“Various Parameter Effects on Friction Stir Welding” A Review

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Abstract - *Friction stir welding and friction stir spot welding are newly evolved solid state joining processes. These techniques are energy efficient, economical, better than conventional welding processes, and versatile. FSW and FSSW are promising and found to be the very important progression in metal joining area. In this review paper, the basic processes and their various parameters are included for understanding of the FSW and FSSW. While most of the information is related to Aluminium and magnesium alloys, important results are also available for other metal and alloys. At this scenario, technology advancement has growing faster and outpaced the fundamental need to just join the materials and their microstructural evolution.*

Key Words: **Friction stir welding, Double-sided FSW, Aluminium alloy FSW, Welding parameters, FSW tool.**

1. INTRODUCTION

Many industrial fields, such as aerospace, ship building and auto-motive industries, have made effort for reducing the weight of body structure. Also recent increase in energy costs has been a major factor to drive the use of light weight alloys in the various industries. Many industries find advantage in using light weight alloys to increase the fuel efficiency and heighten the performance. In this regard, light weight design by substituting steel with Al or Mg alloys have been weighed as assuring initiatives. However, conventional method of fusion welding has suffered problems, such as low strength, a wide heat affected zone, hot cracking, high residual stress, alloy segregation, which bounds the utilize of the magnesium alloys. To overcome these drawbacks, friction stir welding (FSW) process can be used to weld metals like Al, Mg and/or its alloy.

1.1 Working Principle:

Friction stir welding (FSW) was devised at TWI in 1991, and subsequently patented [1]. FSW uses a traversing and rotating non-consumable tool to generate frictional heat and cause mechanical deformation at the joint [1]. In FSW process, because of the friction generated among the surface of the components or plates to be welded and the contact at the surface of the rotating tool the welded material is plasticized. The work piece is located above a backing plate for the support and is held rigidly to a fixture to extinguish any motion. The pin infiltrates into the work piece on the other hand the shoulder rubs on the top surface of the specimen. With work piece thickness the height and diameter of the tool pin changes. The main parameter accountable for the generation of heat and incorporating the plasticized material in the weld zone is shoulder diameter, while pin mixes the material of the specimen to be welded, thus creating a joint. The process takes place at temperature below its melting point and joint is produced by the plastic deformation so problems occurring with fusion welding of Al alloy solidification shrinkage, solubility of gases etc. can be completely eliminated [6].The schematic illustration of FSW process is shown in the Fig.1. [1].

Unlike fusion welding, FSW has only few process parameters such as tool rotational speed, tool traverse feed, plunge depth, tool geometry etc. which can be easily controlled to produce the good weld [6]. Solid joint is produced as a result of this process. Because of different profile of tool geometry and features of the tool, the material movement around the pin can be quite complex [1]. During FSW, the material subjected to intense plastic deformation at high temperature, which afterward resulting in generation of the equiaxed and fine recrystallized grains [1]. Friction stir welding can be used for various types of joints such as lap joints, butt joints, fillet joints and T butt joints [1].

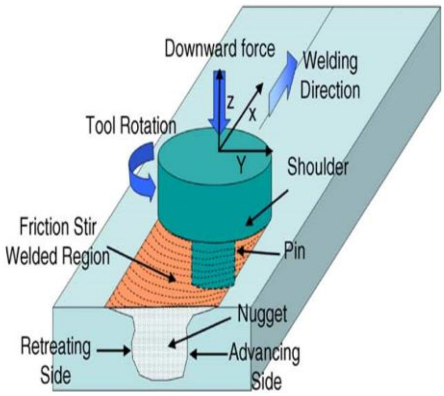


Fig. - 1. Schematic illustration of FSW.

2. LITREATURE REVIEW

2.1 Welding Parameters Based Work:

Karami et al. (2016) interpreted the effect of welding parameters on FSW. This literature work revealed that in FSW at lower rotational speed or higher welding speed due to low flow-ability of the material to be welded and lack of heat input, the friction stir welding, defects such as flanky-surface and tunnel defects were appeared. At the same time, higher rotational speed or lower welding speed, stir zone (SZ) temperature reached to the single austenite region because of considerable increment of heat input. Also higher amount of yield strength along with limited uniform elongation were exhibited by the FSW processed work-piece or specimen in comparison with the starting material. In this work, hot rolled sheet of st37 steel with initial dimensions of 300mm in length, 100mm in width and 2mm in thickness was used along with milling machine for experimental procedure. FSW tool was made from the tungsten alloy bar having 16mm in diameter and length pin of 0.8mm which was produced with simple geometry that include slight taper and tool was tilted at an angle of 3° from normal plate [9].

Scanning electron microscope was used for microscopic analysis of the FSW processed specimen. Fig. 2 shows the macroscopic images of the components subjected to FSW in different welding speed and/or rotation speeds. The rotation rate (rpm) and traversing speed (mm/min) used for various samples is shown in table 1. As can be seen, the direction of welding and pin rotation is shown. Macroscopic images of sample 1 and 2 were relatively perfect also free of any welding defects as shown in fig. 2a and b. On the other side, the images of sample 3 and 4 showed flanky surface in the weld-ment indicating that welding parameters have a major role to obtain perfect weldment during welding process. The reason for such defects was increasing welding speed which lead to the decrease of flow-ability of material and also decrease the contact time between pin and work piece hence whole of a material that are flown by the pin from the advancing side cannot perfectly reach to the retreating side and this caused formation of welding defect [9].

Table - 1 Welding parameters, tool dimensions and sample nomenclature.

Sample ID	Rotational rate (rpm)	Traversing speed (mm/min)
Sample-1	450	50
Sample-2	560	50
Sample-3	450	160
Sample-4	560	160

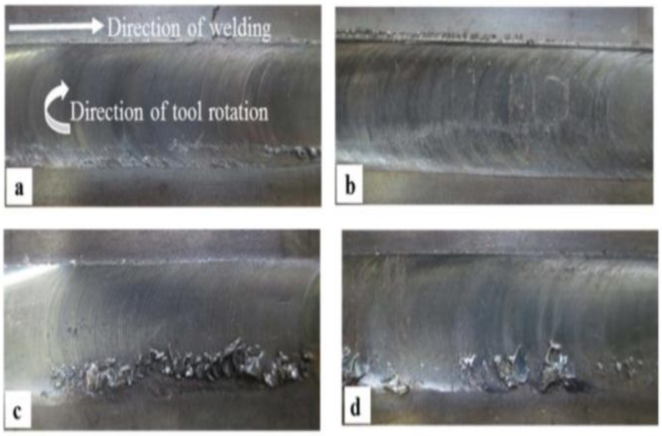


Fig. - 2. Image of the weld a) Smaple-1 b) Sample-2 c) Sample-3 d) Sample-4.

The optical micrographs of HAZ parts obtained from sample 1, 2, 3 and 4 for different welding condition are shown in Fig. 3. General analysis of HAZ part in all samples revealed that the microstructure of HAZ part is nearly same as BM and it implied from equiaxed ferrite grain as main portion in addition to pearlite structure. Fig. 3a and b illustrated the microstructure of HAZ part of sample 2 which shown two kinds of HAZ part which were fully grain refinement and partially grain refinement area. The former one was the areas adjacent to the SZ part and hence its temperature is quite close to single phase austenitic temperature and the later one was the area far from the SZ part. In Fig. 3c and d just partially grain refinement appeared in HAZ part of sample 1 and 2. This shown that the amount of heat input is not sufficient to reach the single austenite region which resulted in only partial grain refinement area in sample 1 and 2 and the temperature of the HAZ part can increase up to the dual phase region. Uniaxial tensile test machine based on ASTM E8 standard specimen at room temperature was used for tensile tests. Table 2 shows the results obtained from tests. Fig. 4 indicates the engineering stress-strain curves for specimens subjected to various welding condition [9].

Table - 2 Tensile properties obtained from tensile curves for different specimen.

Sample ID	Yield Strength (MPa)	Ultimate tensile strength (MPa)	Toughness ($J\ m^{-3}$)	Elongation (%)	The failure situation
Base Metal	250	492	128	33	BM
Sample-1	300	490	66.4	22	BM
Sample-2	305	492	81	19	BM

Sample-3	330	420	7.1	4.2	Nugget
Sample-4	335	425	8.5	3.1	Nugget

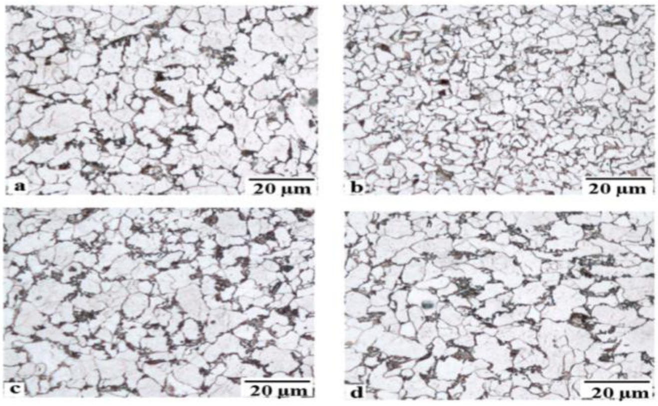


Fig. - 3. Optical micrographs of HAZ regions of friction stir welded mild steel; a) partial grain-refining of HAZ for Sample-2, b) total grain-refining of HAZ for Sample-2, c) partial grain-refining of HAZ for Sample-1, d) partial grain-refining of HAZ for Sample-4.

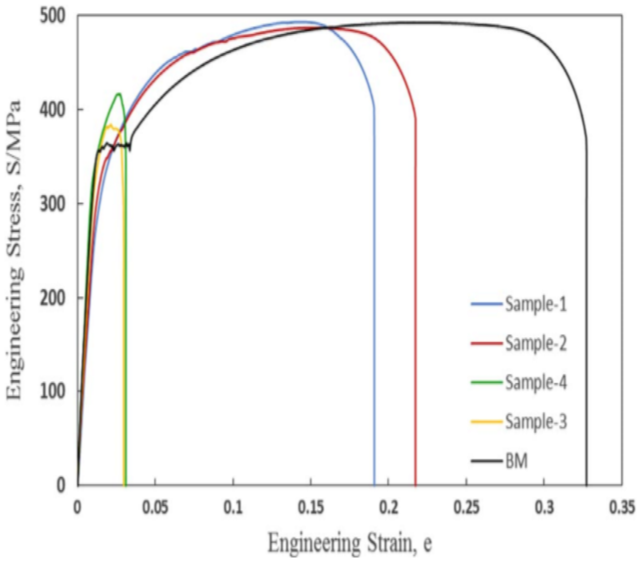


Fig. - 4. Engineering stress-strain curves obtained from tensile test results for different samples.

2.2 Double-Sided FSW:

Chen at el. (2015) analysed the sound joint produced by concave DSFW and the joints had a different characteristic structure than one-sided tool rotation. The results showed that the generated heat during FSW was due to the friction and the plastic deformation [8].

In this work, wrought sheet of AZ31B magnesium alloy were used with sample dimension of 75 mm width, 150 mm length and 4 mm thickness. Fig. 5 shows the tools that were used. The upper tool was made with a slope of 10° and the threaded probe of cylindrical shape while the lower tool was made with concave shape having a hole. The welding parameters for this experiment are shown in table 3. The tilt angle of 3° was given to the upper tool only. The first trial was performed at several rotation rates ranging from 300 rpm to 600 rpm. The results showed that relatively lower rotational rate is preferred for the DSFW. The experiment was also carried out with the flat tools and conventional one-sided FSW was also conducted only with the upper tool [8].

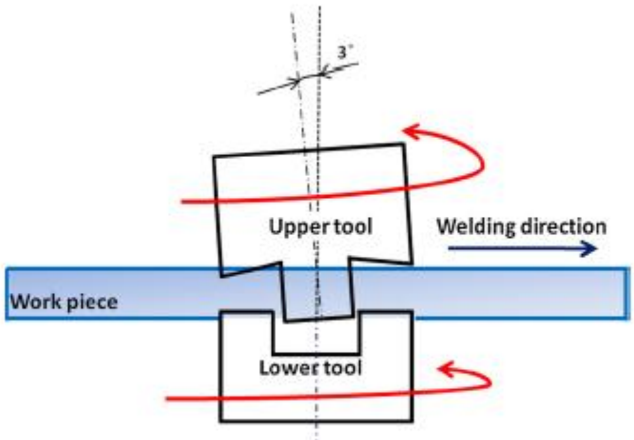


Fig. - 5. Schematic illustration of the DSFW with a concave lower tool

Table - 3 Welding parameters

	Welding Parameters			
	Tool tilt (°)	Rotation Speed (rpm)	Rotation Direction	Travel speed (mm/min)
Upper tool	3	300	CCW	500
Lower tool	0	200, 300	CCW	500

Fig. 6 shows the appearance of the joint produced by DSFW. (a) And (b) shows the flat and the concave-DSFW joints produced at 300 rpm for the upper tool as well as for lower tools. The images shows no defects on surface but the concave DFSW has large flash area on the lower side due to large heat input comparatively. This indicated that application of concave tool made it feasible to perform the FSW at a relatively lower rotation rate without any defects. Fig. 7 shows the base metal and the FSW joint's tensile properties. Results indicated that the DSFW joints have more tensile strength and elongation, whereas the yield strength does not change significantly. Also the stir zone for the concave-DSFW joint is more ductile than that of the flat-DSFW [8].

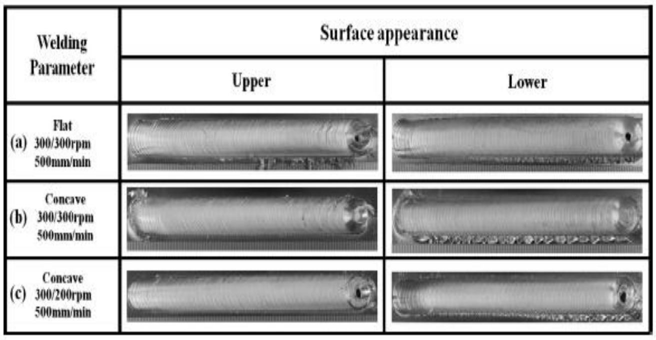


Fig. – 6. Surface appearance of the mg alloys joints made by the flat- or the concave DSFW.

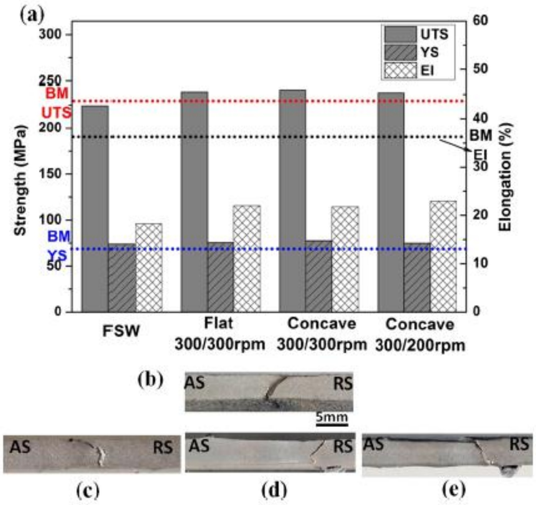


Fig. - 7. Transverse tensile properties (a) and the appearance of the tensile specimens fractured (b-e) of the one sided FSW joints (b), the flat-DSFW joint at 300/300 rpm (c), the concave-DFSW joints at 300/300 rpm (d), or 300/200 rpm (e).

2.3 Shoulder Diameter and Plunge Depth Effect:

Shahu et al. (2014) proposed the effects of shoulder diameter and plunge-depth on mechanical properties and thermal history. This work indicated that less plunging depth gave better tensile properties compare to higher plunging depth because at higher plunging depth local thinning occurs around the welded region. Also with increase in shoulder diameter there was increase I mechanical properties and peak temperature [7].

The experiment was performed with two plates of AM20 magnesium alloy with dimension of 100 X 100 X 4 mm. H13 tool steel was used with shoulder diameter varied in three values while pin length and diameter kept constant. The results showed that hardness of the upper zone is comparatively higher than that of the middle and bottom zone, irrespective of the process parameters selections. Also hardness test showed that hardens in the weld NZ region is higher compare to TMAZ, HAZ and base metal zone. Due to FSW the hardness increased up to 29.5% [7].

Table 4 indicates the effect of mechanical properties on variation of shoulder diameter and Table 5 indicates effects of mechanical properties on variation of plunge depth. Fig. 8 shows the stress vs. strain curve with varying shoulder diameter.

Table - 4 Effect of mechanical properties on variation of shoulder diameter

Exp. No.	Shoulder diameter-r (d) in mm	Tensile strength in MPa	Bending angle in Degree	Hardness at NZ in HV
1	16	66.90	30	54.29
2	20	110.38	40	56.85
3	24	132.17	45	59.57

Table - 5 Effect of mechanical properties on variation of plunging depth

Exp. No.	Plunging Depth (PD) in mm	Tensile strength in MPa	Bending angle in Degree	Hardness at NZ in HV
1	0.03	105.41	40	55.71
2	0.12	132.17	45	59.57
3	0.21	115.26	35	55.16

2.4 Plunge Depth:

Devanathan et al. (2013) indicated the plunge depth influence on the mechanical properties. In this work, Al 6063 plates of dimensions 100 mm x 50 mm x 6 mm was used for butt welding by friction stir welding. High carbon chromium (HcHcr) steel was used as tool material and table 6 shows the dimensions of the FSW tool and table 7 shows the process parameters and their levels. The visual inspection results showed that at zero plunge depth there was no defects while at 0.2mm plunge depth excessive flash was observed. The tensile test results are shown in table 8. Also the hardness value was increased with increase in the plunge depth [6].

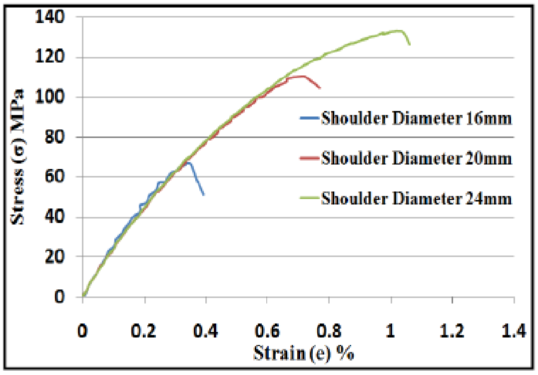


Fig. - 8. Stress vs. strain curve with varying shoulder diameters

Table – 6 Dimensions of the FSW tool

Tool Description	Dimensions
Tool pin profile	Taper cylinder
Tool Shoulder diameter	24mm
Tool pin diameter major diameter	6mm
Tool pin diameter minor diameter	4mm
Tool pin length	5mm

Table – 7 Process parameters and their levels

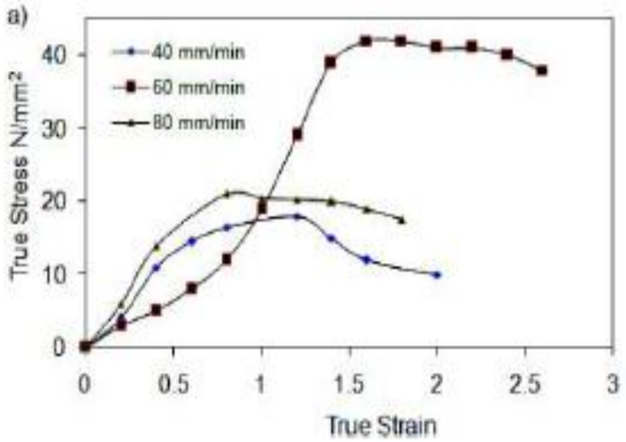
Experiments/ Process parameters	A	B
Spindle Speed (Rpm)	800	800
Feed (mm/min)	9	9
Plunge depth (mm)	0	0.2

2.5 Different Material FSW:

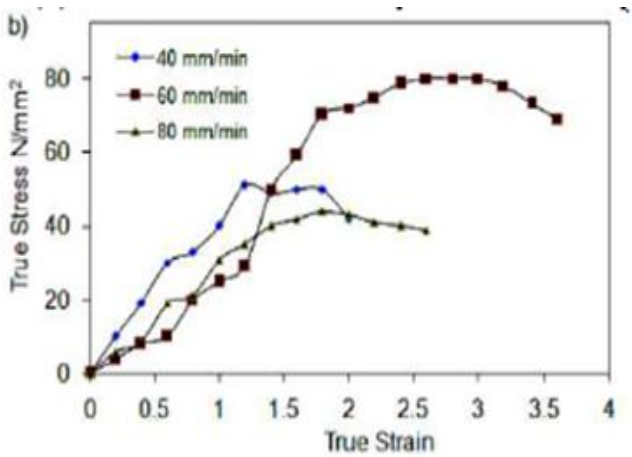
Puviyarasan et al. (2012) checked the feasibility of the friction stir welding process for joining two different aluminium alloys. Also it was found that increasing the tool rotation speed improved the welding strength. The experiment was performed with Aluminium alloy AA2011 and AA6063 plates of dimensions 50 X 50 X 10 mm with the help of CNC vertical milling machine using high speed steel tool hardened to RC-65. Fig. 9 shows the tensile properties variation with the tool rotational speed. The results showed that at 1400 rpm tool rotational speed, defect free weld surfaces were obtained [5].

Table - 8 Properties of the weldment

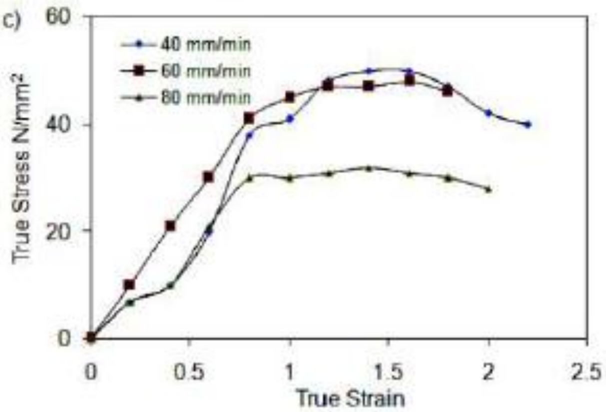
Experiment	Ultimate tensile strength (MPa)	Yield strength (MPa)	% of Elongation	Joint Efficiency
Base Material	150	124	36	-
A	130	105	36	86%
B	76	70	15	50%



(a) At tool rotation speed of 1200 rpm



(b) At tool rotation speed of 1400 rpm



(c) At tool rotation speed of 1600 rpm

Fig. - 9. (a-c) True stress vs. True strain for different tool rotational speeds.

2.6 Magnesium Alloy FSW:

Cao et al. (2011) analysed the change in tensile shear load because of change in the probe length. The experiment was performed on magnesium alloy plates of dimensions 1200X500X2 mm with the welding tool having scrolled shoulder of 19.05 mm diameter. Results showed no significant variation in microstructure at various probe lengths. Also the cavity defects were appeared at relatively low heat input and sound lap joints were obtained at an advancing rate higher than 1.3 mm per revolution. With the increase in probe length and penetration into the bottom sheet the shear strength increases [3].

2.7 Friction Stir Spot Welding:

Yuan et al. (2011) studied the lap-shear separation load variation with the tool rotational speed and plunge depth variation. The experiment was performed with the Al alloy 6061 with two tool profile geometry. One being conventional pin tool (CP) and other one being Off-centre feature tool (OP). Fig. 10 shows the pin profiles used for Experiment [4].

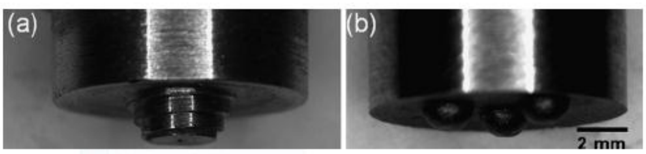


Fig. - 10. Macro images of (a) Conventional pin tool and (b) Off-centre feature tool.

Results showed that larger bond region was obtained at a lower rpm with flat hooking which observed to disappear at the interface of the nugget region. Also higher tool rotational speed resulted in better material flow-ability and hence more material displaced per unit time, and to deform the material less shear and forging components required from the tool. It appeared that at higher tool rotation speeds for both tools the accuracy of the plunge depth was better. Three different separation modes were also observed which were, nugget fracture separation, interfacial separation and upper sheet fracture separation [4].

3. CONCLUSIONS

In this review article current development in friction stir welding and friction stir spot welding have been addressed. Tool geometry is very important parameter for producing good quality welds in the materials. However, at the present scenario, limited information regarding tool geometry and welding parameters and their effects on the weld quality is available in open literatures. From the open literature, it is known that Aluminium and magnesium alloys are most preferable initial material for experimental purpose and also cylindrical threaded pin and concave shoulder are widely used welding tool configuration.
Welding parameters such as welding speed, tool rotation rate and tool tilt angle and tool plunge depth is crucial factor to produce sound and defect free welds. It is widely accepted that the FSW process is complex and the material flow within the weld is still poorly understood. In addition to above, Friction stir welding is also used as a microstructural modification technique and also used to produce desired properties in the metallic materials.

4. Future Scope

Friction stir welding is immerging as the most efficient and feasible welding process in the production field. It is also used for improving the mechanical properties of the material. It is more energy efficient and flexible process enabling the manufacturer to produce varieties of the weld without much laborious work.
In future, there is a lot of scope for work in the Friction stir welding area. As much parameters and large range of their values influences the last resulted joints, various experiments can be carried out to find the optimum or best value to produce sound weld joints. Also work for different tooling and base material can be carried out to find the feasibility range of the friction stir welding process.
In the above mentioned work, various parameters were considered to obtain their effects on the resulted joint. Double-side friction stir welding is also a new technique to produce joint with different mechanical properties. Work for various parameters effect has already been done in the previous work as well as double-side friction stir welding is also performed. However, the combination of the double side friction stir welding and varying values of the welding parameters such as penetration depth, tool tilt angle, overlapping nugget region etc. can be used for the future work to find the combined effects.

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