Frictions Stir Welding: Developments and Trends

Janak Singh [a], Rakesh Kumar [b] and D. G. Mahto [c]
[a], M. Tech. Student HPTU Hamirpur India.
[b] M. Tech. Student HPTU Hamirpur India.
[c] Professor Green Hills Engineering College, Solan, India

Abstract

The Primary incentive for welding process development is the need to improve the total cost effectiveness of joining operations. A great concern over the safety of the welding environment and the potential shortage of skilled technicians and operator in many countries has become important considerations. Friction stir welding (FSW) is a relatively new solid-state joining process, which is energy efficient, environment friendly, and versatile. It is used to join high-strength aerospace aluminum alloys and other metallic alloys that are hard to weld by conventional fusion welding. One can weld similar and dissimilar metals by this process effectively. In this paper a review of the current state of development and trends of the FSW addressed. Particular emphasis has been given to mechanisms responsible for the formation of welds and micro structural refinement, and effects of FSW parameters on resultant microstructure and final mechanical properties.

Keywords: Friction Stir Welding, welding Process, Developments and Trends.

I. Introduction

In modern era, various welding techniques are being employed to join metals. They comprise from the conventional oxyacetylene torch welding to laser welding. The welding can be subdivided into fusion welding and pressure welding. The fusion welding process includes bonding of the metal in the liquefied stage and a filler material if required in form of consumable electrode or a roll of wire. Some processes require an inert ambience in order to overcome oxidation of the molten metal. There are many drawbacks in the welding techniques where the metal is heated to its melting temperatures and then solidified to form the joint. The melting and solidification causes the mechanical properties of the weld in some cases to defects such as low tensile strength, fatigue strength and ductility. The other disadvantages are porosity, oxidation, micro-segregation, hot cracking and micro-structural defects in the joint. The process also restrains the combination of the metals because of the different thermal coefficients of expansion. In solid state welding, coalescence is reached at temperatures below the melting temperatures of the base metal with out any need for the filler material or any inert environment. Examples are friction welding, explosion welding, forge welding, hot pressure welding and ultrasonic welding. The three important parameters time, temperature and pressure individually or in combinations bring forth the joint in the base metal. In solid state welding the metal does not reach its melting temperatures, resulting in lesser number of defects due to the melting and solidification of the metal.

In solid state welding the metals being joined sustain their original properties as melting does not occur in the joint and the heat affected zone (HAZ) is also minor when compared to fusion welding techniques where decay of the strength and ductility begins. Dissimilar metals can be joined easily compared to fusion welding. The application of these processes has in the past been confined, but keeping in view the benefits of automation and the requirement for high-integrity joints in newer materials it is conceived that the use of these techniques will increase. This is a new process originally applied for welding of aerospace alloys, especially aluminum extrusions.

Friction stir devised in 1991 at The Welding Institute (TWI), is a solid-state joining process in which a third body tool is used to join two faying surfaces. Heat is generated among tool and material which forms a very soft region near the FSW tool. It then intermixes (mechanically) the two pieces of metal at the place of their join, then the softened metal (due to the higher temperature) can be joined using mechanical pressure (which is applied by the tool), much like joining clay, or dough. It is primarily used on aluminum, and most often on extruded aluminum (non-heat treatable alloys), and on structures which need superior weld strength without a post weld heat treatment. A rotating non consumable cylindrical-shouldered tool with a profiled nib is transversely fed at a constant rate into a butt joint between two clamped pieces of butted material. The nib is slightly shorter than the weld depth required, with the tool shoulder riding atop the work surface. Frictional heat is produced between the wear-resistant welding components and the work pieces. This heat, along with that generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to get soft and that too without melting. While moving the pin forward a special profile on its leading face forces plasticized material to the rear where clamping force helps in a forged consolidation of the weld. This tool traversing process along the weld line in a plasticized tubular shaft of metal causes severe solid state deformation consisting of dynamic recrystallization of the base material. The solid-state nature of the FSW process along with its unusual tool and asymmetric nature, results in a highly characteristic microstructure.

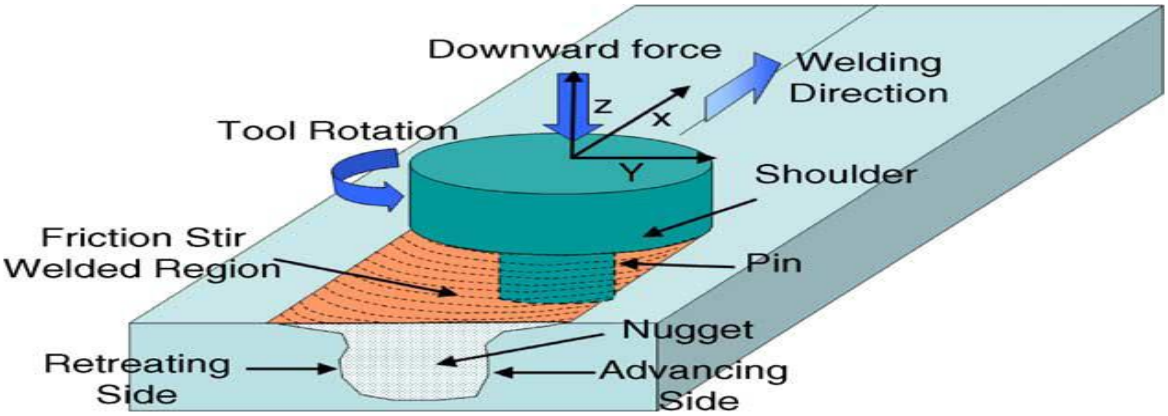

Figure 1: Schematic Diagram of Friction Stir Welding.

II. Important Welding Parameters

➢ Tool rotation and traverse speeds

In friction-stir welding, two important points; how fast the tool rotates and how quickly it traverses the interface. These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle. The increasing the rotation speed or decreasing the traverse speed will result in a hotter weld. In order to produce a sound weld the material surrounding the tool must be hot enough to enable the extensive plastic flow and minimize the forces acting on the tool. If the material is too cold then voids or other flaws may be present in the stir zone and in extreme cases the tool may break. Excessively high heat input, on the other hand may be detrimental to the final properties of the weld.

➢ Tool tilt and plunge depth

The plunge depth is defined as the depth of the lowest point of the shoulder below the surface of the welded plate and has been found to be a critical parameter for ensuring weld quality. Plunging the shoulder below the plate surface increases the pressure below the tool and helps ensure adequate forging of the material at the rear of the tool. The plunge depth must be correctly set, to ensure the necessary downward pressure and to ensure that the tool fully penetrates the weld. Tilting the tool by 2–4 degrees, such that the rear of the tool is lower than the front, also assist this forging process. On the other hand, an excessive plunge depth may result in the pin rubbing on the backing plate surface or a significant under match of the weld thickness compared to the base material.

➢ Tool design

The design of the tool is a critical factor so that the tool material must be strong, tough, and hard wearing at the welding temperature. Further it should have a good oxidation resistance and a low thermal conductivity to minimize heat loss and thermal damage to the machinery further up the drive train. The different shaped tool is shown below:

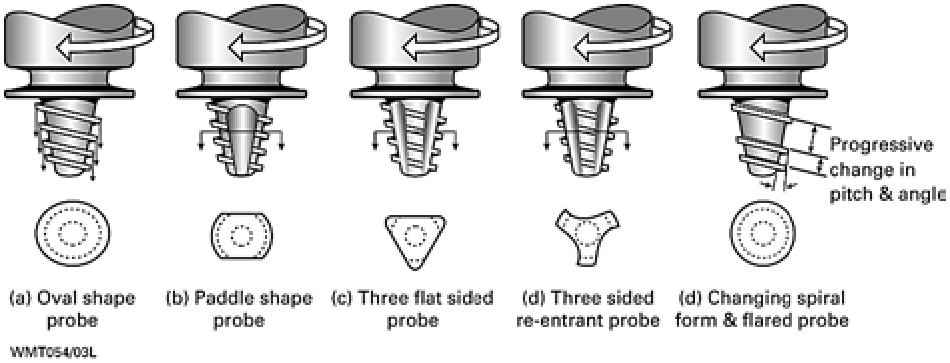

Figure 2: Different types of tools used in FSW

➢ Joint designs

Improvements in tool design have been shown to cause substantial improvements in productivity and quality. TWI has developed tools specifically designed to increase the penetration depth and thus increasing the plate thicknesses that can be successfully welded. The Triflute design has a complex system of three tapering, threaded re-entrant flutes that appear to increase material movement around the tool. The Trivex tools use a simpler, non-cylindrical, pin and have been found to reduce the forces acting on the tool during welding. The majority of tools have a concave shoulder profile which acts as an escape volume for the material displaced by the pin, prevents material from extruding out of the sides of the shoulder and maintains downwards pressure and hence good forging of the material behind the tool. The Triflute tool uses an alternative system with a series of concentric grooves machined into the surface which are intended to produce additional movement of material in the upper layers of the weld.

III Welding Forces and HAZ

During welding a number of forces will act on the tool:

- A **downwards force** to maintain the position of the tool at or below the material surface.
- The **traverse force** acts parallel to the tool motion and is positive in the traverse direction. This force arises as a result of the resistance of the material to the motion of the tool.
- The **lateral force** may act perpendicular to the tool traverse direction and is defined here as positive towards the advancing side of the weld.
- **Torque** is required to rotate the tool, the amount of which will depend on the down force and friction coefficient (sliding friction) and/or the flow strength of the material in the surrounding region.

In order to prevent tool fracture and to minimize excessive wear and tear on the tool and associated machinery, the welding cycle is modified so that the forces acting on the tool are as low as possible and abrupt changes are avoided. The microstructure can be broken up into the following zones:

- The ***stir zone*** comprises of heavily deformed material that rarely corresponds to the location of the pin while welding is being done. The grains in the stir zone are roughly equiaxed and often an order of magnitude smaller than the grains in the parent material. An unusual feature of the stir zone is the common occurrence of several concentric rings which have an "onion-ring" structure. The exact origin of these rings has not been established yet, but variations in particle number density, grain size and texture have been suggested.
- The ***flow arm zone*** is on the upper surface of the weld consisting of material that is scuffed by the shoulder from the receding side of the weld, around the rear of the tool, and deposited on the advancing side.
- **The *thermo-mechanically affected zone*** (TMAZ) is 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 used to describe any region not already covered by the terms stir zone and flow arm.
- The ***heat-affected zone*** (HAZ) is common to all welding processes. As name suggests, 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 long lasting effect if the microstructure is thermally unstable. In fact, this region commonly exhibits the poorest mechanical properties in age hardened aluminum.

Early work on the mode of material flow around the tool used inserts of a different alloy, which had a different contrast to the normal material when viewed through a microscope, in an effort to determine where material was moved as the tool passed. The rotation of the tool draws little or no material around the front of the pin instead the material parts in front of the pin and passes down either side. After the material has passed the pin the side pressure exerted by the "die" forces the material back together and consolidation of the join occurs as the rear of the tool shoulder passes overhead and the large down force forges the material. The material motion occurs by two processes:

1. Material on the advancing front side of a weld enters into a zone that rotates and advances with the pin. This material was very highly deformed and sloughs off behind the pin to form arc-shaped features when viewed from above (i.e. down the tool axis
2. The lighter material came from the retreating front side of the pin and was dragged around to the rear of the tool and filled in the gaps between the arcs of advancing side material. This material did not rotate around the pin and the lower level of deformation resulted in a larger grain size

For any welding process it is desirable to increase the travel speed and minimize the heat input as this will increase productivity and possibly reduce the impact of welding on the mechanical properties of the weld. At the same time it is necessary to ensure that the temperature around the tool is sufficiently high to permit adequate material flow and prevent flaws or tool damage. When the traverse speed is increased, for a given heat input, there is less time for heat to conduct ahead of the tool and the thermal gradients are larger. At some point the speed will be so high that the material ahead of the tool will be too cold and the flow stress too high, to permit adequate material movement, resulting in flaws or tool fracture. If the "hot zone" is too large then there is scope to increase the traverse speed and hence productivity.

The welding cycle can be split into several stages during which the heat flow and thermal profile will be different:

- ***Dwell*:** The material is preheated by a stationary, rotating tool to achieve a sufficient temperature ahead of the tool to allow the traverse. This period may also include the plunge of the tool into the work piece.
- ***Transient:*** When the tool begins to move there will be a transient period where the heat production and temperature around the tool will alter in a complex manner until an essentially steady-state is reached.

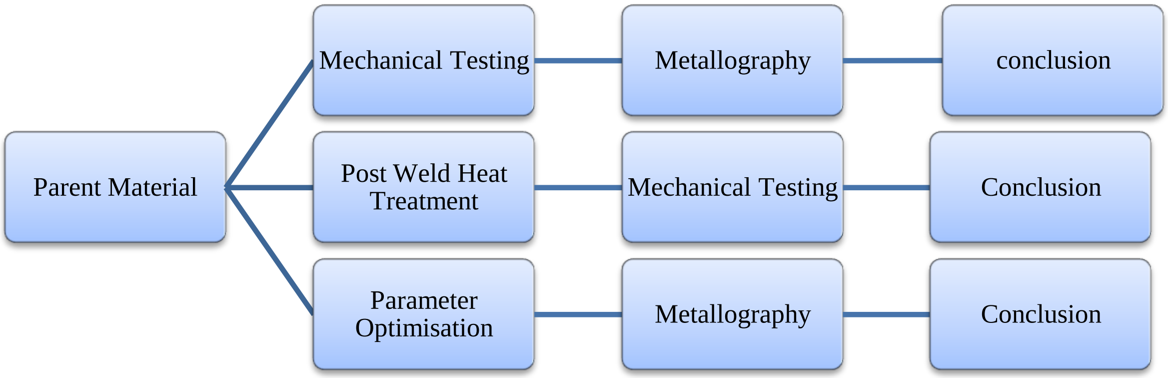

Figure 3: A typical FSW welding cycle

- ***Pseudo steady-state***: Although fluctuations in heat generation will occur the thermal field around the tool remains effectively constant, at least on the macroscopic scale.
- ***Post steady-state***: Near the end of the weld heat may "reflect" from the end of the plate leading to additional heating around the tool.

IV. Literature Survey

The literature surveys have been done considering the metallurgical effects in friction stir welding systems and techniques prevalent in industries. The works of various authors from diverse fields have been referred. Some of the most important and relevant findings have been presented.

G. Padmanaban et al. [1] developed an empirical relationship to predict tensile strength of the laser beam welded by using AZ31B magnesium alloy by incorporating process parameters such as laser power, welding speed and focal position and showed that the welding speed has the greatest influence on tensile strength, followed by laser power and focal position.

Olivier Lorraina et al. [2] conducted a FSW experiments using two different pins of unthreaded but have or do not have flat faces. The analysis revealed a too low vertical motion towards the bottom of the weld, attributed to the lack of threads. 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 with flats.

A work on the influences of rotational and welding speeds on microstructures and mechanical properties of friction stir welding was represented by H. Bisadi et al. [3]. In their study sheets of AA5083 aluminum alloy and pure copper were analyzed by using FSW. The experiments were performed at different rotational speeds each of them with welding speeds of 15 and 32 mm/ min. It was observed that very low or high welding temperatures lead to many joint defects and the best joint tensile shear properties were achieved at the rotational speed of 825 rpm and welding speed of 32 mm/min.

Galvãoa et al. [4] the aim of the work was to study the influence of the shoulder geometry on friction stir welding of 1mm thick copper-DHP plates. For this purpose, three different shoulder geometries flat, conical and scrolled, and varying the rotation and traverse speeds of the tool used. The flat shoulder tool proved to be inadequate for performing welds, the scrolled shoulder tool was more effective than the conical one in the roduction of defect free welds. However, both geometries required a minimum rotational speed to avoid internal defects.

A work on Production and wear characterisation of AA 6061 matrix titanium carbide particulate reinforced composite by enhanced stir casting method presented by S. Gopalakrishnan et al. [5]. In their study Al–TiCp castings with different volume fraction of TiC were produced in an argon atmosphere by an enhanced stir casting method and than, Specific strength of the composite has increased with higher % of TiC addition. Dry sliding wear behaviour of AMC was analyzed with the help of a pin on disc wear and frictions monitor and showed the improved specific strength as well as wear resistance.

Michael et al. [6] worked on Mixed mode I/II experiments in AA2524 friction stir weld specimens showed that changes in microstructure and particularly, reduction in constituent particle volume fraction result in virtual elimination of fracture along constituent particle bands. AA2524 has an increased tendency to transition from local mode I to local mode II crack growth during stable tearing and specific features observed during the fracture process were shown to be directly correlated to both metallurgical differences in the FSW microstructure and local variations in the measured CODcrit

Kim Lau Nielsen et al. [7] Used a modified version of the Gurson model, in which an extra term in the damage evolution law allows for the prediction of failure even at zero or negative values of the mean stress. This was totally purely phenomenological. Various amounts of the additional damage evolution were compared with predictions of the original Gurson model. The analyses carried out for different yield stress profiles transverse to the weld and for different specimen widths and suggested modification depends strongly on the overall stress state, and may have a too strong effect in some cases where the stress triaxiality is rather high.

L. Ceschini et al. [8] described the effect of the FSW process on the microstructure and consequently, on the tensile and low-cycle fatigue behaviour, of an aluminium matrix (AA7005) composite reinforced with 10 volume % of Al2O3 particles (W7A10A). Tensile tests showed a high efficiency of the FSW joints (about 80% of UTS). The low-cycle fatigue tests evidenced a fatigue life reduction for the FSW material respect to the base composite, particularly for high values of total strain range. The fracture mechanisms for the FSW specimens were those typical of metal matrix composites: interfacial decohesion, void nucleation and growth, as well as fracture of reinforcing particles, as shown by SEM analyses of the fracture surfaces.

Shafiei-Zarghani et al. [9] used a technique called friction stir processing (FSP) for the fabrication of Al/Al2O3 nanocomposite surface layer on an Al alloy substrate. The results showed that increase in the number of FSP passes causes a more uniform dispersion of alumina particles and thus, decreases particles clustering. In addition to this a decrease in the matrix grain size of the surface nanocomposite layers observed. The mean micro hardness value of the surface nano-composite layer was found to be improved by almost three times as compared to that of the as-received Al alloy substrate.

A work on friction stir welding was presented by Pedro Vilac et al. [10] in their work, they worked with *i*STIR , a thermal analytical model for 2D and 3D cases when FSW similar and dissimilar materials. The model allows simulation of asymmetric heat field developed below the tool shoulder due to the composition of the rotation and linear speeds, and the hot-to-cold welding conditions, considered in the establishment of the thermal field generated resulting from all the energy sources, i.e., viscous and interfacial friction dissipation. The analytical formulation was described and an application sample based on a friction stir weld produced under cold conditions for butt-welded AA6056-T4, in 3.9mm of thickness evaluated.

P. Wanjara et al. [11] determined that with increasing weld pitch, the occurrence of a “lazy S” defect in the weld nugget of friction stir welded AA6061 became increasingly pronounced, though its impact on the bend performance of the weld was negligible. Fully penetrated welds without metallurgical defects were obtained up to a joint gap of 0.5 mm. Though the overall micro hardness and bend performance of the welds remained unaffected until a joint gap of 0.8 mm, the decrease in the forge force during FSW beyond a joint gap value of 0.5 mm may represent a more critical limit in regards to the industrial application of the process.

M. Ericsson et al. [12] investigated whether the fatigue strength of friction stir (FS) welds is influenced by the welding speed, and also compared the fatigue results with results for conventional arc-welding methods: MIG-pulse and TIG. For this purpose The Al–Mg–Si alloy 6082 was FS welded in the T6 and T4 temper conditions, and MIG-pulse and TIG welded in T6. According to the results, welding speed in the tested range has no major influence on the mechanical and fatigue properties of the FS welds. At a significantly lower welding speed, however, the fatigue performance was improved possibly due to the increased amount of heat supplied to the weld per unit length. The MIG-pulse and TIG welds showed lower static and dynamic strength than the FS welds. This is in accordance with previous comparative examinations in the literature on the fatigue strength of fusion (MIG) and FS welds. The TIG welds had better fatigue performance than the MIG pulse welds.

Working on FSW of titanium alloys L. Fratini et al. [13] a new fixture presented allowing to obtaining the effective FSW joints of titanium blanks, which were investigated through mechanical and metallurgical tests highlighting the peculiarities of FSW of titanium alloys.

Kwansoo Chung a et al. [14] evaluated the macroscopic performance of friction stir welded automotive tailor welded blank (TWB) sheets, the hardening behavior, anisotropic yielding properties and forming limit diagram were characterized both for base (material) and weld zones. Four automotive sheets were considered: aluminum alloy 6111-T4, 5083-H18, 5083-O and dual-phase steel DP590 sheets, each having one or two thicknesses Base sheets with the same and different thicknesses were friction-stir welded for tailor-welded blank (TWB) samples.

Luis S. Rosado et al. [15] in their paper a new non-destructive testing (NDT) system focusing on micro size superficial defects in metallic joints presented. The concept was studied using a Finite Element Method (FEM) tool and experimental verified using a standard defect. The results showed that the system is able to detect superficial defects less than 60 lm deep, which significantly increases the actual state of the art in NDT reliability for micro imperfections detection. The system finds application to a broad range of industries which include manufacturing, maintenance and engineering companies.

S. Cui et al. [16] proposed a better model in the form, M f(w, v),, FSW of an aluminum alloy was conducted over a wide range of o and v values and M was measured. The effect of v on M can approximately be accounted for through linearly relating the model parameters to v. The model decay and the pre-exponential parameters need to be adjusted to make predictions for different aluminum alloys in the low o range. Both the model and experimental data demonstrate a diminishing alloy effect on material flow resistance as o increases. The model allows for a detailed evaluation of the sensitivity of M to changes in o and v.

Using the particle method approach Shigeki Hirasawa et al. [17] studied The effect of tool geometry on the plastic flow and material mixing during friction stir spot welding . Different pin geometries evaluated include tapered pin, inverse tapered pin, triangular pin, convex shoulder, and concave shoulder to predict the material flow for spot welds. The material flow, and there by the resultant hook formation, is quantified using numerical methods and is expressed as standard deviation of the particle movement. A triangular pin with a concave shoulder is the preferred tool geometry from the current study that results in high strength spot welds.

Comparing the fatigue resistance of welded joints produced by FSSW process and riveted joints of AA2024 alloy a work was presented by Malafaia et al. [18] in their study Two welding parameter sets were used, and P-N curves (load versus cycles) were plotted, using 2x106 cycles as the fatigue life limit. The FSSW welding procedures were carried out in a CNC milling machining and the riveted specimens were produced in accordance with aircraft industry parameters. The main failure mode observed in the welded joints was shearing, besides some cases of crack propagation in the perpendicular load direction, while for riveted specimens occurred mainly fretting nucleation followed by crack propagation in the perpendicular load direction

Y.M. Hwang et al [19] experimentally explored the thermal history of a work piece undergoing Friction Stir Welding (FSW) involving butt joining with pure copper C11000. For this purpose K-type thermocouples were used to record the temperature history at different locations on work piece, this data combined with the preheating temperature, tool rotation speeds and tool moving speeds allowed parameters for a successful weld to be determined. The appropriate temperatures for a successful FSW process were found to be between 460 ◦C and 530 ◦C.

Working on Friction stir welding of thick plates of aluminum alloy matrix composite with a high volume fraction of ceramic reinforcement F. Cioffi1 et al. [20] presented a work. Original particle-free regions vanish during the stirring process, leading to a homogeneous particle distribution. Occasional breakage of some large particles occurs. Tunnel defects appear at low rpm, and disappear at high rotational speeds. The size of the thermo mechanically affected zone, TMAZ, increases with increasing rpm. Ductility of the welds in the range of 10-15% achieved in compression test whereas, a rather brittle behavior was obtained in tension. A strength difference, SD, effect between compression and tensile test obtained. This accounts for the little detrimental effect of the FSW process on the matrix-reinforcement interface.

Kim Lau Nielsen [21] analyzed ductile damage development in a friction stir welded aluminum joint subjected to tension numerically by FE-analysis, based on a total Lagrangian formulation. An elastic–visco plastic constitutive relation that accounts for nucleation and growth of micro voids applied. Main focus in the paper was on the interaction between changes in the material parameters in different regions of the weld, the damage development and the position of the final fracture. It was found that damage development is highly influenced by changes in the yield stress profile and a shift in final failure was shown for comparable yield stress in the thermo-mechanically affected zone (TMAZ) and the nugget zone (NG).

Pierluigi Fanelli, et al, [22] the FSSW joint analyzed by means of a complex 3D FE model which allows to evaluate, in a parametric manner, the multifaceted internal geometry of the joint and the distribution of material mechanical characteristics after welding. It is possible to evaluate the structural behavior of the joint when new structural characteristics of the joint have been verified after the welding process. an analysis of a joint connected by Friction Stir Spot Welds (FSSW) was performed from both a numerical and an experimental point of view.

Daeyong Kim et al [23] used four automotive sheets, aluminum alloy 6111-T4, 5083-H18, 5083-O and DP590 steel sheets each having one or two different thicknesses, evaluated experimentally and numerically. To represent the mechanical properties, the non-quadratic orthogonal anisotropic yield function, Yld2000-2d, was utilized along with the (full) isotropic hardening law, while the anisotropy of the weld zone was ignored for simplicity.

Kwansoo Chung et al. [24] evaluated the macroscopic performance of friction stir welded automotive tailor welded blank (TWB) sheets, the hardening behavior, anisotropic yielding properties and forming limit diagram were characterized both for base (material) and weld zones by using the Bauschinger and transient hardening behaviors as well as permanent softening during reverse loading, the modified Chaboche type combined isotropic–kinematic hardening law was applied. As for anisotropic yielding, the non-quadratic anisotropic yield function, Yld2000-2d, was utilized for base material zones, while isotropy was assumed for weld zones for simplicity. As for weld zones, hardening properties were obtained using the rule of mixture and selectively by direct measurement using sub-sized specimen s. Forming limit diagrams were measured for base materials but calculated for weld zones based on Hill’s bifurcation and M–K theories.

M. Chiumenti et al. [25] described the formulation adopted for the numerical simulation of the friction stir welding (FSW) process.. The process was primarily used on aluminum alloys, and most often on large pieces which cannot be easily heat treated to recover temper characteristics. Heat was induced by the friction between the tool shoulder and the work pieces or generated by the mechanical mixing (stirring and forging) process without reaching the melting point (solid-state process). To simulate this kind of welding process, a fully coupled thermo-mechanical solution is adopted. The orthogonal subgrid scale (OSS) technique is used to stabilize the mixed velocity–pressure formulation adopted to solve the Stokes problem. The material behavior was characterized by Norton–Hoff or Sheppard–Wright rigid thermo-viscoplastic constitutive models. Both the streamline-upwind/Petrov–Galerkin (SUPG) formulation and the OSS stabilization technique have been implemented to stabilize the convective term in the balance of energy equation. The numerical simulations presented are intended to show the accuracy of the proposed methodology and its capability to study real FSW processes where a non-circular pin is often used.

VI. Disscussion And Conclusions

The solid-state nature of FSW leads to several advantages over fusion welding methods as problems associated with cooling from the liquid phase are avoided. Issues such as porosity, solute redistribution, solidification cracking and liquation cracking do not arise during FSW. In general, FSW has been found to produce a low concentration of defects and is very tolerant of variations in parameters and materials. Nevertheless, FSW is associated with a number of unique defects. Insufficient weld temperatures, due to low rotational speeds or high traverse speeds, for example, mean that the weld material is unable to accommodate the extensive deformation during welding. This may result in long, tunnel-like defects running along the weld which may occur on the surface or subsurface. Low temperatures may also limit the forging action of the tool and so reduce the continuity of the bond between the material from each side of the weld. The light contact between the material has given rise to the name "kissing-bond". This defect is particularly worrying since it is very difficult to detect using nondestructive methods such as X-ray or ultrasonic testing. If the pin is not long enough or the tool rises out of the plate then the interface at the bottom of the weld may not be disrupted and forged by the tool, resulting in a lack-of-penetration defect. This is essentially a notch in the material which can be a potential source of fatigue cracks.

In this paper current development in process modeling, microstructure and properties, material specific issues, applications of friction stir welding/processing have been addressed:

- Compared to the traditional fusion welding, friction stir welding exhibits a considerable improvement in strength, ductility, fatigue and fracture toughness. Moreover, 80% of yield stress of the base material has been achieved in friction stir welded aluminum alloys with failure usually occurring within the heat-affected region, whereas overmatch has been observed for friction stir welded steel with failure location in the base material. Fatigue life of friction stir welds are lower than that of the base material, but substantially higher than that of laser welds and MIG welds. After removing all the profile irregularities from the weld surfaces, fatigue strengths of FSW specimens were improved to levels comparable to that of the base material. The fracture toughness of friction stir welds is observed to be higher than or equivalent to that of base material.

- Material flow process during FSW is quite complicated and poorly understood. Complete understanding of material transport around rotating tool is crucial to the optimization of FSW parameters and design of tool geometry. Thus new experimental techniques, theoretical and computational models are needed to understand the material flow pattern during FSW.
- For friction stir welding of high melting point materials (steel and titanium) and wearable materials tool wear has been identified as a serious problem. However, very limited studies on the tool wear during FSW have been reported. Most of tool designs are based on intuitive concepts. Integration of computational tools is important for visualization and optimization. The tool

  wear and shape optimization are closely associated with the tool materials.

  - Normally the friction stir welds are used in the as-welded condition or with stabilization aging when base material is in the hardened conditions (T6 and T4 tempers). However, when welding is conducted with the base material in soft condition, there are some advantages. Therefore, it is important to understand the effect of PWHT on the microstructure and properties of FSW joints. A few studies reported so far indicate that PWHT (solution treatment + aging) results in abnormal grain growth, thereby leading to the reduced properties of welds. In an optimum processing window, combination of tool rotation rate and traverse speed no abnormal grain growth is observed. Therefore, it is important to understand the effect of alloy chemistry, FSW/FSP parameters on the thermal stability of fine-grained microstructure of FSW/P aluminum alloys.

- Tool geometry is very important factor for producing sound welds. From the literature survey, it is known that a cylindrical threaded pin and concave shoulder are widely used welding tool features. Besides, tri-fluted pins such as MX Trifute TM and Flared-Trifute TM have also been developed. Welding parameters, including tool rotation rate, traverse speed, spindle tilt angle, and target depth, are crucial to produce sound and defect-free weld.

- Based on the basic principles of FSW, a new generic processing technique for microstructural modification, friction stir processing (FSP) has been developed. FSP has found several applications for microstructural modification in metallic materials, including microstructural refinement for high- strain rate superplasticity, fabrication of surface composite on aluminum substrates, and homogenization of microstructure in nanophase aluminum alloys, metal matrix composites, and cast Al–Si alloys.

- As in traditional fusion welding, butt and lap joint designs are the most common joint configurations in friction stir welding. However, no special preparation is needed for the butt and lap joints of friction stir welding. Two clean metal plates can be easily joined together in the form of butt or lap joints without concern about the surface conditions of the plates.

- FSW results in significant temperature rise within and around the weld. A temperature rise of 400–500 8C has been recorded within the weld for aluminum alloys. Intense plastic deformation and temperature rise result in significant microstructural evolution within the weld, i.e., fine recrystallized grains of 0.1–18 mm, texture, precipitate dissolution and coarsening, and residual stress with a magnitude much lower than that in traditional fusion welding. Three different microstructural zones have been identified in friction stir weld, i.e., nugget region experiencing intense plastic deformation and high-temperature exposure and characterized by fine and equiaxed recrystallized grains, thermo-mechanically affected region experiencing medium temperature and deformation and characterized by deformed and un-recrystallized grains, and heat-affected region experiencing only temperature and characterized by precipitate coarsening

- As for corrosion properties of friction stir welds, contradicting observations have been reported. While some studies showed that the pitting and SCC resistances of FSW welds were superior or comparable those of the base material, other reports indicate that FSW welds of some high-strength aluminum alloys were more susceptible to intergranular attack than the base alloys with preferential occurrence of intergranular attack in the HAZ adjacent to the TMAZ.
- In addition to aluminum alloys, friction stir welding has been successfully used to join other metallic materials, such as copper, titanium, steel, magnesium, and composites. Because of high melting point and/or low ductility, successful joining of high melting temperature materials by means of FSW was usually limited to a narrow range of FSW parameters. Preheating is beneficial for improving the weld quality as well as increase in the traverse rate for high melting materials such as steel.

V. Scope Of Work

Frictions stir welding being a novel process and facilitate welding of plate to plate joints required for several applications. This alloy finds use for structural and other industrial applications. Since tool geometry and interaction of tool with base metal is important for getting good quality welds, different tool geometries were designed and manufactured. Since mechanism of bonding involves efficient movement of plasticized material around tool profile, the joints were investigated thoroughly for defects under varying conditions of process parameters. The optimization of process parameters was carried out using design of experiments approach and the joint properties were evaluated by conducting tensile, hardness tests. Also the quality of the joints was confirmed by macro and micro structural investigation. A detailed analysis was carried out and finally the best welding conditions and best tool profile to get defect free welds was recommended. The results will be of immense use for applying to other aluminium alloys and to other joint designs apart from the present material under investigation.

VI. References

1. G. Padmanaban, V. Balasubramanian "Optimization of laser beam welding process parameters to attain maximum tensile strength in AZ31B magnesium alloy" Optics & Laser Technology 42 (2010) 1253–1260.
2. Olivier Lorrain, Véronique Favier, Hamid Zahrouni, Didier Lawrjaniec "Understanding the material flow path of friction stir welding process using unthreaded tools" Journal of Materials Processing Technology 210 (2010) 603–609.
3. H. Bisadi, A. Tavakoli, M. Tour Sangsaraki, K. Tour Sangsaraki "The influences of rotational and welding speeds on microstructures and mechanical properties of friction stir welded Al5083 and

commercially pure copper sheets lap joints" Materials and Design 43 (2013) 80–88.

4. I. Galvão, R.M. Leala,, D.M. Rodriguesa, A. Loureiroa "Influence of tool shoulder geometry on properties of friction stir welds in thin copper sheets" Journal of Materials Processing Technology 213 (2013) 129–135.
5. S. Gopalakrishnan, N. Murugan "Production and wear characterisation of AA 6061 matrix titanium carbide particulate reinforced composite by enhanced stir casting method" Composites: Part B 43 (2012) 302–308.
6. Michael A. Sutton, A.P. Reynolds, Junhui Yan, Bangcheng Yang, Ning Yuan "Microstructure and mixed mode I/II fracture of AA2524-T351 base material and friction stir welds" Engineering Fracture Mechanics 73 (2006) 391–407.
7. Kim Lau Nielsen, Viggo Tvergaard "Effect of a shear modified Gurson model on damage development in a FSW tensile specimen" International Journal of Solids and Structures 46 (2009) 587–601.
8. L. Ceschini, I. Boromei, G. Minak, A. Morri, F. Tarterini "Effect of friction stir welding on microstructure, tensile and fatigue properties of the AA7005/10 vol.%Al2O3p composite" Composites Science and Technology 67 (2007) 605–615.
9. Shafiei-Zarghani, S.F. Kashani-Bozorg, A. Zarei- Hanzaki "Wear assessments of Al/Al2O3 nano-composite surface layer produced using friction stir processing" Wear 270 (2011) 403–412.
10. Pedro Vilac¸ Lu´ısa Quintino, Jorge F. dos Santos" *i*STIR—Analytical thermal model for friction stir welding" Journal of Materials Processing Technology 169 (2005) 452–465.
11. P. Wanjara, B. Monsarrat, S. Larose "Gap tolerance allowance and robotic operational window for friction stir butt welding of AA6061" Journal of Materials Processing Technology 213 (2013) 631– 640.
12. M. Ericsson, R. Sandstro¨m "Influence of welding speed on the fatigue of friction stir welds, and comparison with MIG and TIG" International Journal of Fatigue 25 (2003) 1379–1387.
13. L. Fratini, F. Micari, G. Buffa, V.F. Ruisi "A new fixture for FSW processes of titanium alloys" CIRP Annals - Manufacturing Technology 59 (2010) 271–274.
14. Kwansoo Chung, Wonoh Lee Daeyong Kim, Junehyung Kim, Kyung-Hwan Chung, Chongmin Kim, Kazutaka Okamoto, R.H. Wagoner "Macro-performance evaluation of friction stir welded automotive tailor-welded blank sheets: Part I – Material properties" International Journal of Solids and Structures 47 (2010) 1048–1062.
15. Luis S. Rosado, Telmo G. Santos, Moisés Piedade , Pedro M. Ramos, Pedro Vilaç "Advanced technique for non-destructive testing of friction stir welding of metals" Measurement 43 (2010) 1021–1030.
16. S. Cui , Z.W.Chen, J.D.Robson "A model relating tool torque and its associated power and specific energy to rotation and forward speeds during friction stir

welding/processing” International Journal of Machine Tools & Manufacture 50 (2010) 1023–1030.

17. Shigeki Hirasawaa, Harsha Badarinarayanb, Kazutaka Okamotoc, Toshio Tomimurad, Tsuyoshi Kawanamia “Analysis of effect of tool geometry on plastic flow during friction stir spot welding using particle method” Journal of Materials Processing Technology 210 (2010) 1455–1463.
18. Malafaia, A. M. Sa, Milan, M.T. Oliveira, M. F.a, Spinelli, “Fatigue behavior of friction stir spot welding and riveted joints in an Al alloy” Procedia Engineering 2 (2010) 1815–1821.
19. Y.M. Hwang, P.L. Fan, C.H. Lin “Experimental study on Friction Stir Welding of copper metals” Journal of Materials Processing Technology 210 (2010) 1667–1672.
20. F. Cioffi, R. Fernández1, D. Gesto, P. Rey, D. Verdera, and G. González-Doncel “Friction stir welding of thick plates of aluminum alloy matrix composite with a high volume fraction of ceramic reinforcement” Composites: Part A.
21. Kim Lau Nielsen “Ductile damage development in friction stir welded aluminum (AA2024) joints” Engineering Fracture Mechanics 75 (2008) 2795–2811.
22. Pierluigi Fanelli, Francesco Vivio, Vincenzo Vullo “Experimental and numerical characterization of Friction Stir Spot Welded Joints” Engineering Fracture Mechanics 81 (2012) 17–25.
23. Daeyong Kim, Wonoh Lee, Junehyung Kim, Kyung-Hwan Chung, Chongmin Kim Kazutaka Okamoto, R.H. Wagoner, Kwansoo Chung “Macro-performance evaluation of friction stir welded automotive tailor-welded blank sheets: Part II – Formability” International Journal of Solids and Structures 47 (2010) 1063–1081.
24. Kwansoo Chung, Wonoh Lee ,Daeyong Kim, Junehyung Kim, Kyung-Hwan Chung, Chongmin Kim, Kazutaka Okamoto, R.H. Wagoner “Macro-performance evaluation of friction stir welded automotive tailor-welded blank sheets: Part I – Material properties” International Journal of Solids and Structures 47 (2010) 1048–1062.
25. M. Chiumenti, M. Cervera, C. Agelet de Saracibar, N. Dialami “Numerical modeling of friction stir welding processes” Comput. Methods Appl. Mech. Engrg. 254 (2013) 353–369.