A REVIEW ON FRICTION STIR WELDING FOR DISSIMILAR ALUMINIUM ALLOYS

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Abstract

Friction stir welding is a refreshing approach to the joining of metals. Although originally intended for aluminium alloys, reach of FSW has now extended to a variety of materials including steels and polymers. It is a solid state welding process which involves joining similar or dissimilar metals using a rotating tool. Tool geometry and traverse speed and rotating speed of motion of the tool, tool axial force and tilt angle are some of the variables in this process. Many materials like Aluminium alloy 2000, 5000, 6000 and 7000 series have been joined using this technique. Mechanical characterization, similar and dissimilar combinations, micro structural characterization, material flow pattern, Influence of tool pin profiles and modeling for FSW processes are some of the important areas of research. This reviews deals with the work for dissimilar aluminium alloys in the above mentioned areas and concludes by suggesting further scope for research in friction stir welding for dissimilar aluminium alloys

I. INTRODUCTION

In recent times, focus has been on developing fast, efficient processes that are environment friendly. 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. Fig.1 shows the schematic drawing of friction stir welding representing all the relevant parameters of the process. The principal advantages of FSW, being a solid-state process, are low distortion, absence of melt-related defects and high joint strength, even in those alloys that are considered non weld able by conventional techniques. Furthermore, friction stir (FS) welded joints are characterized by the absence of filler-induced problems / defects, since the technique requires no filler, and by the low hydrogen contents in the joints, an important consideration in welding steels and other alloys susceptible to hydrogen damage. FSW can be used to produce butt, corner, lap, T, spot, fillet and hem joints, as well as to weld hollow objects, such as tanks and tubes / pipes, stock with different thicknesses, tapered sections and parts with 3-dimensional contours. The advancing side (AS) is the side where the velocity vectors of tool rotation and traverse direction are similar and the side where the velocity vectors are opposite is referred as retreating side. The FSW process takes place in solid state and a permanent bond is obtained as a result of the stirring of plasticized and deformed material along the lines of contact between the pressure-welded elements. The plasticization and deformation of the material are effected during the translation of the rotating mandrel and rim of its back-up along the line of the joint.

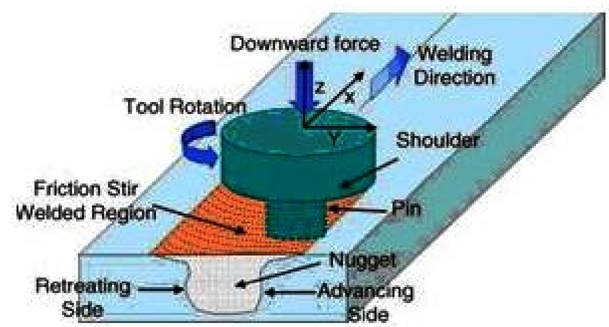


Fig. 1. Schematic of friction stir welding process

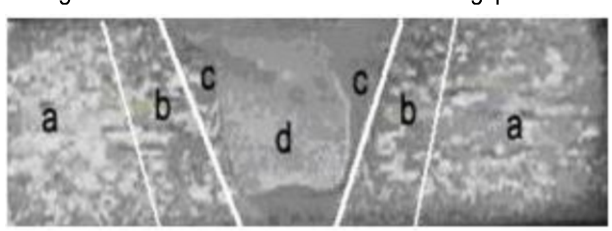


Fig. 2. Different regions of FSW joint: (a) unaffected base metal; (b) heat affected zone (HAZ); (c) thermo-mechanically affected zone (TMAZ); (d) friction stir processed (FSP) zone.

A very good overview of friction stir welding has been given by Terry Khalid.[1]. FSW joints usually consist of four different regions as shown in Fig. 2. They are: (a) unaffected base metal, (b) heat affected zone (HAZ), (c) thermo-mechanically affected zone (TMAZ) and (d) friction stir processed (FSP) zone. The formation of above regions is affected by the material flow behaviour under the action of rotating non-consumable tool. In an attempt to avoid confusion and duplication, TWI proposed an initial basic terminology at an early stage of the development of friction stir welding (FSW). This terminology has since been revised and extended in consultation with licensees and other interested parties are summarized. A definitive standard on FSW is being prepared by Working Group B1 of Commission III of the International Institute of Welding is expected to adopted as an ISO standard. This terminology is given by P. L. Threadgill [2]. In another review by R. Nandan et al [3] deals with the fundamental understanding of the process and its metallurgical consequences focused on heat generation, heat transfer and plastic flow during welding, elements of tool design, understanding defect formation and the structure and properties of the welded materials. R.S. Mishra & Z.Y. Ma [4] in another review article explains the current state of understanding and development of the FSW and FSP and emphasizes particularly on mechanisms responsible for the formation of welds and microstructural refinement, and effects of FSW/FSP parameters on resultant microstructure and final mechanical properties related to aluminum alloys. Y.D. Sato & H. Kokawa reviewed the microstructure and mechanical properties of FSW welds and its various applications [5]. More review information's are given under [6,7].

II. MATERIAL COMBINATIONS STUDIED

A. Similar metal combinations

a. FSW of same Aluminium alloys.

AA 7075 -T6 alloys have been friction welded under different welding conditions. Appearances of welded surfaces have been researched upon and the mechanism of friction stir welding has been discussed by M. Kimura et al [8]. M.A.Sutton et al [9] explains the FSW process creates a segregated bonded microstructure consisting of alternating hard particle rich and poor regions. The bands are a result of FSW process which manipulates the process parameters to modify the weld micro structure in improving mechanical properties. Y.J. Chao et al [10] reveals the friction stir welding reduced the yield strength for both AA2024-T3 and AA7075-T7351 under both high strain rate and quasi static loading conditions. Strain hardening is similar for both materials at various strain rates indicate the application of material flow characteristic and load carrying capacity. T.Venugopal et al [11] have referred to the fine crystallized grains in weld nugget which has been attributed to friction heating and plastic flow. The process also produced a softened region in the weld nugget which may be due to the dissolution and growth of possible precipitates.

B. DISSIMILAR METAL COMBINATIONS

a. FSW of Aluminium - Aluminium alloys and Aluminium - other alloys

Steurs et al [12] have studied the The effect of process parameters on residual stress during the friction stir processing of 5083 to 6082 Aluminium alloys. Friction stir welding of AA 2024 to 7075 has been carried out by Saad Ahmed et al. Onion ring pattern has been observed at the friction stir zone and also a heterogeneous mixture of alloying elements has been seen.[13]. FSW of Aluminium to steel –Takahiko Watanabe et al tried to butt-weld an aluminum alloy plate to a mild steel plate by friction stir welding, and investigated the effects of a pin rotation speed, the position for the pin axis to be inserted on the tensile strength and the microstructure of the joint.The maximum tensile strength was about 86% of the parent Aluminium metal.[14].FSW of Aluminium to Magnesium-Dissimilar metal weld was performed between Aluminium and Magnesium.A maximum tensile strength of 132 MPa was obtained for a tool rotational speed of 100 RPM- Y.J. Kwon et al [15]. The joining of Al 6061 to AISI 1018 steel has been performed by the combined effects of fusion and solid state welding. The process is derived from friction stir welding (FSW) but with an adjustable offset of the probe location with respect to the butt line. It appears that the joining of an Al 6061 alloy to AISI 1018 steel with a sound heterogeneous weld microstructure is feasible using this process and the tool breakage can be detected by the AE sensing technique - C.M. Chen et al [16]. A mechanical and metallurgical characterization of friction stir welded butt joints of aluminium alloy 6061-T6 with 6082-T6 was carried out. The friction stir welded dissimilar joint present intermediate mechanical properties when compared with each base material. In tensile tests the dissimilar joint displayed intermediate properties. For instance in the hardness profile the lowest values were obtained in the AA6082-T6 alloy plate side where rupture occurred, and in the nugget all type of joints present similar values - P.M.G.P. Moreira et al [17]. The various micro structure of the above dissimilar joint refers in Fig .4.

b. FSW of Aluminium Alloy-Composites

Friction stir welding of SiC to Al 2124 has been carried out. SEM, EDX analysis has been done. Electrical conductivity measurements have also been carried out - Huseyin Uzun et al [18]. The aim of this study was to investigate the fatigue resistance of FSW joints on an as-cast particulate reinforced aluminium based composite (AA6061/ 22 vol. %/Al2O3p). The mechanical properties of the FSW composites were compared with those of the base material and the results were correlated to the microstructural modifications induced by the FSW process on the aluminium alloy matrix and the ceramic reinforcement. FSW reduced the size of both particle reinforcement and aluminium grains, and also led to a significant increase in interparticle matrix microhardness, for all process parameters - G. Minak et al [19]. The weldability, microstructure evolution and mechanical properties of an AA6063 aluminium alloy and of two composites with AA6063 matrix reinforced with 6 and 10.5 vol. % B4C during friction stir welding are investigated. A joint efficiency higher than 60% was obtained and increased to over 80% after artificial ageing. The B4C particles size and shape were not affected by the welding process and the particle distribution in the matrix was kept uniform in the weld zone – X.G. Chen et al [20]. The microstructural characterization evidenced, in the FSW zone, a substantial grain refinement of the aluminium alloy matrix (due to dynamic recrystallization induced by the plastic deformation and frictional heating during welding) and a significant reduction of the particles size (due to the abrasive action of the tool). Tensile tests showed a high efficiency of the FSW joints (about 80% of the ultimate tensile strength)- L. Ceschini et al [21].

III. MATERIAL CHARACTERIZATION

Abnormal grain growth has been observed while friction stir welding Aluminium alloys like 7474,7050,7075,2024 and 2519 showed abnormal grain growth.It has been observed only when normal grain growth is suppressed- I.Charit et al [22]. In 6013-T6 alloys, studies have shown that reduction in strength is due to dissolution, coarsening and transformation of Mg_2Si precipitates. Coarse intermetallic particles formed during solidification are broken up during processing - C.G.Derry et al [23]. In a study on dissimilar joints it was found that the weld zones in AA 5754 and AA 5182 joints undergo homogeneous dynamic recrystallization throughout the thickness resulting in uniform mechanical properties. Electron Channeling SEM images were also taken to characterize the samples- H. Jin et al [24]. The transition between the two alloys the lighter colour represents the AA6061-T6. The different structure of the two alloys is easily identified; the AA6061-T6 is characterized by larger grains and the AA6082-T6 by precipitates dispersed in a finer matrix. It is possible to notice a trace of particle concentration at the root of the weld bead, typical of the materials processing with conventional FSW. This feature is more visible in the macrostructure of the dissimilar weld - P.M.G.P. Moreira et al [17].

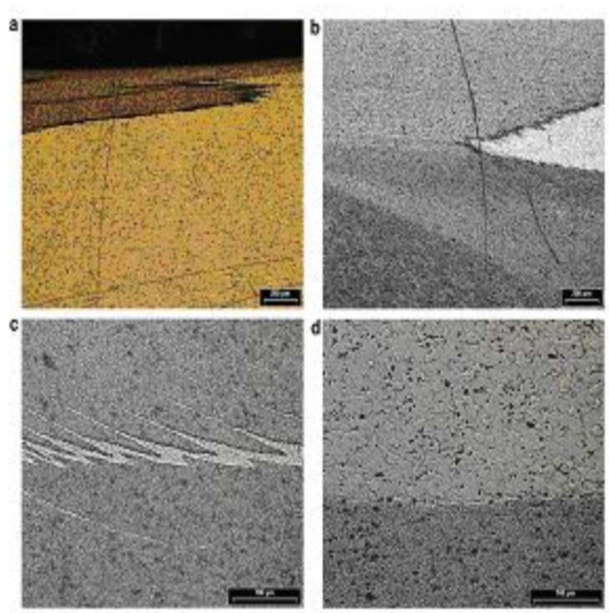


Fig. 4 Microstructure details of the dissimilar joint: (a) detail of the mixture of the two alloys at the shoulder side, microstructure 1; (b) three different zones in the mixture of the two alloys, microstructure 2; (c) striations formed due to the pin rotation, microstructure 3; (d) transition between friction stir welded materials in the weld nugget, microstructure 4 - P.M.G.P. Moreira et al [17].

Because inhomogeneous plastic deformation was introduced by the process, individual grains in the final microstructure have undergone different evolution mechanisms. These are either from growth of initially recrystallized grains or are the result of CDRX of subgrains formed during DRV. Grains within the processed region exhibit different densities of dislocations and are in various degrees of recovery- Jian-Qing Sua et al [25].

IV. MECHANICAL TESTING

K. Elangovan et al [40] referred the three tool rotational speeds used in investigation to fabricate the joints, the joints fabricated at a rotational speed of 1600 rpm showed better tensile properties, irrespective of tool pin profiles. Of the 15 joints fabricated in this investigation, the joint fabricated using square pin profiled tool at a rotational speed of 1600 rpm showed superior tensile properties. K. Elangovan et al [26] Three PWHT methods examined in this investigation, a simple artificial aging (AG) treatment enhanced the tensile properties of the friction stir-welded AA6061 aluminum alloy joints. As-welded joints ofAA6061 alloy yielded a joint efficiency of 66%. This was increased to a joint efficiency of 77% by the artificial aging treatment Fig.5 shows the SEM fractographs of tensile tested specimen for various FSW joints.

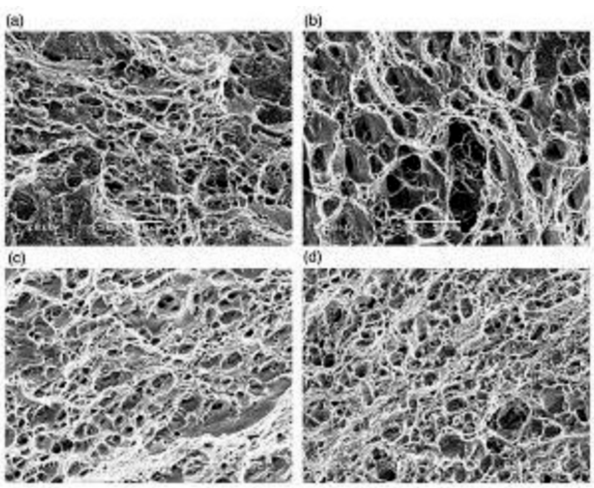


Fig. 5. SEM fractographs of the weld centers of tensile tested specimens. (a) As-welded (AW) joint, (b) solution treated (ST) joint, (c) solution treated and aged (STA) joint, (d) artificially aged (AG) joint - K. Elangovan et al [26]

H.J. Liu et al [27] showed that the tensile properties and fracture locations of the joints are significantly affected by the welding process parameters. When the optimum revolutionary pitch is 0.07 mm/rev corresponding to the rotation speed of 1500 rpm and the welding speed of 100 mm/min, the maximum ultimate strength of the joints is equivalent to 82% that of the base material. Though the voids-free joints are fractured near or at the interface between the weld nugget and the thermo-mechanically affected zone (TMAZ) on the advancing side, the fracture occurs at the weld center when the void defects exist in the joints. K. Elangovan et al [28] referred out of the three welded joints, the joints fabricated by FSW process exhibited higher strength values and the enhancement in strength value is approximately 34% compared to GMAW joints, and 15% compared to GTAW joints. Hardness is lower in the weld metal (WM) region compared to the HAZ and BM regions irrespective of welding technique. Very low hardness is recorded in the GMAW joints (58 VHN) and the maximum hardness is recorded in the FSW joints (85 VHN).The formation of fine, equiaxed grains and uniformly distributed, very fine strengthening precipitates in the weld region are the reasons for superior tensile properties of FSW joints compared to GTAW and GMAW joints. Fig.6 shows the fracture locations of tensile specimen for GMAW, GTAW and FSW joints.

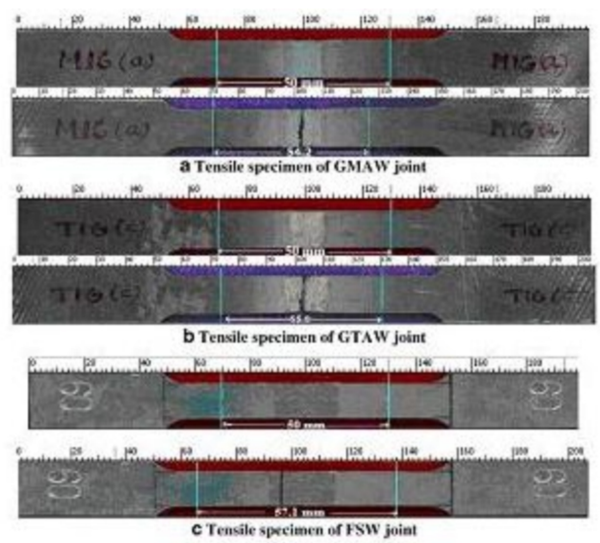


Fig. 6. Fracture location of tensile specimens - K. Elangovan et al [28]

V. MATERIAL FLOW PATTERN

Z. Zhang et al [9] refers the numerical results indicate that the border of the shoulder can affect the material flow near the shoulder–plate interface. The mixture of the material in the lower half of the friction stir weld can benefit from the increase in the angular velocity or the decrease in the welding speed. But flaws may occur when the angular velocity is very high or the translational velocity is very small. When the angular velocity applied on the pin is small or the welding speed is high, the role of the extrusion of pin on transport of the material in FSW becomes more important. Swirl or vortex occurs in the tangent material flow and may be easier to be observed with the increase in the angular velocity of the pin. Satish V. Kailas et al [30] referred the material flow pattern in the weld produced in a special experiment, where the interaction of the friction stir welding tool with the base material is continuously increased. The results show that there are two different modes of material flow regimes involved in the friction stir weld formation; namely "pin-driven flow" and "shoulder-driven flow". These material flow regimes merge together to form a defect-free weld.

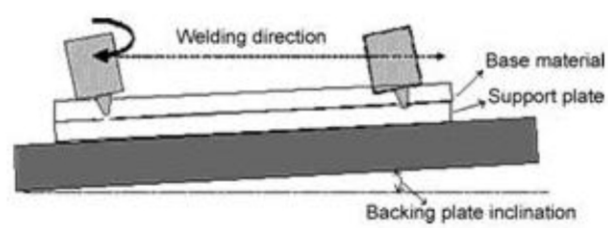


Fig. 7. Experimental details. The backing plate was kept at an angle such that the axial load can be linearly increased (from 4 to 10.9 kN) by linearly increasing the interference between tool and material being welded. Satish V.Kailas et al [30]

H.N.B.Schmidt et al [31] refers the two- and three-dimensional CT images are used in parallel with micrographs for visualization of the flow field. Two procedures for estimating the average velocities for material flowing through the shear layer are presented. The procedures depend on the configuration of marker material relative to the welding direction, i.e. longitudinal and transverse. Fig .7 shows the schematic diagram of the backing plate was kept at an angle such that the axial load can be linearly increased the interference between tool and material being welded and the Fig.8 shows the merging of pin driven flow and shoulder driven flow at various tool axial force inter action with the base metal.

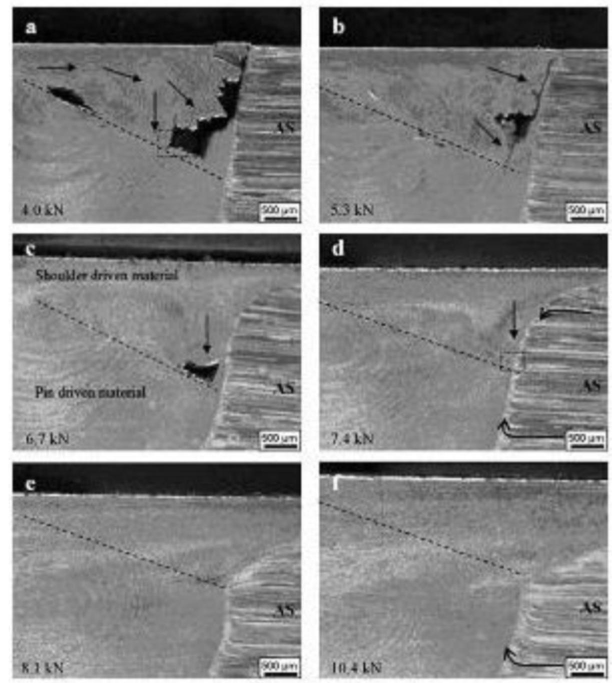


Fig. 8. Presence of pin- and shoulder-driven material flows. The arrow marks indicate the direction of material flow. The dotted parting lines indicate boundary between pin- and shoulder-driven material flow regions. Note that the relative position of pin-driven layer is unchanged. Satish V.Kailas et al [30]

VI. MODELLING

H.W. Zhang et al [32] referred Material flow in friction stir welding (FSW) under different process parameters can be simulated by using the finite element technique based on the nonlinear continuum mechanics. Results indicate that the distribution of the equivalent plastic strain correlates well with the distribution of the microstructure zones in the weld. It seems that there is a quasi-linear relation between the change of the axial load on the shoulder and the variation of the equivalent plastic strain. The material flow can be accelerated with the increase of the translational velocity and the angular velocity of the pin. There exists a swirl on the advancing side and the material flow in the swirl on the advancing side becomes faster with the increase of the translational velocity. G. Buffa et al [33] have studied a continuum based FEM model for friction stir welding process is proposed, that is 3D Lagrangian implicit, coupled, rigid-viscoplastic. This model is calibrated by comparing with experimental results of force and temperature distribution, and then is used to investigate the distribution of temperature and strain in heat affect zone and the weld nugget. The model correctly predicts the non-symmetric nature of FSW process, and the relationships between the tool forces and the variation in the process parameters. It is found that the effective strain distribution is non-symmetric about the weld line while the temperature profile is almost symmetric in the weld zone. C.M. Chen et al [34] model incorporates the mechanical reaction of the tool and thermomechanical process of the welded material. The heat source incorporated in the model involves the friction between the material and the probe and the shoulder. In order to provide a quantitative framework for understanding the dynamics of the FSW thermomechanical process, the thermal history and the evolution of longitudinal, lateral, and through-thickness stress in the friction stirred weld are simulated numerically. It is anticipated that the model can be extended to optimize the FSW process in order to minimize the residual stress of the weld. Hasan Okuyucu et al [35] have studied a artificial neural network (ANN) model was developed for the analysis and simulation of the correlation between the friction stir welding (FSW) parameters of aluminium (Al) plates and mechanical properties. The input parameters of the model consist of weld speed and tool rotation speed (TRS). The outputs of the ANN model include property parameters namely: tensile strength, yield strength, elongation, hardness of weld metal and hardness of heat effected zone (HAZ). Good performance of the ANN model was achieved. Diego H. Santiago et al [36] studied in simulating the Friction Stir Welding process as a three-dimensional thermally coupled viscoplastic flow. A Finite Element technique is employed, within the context of a general purpose FEM framework, to provide the temperature distributions and the patterns of plastic flow for the material involved in the welded joints. P. Ulysse [37] has attempt to model the stir-welding process using three-dimensional visco-plastic modeling. It is found that pin forces increase with increasing welding speeds, but the opposite effect is observed for increasing rotational speeds. Numerical models such as the one presented here will be useful in designing welding tools which will yield desired thermal gradients and avoid tool

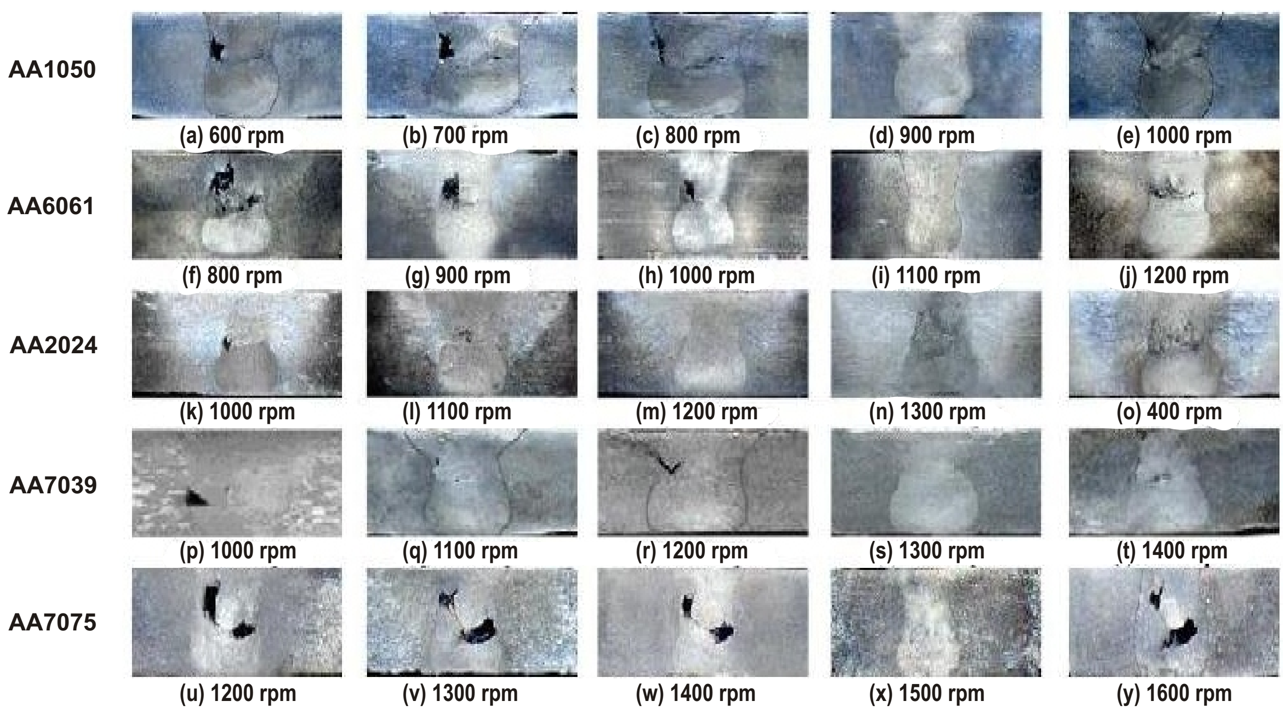


Fig. 9. Effect of tool rotational speed on macrostructure of aluminium alloys (welding speed = 75 mm/min and axial force = 8 kN). V. Balasubramanian [39]

breakage. K. Elangovan et al [38] have attempt to develop a mathematical model to predict tensile strength of the friction stir welded AA6061 aluminium alloy by incorporating FSW process parameters. Four factors, five levels central composite design has been used to minimize number of experimental conditions. Response surface method (RSM) has been used to develop the model. Statistical tools such as analysis of variance (ANOVA), student's t-test, correlation co-efficient etc. have been used to validate the developed model. The developed mathematical model can be effectively used to predict the tensile strength of FSW joints at 95% confidence level. V. Balasubramanian [39] In this investigation, an attempt made to establish relationship between the base material properties and FSW process parameters. FSW joints have been made using five different grades of aluminium alloys (AA1050, AA6061, AA2024, AA7039 and AA7075) using different combinations of process parameters.

Fig. (9 & 10) shows the effect of tool rotational speed and welding speed on macro structures of different aluminium alloys. Macrostructural analysis has been done to check the weld quality (defective or defect free). Empirical relationships have been established between base metal properties and tool rotational speed and welding speed, respectively. The developed empirical relationships can be effectively used to predict the FSW process parameters to fabricate defect free welds.

VII. INFLUENCES OF TOOL PIN PROFILE

K. Elangovan et al [40] attempt an investigation to understand the influences of rotational speed and pin profile of the tool on friction stir processed (FSP) zone formation in AA2219 aluminium alloy. Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) have been used to fabricate the joints at three different tool rotational speeds. The formation of FSP zone has been analysed macroscopically. Tensile properties of the joints have been evaluated and correlated with the FSP zone formation. Mustafa Boz et al [41] The influence of stirrer design on the welding process was investigated with five different stirrers, one of them square cross-sectioned and the rest were cylindrical with 0.85, 1.10, 1.40 and 2.1 mm screw pitched were used to carry out welding process. Bonding could be affected with the square, 0.85 and 1.10 mm screw

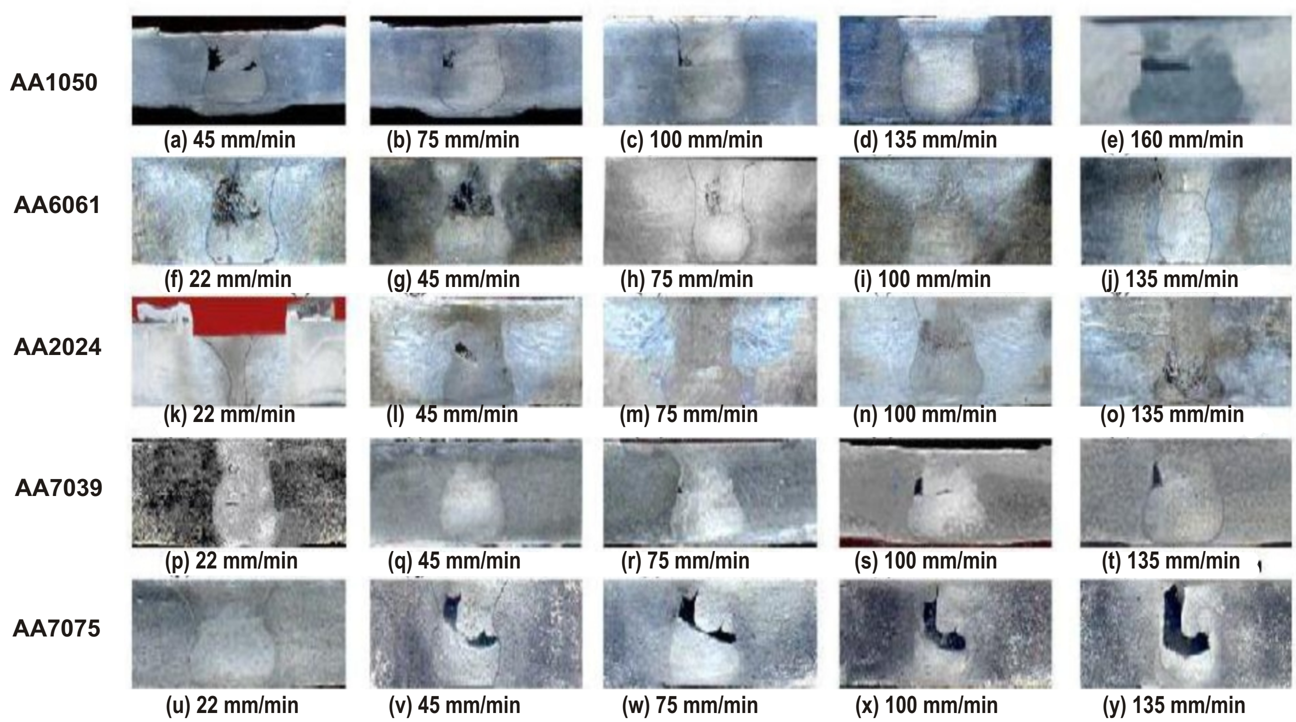


Fig.10. Effect of welding speed on macrostructure of aluminium alloys (tool rotational speed = 1200 rpm and axial force = 8 kN). V. Balasubramanian [39]

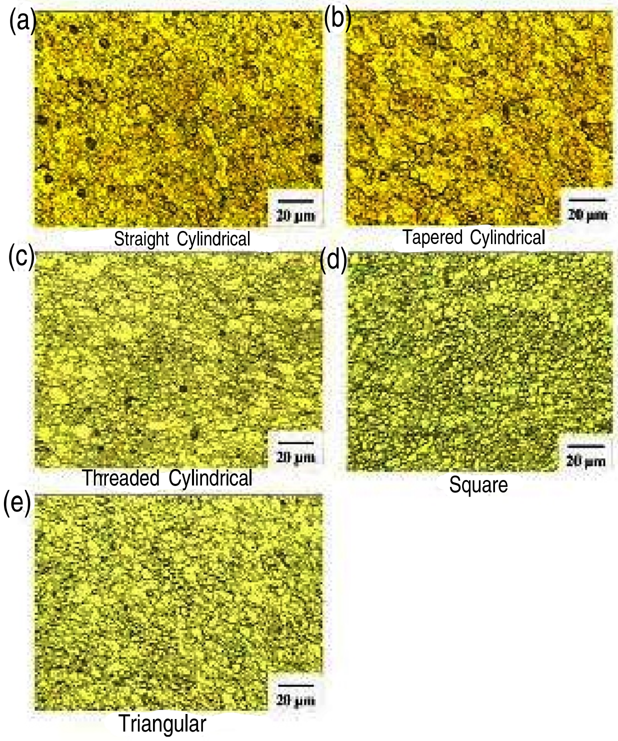


Fig. 11. Effect of tool profiles on microstructure of FSP zone. (a) Straight Cylindrical, (b) Tapered Cylindrical, (c) Threaded Cylindrical, (d) Square, (e) Triangular. K. Elangovan et al [43]

pitched stirrers. Microscopic examination of the weld zone and the tension test results showed that the best bonding was obtained with 0.85 mm screw pitched stirrer. K. Elangovan et al [42] referred Five different tool pin profiles (straight cylindrical, tapered cylindrical, threaded cylindrical, triangular and square) have been used to fabricate the joints at three different axial force levels. The formation of FSP zone has been analysed macroscopically. Tensile properties of the joints have been evaluated and correlated with the FSP zone formation. From this investigation it is found that the square tool pin profile produces mechanically sound and metallurgically defect free welds compared to other tool pin profiles. Fig. 11 shows the micro structure of FSP zone in effect of different tool pin profiles for AA6061 aluminium alloy.

K. Elangovan et al [43] referred the formation of FSP zone has been analysed macroscopically. Tensile properties of the joints have been evaluated and correlated with the FSP zone formation. From this investigation it is found that the square pin profiled tool with 18 mm shoulder diameter produced mechanically sound and metallurgically defect free welds compared to other tool pin profiles.

Table 1. Microstructure and observations of the joints fabricated by Straight Cylindrical (SC) pin profiled tool

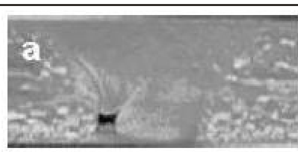
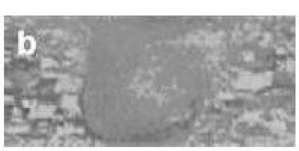
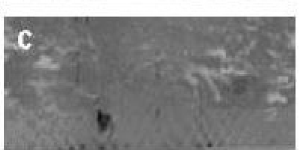
Shoulder diameter (mm)	Macrostructure	Size of FSP zone (mm)		Shape of FSP zone	Name of the defect and location	Quality of weld metal consolidation	Probable reason
	RS AS	W	H				
15		10 6 5	5.9	Inverted trapezoidal	Tunnel in the bottom portion at the retreating side of the weld	Poor	Insufficient heat generation due to smaller shoulder contact area
18		8 6 4.6	5.9	Eliptical	No defect	Good	Sufficient heat generation and flow of the metal
21		10.8 6.1 5	5.9	Not discernible	Tunnel in the bottom portion at the retreating side of the weld	Poor	Excess heat generation and working of the metal

Table 2. Microstructure and observations of the joints fabricated by Tapered Cylindrical (TC) pin profiled tool

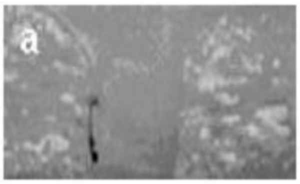
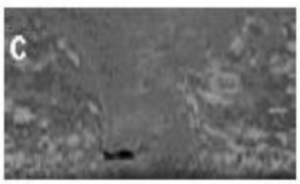
Shoulder diameter (mm)	Macrostructure (RS / AS)	Size of FSP zone (mm) W	H	Shape of FSP zone	Name of the defect and location	Quality of weld metal consolidation	Probable reason
15		8.6 5 4.1	5.9	Inverted trapezoidal	Crack in the bottom portion of the weld at the retreating side	Poor	Insufficient heat generation due to smaller shoulder contact area
18		8.6 5 4.2	5.8	Inverted trapezoidal	No defect	Good	Sufficient heat generation and flow of the metal
21		8 5.3 4	5.9	Inverted trapezoidal	Tunnel in the bottom portion of the weld at the retreating side	Poor	Excess heat generation and flow of the metal in the weld zone

Table 3. Microstructure and observations of the joints fabricated by Threaded Cylindrical (TH) pin profiled tool

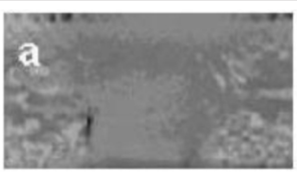
Shoulder diameter (mm)	Macrostructure (RS / AS)	Size of FSP zone (mm) W	H	Shape of FSP zone	Name of the defect and location	Quality of weld metal consolidation	Probable reason
15		10 6 5	5.9	Inverted trapezoidal	Pin hole at lower portion of the weld cross section in retreating side	Poor	Insufficient heat input due to smaller shoulder diameter
18		10 5.3 4	5.9	Elliptical	No defect	Good	Sufficient heat input
21		10 6.6 4.3	5.8	Not discernible	No defect	Good	Wider FSP due to excess heat input caused by bigger shoulder diameter

Table 4. Microstructure and observations of the joints fabricated by Square (SQ) pin profiled tool

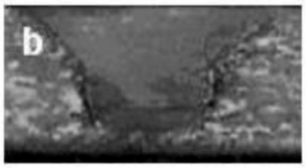
Shoulder diameter (mm)	Macrostructure (RS – AS)	Size of FSP zone (mm) W	H	Shape of FSP zone	Name of the defect and location	Quality of weld metal consolidation	Probable reason
15		9.6 5 4.6	5.9	Inverted trapezoidal	Tunnel defect in the bottom portion of weld at retreating side of the weld	Poor	Insufficient heat input due to smaller shoulder diameter
18		11.3 5.6 4.6	5.9	Inverted trapezoidal	No defect	Good	Sufficient heat input and flow of metal caused by square profiled pin
21		11.0 6.6 5.0	5.9	Inverted trapezoidal	No defect	Good	Wider FSP due to excess heat input caused by bigger shoulder diameter

Table 5. Microstructure and observations of the joints fabricated by Triangular (TR) pin profiled tool

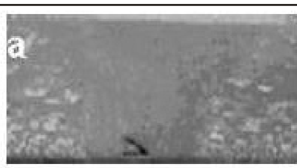
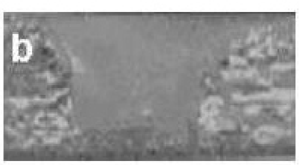
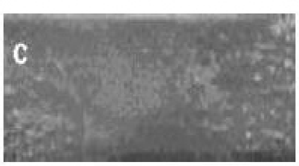
Shoulder diameter (mm)	Macrostructure (RS – AS)	Size of FSP zone (mm) W	H	Shape of FSP zone	Name of the defect and location	Quality of weld metal consolidation	Probable reason
15		9.6 6.3 5.0	5.9	Inverted trapezoidal	Tunnel in bottom portion of the weld	Poor	Insufficient heat input due to smaller shoulderdiameter
18		8.6 5.3 4.6	5.9	Inverted trapezoidal	No defect	Good	Sufficient heat input and working of metal caused by triangular profiled pin
21		9.3 6.6 5.6	5.9	Inverted trapezoidal	No defect	Good	Wider FSP due to excess heat input caused by bigger shoulder diameter

Table 1 – 5 referred by K. Elangovan et al [43]

Table 1 to 4 reveals the important conclusions ie (i) Of the five tool pin profiles used in this investigation to fabricate the joints, square pin profiled tool produced defect free FSP region, irrespective of shoulder diameter of the tools. (ii) Of the three tool shoulder diameters used in this investigation to fabricate the joints, a tool with 18 mm shoulder diameter produced defect free FSP region, irrespective of tool pin profiles.

(iii) Of the 15 joints fabricated in this investigation, the joint fabricated using square pin profiled tool with shoulder diameter of 18 mm showed superior tensile properties.

VIII. SUMMARIES AND FUTURE OUTLOOK

Tool geometry is a very important factor for producing sound welds. However, at the present stage, tool designs are generally proprietary to individual researchers and only limited information is available in open literature. Mostly cylindrical threaded pin and concave shoulder are widely used welding tool features. Welding parameters, including tool rotation rate, traverse speed, spindle tilt angle, and target depth, are crucial to produce sound and defect-free weld. FSW results in significant temperature rise within and around the weld. A temperature rise of 400–500 degC 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. 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. 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. 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. In future Friction stir welding windows are to be developed to fabricate defect free welds. Relationship between yield strength of base materials and friction stir welding process parameters is to be established for different tool profiles. Evaluation of fatigue and fracture toughness properties of FSW joints are to be evaluated

IX. REFERENCES

[1] Terry Khalid, 2005, "An outsider looks at friction stir welding", Report #ANM-112N-05-06.

[2] Threadgill P.L., 2007, "Terminology in friction stir welding", Science and Technology of Welding and Joining Vol 12 No 4 357-360.

[3] Nandan R., DebRoy T., Bhadeshia H.K.D.H., 2008, "Recent advances in friction-stir welding – Process, weldment structure and properties", Progress in Materials Science 53 980–1023.

[4] Mishra R.S., Ma Z.Y., 2005, "Friction stir welding and processing", Materials Science and Engineering R 50 1–78.

[5] Sato Y.D. & Kokawa H., 2003, "Friction stir welding (FSW) process", Welding International 17 (11) 852-853.

[6] Kumagai M., 2003, "Recent technological developments in welding of Aluminium and its alloys", Welding International 17 (3) 173-181.

[7] Enomoto M., 2003, "Friction stir welding:Research and industrial applications", Welding International, 17 (5) 341-345.

[8] Kimura M., Kusaka M., Seo K. and Fuji A., 2005, "Joining phenomena during friction stage of A7075-T6 aluminium alloy friction weld", Science and Technology of Welding and Joining Vol 10 No 3 378.

[9] Sutton M.A., Yang B., Reynolds A.P., Taylor R., 2002, "Micro structural studies of friction stir welds in 2024-t3 aluminium", Materials Science and Engineering A 323 160–166.

[10] Chao Y.J., Wang Y., Miller K.W., 2001, "Effect of friction stir welding on dynamic properties of AA2024-T3 and AA7075-T7351", Welding research supplement, 2001-196-200.

[11] Venugopal T., Srinivasa rao K., Prasad rao K., 2004, "Studies of friction stir welded AA7075 Aluminium alloy", Trans.Indian Inst.met. Vol 57, No 6 659 – 663.

[12] Steuwer A., Peel M.J., Withers P.J., 2006, "Dissimilar friction stir welds in AA5083–AA6082: The effect of process parameters on residual stress", Materials Science and Engineering A 441 187–196.

[13] Saad Ahmed Khodir, Toshiya Shibayanagi, 2008, "Friction stir welding of dissimilar AA2024 and AA7075 Aluminum alloys", Materials Science and Engineering B 148 82–87.

[14] Takehiko Watanabe, Hirofumi Takayama, Atsushi Yanagisawa, 2006, "Joining of aluminum alloy to steel by friction stir welding", Journal of Materials Processing Technology 178 (2006) 342–349.

[15] Kwon Y.J., Shigematsu I., Saito N., Kwon Y.J., Shigematsu I., Saito N., 2008, "Dissimilar friction stir welding between magnesium and aluminum alloys", Materials Letters 62, p 3827–3829.

[16] Chen C.M., Kovacevic R., 2004, "Joining of Al 6061 alloy to AISI 1018 steel by combined effects of fusion and solid state welding", International Journal of Machine Tools & Manufacture 44 (2004) 1205–1214.

[17] Moreira G.P., Santos T., Tavares S.M.O., Richter-Trummer V., Vilaça P., de Castro P.M.S.T., 2009, "Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6", Materials and Design 30 (2009) 180–187.

[18] Huseyin Uzun, 2007, "Friction stir welding of SiC particulate reinforced AA2124 Aluminium alloy matrix composite", Materials and Design 28 1440–1446.

[19] Minak G., Ceschini L., Boromei I., Ponte M., 2010, "Fatigue properties of friction stir welded particulate reinforced aluminium matrix composites", International Journal of Fatigue 32 (2010) 218–226.

[20] Chen X.G., Silva M.da, Gougeon P., Georges L.St-, 2009, "Microstructure and mechanical properties of friction stir welded AA6063–B4C metal matrix composites", Materials Science and Engineering A 518, 174–184.

[21] Ceschini L., Boromei I., Minak G., orri A., Tarterini F., 2007, "Effect of friction stir welding on microstructure, tensile and fatigue properties of the AA7005/10 vol.%Al2O3p composite", Composites Science and Technology 67 605–615.

[22] Charit I. and Mishra R.S., 2008, "Abnormal grain growth in Friction stir processed alloys", Scripta Materialia, 58, 367-371.

[23] Derry C.G., Robson J.D., 2008, "Characterisation and modelling of toughness in 6013-T6 aerospace aluminium alloy friction stir welds", Materials Science and Engineering A 490 328–334.

[24] Jin H., Saimoto S., Ball M., and Threadgill P.L., 2001, Characterisation of microstructure and texture in friction stir welded joints of 5754 and 5182 Aluminium alloy sheets, Materials Science and Technology December Vol. 17 1605-1610.

[25] Jian-Qing Sua, Tracy W. Nelson, Colin J. Sterling, 2005, "Microstructure evolution during FSW/FSP of high strength aluminum alloys", Materials Science and Engineering A 405 277–286.

[26] Elangovan K., Balasubramanian V., 2008, "Influences of post-weld heat treatment on tensile properties of friction stir-welded AA6061 aluminum alloy joints", Materials characterization, M 59 (2008) 1168-1177.

[27] Liu H.J., Fujii H., Maeda M., Nogi K., 2003, "Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy", Journal of Materials Processing Technology 142 692–696.

[28] Lakshminarayanan A.K. & Balasubramanian V., Elangovan K., 2007, "Effect of welding processes on tensile properties of AA6061aluminium alloy joints", Int J Adv Manuf Technology, pages-11.

[29] Zhang Z., Chen J.T., 2008, "The simulation of material behaviors in friction stir welding process by using rate-dependent constitutive model", J Mater Sci 43:222–232.

[30] Kumar K., Satish V. Kailas, 2007, "The role of friction stir welding tool on material flow and weld formation", Materials Science and Engineering A pages-8.

[31] Schmidt H.N.B., Dickerson T.L., Hattel J.H., 2006, "Material flow in butt friction stir welds in AA2024-T3", Acta Materialia 54 1199–1209.

[32] Zhang H.W., Zhang Z., Chen J.T., 2007, "3D modeling of material flow in friction stir welding under different process parameters", Journal of Materials Processing Technology 183 62–70.

[33] Buffa G., Hua J., Shivpuri R., Fratini L., 2006, "A continuum based fem model for friction stir welding—model development", Materials Science and Engineering A 419 389–396.

[34] Chen C.M., Kovacevic R., 2003, "Finite element modeling of friction stir welding — thermal and thermomechanical analysis", International Journal of Machine Tools & Manufacture 43 1319–1326.

[35] Hasan Okuyucu, Adem Kurt, Erol Arcaklioglu, 2007, "Artificial neural network application to the friction stir welding of aluminum plates", Materials and Design 28 78–84.

[36] Diego H. Santiago, Guillermo Lombera, Santiago Urquiza, Anibal Cassanelli, Luis A. de Vedia, 2004, "Numerical Modeling of Welded Joints by the "Friction Stir Welding" Process", Materials Research, Vol.7, No. 4, 569-574.

[37] Ulysse, P. 2002, "Three-dimensional modeling of the friction stir-welding process", International Journal of Machine Tools & Manufacture 42 1549–1557.

[38] Elangovan K., Balasubramanian V., Babu S., 2009, "Predicting tensile strength of friction stir welded AA6061 aluminium alloy joints by a mathematical model", Materials and Design 30 188–193.

[39] Balasubramanian V., 2008, "Relationship between base metal properties and friction stir welding process parameters", Materials Science and Engineering A 480 397–403.

[40] Elangovan K., Balasubramanian V., 2007, "Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminium alloy", Materials Science and Engineering A 459 7–18.

[41] Mustafa Boz, Adem Kurt, 2004, "The influence of stirrer geometry on bonding and mechanical properties in friction stir welding process", Materials and Design 25 343–347.

[42] Elangovan K., Balasubramanian V., Valliappan M., 2007, "Influences of tool pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminium alloy", Int.J.Adv Manuf Technology, 25-30.

[43] Elangovan K., Balasubramanian V., 2008, "Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminium alloy", Materials and Design 29 362–373.