



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

# IJIRSET

International Journal of Innovative Research in  
**SCIENCE | ENGINEERING | TECHNOLOGY**

# INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 11, Issue 8, August 2022

**ISSN** INTERNATIONAL  
STANDARD  
SERIAL  
NUMBER  
INDIA

Impact Factor: 8.118

 9940 572 462

 6381 907 438

 [ijirset@gmail.com](mailto:ijirset@gmail.com)

 [www.ijirset.com](http://www.ijirset.com)



# Study on Material Flow Behavior and Properties of Friction Stir Welded Joints

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**ABSTRACT:** Friction stir solid state welding is the most popular state-of-the-art joining technique for low melting points metal and alloys. The joints formed using this technique are free from the defects that develop during the conventional welding process. No bulk melting occurs in this process which allows dissimilar joining of metals that are incompatible or difficult to join by fusion welding processes. In situ microstructure and mechanical properties, the modification takes place during the process. Starting with the introduction this study presents progress in friction stir joining techniques and variants, techniques to visualize flow behavior, and the influence of critical process parameters on flow behavior. Various noteworthy contributions have also been presented along with the research gap for future directions.

**KEYWORDS:** Material flow, solid state processing, microstructure, flow visualization, the marker material

## I. INTRODUCTION

Friction stir welding (FSW) is novel joining technology developed by Wayne Thomas at the Welding Institute (WI) in London, United Kingdom, in 1991 [1]. The technique offers several metallurgical, environmental, and energy benefits and produces low distortion and high strength joints compared with most fusion joining techniques [2]. This provides a unique opportunity to alter the microstructure by controlling various parameters involved during the process and therefore Use the "Insert Citation" button to add citations to this document.

the performance of joints and surface quality improves to an extent that is difficult to achieve with conventional fusion welding processes. FSW processes are characterized by a unique mix of high temperatures, enormous strains, and strain rates, as well as their reliance on processing parameters [3]. Joints in the workpiece develop due to physical displacement induced by the string action of plasticized material around the tool pin [4]. The developed microstructure of the stir zone affects the response of joints under various loading conditions. In-depth understanding and investigation of material-flow behavior under the influence of the type of tool profiles employed and material in the FSW process is meaningful for controlling microstructure, analyzing welding defects, and optimizing process parameters, properties, and performance of welds. Understanding the substantial flow and strain rate is therefore essential for obtaining a good joint [5].

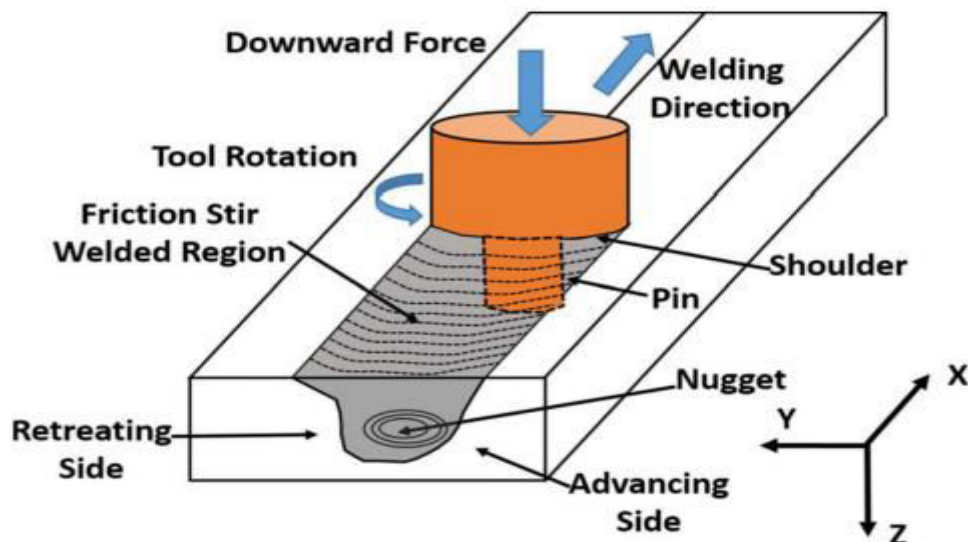


Figure: 1 Rational representation of friction stir welding [6]

Heat treatable aluminium alloys in the 2xxx, 6xxx, and 7xxx series [7] because of their high strength-to-weight ratio characteristics are largely used in self-propelled vehicles, shipbuilding, rail, and in modern and future aircraft manufacturing industries. Components made of aluminium such as bumper beams, rear spoilers water coolers, stiffening frames console, and attachment of hydro-formed tubes are easily weldable using FSW which is challenging to weld using typical welding methods due to their inherent characteristics [2]. Currently, aluminum alloys are employed in automobile connector stock, seamless and structural tubing, structural components, ladder constructions, and handrail tubing, among other applications. The scarcity of publications is in the domain of understanding the material flow behavior due to the coupling effect of shoulder and probe surfaces.

## II. FSW PROCESS

FSW technology is a patented solid-state technology that was discovered in 1991 at TWI and proved itself as the key technology for joining low-temperature melting point alloys, particularly aluminum and its alloys [8]. FSW can weld like and unlike materials from the same or different categories of dissimilar physical and chemical properties which are extensively used in productions such as auto vehicles and air travel [5–11]. Friction stir welding (FSW) potentially overcomes the defects like solidification cracking, grainy dendritic structures, large distortions, gas and shrinkage porosities, macro and micro suspended, etc. [12–13].

The tool performs a key role in collaborating the flow of materials and joint formation mechanism of the FSW process. The suitable tool selection for the FSW process depends on workpiece material, thickness to be joined, processing parameters, and joint configuration. Numerous studies have recorded and documented on FSW tool patterns, material selection, strength, failure mechanisms, failure prevention, and so on. Material flow is connected to microstructure formation in the FSW process and has a substantial influence on weld joint properties. Controlling the microstructure and characteristics of welds needs a comprehensive understanding of the material-flow behavior of this process. Several techniques have been used to understand the intermixing of material in the process of FSW. Different techniques, equipment, and processing factors cause variations in material flow and strain rate [13]. FSW's methodologies, processes, and tooling have all evolved dramatically since its inception. Priorities include understanding heat generation and transmission processes, material flow mechanism, probe geometry features, flaw generation, and structure of the welded materials [16].

## III. PROGRESS IN RESEARCH TECHNIQUES AND TOOLS

### 3.1 Research progress in friction stir joining techniques and variants

FSW revolutionized the efficient bonding of chemically incompatible, low melting points, and softer metals. Substantial development has been conducted since its origination. The joining takes place due to the stirring action of the tool and the transportation of material around it [25]. The whole joint formation process finishes in four stages: Plunging,



dwelling, welding, and Retracting/cooling stage. Less traverse speed, high axial load, and great torque on weldments, heavy machinery, higher tool wear rate, and other process-related challenges make it more lucrative for potential researchers. To resolve these issues, FSW has been regularly rebuilt, enhanced, modified, and altered in terms of the machine, tool, and process. SSFSW was developed at TWI to address concerns about temperature gradients in titanium-based alloys. In SSFSW, the revolving pin in the stationary shoulder glides across the surface to be joint. The advantages of steady shoulder friction stir joining include improved weld mechanical qualities and microstructural uniformity. The stationary shoulder friction stir welding (SSFSW) is a promising technique for the welding of aluminium alloys and other metals. Uneven torque is produced on the workpiece on the advancing and retreating sides which reduces the stability of the workpiece and increases the number of fixtures required. Allowing the shoulder and probe to rotate independently of one another solves this problem. The pin rotates at a higher speed than the shoulder. The manually opposite movement of the pin and tool reduces the overall torque exerted on the workpiece. Due to which less number of clamps require to firm the workpiece [16].

The discrepancy in induced microstructure and properties of retreating and advancing sides is another significant challenge to the FSW process. The temperature distribution asymmetry across the AS and RS is controlled by keeping the rotation of the pin and shoulder within a specified range and controlling the other significant process and tool parameters.

The dual rotation speed FSW procedure is also similar to RDRFSW. The shoulder and probe rotate separately at different rates, but in the same direction in DRFSW. By rotating the shoulder and pin in different directions and reducing asymmetry around the weld center line, the weld properties are enhanced. In addition to this better welding efficiency is observed at higher rotation speed whereas better weld formation takes place at the lower rotation speed of the shoulder. A bobbin tool is used in the BTFSW process, which has two shoulders, one above and one below the workpiece acts simultaneously on the workpiece surface to generate enough frictional and deformation heat on both sides due to which the reactive forces are confined within the limit which eliminates the potential of pin compression deformation [7].

Friction stir spot welding (FSSW) is a special type of friction stir welding that is primarily used to combine difficult-to-join sheets in an overlap configuration invented to eliminate the need for riveting. The procedure of FSSW is similar to FSW but without the lateral tool movement. This FSW variant is being used by several industries like Kawasaki Heavy Industries Ltd, Mazda, NorskHydro, and Sumitomo Light Metal Industries Ltd [15-18]. There are several different types of FSSW procedures, including traditional FSSW, Refill Friction SSW (RFSSW), and pin-less techniques such as rotating anvil stationary shoulder friction stir welding (RAFSSW) and double-sided FSSW. Stitch FSSW and swing FSSW are other types of FSSW processes used in special cases [18]. In recent years, friction stir-based driving /fastening (FSR) introduced to overcome the limitations of solid-state processes for securing lightweight materials such as friction stir spot welding (FSSW), friction taper stud welding (FTSW), friction hydro pillar processing (FHPP) and self-piercing riveting (SPR). Successful lap joining of chemically incompatible materials with substantial melting point variations is difficult through conventional friction stir welding. To overcome the challenges that come with lap joining configuration the friction stir scribe (FSS) method was developed. It uses a particularly designed tool that combines the tool pin's tip with a scribe cutter placed off the pin's center [19]. Very limited research work was found on the FSW of 6110 aluminum alloy.

### 3.2 Influence of tool profile/geometry on Flow behavior

The probe is the soul of the friction stir welding technique that generates frictional heat which creates a third body region [18]. A specially designed tool is inserted into the adjoining edges of the material to be joined and travel along the abutting edges [20]. Substantial movement and intermixing around the tool causes the joining of the edges of sheets. Extrusion or chaotic mixing takes place in FSW depending on the location in the weld zone. Various types of flow patterns like a lamellar, vortex, whorl, and swirl features were observed in the study which was the characteristic of chaotic-dynamic mixing [29,30]. The surface layers flow towards the deformed material from one place to another and are deposited towards the trailing edge forming a nugget microstructure made up of alternate layers [23]. The material flow pattern, magnitude, and degree of deformation mixing are governed by the tool probe and shoulder design. Which are extremely significant for the realization of the FST, sustainability, performance, and durability of tools [15,18]. Tool geometry includes the shape, size, and dimensions of various tool elements. Pin and shoulder shape and geometry determine the nature of material flow, jointly produced, and defects incurred. In most of the butt joining configurations the pin length is usually kept shorter than the thickness of the plates to be welded [15,18]. Various types of tool geometries such as cylindrical, triangular, square, pentagonal, hexagonal, conical with flat or flute, etc. are employed for joining. Interaction between the workpiece and the rotating tool, rotational speed, and traverse speed governs the extent of temperature, heat generation, plastic deformation, and intermixing of the workpiece



materials[18].The applied forging force efficiently fills the void formed during the tool's forward motion. Atomic or diffusion bonding of stir material depends on the temperature and pressure results a joint[18].

The shoulder end surface plays a vital role to increase the friction, shear, deformation, and movement of workpiece surface material T Scrolls are the most commonly used shoulder features[20].Evaluation of the influence of probe and shoulder profile on material flow behavior and mixing during friction stir welding of similar and dissimilar alloys is critical. Which is essential for the best tool/pin design based on scientific principles. The researchers used a variety of experimental and numerical modeling methods to attempt a thorough explanation of material flow characteristics influenced by tool geometry. [24].

The probe's outer surfaces can be cylindrical, tapered, screwed, flat, or fluted, along with other shapes and features. 12 mm thick similar and dissimilar AA sheets have been successfully welded using cylindrical probes.The tapered probe has its advantages. It generates high hydrostatic pressure and generates more frictional heat owing to the larger surface area, which also increases the plastic deformation of weldments.Material stirring and nugget integrity benefit from the greater surface area.Multi-faceted geometries are produced on the surface to facilitate material deformation and blending and vary processing load[20].

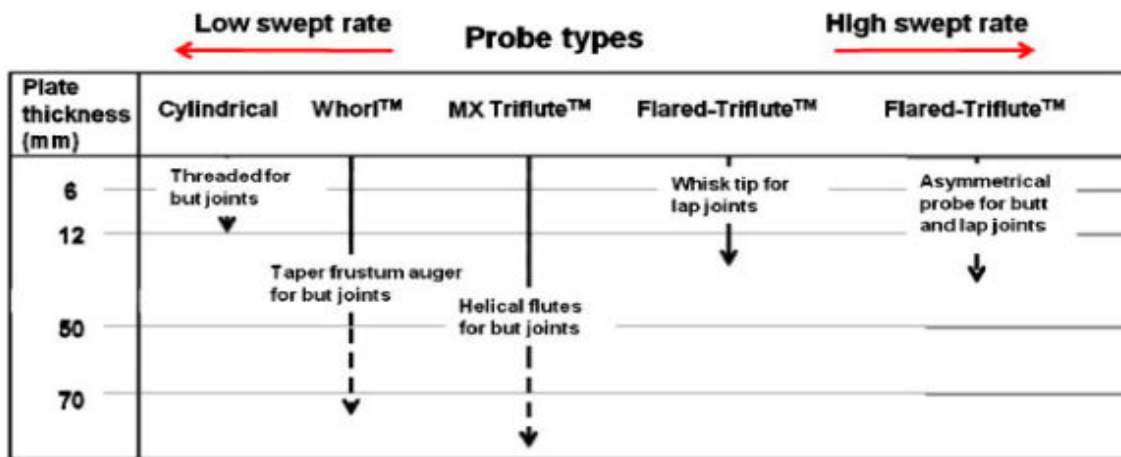


Figure:2 Types of tools introduced by TWI[20]

Threadless probes are preferred for high strength and highly abrasive alloy even though the tools without threads result in cavities whereas two threaded tools generated entirely united welds. The material is pulled towards the bottom by the threads along the tool surface when a left-handed threaded probe rotates clockwise[1]. More consistency on rings produce due to the creation of the screw profile similar flow within intermixed zone next to the revolving pin using threaded pin type[25]. The material gets settled towards the trailing edge of the tool after rotating many times around the tool causing better material stirring, void closure, and oxide breakdown[20].

The flat introduced on the cylindrical tool surface acts as paddles and increases the local deformation and [9]. Flat increases the temperature of the nugget area and promotes effective mixing by trapping and releasing the material[19,20]. An increase in tensile strength is observed with the increase in the number of edges of the tool [24].

The addition of flats on the conical probe tool alters the material flow pattern and onion rings without varying the chemical composition [28]. The number of flat surfaces introduced on the tapered shoulder directly corresponds to the reduction in transverse force and tool torque [27]. The triflate tool develops a larger deformation zone than conical[29]. The plasticized material adheres to the flat faces of the Polygonal pin which causes a nonuniform microstructure of the nugget zone. The sample generated by the square pin tool, on the other hand, has a homogeneous microstructure in the stir zone without cavitation[30].

Significant changes were found in the FS Weldments structure were produced through the introduction of varying numbers of flats onto the threaded cylindrical pin tools. A hybrid threaded flat tool changes the textural banding shape and introduces sub-bands[31]. When the flat surface pin is used, movement of material takes place in pieces and the size of these pieces is reciprocal to the flat faces on the tool surface. The material adjacent to the pin whirls and the magnitude of whirling depends on the weld pitch and the number of faces on the pin surface. In the case of the circular pin, micro-level whirling takes place[32].

Whorl and MX Triflute probe volumes are less as compared with cylindrical or polygon profile probes. This profiling tool achieves a high swept rate with reduced welding forces. 60–70% reduction in displaced volume may effectively obtain by using these probes. These design elements aid plunging material flow, enhance the contact area between the tool surface and the plasticized materials, and generate heat, allowing the plasticized material to flow more easily. Due to the increased mixing and stirring action of the material, a tool intended to achieve a higher sweep rate decreases voids and allows surface oxides to be disturbed and diffused more efficiently inside the nugget [20]. Analysis of dissimilar joining of AA7075-T651 and AA2024-T351 aluminum alloys revealed that the strongest joints are made with a welding pin tool with a flute radius equal to the pin regardless of the position of the material.

Pin and shoulder-driven material flow regimes involving the joint development process in FSW. These two flows converge and create the defect-free weld. The straight hexagonal bolt head (SHBH) improves the material flow behavior, uniform distribution of plasticized material, and reduced macroscopic defects on the welded zone [33]. Many authors have studied the effect of several pin profiles on material flow behavior in similar/dissimilar joining of various materials but very few of them have investigated the coupling effect of shoulder and pin on flow behavior.

### 3.3 Techniqueto visualize flow patterns

Various analytical, numerical modeling, and experimental techniques have been used to understand different material flow patterns, deformation of plasticized material, formation of onion ring layers and sub-layers, and material mixing at various locations in the welded structure formed in FSW. A brief of these techniques is summarised in this section.

Microstructure study of developed patterns is used to reveal the type of flow. Chaotic dynamic mixing of materials produces typical intercalated laminar-like flow patterns that form a vortex, whorl, and swirl landscapes [22]. Two types of flow, first, layer-by-layer flow, attributes to shearing action, and second, extrusion of the plasticized metal around the tool pin observed [21]. Locating the tracers implanted in the welding route using the “stop action” technique provides detailed insight into the movement of material while joint formation. Tracking of tracers in the stirrer zone is comparatively easy now with the radiographic techniques. This revealed that the tracer rotates multiple times around the pin before leaving the rotational zone [4]. Colligan [26] investigated the developed material flow patterns due to the threaded tool around the rotating tool by inserting tracer during operation and immediately suspending the process i.e. ‘stop action’ method. The outcomes delivered in-depth information due to the threads and rotational speed on material flow patterns, along with some metallurgical details and temperature distribution in the deformed zones. The asymmetric material movement was observed in the dissimilar butt joining of aluminum and magnesium AA2195–T8 and the tracers found behind the initial position [21].

0.1mm thin copper foil instead of spherical tracers was used in the sudden stopping technique in an investigation of material flow during the joining of 6.3mm thick AA6061 Al alloy. Metallographic investigation revealed separate transitional and rotational zones around the probe and material flow with a higher velocity toward the retreating side than the average velocity observed [3,32-33].

Material displacement pattern, velocity, strain, and strain rate are estimated by grid formation and tracking the initial and final position of these tracers in these grids [4]. Material flow is analogous to the straight current that skips the tool pin and turbulence current that revolves around and with the pin several times [31].

Modeling of friction stir welding is another perfect tool to explore the material flow patterns and temperature field. Plastic flow modeling of FSW has been used to determine the material displacement velocity around the tool during the process and strain rate with correlation to grain size.

Material particles from the leading edge tend to pass and settle behind the trailing edge of the pin. Five new unique zones in the stirring zone were identified as a result of the findings of DEFORM 3D simulation [36]. Asymmetric temperature distribution and asymmetric material flow about the weld line were observed using the thermo-mechanically coupled FEA model [21]. FE analysis based on Lagrangian, Eulerian, and Coupled Eulerian-Lagrangian formulation is used to establish the relation between pin profile and banded structure formed [28].

The visco-plastic deformation of the material and heat transmission during friction stir joining were effectively investigated using numerical solutions of momentum, mass, and energy conservation equations [21].

Computational Fluid Dynamics based mathematical model developed to analyze the flow pattern and introduced a concept of stagnation point toward the advancing side [20,35,36]. These models were used to do a quantitative examination of temperature-dependent physical events of various probe types shapes (asymmetrical Triflat tool, axisymmetric & tapering tool) [29].

Crystallography techniques are used to discover the orientation of texture formed due to the oscillation of an off-centered tool along the weld line [39].

PIV is a cutting-edge method that provides an immediate velocity field, live-in-process imaging of material flow, and exact strain rate calculation during the operation [40].

Plastic modeling and simulation of material mixing during FSW reveal two major material flow groups: first is shoulder driven another is pin driven. An efficient bond is a result of successfully mixing these flows as well as with the freshly formed surfaces on the advancing side after the pin [25]. Even though there has been a huge amount of research on material flow behavior, there hasn't been much-published research on the effect of location, the density of tracers, and shoulder profile on flow characteristics. This research aims to gain a better knowledge of the process by looking at the impact of tracer position and size on mechanical characteristics and material flow behavior in friction welding of aluminium alloys. From studying the literature review very limited work was found using shot tracer to visualize the flow.

### 3.4 Critical process parameters and their influence on flow behavior

FSW is a fairly basic technology that has a lot of potential for connecting and processing low-temperature materials. The tool traverse speed ( $V_{trans}$ ), rotational speed ( $\omega$ ), downward force ( $F$ ), tool tilt angle, penetration depth, and design play crucial roles in severe plastic deformation, flow behavior, and material intermixing. These parameters play a significant role in grain structure formation in the nugget zone and therefore define weld quality [38]. The percentage of material mixing, the size of the distorted Al-alloy lamina, and the material flow patterns are all affected by the nugget zone's relevant locations and processing parameters [5]. The tool's rotation causes the material to stir around the tool probe, while the tool's translation transfers the stirred material from the front to the rear of the probe. [23]. Higher traversal rates result in a speedier operation and aid in the development of a smoother plastic deformation transition providing a well-stirred welded connection, whereas the rotating rate is the primary component in producing friction load and generating localized heat between the contact surfaces of the workpiece and tool. High travel velocity in the weld nugget results in voids and unfavorable porosity content. During stirring, the softened components mix and travel through a succession of stick and slip movements before settling behind the tool to finish the joint. Stirring necessitates significant material deformation and mixing, which happens in weld nuggets at elevated temperatures (below the melting point) and high strain rates [32]. Insufficient intermixing and deformation leads to joint line remnant defect and failure of joint.

Material intermixing and joint strength increase with the increasing tool rotational speed in the welding of 5 mm thick AA6061 and AA7050. Inadequate material intermixing is the cause of low mechanical strength and failure through the stir zone. The failure occurs in the HAZ in the joints which are developed at a higher rotation speed due to excess softening of material [41].

Better intermixing of material is obtained at tool travel speed 20 mm/min, rotation speed 900 rpm, tool inclination angle  $1^\circ$  and an offset from joint line 1.50 mm for quality weld between dissimilar AA6061/AA2014 using mix square pin profile. Defect-free welds were developed at weld speed 31.5 mm/min, tool speed 900 rpm, tilt angle  $2^\circ$ , and offset 0 mm using the same probe profile [42].

The thickness of partially formed layers varies with tool rotation or travel speed. During stirring these layers sheared away and formed islands [43]. Better intermixing between aluminum and polymer occurs on increasing plunge depth whereas at lowering the inclination angle the contour of dissimilar weld broken due to intermittent material displacement from the leading edge of the tool to the trailing edge in dissimilar lap joining of AA5058 to PMMA. Because of severe wear phenomena and larger surface tractions during stirring, the size of aluminum pieces and interlocks grows as the tool tilt angle increases [44].

## IV. NOTEWORTHY CONTRIBUTIONS

Significant work has been conveyed in the field of friction stir welding since its invention by Wayne Thomas at TWI. Remarkable work has been reported by various authors in the development of FSW variants, tools, processes, and techniques and in the direction of improving the process efficiency and reducing the limitations of this solid-state joining technique. A brief of a few noteworthy contributions is being presented here.

### 4.1 Development of FSW variants

The systematic development of FSW has led to several variants of the technology. Twin-stir, skew-stir, Re-stir, Duel rotation stir, and pro-stir are a few process variants based on FSW technology [45]. Twin-stir concept uses paired tool rotates on opposite sides, therefore, reducing responsive torque and developing more uniform heat distribution and symmetric weld. In a skew-stir variant, the tool is tilted to that of the machine spindle for increasing the swept ratio and additionally to re-entrant features on the surface which increases the process efficiency.

The FSW technique induces softening in heat-treatable aluminium alloy joints due to the involved thermal cycles required. Mechanical properties of joints get reduced due to coarsening of the strengthening precipitates. Underwater



friction stir joining (UFSJ) minimizes the limitations associated with the joining of heat-sensitive alloys and improves mechanical properties by reducing many welding defects like solidification cracking, shrinkage, and porosity. UFSW is useful for a variety of maritime and offshore applications, including shipbuilding, oil and fuel tanks, and fabrication and repair of different offshore structures [10,43].

#### 4.2 Development of the tools

The development of various profile tools for joining the variety of materials is a remarkable contribution made by several researchers. A stationary shoulder develops 30% less heat than a rotating one. The stationary shoulder produces a thinner weld and low HAZ. Joints developed using Stationary shoulder tools exhibit better tensile strength and higher surface finish [47]. The tool geometries have changed dramatically as our understanding of material movement has progressed. The conventional cylindrical threaded probes are limited to efficient butt joining of Aluminium sheets up to 12 mm thickness. More complicated features have been added to the probe to help with material flow, mixing, and reducing process stresses. Which increases the probability of successfully joining greater thick materials. MX Triflute and Whorl tools have been used to join 50-60 mm thick similar/dissimilar sheets successfully [5,13,17]. Because of the increased mixing and stirring action for the material movement, these tools are operated at extremely high speeds and produce a high sweep rate, which decreases holes and permits the surface oxides to be more thoroughly disturbed and disseminated inside the nugget [20].

#### 4.3 Development in Flow Visualization Technique

The correlation between material flow and microstructure evolution is an outstanding contribution to flow analysis [21]. Because cylindrical sheets of material are extruded during every rotation of the tool, and cutting through the section of the material forms an apparent onion ring, the creation of onion rings is concluded to be a geometric consequence. Various types of modeling of this technology have proven to be a milestone in research. With the aid of these techniques, the effect of varying the type of tools/process can be predicted with reasonable cost and time. Tracking tracer, through stop action and radiography or PIV technique to visualize the flow behavior is also the remarkable achievement of the investigator through which the in-depth material flow characterization became possible. The use of crystallographic texture research to characterize material flow is a new method. The completeness of mixing is determined by the kind of material flow around the tool. Hence flow analysis is a lucrative field of experimental inquiry, its consequence on microstructure development, properties, and quality of joints produced by employing cylindrical tools with scroll shoulder profiles.

### V. CONCLUSION

Friction stir welding has been successfully used to join low melting points, difficult to weld metals. This technology is spreading for similar and dissimilar joining of some high-strength metals such as steel and titanium. In this paper, the development of friction stir welding, the development of tools, and the various techniques for material mixing and transportation have been presented. The various process parameters involved in research activities and progress to date in the development of friction stir welding have been reviewed.

The main goal of the paper is to review recent progress in friction welding and to provide a basis for further research.

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