accumulative Roll-Bonding), mechanical powder mixing, retrogression and retrogression & reaging (RRA), use of high-power diode laser arrays for pre-and post-weld heating during FSW, annealing at 400°C for 2 hours before welding, isothermal ageing, solution heat treatment and immediately pouring of water. Introducing the shielding gas around the tool, ultrasonic assisted aging are also discussed. The change in microstructural and mechanical properties, distributions of the microstructures and hardness is reviewed. The effect of the FSW process on matrix grain size and reinforcement particles is evaluated. Formation of intermetallic phases under the influence of power ultrasonic process is studied. The flow patterns are analyzed. A systematic literature review based on the different tool material, profile and pre/post treatments and their effects on microstructural and mechanical properties is highlighted in this paper.*
***Keywords:*** *Characterization of microstructural and mechanical properties, friction stir welding, pre/post treatments, tool material, tool profile.*

## I. Introduction

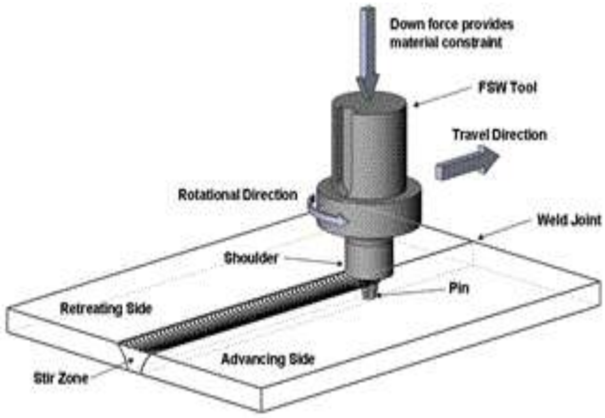


**Fig.1** Friction stir welding schematic.

Friction stir welding (FSW) is a solid state joining process (the metal not melted). It transforms the metal from solid state into a plastic state, and then mechanically stirs the materials together under pressure to form a welded joint. In the process a rotating FSW tool is plunged between two clamped plates. Heat is generated by friction between the rotating tool and the workpiece material, which leads to softened region near the FSW tool. The frictional heat causes a plasticised zone to form around a tool. The rotating tool moves along a joint line. A consolidated solid state joint is formed. It is a new joining technology used for joining soft materials such as aluminium, copper and other alloys. Due to variation in chemical composition and mechanical properties of the base materials of two dissimilar materials, it becomes challenging. FSW is currently employed in a number of industries including: aerospace, maritime, railroad and automobile.

## II. Literature Review

Alexander et al. [1] joined 10 mm thick AA 2024 Aluminium alloy plates. Conical tool of height 9.8 mm was used for experimentation. The axial pressure applied was 32.28 KN. Ultrasonic assisted aging treatment was used while FSW. It is resulted that, UAFSW sample has more uniform distribution of hardness numbers across the zones as compared to the FSW one and therefore this weld seam was more balanced in terms of strength. The microhardness of metal in UAFSW TMAZ and HAZ are notable lower than that of FSW resp. zones. The microhardness of UAFSW SZ metal proved to be notably higher as compared to that of plain FSW and that was taken into account the precipitation hardening kinetics. Main precipitation hardening particles in 2024 alloy were ($Al_2$ Cu Mg) (S- phase) and ($Al_2$ CU) (Θ phase). Also these were Al-Mg-Cu-Si, Al-Mn-Cu, and Al-Cu-fe particles which do not contribute to the precipitation hardening and more ever deplete the solid solution for alloying elements thus reduced its hardness level. It was treated as a group of "Coarse" particles of composition Al-Cu-Mn-Fe-Si 0.3-2.0 µm S- particles are spherical while 2.0-4.0 µm size Θ particles are ellipsoidal ones. The Al-Cu-Mn-Fe (Si) particles were of irregular shape and have size in the range 2.0 and 8.0 µm. The aggregates of such particles are as large as 32.5 µm and elongated either with respect rolling direction in both BM & HAZ or with respect to stirred metal flow direction in TMAZ. The tensile strength of both weld joints was considerably lower that of BM, namely by the factor of 4.17 to 2.75 because both sample contain macropores. UAFSW served considerably reduce porosity. SZ area was same for both welds. UAFSW TMAZ area was 21% larger than that of FSW one, i.e. indirect support in favour of reducing the effective viscosity of the metal by acoustoplastic effect. UAFSW HAZ total area was smaller than that of FSW one. While the total area occupied by the three zones is 8 % lower for UAFSW.

Sergei Tarasov et al, [2] studied the FSW with an ultrasonic application to 2 mm thick Al-Cu-Li-Mg aluminium alloy. A laser scanning Doppler vibrometer Poltech PSV-500-3D-HV used for experimentation. Axial pressure was applied 70 & 60 KN. In their investigation they found that, by using an ultrasonic application it established a uniform vibration velocity distribution both along and across workpiece. It serves to reduce the recrystallized grain size in the stirring zone of the weld. Microstress level: UAFSW & FSW microstress= $\langle\varepsilon\rangle$=0.11 & 0.07 % resp., Base Metal= 0.14%.

B. Malard et.al. [3] studied FSW process on AA 2050 T34 plate of 20 mm thick. A threaded conical pin with a three flat tool used for experimentation. The plated used in the naturally aged temper, as well as subsequent post-welding heat treatment. Their investigation revealed that-1) Two critical temperature ranges are around 200°C, where clusters initially present dissolve but do not re-form after welding presumably because of a shortage of vacancies, and 250-300°C where the precipitation of platelet phases is most pronounced during welding. 2) The different zones of the weld exhibit very different ageing kinetics when subjected to post-welding heat treatment. Firstly, a much lower dislocation density in the weld nugget and a part of the TMAZ as compared to the initial T34 material, which results in a slow precipitation of Θ instead of a fast precipitation of T1 in the base material. Secondly, the presence, most pronounced at the bottom of the nugget, of a higher fraction of Cu-containing intermetallic particles formed during welding. 3) These differences in hardening kinetics explain the hardness heterogeneity observed after subjecting the T3 state to a post-welding T8 heat treatment.

T. Kumbhar et al, [4] used partially recrystallized aluminium 5052 alloy plates for FSW experiment. High speed steel tool of pin length 4.8 mm was used for experimentation. They studied the microstructural development associated with FSW of AA 5052 and correlate these with associated mechanical properties. Their investigation revealed that the FSW specimens showed superior mechanical properties i.e. in general, the specimens showed ductile mode of fracture.

Mostafa S.S. El-Deeb et. al. [5] used AA 6061 plates for FSW. H 13 alloy steel was used as a tool material. Tool dimensions were, shoulder diameter 30 mm, threaded probe diameter 12 mm, 1.75 mm pitch, and 7.8 mm height post weld heat treatment was carried out immediately after welding and the samples were heated in furnace at 550°C for 2 hrs, and then quenched in water (T-4). Their results show that-1) The grain size of the stir zone increased by increasing the rotational speed or by decreasing welding speed. 2) Hardness significantly decreased as rotation speed increased and the values of hardness for the welded joints after artificial aging (T6) are greater than solution heat treatment (T4).

Jeong-Ung Park et. al. [6] used EH 47 steel for FSW process. Tool was made of WC-CO material. Tool dimensions were, Shoulder diameter 6-12 mm, pin diameter 2-4 mm, and pin length 1.5-2 mm. Post weld treatment-friction stir processing (FSP) was carried out. Their investigation results show that fatigue life was improved by around 42% compared to that of the as-welded specimen.

R.W. Fonda et al, [7] used 25 mm thick 2195 aluminium-lithium alloy for FSW. They used flat, scrolled shoulder and a threaded, frustum shaped (truncated cone) pin with three flats. Water was immediately poured onto the workpiece and welding tool to cool the plate. This arrested the tool rotation within or 54° of rotation and cooled the plate to less than 100°C within about 1 min. His study revealed that, bands of refined grains develop ahead of the fully refined region, likely reflecting different relative stabilities of the original grain orientations to the applied deformation. Fine subgrains form in response to the predominantly simple-shear deformation field and gradually develop greater microorientations to produce the refined grains observed adjacent to the tool. This region displays a typical FCC shear texture after suitable rotations are applied. The primary mechanism of grain refinement in this weld, therefore, appears to be subdivision induced by deformation and dynamic recovery processes, without the need to invoke a dynamic recrystallization mechanism.

L.M. Marzoli et al, [8] in their investigation, they studied 7 mm thick $AA6061/Al_2O_3/20p$ reinforced alloy used. Tool specifications were shoulder diameter 20 mm, and pin diameter 8 mm. This alloy heat treated to T-6 condition. They found that the tool's stirring effect has a substantial influence on the reinforcement particles distribution and shape. It breaks off the sharp edges of the bigger particles, rounding them up at the same time. This action results in smaller, round particles in the nugget.

L. Ceschini et al, [9] studied 7005 (Al-Zn-Mg) aluminium alloy matrix 10% $Al_2O_3$ (W7A10A composite) 12 KN axial pressure. Ferro-Titanit used as a tool material. Tool dimensions were, Shoulder diameter 18 mm, probe diameter 8 mm, and pin length-6.8 mm, left handed screw with 1.25 mm pitch. The as-cast composite was extruded up to a rectangular plate, then heat treated at the T-6 condition (solubilisation at 465°C for 1h, water quenching, artificial aging at 95°C for 1 h and 145°C for 16 h). Their study revealed that the tensile test evidenced a FSW joint efficiency of 80% respect to ultimate tensile strength. Low-cycle fatigue life of the FSW composite was always lower than that of the base material. The cyclic stress response curves of the FSW composite showed evidence of progressive hardening to failure for high cyclic strain amplitudes, while, for smaller strain amplitudes, the FSW composite showed neither hardening nor softening. SEM analysis of fracture mechanisms typical of MMCs. Different fracture morphologies in tensile and fatigue specimens from the upper to the bottom zones were observed in the FSW samples, due to the effects of the welding process.

A. Barcellona et al [10] made an attempt to investigate FSW of 3 mm thick AA 2024-T4 and AA 7075-T6 aluminium copper alloy. Tool used was H 13 steel quenched at 1020° C. Tool dimensions were, cylindrical pin diameter 3 mm, and pin length- 2.8 mm.Post welded heat treatment is done as: 1) AA 2024 T-4 heat treatment, which was composed of a solubilisation, a quench in cold water and a natural ageing. 2) AA 7075 T-6 heat treatment, which was composed of a solubilisation, a quench in water and an artificial ageing. They revealed that post-welding heat treatments can improve the material mechanical characteristics and overall can increase the joints resistance.

P.M.G.P. Moreira et al, [11] in their investigation, a 3 mm thick AA 6061-T6 & AA 6082 -T6 Aluminium alloy were used. Tool was made with M5 threaded pin. Shoulder was smooth and 7° concave with diameter 17 mm. The T6 condition was obtained through artificial ageing at a temperature of approximately 180°C. They obtain a defect free joint with same properties as that of base material.

T. Saeid et al, [12] used 2 mm thick 2205 duplex stainless steel for FSW. Quenched and tempered steel tool was used for experimentation. Tool dimensions were, Shoulder diameter 15 mm, left handed threaded pin diameter 5 mm and 6.5 mm, and pin length-5.7 mm. The process was done with 14 KN axial pressures. In order to avoid the surface oxidation, Ar shielding gas was introduced around the tool at flow rate of 18 L/min). Sound joints were produced at welding speeds of 50,100,150 and 200 mm/min and a groove like defect caused by insufficient heat input obtained at the speed of 250 mm/min. Increasing the welding speed decreased the size of the $\alpha$ and $\gamma$ grains in the SZ, and hence, improved the mean hardness value and the tensile strength of the SZ. These results are interpreted with respect to interplay between the welding speed and the peak temperature in FSW.

Olivier Lorrain et al, [13] in their investigation 4 mm thick Aluminium alloy 7020 used in T-6 rolled condition. High carbon steel tool was used. The profile of the tools was: 1) The first tool was a straight cylindrical pin (SC) profile. Whereas the second tool was a tapered cylindrical pin (TC3F) profile with three flats. 2) The two tools were unthreaded pin. 3) Their shoulder was concave. The process was carried out with 1200 kg axial pressure. Material flow with unthreaded pin was found to have same features as material flow using classical threaded pins; material deposited in the advancing side (AS) in the upper part of the weld in the retarding side (RS) in the lower part of the weld; a rotating layer appears around the tool. The product of the plunge force and the rotational speed was found to affect the size of the shoulder dominated zone. This effect is reduced using the cylindrical tapered pin flats.

P. Prasanna et al, [14] used 5 mm thick AA6061 aluminium alloy plate with annealing and normalising heat treatment. High carbon high chromium steel tool was used. Shoulder diameter was 18 mm and pin diameter was 6 mm. Pin length 4 was mm The FSW process was conducted with 14 KN axial pressure. Hardness was more in hexagonal pin profile tool. The microstructure of FSW region conical fine equiaxed grains and very fine uniformly distributed strengthening precipitates ($Mg_2Si$) throughout the matrix of hexagonal pin profile. This may be reason for superior tensile properties of these joints.

M. Thoma et al, [15] investigated the FSW process with 3.3 mm thick die cast alloys Al & Mg. Hot worked steel tool was used. Shoulder diameter was 16 mm and pin length was 3.1 mm. The process was conducted with ultrasonic application. The process was performed in single setting. The ultrasound has an influence on the nugget shape and also on the microstructure of the welded joint. The use of ultrasound strongly intensified the mixing of the joining materials within the nugget. Two continuous intermetallic layers could be found at the interface of Mg and nugget. The aluminium rich $Al_3Mg_2$ is cracked the ultrasound and then dispersed over the nugget. For US-FSW the more intensive stirring of the material in the joining area was clearly recognizable.

Sunil Sinhmaret al,[16] studied the FSW process with 5 mm thick AL-Zn-Mg alloy (AA7039). Multi-pass FSW process was conducted. Die steel tool was used. Tool shoulder diameter was 20 mm, pin diameter was 5 mm, and conical pin length was 2 mm. Their investigation revealed that the multi-pass friction stir processing led to slight coarsening of grain structure of zone processed by previous passes. It increases ductility form about 13.5 % to 23.6 % while the ultimate and yield strength were adversely affected. It results in higher ductility longitudinal direction than the traverse direction. The multi-pass friction stir processing produces higher hardness than the single pass friction stir processing. Hardness of friction stir processed AA 7039 was lower than the unprocessed alloy.

Jinmyun Jo, [17] made an attempt to investigate the effect of preheating the material before FSW. Aluminium alloy plate of 6 mm thickness was used for study. Tool Shoulder diameter was 15 mm, pin diameter was 7mm, and pin length was 6 mm.The results obtained stated that the thermal speed in the insulated workpiece was faster than in the not-insulated workpiece.

Dwight Burford et al, [18] investigated the FSW process with post welded aging of 7075 and 2024 alloy. They used scrolled shoulder with diameter 0.5 inch with scrolls extending the edge of shoulder face. Pin diameter was 0.125 inch. Their investigation revealed that, overaged temperatures such as T-81 and T 73 were considerably more stable in terms of precipitate morphology i.e. they were less susceptible to microstructural change during welding than the peak hardness temper i.e. T-3 and T-6 temper. When joining higher strength 7000 series aluminium alloy, post weld aging was necessary to stabilize the microstructure in the friction stir welded region.

M. A. Tashkandi et al [19] used 6061 aluminium alloy as a base metal and alumina particles added to welding zone to form metal matrix composites. Magnesium particles were used to enhance the bonding between the alumina particles and the matrix of 6061 aluminium alloy. Tool material was high carbon steel. A 6 mm pin with a square profile and a flat shoulder diameter of 21 mm was used to weld and mix the alumina particles along with the base metal in the welding area during welding process. Their experimental results showed that incorporating volume fraction of alumina particles up to 6 vol. % into the welding zone led to higher strength of the composite welded joints as compared to plain welded joints, but lead to decrease in the elongation of the joints.

W. Boonchouytan et al [20] studied pre/post FSW T-6 heat treatment on 4 mm thick SSM 356 aluminium alloy with tilt angle 3 degree and straight cylindrical pin tool. Straight cylindrical tool pin with shoulder diameter 20 mm, and pin diameter 5 mm was used. Pin length was length 3.8 mm. The optimum welding parameter on joint was a rotating speed 1320 rpm, the welding speed 160mm/min, heat treatment condition of weld T-6 which obtained the highest tensile strength 228.93 MPa, as well as highest hardness of 98.1 HV.

K. Reshad Seighalani et. al. [21] done FSW experimentation on titanium material. Tool shoulder material was titanium and tool pin material was tungsten carbide. The dimensions was: tool pin height- 2.85 mm, threaded cylindrical pin diameter 5 mm, and shoulder diameter 18 mm. Spindle speed was 1250 and 1500 rpm. Welding speed was 32mm/min. The work plates were annealed at 700°C/1h. They revealed that simple cylindrical WC pin and W shoulder together with the application of compressed air jet as a coolant, Argon as a shielding gas, and a tilt angle of 1°for the tool can lead to a defect-free weld joint.

D.M. Rodrigues et. al. [22] studied FSW experiment on AA 6016-T-4 on 1 mm thick plate. Tool dimensions were: 1) Conical shoulder with 8° inclination cavity and 10 mm in diameter. 2) Scrolled shoulder with 14 mm in diameter. (The geometry of the probe was the same for both tools, a cylindrical probe with 3 mm in diameter, 1mm long for the conical shoulder and 0.85 mm long for the scrolled shoulder.) They kept 1800 rpm and 1120 rpm for tool one and two respectively. Plates were heat treated and naturally aged to a T4 stable condition. Their investigation revealed that 1) The differences in tool geometry and welding parameters induced significant changes in the material flow path during welding as well as in the microstructure in the weld nugget. 2) The welds produced with the conical shoulder (HW) displayed a larger nugget grain size with few coarsened precipitates as opposed to the welds done with the scrolled shoulder (CW), which showed a smaller grain size containing many coarsened precipitates. These differences in microstructure conducted to a reduction in hardness around 15% in the CW welds contrarily to the HW welds where an even match condition was reached.

3) A reduction in elongation of 30% and 70% , respectively, for the HW and CW welds was observed due to the microstructural alteration reported as well as to the thickness reduction registered in the HW welds. 4) The CW tailored blanks displayed good deep-drawing behaviour. Under the same deep-drawing conditions the even matched HW cups displayed strong wrinkling.

K.V. Jata et. al. [23] evaluated FSW process on Al-Li-Cu alloy of 7.6 mm thickness. Tool pin diameter was 7.6 mm. The plates were hot rolled, homogenized, solution heat treated, water quenched and naturally aged prior to joining. They found that recrystallized grains in the DRX region form by a continuous dynamic recrystallization mechanism.

G. Liu et. al. [24] welded AA 6061-T6 aluminium alloy. They used 6.3 mm thick plate. Hardened carbon steel tool was used. Tool dimensions were, shoulder diameter 12.5 mm, pin diameter 6.3 mm, and pin length was 5.8 mm. The rotational speed was 300 to 1000 rpm. Welding speed was kept 15 to 25 mm/s. The plates were heat treated at T-6 condition. Their investigation revealed that considerable softening throughout the weld zone compared to the workpiece / plate hardness; even though the average grain size was reduced by a factor of about 10.

Y.G. Kim et.al. [25] studied the FSW process on aluminium die casting alloy plates of 5 mm thickness. The tool dimensions were: shoulder diameter 15 mm, pin diameter 6 mm, and pin length-4.7 mm. Tool rotational speed was 1500 rpm. Welding speed was 25 to 600 mm/min. The result of the experiment was: when the revolutionary pitch is greater than a definite value (e.g. 13 mm/rev), some void defects were exit in the joints, the tensile properties of the joints were considerably low, and the joints were fractured at the weld center. On the other hand, when the revolutionary pitch was smaller than the definite value, no defects were formed in the joints, the tensile properties of the joints were at comparatively high levels, and the joints were fractured near or at the interface between the weld nugget and the TMAZ on the advancing side. Under the condition of an optimum revolutionary pitch of 0.07 mm/rev, the ultimate strength of the joint was maximum, equivalent to 82% that of the base material.

Lakshminarayanan et. al. [26] used rolled plates of RDE-40 aluminium alloy (Al-Zn-Mg alloy) [closely confirming with the specifications of AA7039 alloy) for FSW experiment. Plate thickness was 6 mm. A threaded cylindrical tool made up of high carbon steel was used. Tool rotational speed was kept 1200, 1400 and 1600 rpm. Welding speed was 22, 45, and 75 mm/min. Their investigation revealed that tensile strength was at maximum when rotational speed, welding speed and axial force were 1400 rpm, 22 mm/min.

K. Kumar et. al. [27] studied the FSW process on 7020-T6 Aluminium alloy (hardenable Al-Zn-Mg alloy). H-13 steel tool was used. 4.2 mm long frustum shaped pin of 6 mm top diameter and 4 mm bottom diameter with 20 mm diameter flat shoulder used for experimentation. Spindle speed was 1400 rpm and welding speed was 80 mm/min. T-6 heat treatment applied for the process. When the shoulder-driven material does not reach the advancing side of the weld; this condition produced the groove like defect in the weld. The shoulder-driven material was not enough to fill the cavity and this leads to the groove and void like defects in the weld.

P. Cavaliere et. al. [28] joined 2.5 mm thick 2024 and 7075 Al alloy by FSW process. The plates were T3 & T6 condition respectively. Tool shoulder diameter was 20 mm, nib diameter was 6 mm, and pin length was 2.5 mm. Welding speed was 2.67 mm/s. In both low and high cycle load specimen regions the microscopic crack growth has been associated with some degree of material behaviour, showing the typical fracture surfaces of very fine grain size structure into the welded section.

Huseyin Uzun et. al. [29] studied FSW process on 6 mm thick AA2124/SiC/25p composite materials. Tool shoulder diameter was 18 mm, probe diameter was 6 mm, and pin length was 5.8 mm. TiAIN - coated HSS-Steel tool was used for process. Tool rotational speed was 800 rpm and welding speed was 120 mm/min. Their investigation revealed that the parent composite exhibits an average hardness value of 250 Hv. The average hardness values in the TMAZ were slightly lower than in the weld nugget.

## III. Conclusion

Conical tool of height 9.8 mm with Ultrasonic assisted aging treatment resulted in more uniform distribution of hardness numbers across the zones. High speed steel tool with pin length 4.8 mm showed ductile mode of fracture. H 13 alloy steel with threaded probe diameter 12 mm, 1.75 mm pitch, and 7.8 mm height resulted in increased in grain size by increasing the rotational speed or by decreasing welding speed. Tool made of WC-CO material with dimensions, shoulder diameter 6-12 mm, pin diameter 2-4 mm, and pin length 1.5-2 mm shows improved fatigue life. For the same friction stir processing (FSP) was carried out. By using tool of pin diameter 8 mm resulted in tool's stirring effect has a substantial influence on the reinforcement particles distribution and shape.

The said process was carried out in T6 condition. Ferro- Titanit tool with left handed screw with 1.25 mm pitch resulted that joint efficiency of 80% respect to ultimate tensile strength. Tool made with M5 threaded pin and shoulder with 7° concave with diameter 17 mm resulted in defect free joint with same properties as that of base material. Application of high carbon high chromium steel tool results in superior tensile properties of joints. Hot worked steel tool with pin length 3.1 mm showed intensive stirring of the material in the joining area. UAFSW was used with the said combinations. Simple cylindrical WC pin and W shoulder together with the application of compressed air jet as a coolant, Argon as a shielding gas, and a tilt angle of 1°for the tool can lead to a defect-free weld joint. The welds produced with the conical shoulder (HW) displayed a larger nugget grain size with few coarsened precipitates as opposed to the welds done with the scrolled shoulder (CW), which showed a smaller grain size containing many coarsened precipitates. Considerable softening throughout the weld zone compared to the workpiece / plate hardness was obtained by using hardened carbon steel tool. The tool pin diameter was 6.3 mm and height was 5.8 mm. When the shoulder-driven material does not reach the advancing side of the weld; this condition produced the groove like defect in the weld. TiAIN - coated HSS-Steel tool results in hardness values in the TMAZ slightly lower than in the weld nugget. The tool was having tool pin diameter 6 mm and length 5.8 mm.

## IV. Future Aspects For Investigation

1. To find out the process in which FSW and post weld aging treatment can be done in one setting to reduce cost and time of the process.
2. To find the process to control grains coarsening in multi pass FSW.
3. To improve the corrosion resistance in ultrasonic assisted FSW.
4. To develop special materials/tool design for the joining of steel, zirconium and titanium alloys.

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