A Literature Review On Friction Stir Welding Process

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Abstract- *Friction stir welding is a solid state welding process which involves joining similar or dissimilar metals using a rotating tool. The process makes the use of non-consumable tool with a specially designed shoulder and pin. The rotating tool pin gets inserted in to abutting surface of the plates to be joined and the rotating tool translated along the weld direction to cause severe plastic deformation (SPD) in the nugget zone to produce a permanent weld joint. It is an environment friendly welding technique. Because, conventional welding techniques like arc welding, tungsten inert gas welding (TIG), metal inert gas welding (MIG) etc, causes health problems like bronchitis, airway irritation, lung function changes, lung fibrosis, asthma and a possible increase in the incidence of lung cancer due to the emission of exhaust gases coming from the traditional arc welding. In this context an environment friendly technique has been invented at The Welding Institute (TWI), U.K. known as Friction Stir Welding. This paper presents a review on FSW process parameters and effect of input parameters.*

Keywords- severe plastic deformation, micro structural properties, FSW, MIG, TIG

I. INTRODUCTION

1.1 INTRODUCTION

It is a method of solid phase welding, which allows a wide range of parts and geometries to be welded are called Friction Stir Welding (FSW), was invented by W Thomas and his colleagues at The Welding Institute (TWI), in 1991. The process proves predominance for welding non-heat treatable to which the fusion welding cannot be applied. Friction stir welding has a wide application potential in aerospace, ship building, automobile and other manufacturing industries. Thus fundamental studies on the weld mechanism, the relation between microstructure, mechanical properties and process parameters have recently been started. Friction stir welding is a relatively simple process as shown in Fig 1. In recent times, focus has been on developing fast, efficient processes that are environment friendly to join two dissimilar materials. The spotlight has been turned on Friction stir welding as a joining technology capable of providing welds that do not have defects normally associated with fusion welding processes. Friction stir welding (FSW) is a fairly recent technique that utilizes a non consumable rotating welding tool to generate frictional heat and plastic deformation at the welding location, thereby affecting the formation of a joint while the material is in the solid state. The rotating tool is pushed against the surface of two overlapping plates. The side of the weld for which the rotating tool moves in the same direction as the traversing direction, is commonly known as the advancing side, the other side, where tool rotation opposes the traversing direction is known as the retreating side.

By keeping the tool rotating and moving it along the seam to be joined, the softened material is literally stirred together forming a weld without melting (Rowe C.E.D. et al., 2005).The welding tool is then retracted, generally while the spindle continues to turn. After the tool is retracted, the pin of the welding tool leaves a hole in the work piece at the end of the weld. These welds require low energy input and are without the use of filler materials and distortion.

Table 1
Key benefits of FSW are summarized below.

Metallurgical benefits	Environmental benefits	Energy benefis
Solid phase process Low distortion of wark piece Good dimesional stability Repeatability No loss of alloying elements Fine microstructure Absence of cracking	No shielding gas required No surface cleaning required Eliminate grinding wastes Consumable materials saving such as rugs, wire, or any other gases	Improved material use (eg. Joining different thickness) allows reduction weight Decreased fuel consumption in light weight air craft automotive and ship application

1.2 PRINCIPLE OF FRICTION STIR WELDING

Friction stir welding (FSW) is a solid-state joining technique in which coalescence occurs owing to thermomechanical deformation of workpieces as the resulting temperature exceeds the solidus temperature of workpieces. The fundamental concept of FSW technique is depicted in Figure 1. It consists of a non-consumable rotating tool having a specially designed tool pin and shoulder. Tool pin is plunged into the faying faces of sheets or plates to be joined thus tool moves in the transverse direction along the length. The tool rotates in the clockwise direction and translates from front to back as shown in Figure 1. The left side where the direction of tool rotation is same of tootravel direction is termed as advancing side. It is opposite to the direction of metal flow. The side opposite to advancing side where rotation of tool is reverse of direction of tool travel is termed as retreating side. Owing to frictional heat between tool and workpiece, material around the pin is softened and a solid state joint is produced without melting

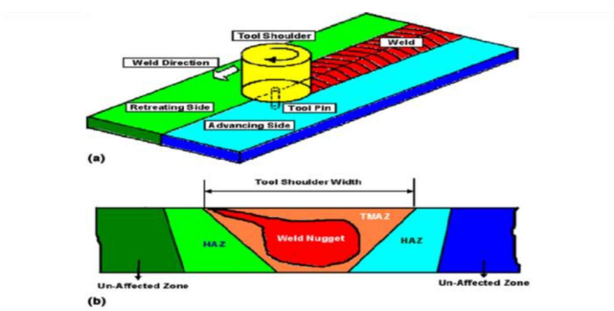

Fig 1: Friction Stir Welding

In FSW joints various microstructural regions can be observed as illustrated in Figure 2. The parent metal region is unaffected by heat as it is far away from the recrystallized zone and hence microstructural and mechanical properties of this region remains unaltered. The second region is heat-affected zone that is next to parent metal and is affected by heat but no plastic deformation takes place in this region; however, mechanical and microstructural property changes. The next region is thermo- mechanically affected zone that is very near to weld nugget and it is plastically deformed by means of tool. In this region material deforms without recrystallization. Next region is nugget zone or stir zone or fully recrystallized zone in which tool pin rotates and produces frictional heat; results in severe plastic deformation

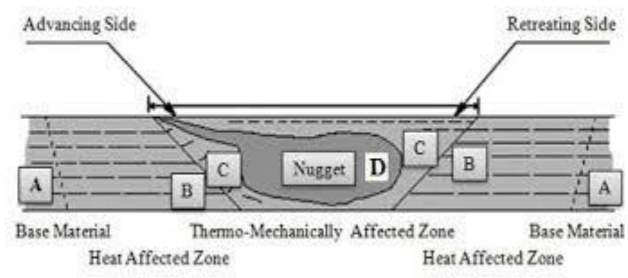

Fig. 2. Micro structural regions of friction stir welding

1.3 PROCESS PARAMETER

The process parameters for friction stir welding are broadly classified into three groups: (a) tooling related parameters: shoulder and pin material, shoulder diameter, pin length, pin diameter, feature geometry, thread pitch, etc.; (b) machine related parameters: welding speed, plunge force or depth, spindle speed, tool tilt angle, etc.; and (c) other parameters: anvil material, anvil size, workpiece size, workpiece properties, etc. (Lohwasser and Chen, 2010). The influencing process parameters are illustrated using a cause-effect diagram in Fig. 3.

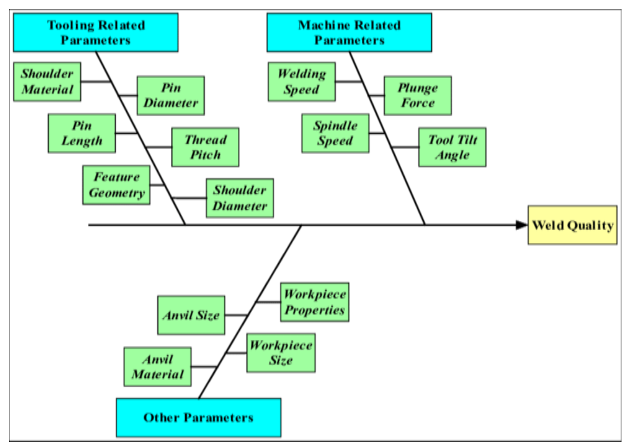

Fig.3 Process Parameter

Table:2
General FSW Process Parameters.

FSW Parameter	Range of Values
Shoulder diameter (f_s)	10-25 mm
Pin/probe diameter (f_p)	4-7.5 mm (root), 3-4 mm (tip)
Pin/probe length (l_p)	2.5-7.5 mm
Tool tilt angle (a)	0–12°
Rotation speed (N)	300-5400 rpm
Tool traverse speed (v)	20-475 mm/min
Axial (plunging) force (F_z)	220-12,000 N

1.3.1 Tool Material

A tool material is art of the friction stir welding process. The quality of the weld and tool wear are two important consideration in the selection of tool material, the properties of which may affect the weld quality by influencing heat generation and dissipation. The microstructure of the welded material may also affect as a result of with eroded tool material. [30]

Table.3 Types of tool materials use in friction stir welding. [31]

S. No	Tool Material	Rotation Speed
1	H13 steel	1000–3000 rev/ min
2	H13 steel,46-48 HRC	500–1820 rev min
3	Mild steel	1600 rev /min
4	Tool steel	1000 rev min[21]
5	High carbon steel	300–1620 rev min
6	AISI oil hardened tool steel	500–2000 rev/min
7	High C high Cr	2000rev/min
8	PcBN	200 rev min
9	W–La alloy	150–750 rev min

1.3.2 Tool geometry

‘‘Tool geometry” is one of the most dominant characteristics of process optimization. It is very vital in governing material flow, as it regulates the traverse rate of the ‘‘FSW tool”. The common FSW tool geometry is illustrated in Fig.4, with permission from Elsevier). The tool is designed to fulfill the key purposes such as localized heat generation, smooth material flow, encouragement of mixing, plastic deformation, the formation of forging force. The heat generates mainly by virtue of friction amidst the tool probe and base material, at the early phase of the tool plunge. While further heat generates due to workpiece material deformation. The FSW tool is allowed to plunge up to a moment at which shoulder and material surface are not in contact with each other. The major component of heat generation is the friction amidst the shoulder-material interface. The tool shoulder is defined by the ‘‘shoulder diameter ($ø_s$)” measured in ‘‘mm”, which may be flat, concave, and convex or scrolled. While, tool probe (or pin) is usually defined by its ‘‘probe diameter ($ø_p$)” and ‘‘probe length (or insertion depth) (l_p)” both measured in ‘‘mm”, which may be flat, tapered, threaded or fluted.

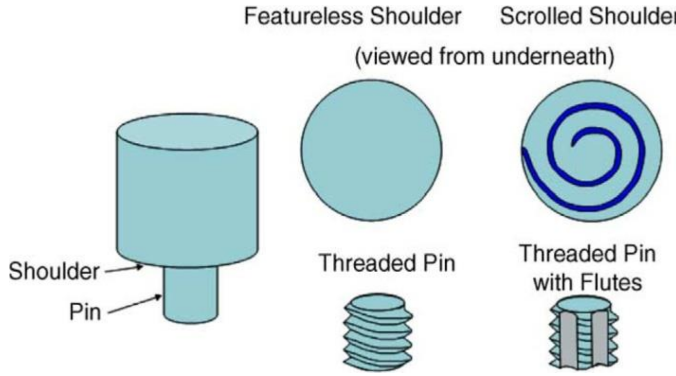

Fig. 4. Schematic representation of the FSW tool

(SSFSW)” to join high strength Al alloys. Through experimental verification assuming optimal circumstances, it was clear that SSFSW had about 30% lesser heat input compared to FSW. Also, thinner welds were produced having diminished ‘‘heat affected zone (HAZ) width”, by virtue of stationary shoulder. It also showed better performance in ‘‘cross-weld tensile tests” and also exhibited higher surface finish.

1.3.3 Joint design

‘‘Butt”, as well as ‘‘lap” weld joints, are one of the most conventional joint configurations generally been used in FSW. In order to avoid any separation between the adjoining joint surfaces of two identically thick plates, it is necessary to fasten these plates rigidly to the ‘‘backing plate”. Also, fastening becomes excessively important during the course of the initial ‘‘tool plunge” where a greater degree of forces is being experienced. In case of a lap joint, two plates fastened to the ‘‘backing plate” in a lap configuration, are welded to each other by plunging an FSW tool orthogonally into the bottom plate through the top one and traversing it along the welding direction. Apart from the common ‘‘butt” as also ‘‘lap joint” conformations, numerous additional configurations are also possible as can be seen in Fig.5

FSW with ‘‘innovative overlap joint” which consisted of a ‘‘wave-shaped interface” was created on the steel through direct processing with the help of tool probe tip . It was reported that altogether superior mechanical characteristics were achieved, comprising of about half of original material’s ‘‘ultimate tensile strength”, during ‘‘tensile shear tests”, with the application of ‘‘innovative overlap joint” with ‘‘2-pass weld”. It was consequently possible because of greater stir efficiency and relatively even joining section. Whereas in the case of ‘‘1-pass welds”, compared to the traditional joint greater resistance was been experienced during the ‘‘peeling tests” with ‘‘innovative over- lap joint”. As a result, it was concluded that fairly superior mechanical characteristics can be achieved by means of comparatively smaller ‘‘weld pitch ratio”, with the application of ‘‘innovative overlap joint”.

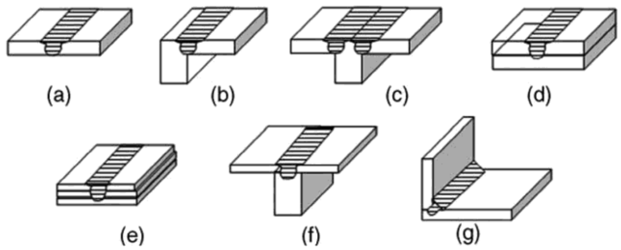

Fig. 5 Joint design of FSW

1.4 WELDING PARAMETER

FSW involves complex material movement and plastic deformation. Welding parameters, Tool geometry and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material. Therefore, welding speed, the tool rotational speed, the tilt angle of the tool, tool material and the tool design are the main independent variables that are used to control the FSW process.

The main process parameters and there effects in friction stir welding are given below Table 2 (FSW-Technical-Handbook).

Table:4
Main Welding parameters in friction stir welding

Parameter	Effects
Rotation speed	Frictional heat, —stirring, oxide layer breaking and mixing of material.
Tilting angle	The appearance of the weld, thinning.
Welding speed	Appearance, heat control.
Down force	Frictional heat, maintaining contact Conditions.

a. Tool rotation and Transverse speed

For FSW, two parameters are very important: tool rotation rate (v, rpm) in clockwise or counter clockwise direction and tool traverse speed (n, mm/min) along the line of joint. The motion of the tool generates frictional heat within the work pieces, extruding the softened plasticized material around it and forging the same in place so as to form a solid-state seamless joint. As the tool (rotates and) moves along the butting surfaces, heat is being generated at the shoulder/work-piece and, to a lesser extent, at the pin/work-piece contact surfaces, as a result of the frictional-energy dissipation (Grujicic M. et al., 2010). The welding speed depends on several factors, such as alloy type, rotational speed, penetration depth, and joint type (Sakthivel T. et al., 2009). Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the traverse movement of the tool, and this transferred material, are consolidated in the trailing edge of the tool by the application of an axial force (Kumar K., et al., 2008).

b. Tool tilt and Plunge depth

In addition to the tool rotation rate and traverse speed, another important process parameters are tool tilt with respect to the work piece surface and plunge depth. A suitable tilt of the spindle towards trailing direction ensures that the shoulder of the tool holds the stirred material by threaded pin and move material efficiently from the front to the back of the pin. The tool is usually characterized by a small tilt angle (θ), and as it is inserted into the sheets, the blanks material undergoes to a local backward extrusion process up to the tool shoulder. (Fratini L. et al., 2009). Further, the plunge depth of pin into the work pieces (also called target depth) is important for producing sound welds with smooth tool shoulders.

c. Tool Design

Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. Tool geometry such as probe length, probe shape and shoulder size are the key parameters because it would affect the heat generation and the plastic material flow (Gopala Krishnan S. et al., 2011). The tool is an important part of this welding process. It consists of a shoulder and a pin. Pin profile plays a crucial role in material flow and in turn regulates the welding speed of the FSW process.

The shoulder generates most of the heat and prevents the plasticized material from escaping from the work-piece, while both the shoulder and the tool pin affect the material flow. Friction stir welds are characterized by well-defined weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used.

The commonly used five pin profiles i.e., straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square pins to fabricate the joints, in FSW are shown schematically in Fig. 6 (Elangovan K. et al 2009).

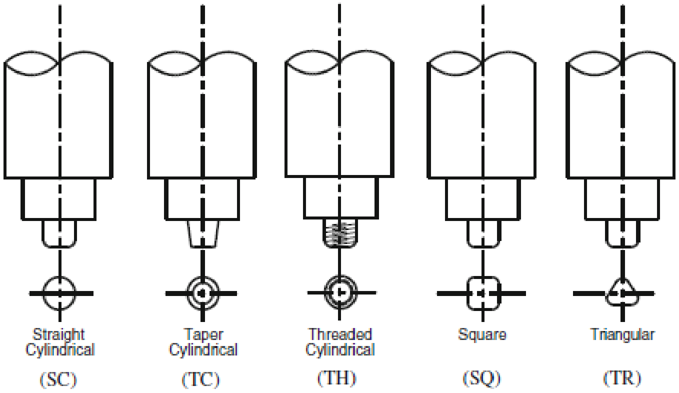

Fig.6. Schematic drawing of the FSW tool.

1.5 Microstructure Classification

The first attempt at classifying microstructures was made by P L Threadgill (Bulletin, March 1997). This work was based solely on information available from aluminium alloys.]. For butt joints the generalized profile proposed by TWI was an inverted trapezoid with four zones which is shown in the fig. (7)

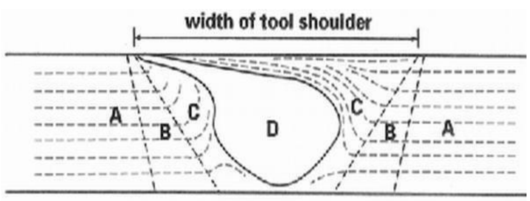

Figure 7: Microstructure of friction stir welded joint

Unaffected Material or Parent Metal (A): This is the material remote from the weld, which is neither deformed, nor affected by the heat in terms of microstructure or mechanical properties.

Heat-Affected Zone (HAZ) (B): It is common to all welding processes. As indicated by the name, this region is subjected to a thermal cycle but is not deformed during welding. The temperatures are lower than those in the TMAZ but may still have a significant effect if the microstructure is thermally unstable. In fact, in age-hardened aluminium alloys this region commonly exhibits the poorest mechanical properties

Thermo-Mechanically Affected Zone (TMAZ) (C): It occurs on either side of the stir zone. In this region the strain and temperature are lower and the effect of welding on the microstructure is correspondingly smaller. Unlike the stir zone the microstructure is recognizably that of the parent material, albeit significantly deformed and rotated. Although the term TMAZ technically refers to the entire deformed region it is often used to describe any region not already covered by the terms stir zone and flow arm.

Stir Zone (Nugget, Dynamically Recrystallised Zone) (D): It is a region of heavily deformed material that roughly corresponds to the location of the pin during welding. The grains within the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material.

II. LITERATURE REVIEW

Arora et al. 2011 [1] states that computed temperatures for maximum shoulder diameter are to the extent of high temperatures normally faced in FSW of AA 6061.

Bhatt et al. 2012 [2] studied consistent rotational speed of tool and tool of same geometry. Change in the traverse speed of tool has total results on temperature and flow stress in FSW of AA 7050-T7451 aluminium.

Biswas et al. [3] have analyzed that concave shoulder and conical pin were preferable to FSW of AA1100 to continue the diameter of the tool pin so tiny as to present a wormhole defect.

Lienert et al. 2003[4] viewed the suitability of FSW of steel to retain its tensile characteristics. FSW of change of tough, HSLA and stainless steels could be possible. The computed results of the analysis made.

Nandan et al. [5] shows that significant flow has an effect on movement of heat inside the work piece, the tool rotational and linear movement and lack of symmetry of production of heat around the surface of the tool pin. The system of FSW and the function of the tool in forming welds in aluminium alloys 7020-T6 were gone

Kumar et al. 2005 [6]. A tool having frustum pin of H13 as hard as 55 HRS was used by them. With a vertical milling machine they performed experiments maintaining consistent welding characteristics which are 140 r.p.m. of the speed of rotation, 80 mm/min of the speed of welding and the angle of tilt 2º. It was found by them that while the contact surface of the tool enhances, the defect of the weld gets reduced. They further testified that in the initial part of welding, the shoulder of the tool does not come in contact with the metal to the full extent as a result of which the force around the axis will not be sufficient to generate heat. As such the joint becomes imperfect. The point is that when contact surface between shoulder and metal extends, the force of the axis also enhances. Which the force of the metal will be confined to the cavity of the welds. It will generate enough heat and hydrostatic power. This will ensure a weld that has no fault.

According to **Oliver Lorrain et al. [7],** threaded pins are used in industrial application. In the initial stages there is a possibility of threaded tools becoming unthreaded. This happens due to the wear of the tool when the toll is used for alloys of a high melting point as well as aluminum alloys that are strengthened. They conducted FSW tests with two variant pin profiles. The two pins are unthreaded with or without level faces. The main idea of this experiment is to study the flow when unthreaded pins are used to weld plates that are thin. To examine the flow of the material welds with cross and longitudinal sections were studied with or without using material marker. Both the threaded and unthreaded pins were observed to process the same material flows. The material is placed in the advancing side in upper portion of the weld which in the retreating side it is placed in the lower portion of the weld with a rotating layer appearing around the tool. This study shows a very low vertical movement towards the weld's bottom due to the absence of threats. The force of the plunge and the speed of the rotation affected the size of the zone controlled by the shoulder. This can be diminished by the use of cylindrical frustum pin having flats. Numerous studies on transfer of heat and flow of material during FSW were made.

Askari et al. 2001[8] employed a 3D finite difference hydrodynamics code to demonstrate the joining of geometry, production of heat and flow of plastic during the process of FSW. The flow of material around the tool was initiated

Zhao 2005[9]. Arbitrary Lagrangian-Eulerian procedures were used by Zhao with a moving mesh to handle extreme plastic distortions around the rotating tool. Using commercial code based fluid dynamic procedures,

Colegrove and Shercliff 1998[10] offered a 2D model to study the flow of material around the welding tool.

O F Valero 1996 [11] made an attempt to identify the tensile characteristics of the joint performed in different conditions of welding. This study showed the least tensile strength and malleability at the lowest spindle speed for a specific traverse speed. When the speed of the spindle extended, there was increase in strength and elongation attaining the highest point before falling down due to high speed of rotation. In FSW the speed of rotation and the input of heat increase simultaneously. Therefore the speed of the tool rotation must be maximized to achieve the highest tensile of the joints. When the speed of welding rises, the width of the exerted area and the value of the maximum exertion go down. Then the area of the maximum exertion slowly moves to the retreating side of the joint from its advancing side. The tensile strength diminishes considerably as the speed of welding rises. The area which is softened is narrower for higher speeds of welding than for lower speeds of welding. Therefore the Speed of welding must be maximized to obtain maximum tensile characteristics of the FS joints.

Thomas et al. [12] explained the results of microstructure analyses, hardness measurements and tensile tests of Friction stir welded sheets of two aluminium alloys Al Mg4.5Mn0.7 (AA5083) and AlZn6Mg2Cu (AA7075). The macrostructures and microstructures of FSW welds are similar to these produced by hot working. They strongly depend on sheet thickness, as do also their tensile properties. The variation of hardness through weld width is small in alloy AA5083 and more important in AA7075. The strength of FSW welds in AA5083 and AA7075 6.0mm sheets are as high as 100% and 72% respectively of parent material strength.

Z.H. Fu, et al. 2005 [13] investigated that Joining by FSW of aluminium is done at low temperature that eliminates the major problem of conventional welding processes, which must be performed under inert gas to present the dissolution of atmosphere gases in the melted material of the joint.

Schmdt and Hattel 2008 [14] employed a commercial FE code, ABAQUS, to anticipate an extreme plastic distortion in the process of FSW. To solve coupled thermomechanical problems during the operations of FSW, Nandan et al. [15] prepard a 3D visco-plastic finite element model.

Liu and Fuji 2003 [16] discovered that at a low fore of the axis, the shape of non- symmetrical semi-circular units at the top of the weld surface shows mediocre plasticization, through the combination of the material under the sway of the shoulder of the tool, has a proper quality. The structure shear lips and flashes that is extremely high on the advancing as well as retreating sides of the weld line rendering the metal in the area of the weld too thin giving mediocre tensile characteristics, all due to greater force. To prevent this, the force of the axis must be optimized so that optimum tensile characterizes may be obtained.

According to Zaho et al 2005 [17] the profile of the pin exercises a crucial role in the flow of the material and thus regulate the welding characteristics of the process of FSW. FSW has a weld lump and flow contour almost round in structure. The flow contour depends on the design of the tool as well as the characteristics and process of welding.

Hidetoshi Fujii 2006 [18] studied the effect of the profile of the tool on the mechanical characteristics and microstructures of welded aluminium plates that are 5mm thick. He maintained that the simplest profile without threads and the ordinary profile with threads along with triangular prism shaped profile be used for welding three types of aluminium alloys. For 1050-H24 define to impairment is minimum and a columnar tool without threads produces the weld with maximum mechanical characteristics. In the case of 6061-T6 the power to resist impairment is minimum and the profile of the tool has minimum effect on the microstructures and mechanical characteristics. If the speed of rotation is as low as 600 rpm, the profile of the tool has no notable effect on the microstructures and mechanical characteristics of the joints. **P. Cavaliere [19]** analyzed the effect of processing characteristics on mechanical and microstructural articles of AA 6056 joints formed by FSW. Many samples were procured by using rotational speeds of 500, 800 and 1000 rpm and welding speeds of 40, 56 and 88 mm/min. The mechanical characteristics of the joints were assessed using micro hardness (HV) and tests of tensility at room temperature.

Sato Y.S. et al. [20] worked on FSW of extremely fine grained Al alloy 1100 provided by stored roll bonding. Friction Stir Welding brought about a repetition of very fine grains in the stir zone and little expansion of the very fine grains of the ARBed material at the outer surface of the stir zone. FSW has enormous hidden cuts of toughness in the ARBed material, though the stir zone and TMAZ had few cuts of toughness on account of active formation and retrieval. Subsequently, FSW efficiently prohibited the softening in the ArBed alloy.

S. Benavides et al. 1999 [21] made a study of minimum temperature FSW of 2024 aluminium. They used active reformation of superfine equiaxed grain forms to make possible super plastic impairment as the welding and unification mechanism. 2024 Al alloy was friction stir welded at an initial heat of 230°C and the maximum heat of the weld zone was within 640°C. The remaining FSW zone grain form had equiaxed fine grains having an identical size of nearly 0.8mm, all though which could be compared with a central weld zone grain of nearly 10 mm in 2024 Al FSW at an initial of 30°C, where the maximum heat was 330°C. A cut is obvious in the softening close to the boundary of the weld one around the weld HAZ when the heat is minimum through no similar softening exists in the weld zone contrary to the room heat of the weld zone. It causes reversal of toughness in similar weld zones.

H.G. Salem 2003 [22] used friction stir technology to link actively reconstituted Al alloy light sheets for structural parts fulfil the demand for generation and hardness of macrostructures as well as microstructures. FSW at 1000 rpm speed of tool rotation and 4.2 mm/s weld feeding rate were accomplished without grain growth. FSW in created the fine equiaxed structure with high grain boundary angles.

Fonda R.W. et al. 2004 [23] made a study of the growth of grain structure at some stage in friction stir welding. They observed that a stop action FSW was arranged in Al-Li 2195 to free in the active impairment area adjacent to FSW tool. An examination of a plan view section of the weld shows important new information of evolution of the structure of grain and the development of the texture near the FSW tool. Strips of grain develop in front of the fully polished area showing divergent stabilities of the earlier grain adjustments to the applied impairment. Polished sub-grains develop in the area of impairment and slowly develop higher disorientations to bring about finer grains as noticed near the tool. This area shows an fcc shear texture following application of appropriate rotations. Thus in this weld the main process of purification of grain is the subdivision caused by impairment and active retrieval processes. There is no need to evoke an active restructuring process.

Liu G. et al. 1997 [24] studied the microstructural issues of FSW of 6061-T6 aluminium and stated that LM and TEM were used to describe the microstructures in the FSW area and compare these microstructures with the primary 6061-T6 aluminium alloy plate which was about 0.65 cm in thickness. They calculated the profile of microhardness stretching from work piece and through zone of the weld. They also conducted many butt and assumed welds in stable plate divisions at the speeds of rotation extending from 300 to 1000 rpm and traverse speeds of 0.15 to 0.25 cm/s. The tempered carbon steel welding head pin was 0.63 cm in diameter and 58 cm/s long. The main results that were obtained were that the FSW area in 6061-T6 aluminum was represented by an active and continuous restructuring of microstructure. The particles in the next phase of the work piece are stirred into the weld area where the remaining toughness varies from 55 VHN near the bottom of the weld. These contracts with the toughness of the work piece varying from 85 and 100 VHN. The size of the weld area grain had an average of 10 μm as against 100 μm of the work piece.

III. APPLICATIONS OF FSW

As mentioned earlier, FSW has extensive applications in numerous fields. The concept of FSW has been effectively used to develop the technique known as ‘‘friction stir processing (FSP)” [31]. It uses the concept of localized plastic deformation just as FSW to enhance the properties of metals. Various space launch vehicles manufactured by ‘‘Lockheed Martin, Boeing USA’s Delta II and Delta IV rockets, NASA’s new Orion spaceship and Space Launch

System (SLS) [32], SpaceX Falcon 9 [33]", etc. used FSW. FSW technique is also being used by numerous train manufacturers such as ''Hitachi, KHI, Nippon Sharyo, etc." to build a high speed, passenger as well as long-distance trains [34]. Numerous automobile manufacturers such as ''Audi [35], Ford [36], Mazda [37] as well as Tesla" has adopted FSW for lightweight construction. The FSW technique was used by ''Airbus (or EADS) (in A340, A350, A380, A400M) [38], Boeing, Lockheed Martin, Bombardier [39], BAE systems, Embraer (Legacy 450 and 500) [40] as well as Eclipse Aerospace (in Eclipse 500)" for building aircrafts, thereby, joining various components by avoiding the use of rivets for lighter construction. Apple Inc. adopted FSW technique in their ''2012 Apple iMac", thus building the device 40% thinner [41]. The technique of FSW will persistently evolve and develop with the progress in the study in the near future. FSW technique has been planned to be used by Sweden and Finland for encapsulating nuclear waste in huge vessels made up of Cu which can survive for 0.1 million years [42]. Further work in this area is required to fulfill the requirements of aerospace, petrochemical and naval industries, due to the extreme corrosion resistant and mechanical properties of Ti alloys [43]. There may be other future prospects of FSW which can be investigated and developed with extensive research.

IV. CONCLUSIONS AND FUTURE SCOPE

In this chapter, a literature review of different aspects of FSW technique has been illustrated. It has been decided to present the major findings related to FSW at one place so as to provide a clear picture to the reader. Following points can be concluded:

- Friction stir welding owing to its unique characteristics: low distortion and shrinkage even in long welds, free of arc, filler metal, and shielding gas, low HAZ, free of spatter and porosity defect is emerging as an alternative to fusion welding. FSW is found suitable for joining similar or dissimilar metals or alloys including aluminium, magnesium, copper, steel, zinc, nickel and its alloys, plastics, etc.
- Like traditional fusion welding butt and lap joint can be carried out in friction stir welding. Although, no special preparation is needed. Moreover, it is observed that FSW shows significant enhancement in tensile strength, ductility, fatigue, and facture toughness as compared to fusion welding.
- It is evident that FSW process parameters: tool rotation rate, traverse speed, spindle tilt angle influence the mechanical and metallurgical behaviour of joints and hence, are crucial to produce sound and defect-free weld.
- It is obvious that FSW tool regulates the amount of material stirred and frictional heat and hence, geometry of pin and shoulder are deciding factor to obtain sound welds. Despite of considerable attention on FSW technique, following issues have not received enough attention and need to be addressed:
- According to available literature, most of the research work is focused on friction stir welding of aluminium, copper and magnesium. Friction stir welding of alloys, plastics, composite materials, etc. is having huge scope for future research.
- The influences of the input process parameters on process performance characteristics and interaction effects are not significantly explored. In-detail study of contribution of the individual input process parameters on process performance characteristics is lacking in literature.
- Mechanism of materials flow, tool geometry design, wearing out of welding tool, force distribution during welding needs proper attention.
- The tribological, corrosional and surface topographical behaviour of friction stir welded joints are not elaborately discussed in literature.
- In-detail study is required to explore the effect of preheating, nanoparticle inclusion and quenching on mechanical and metallurgical behaviour of FSW joints.
- No proper guideline in terms of mathematical/theoretical model of process performance parameters of FSW is available for selecting input parameters to obtain desired output.

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