International Journal of Engineering and Techniques-Volume 11 Issue 6, Novmeber - December - 2025

A Review on Process Parameters, Microstructure and Mechanical Properties in Friction Stir Welding

Subodh Debbarma
Department of Mechanical Engineering, The ICFAI University Tripura
*Corresponding authors; e-mail: imsdbarma@gmail.com

ABSTRACT

Friction stir welding (FSW) is a new, efficient way of solid state welding technology used to join ferrous and non-ferrous materials such as aluminium alloys and steels with ease. FSW technique produces reliable similar and dissimilar joints. In FSW the major process parameters namely the tool rotational speed, tool transverse speed, axial force and tool geometry which are affecting the microstructure characteristics of weld zone and the mechanical properties of the joint. The purpose of this assess is to provide a widespread overview of friction stir welding (FSW), in addition to introduce current research and applications concerning this relatively new process. As well as highlights of current research in this area and applications of this process in various industries will also be presented and discussed.

Keywords: Friction Stir Welding, Process parameters, mechanical properties, microstructure characteristics, aluminium, dissimilar metals, applications.

1. Introduction

FSW is a novel material joining technique invented by the Welding Institute (TWI) of the United Kingdom in 1991 [1]. It is a solid state joining process and is mainly capable of joining aluminium alloys that are always difficult to be welded by the traditional fusion methods. In addition, this process results in lower temperatures leading to reduced thermal gradients within the weld zone compared too many fusion welding techniques. In FSW a non consumable rotating tool pin is forced to plunge into the butting edges of the work pieces to be joined and moved along their contact line as shown in fig.1 [2, 3].

As the tool travels at a higher rotational speed with a certain axial force, it generates a localized frictional heat that softens the material around the tool pin resulting in plastic deformation of the material in the stir zone (SZ). The softened material is forced to stir from the front of the pin and back of the pin resulting to produce a solid state weld. FSW microstructure consist of four different zones namely dynamically recrystallized zone (nugget), thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and unaffected base material as shown in fig.2 [4].

The microstructure evaluation and the resulting mechanical properties depend strongly on the variation of the processing parameters such as tool rotational speed, transverse speed, axial force, tool geometry, leading to a wide range of possible performances [5]. The principal advantages of FSW are, due to low input of total heat, no melting occurs and the overall heat energy in the system is significantly reduced, in addition to this, it eliminates the dendritic microstructure common to fusion welding process [6].

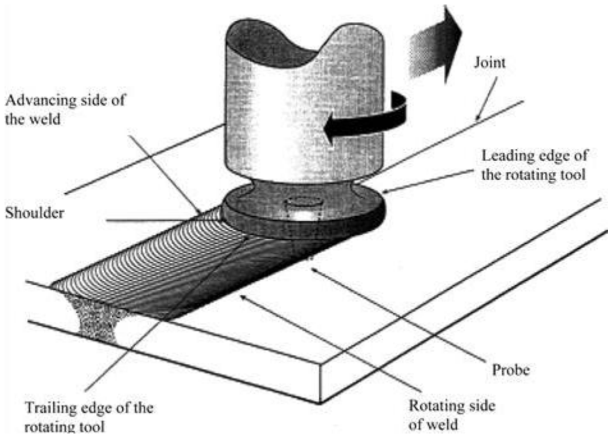

Fig.1:Schematic diagram of FSW

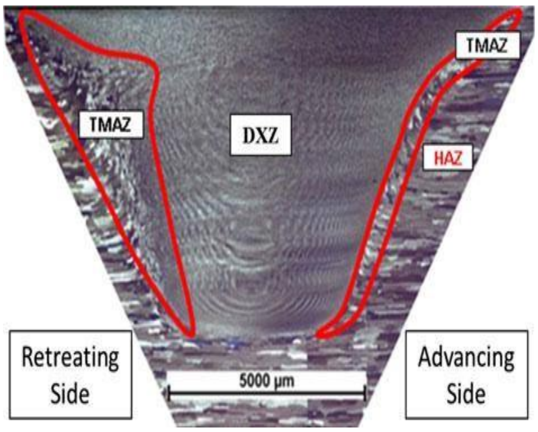

Fig.2: Microstructural zones in a FSW joint

2. Study of FSW for materials and combinations

The main welding parameters in FSW that can be controlled are rotational speed of tool, axial force of the tool shoulder on the work piece, traverse speed of the tool and the tool geometry. These processing parameters greatly influence overall weld quality, heat input, porosity, mechanical and micro structural properties of the joint.

A. **FSW of Aluminum:**

Peel et al. [8] conducted experiments on AA5083 and concluded that, the increase in traverse speed results less overall heat received by the system and thereby reduction in the amount of frictional heating. Changbin shen et al. [9] conducted experiments on AA 5083 and AA 6082 alloys and observed the average corrosion rate of the FSW weld was less than those of parent materials at a specified process parameters(tool rpm-300, tool tilt angle-3^0, traverse speed-1.6m/min). Experiments conducted by Muthukrishnan and Marimuthu [10] on FSW of Al

6082-T6 plates with thickness of 3mm and with different combinations of process parameters results in the tensile strength of weld is directly proportional to the welding speed and hardness drop was observed in the weld region. A mathematical model was developed by Heidarzadeh et al. [11] using response surface methodology to predict tensile properties of FSW AA 6061-T4 aluminum alloy at 95% confidence level and applied analysis of variance to validate the predicted model. FSW of 5mm AA 7020-T53 aluminum plate at 1400 rpm and 40mm/min shows that: the temperatures are high on advancing side than retreating side along the weld line and maximum temperature attained during welding is 70% of the melting point of parent metal [12].

B. FSW of Dissimilar metals

The dissimilar metal butt joint for AA6061 and SS400 was successfully produced by FSW at low traverse speed and rotational speed resulting in higher impact values [13]. Salehi et al. [14] investigated the effect of four factors (rotational speed, transverse speed, tool penetration depth and pin profile) on ultimate tensile strength (UTS) of AA6061/SiC nano composites using design of experiment (DOE) and determined the optimum process parameters using Taguchi method. This study results that UTS is larger for threaded pin compared to square pin. Kalaiselvanet al. [15] studied the role of FSW process parameters on AA 6061-B4C composite joints as shown in fig.3, developed an optimized model to maximize the tensile strength using the generalized reduced gradient method. Zhang and Zhang et al. [16] studied the effects of welding parameters upon quality, temperature distribution and residual stresses and determined that, the weld quality could be accurately predicted and controlled by the rotational speed of the tool. 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 were investigated by Takehiko Watanabe et al. [17] on butt-welding of an Al alloy plate to a mild steel plate by FSW. The maximum tensile strength of the joint was about 86% of that of the aluminum alloy base metal. The fragments of the steel were scattered in the aluminum alloy matrix and the oxide film removed from the faying surface of the steel by the rubbing motion of a rotating pin was observed at the interface between the steel fragments and the aluminum alloy matrix.

3. Effects of Process Parameters on Mechanical Properties

A. Aluminum

FSW of aluminum alloys AA2024-T4 and AA7075-T6 under various conditions of process parameters on micro hardness and microstructure were investigated by Dinakaran et al. [18] and concluded that mechanical properties and joint efficiencies are superior to the conventional welding methods of aluminum alloys.

Rajakumar et al. [19] established a relationship between the FSW parameters (welding speed, axial force, rotational speed, shoulder diameter, pin diameter, and tool hardness)and the responses (Tensile strength (TS), Hardness (WH) and Corrosion rate (CR)).

$$(TS) \text{ or } (WH) \text{ or } (CR) = b_0 + b_1(N) + b_2(S) + b_3(F) + b_4(D) + b_5(P) + b_6(H) + b_{11}(N^2) + b_{22}(S^2) + b_{33}(F^2) + b_{44}(D^2) + b_{55}(P^2) + b_{66}(H^2) + b_{12}(NS) + b_{13}(NF) + b_{14}(ND) + b_{15}(NP) + b_{16}(NH) + b_{23}(SF) + b_{24}(SD) + b_{25}(SP) + b_{26}(SH) + b_{34}(FD) + b_{35}(FP) + b_{36}(FH) + b_{45}(DP) +$$

$b_{46}(DH)+b_{56}(PH)$

In this study the tensile strength and hardness along with the corrosion rate of Friction stir butt welded joints of AA6061-T6Aluminiumalloywereinvestigatedandidentified the optimal welding condition to minimize corrosion rate and to increase the tensile strength by using Response surface methodology (RSM). Jayaraman et al. [20] studied the effect of process parameters on the tensile strength of cast A356 Al alloy and quality of weld zone was analyzed by macrostructure and microstructure analysis. The joint fabricated using axial force of 5KN, welding speed of 75mm/min and tool rotational speed of 1000 rpm resulted in higher tensile strength compared to other joints.

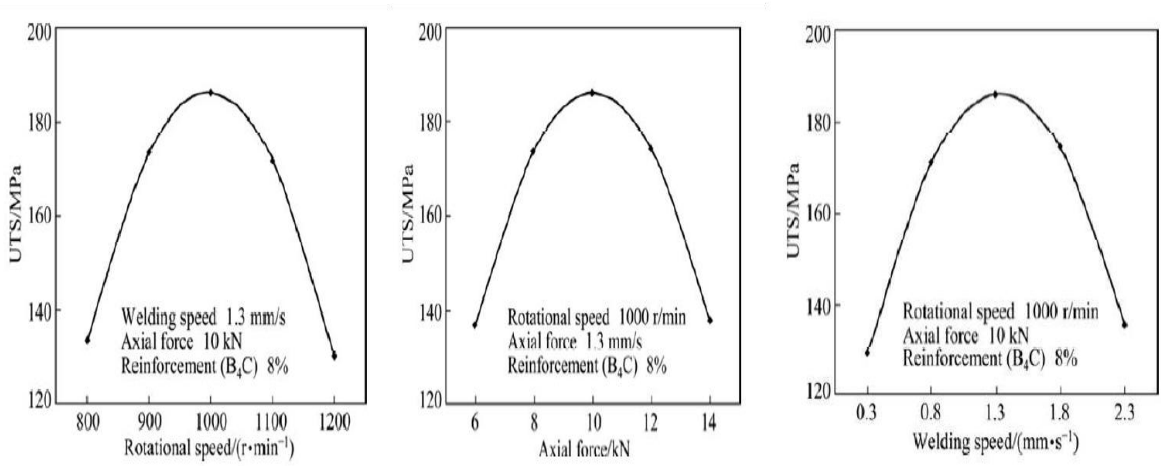

Fig.3:EffectofprocessparametersonAA6061-B4Ccompositejoint[15].

B. Dissimilar metals:

Dissimilar FSW between A5052P-O and AZ31B-O alloy plates with 2mm thickness, for tool rotational speeds of 1000, 1200 and 1400rpm results in a defect free weld suggesting that, these are the optimum tool rotational speeds for dissimilar FSW [21]. M.Simoncini et al. [22] studied the effect of welding parameters and tool configuration on mechanical and micro-structurural properties of similar and dissimilar FSW joints. The results concluded that, the elongation of dissimilar metals is not significantly affected by the process parameters, even as the ultimate tensile joint is influenced by rotational and welding speeds. Ming-Der Jeanet al. [23] carried out experiments to optimize the tensile properties of FSW butt joints and achieved the maximum tensilestrengthatrotatingspeedof500rpm and by tilting the angles of spin at 5^0. Sato et al [24] carried out an experiment to find microstructure and mechanical properties of SAF2507 super duplex stainless steel using polycrystalline cubic boron nitride tool which resulted in high quality full penetration welds and there is an increase in hardness and strength in stir zone due to smaller grains of ferrite.

4. Effects of process parameters on microstructures

A. Aluminum:

B.F. Chenelle et al. [25] observed a noticeable effect on both grain size and the band spacing with respect to change in process parameters, also observed that as the tool rotational speed increases from 1000 to 1500 rpm, the grain size in the stir zone increased from 8 to 18 lm. M.A Sutton et al [26] observed that FSW process creates a segregated bonded microstructure consisting of alternating hard particles in rich and poor regions. The bands are a result of FSW process which manipulates the process parameters to modify the weld microstructure in improving mechanical properties. The influence of tool profile on the welding process was investigated by Mustafa Boz et al. [27] with five different tool profiles. One of them was square cross-sectional and the rest were cylindrical with 0.85, 1.10, 1.40 and 2.1mm screw pitched was used. Bonding was affected with the square, 0.85 and 1.10mm screw pitched stirrers. Microscopic examination of weld zone and the tension test results showed that the best bonding was obtained with 0.85mm screw pitched stirrer.

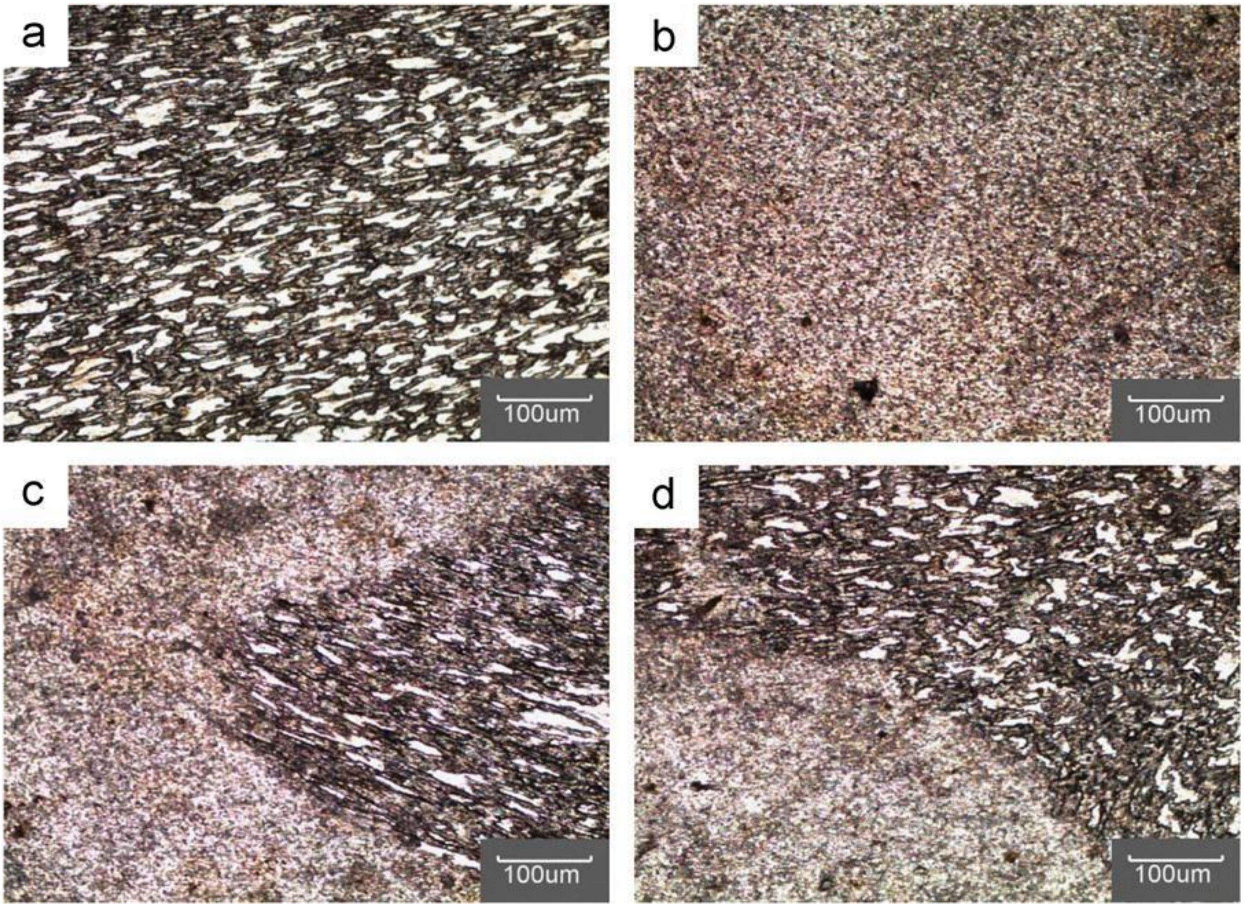

Fig.3: Optical photomicrograph of dissimilar joint a) unmixed region of cast aluminium alloy, b)unmixed region of wrought aluminium alloy, and c) and d) mechanically mixed region.

B. Dissimilar metals

FSW of AISI 1018 mild steel plates with thickness 5mm by using tungsten based alloy tool with a specific process parameters resulted in finer grains at weld nugget region and these finer grains increased the tensile strength up to 8% of base metal, but ductility and impact toughness were decreased due to inclusion of tungsten particles in weld region [28].FSW of SAF 2205 duplex stainless steel using WC base materialtoolataconstantrotationalspeedof600rpm produced a sound weld. But increase in weld speed decreased the size of $\alpha$and γgrains in the stir zone which results the improved mean hardness value and tensile strength of the stir zone[29]. R. Beygi et al. [30]conducted experiment on butt joining of Al-Cubi layer sheet and observed a defect free joint. Due to formation of banded microstructure along with Al- Cu inter metallic compounds on advancing side resulted in the increase of hardness value compared to retreating side. I. Dinaharan et al. [31] conducted experiments on FSW to investigate the effects of material location and tool rotational speed on dissimilar friction stir welded cast and wrought aluminum alloy. Due to material flow behavior, as the tool rotational speed increase the micro hardness of weld zone approaches the micro hardness of the re-crystallized dominant structure of weld zone depending on material location, also the weld zone represents two kinds of regions namely unmixed region and mechanically mixed region. Fig.3 represents the optical photomicrograph of dissimilar joint of friction stir welded cast and wrought aluminum alloy.

5. Applications of FSW in Industry

FSW is extensively used in the aero, train and marine fields, particularly to join sheet metals. The use of FSW on floor and wall panels were done on commuter trains by Alstom LHB et al. [32]. FSW is well suited to the construction of hermetic seals and tanks, which are of vital importance to the nuclear industry. Y.S Sato et al. [33] explained that, FSW is a very attractive substitute to fasteners and rivets due to its ease of manufacture, reduced part complexity, weight savings and cost reduction up to 30%. FSW has been successfully used by numerous automotive companies. The three piece suspension arm on the BMW 5 series are friction stir welded in order to reduce road noise and weight by eliminating the use of fasteners and bolts. FSW is applicable to nearly every type of aluminum alloy used in automotive industry. Joining of an Inconel 600 plates at an optimized speed of 400 rpm and 150 to 200 mm/min using a WC-Co tool resulted in reduction of grain size from 19 micron meters in the parent material to 3.4 micron meters in the nugget region, the improvements in hardness and tensile strengths from parent material to nugget region were observed [34]. Many applications of FSW are under development such as, using 7075 and 2297 aluminum alloys for the wing box on the fighter aircraft. Also, the C-130 freight aircraft uses FSW on 7249aluminum alloy for the cargo bay floors [35].

6. Summary of the Review

Author	Process Parameter					Remarks	
	Material	Tool rotational speed (rpm)	Tool speed (mm/min)	Axial force (KN)	Tool Tilt angle(°)	Micro-structure	Mechanical properties
Lakshminarayanan etal.[28]	AISI108Mild steel	1000	50	15	0	Formation of fine equiaxed ferrite and pearlite grains in Stir zone	Tensile strength and Hardness were increased
Satoetal.[24]	SAF2507stainless steel	450	60	-	3.5	Smaller ferrite an daustenite grains formed in the stir zone	Hardness and strength increases in stir zone
Heidarzadehet al. [11]	AA6061-T4Al alloy	1300	60	8	-	Grain coarsening, growth of precipitates at weld zone, Lowering dislocation density	Tensile elongation increased
Rajakumaretal. [19]	AA6061-T6 Aluminiumalloy	1100	80	5	-	Finer grains appeared in stir zone	Increase in tensile strength and decrease in Corrosion rate

Saeidetal. [29]	Duplexstainless steel	800	50	-	2.5	Finer grains appeared in stir zone	Higher plastic deformation
Thaiping Chenet al. [12]	AA6061 and SS400	550	54	-	1	Intermetallic compounds were not produced due to Low rotational speeds	Higher C-notch chirpy im pactvalue

7. Conclusion

FSW is capable of welding both similar and dissimilar metal and is having a enormous growth potential due to its inherent benefits. This review gives a clear idea about the trend of research going on in this new field, the effect of process parameters on weld joint and applications of FSW in industrial sector. Some essential conclusions listed from this review are:

- FSW controls the formation of intermetallic compounds and produces a fine recrystallized grain structure in the weld zone.
- Process parameters greatly influence the microstructure and mechanical properties of the weld joint.
- FSW has many applications in various industries like aerospace, defense, nuclear and transportation.

The further research can be carried out on FSW to predict process parameters using new techniques such as neural networks, response surface methodology.

Funding: No funding has been received.

Declaration of competing interest:
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] TWIWebsite.www.twi.co.uk
[2] C H Chien, T P Chen, Y J Chao, *Thermal Modeling and Optimal Tool Moving Velocity for Friction Stir Welding*, J.CSME, Vol. 26, no.2, pp. 195-200, Apr. 2005.
[3] T P Chen, C H Chien, W B Lin, Y J Chao, *Optimization of the FSW Process for Aluminum Alloy AA5083 by the grey based Taguchi method,* ICEM 13, Alexanroupolis, Greece, paper. 30
[4] B F Chenelle, D A Lados, *Friction Stir Welding in 6061Aluminium Alloys: Microstructure, Residual Stress and FatigueCrackGrowthMechanisms*,IntegrativeMaterialsDesignCentreInternal Report, June 2010.
[5] P. Cavaliere, M. Cabibbo, F. Panella and A. Squillace, *2198 Al-Liplates joined by Friction Stir Welding: Mechanical and microStructural behavior*,Materials and Design,Vol.30,pp.3622-3631,2009.
[6] R S Mishra, M W Mahoney, *Friction Stir Welding and Processing,* ASM International, Materials Park, OH, 2007, p.359.
[7] Hoon-Hwe Cho, Suk Hoon Kang, Sung-Hwan, Kyu Hwan Oh,Heung Ju Kim, Woong-Seong Chang and Heung Nam Han, *Microstructural evolution in friction stir welding of high-strength line pipe steel*, Materials and Design, Vol. 34, pp. 258-267,2012.

[8] MPeel,ASteuwer,Mpreuss,ActaMater,2003,Vol.51(16), pp.4791-4801.

[9] Changbin shen, Jiyan Zhang, Jiping Gem, " Microstructure and electrochemical behaviours of friction stir welding dissimilar weld" journal of environmental sciences, 23(supplement) S32-S35,2011.

[10]M. Muthukrishnan and K. Marimuthu, *Some Studies on Mechanical Properties of Friction Stir Butt Welded Al-6082-T6Plates.*

[11]A. Heidarzadeh, H. Khodaverdizadeh, A. Mahmoudi and E.nazari, *Tensile behavior of friction stir welded AA 601-T4aluminium alloy joint*s, Materials and Design, Vol. 37, pp. 166-173,2012.

[12]Thaiping chen, Wei-bang lin, A *Study on Dissimilar FSW process parameters in Aluminium alloy and low carbon steel*, "international conference on smart manufacturing application"April.9-11,2008.

[13]Dr. Muhsin Jaber Jweeg, Dr. Mneer Hameed Tolephih andMuhammed Abdul-Sattar, *Theoretical and Experimental Investigation of Transient Temperature Distribution in Friction Stir Welding of AA 7020-T53*, Journal of Engineering, Vol. 18,2012.

[14]M.Salehi, M. Saadatmand and J. Aghazadeh Mohandesi,*Optimization of process parameters for producing AA 6061/Si Cnano composites by friction stir processing*, Trans. Non ferrousMet. Soc. China, Vol. 22, pp. 1055-1063, 2012.

[15]K.Kalaiselavan, N.Murugan, "*Role of friction stir welding parameters on Tensile strength of AA6061-B4C composite joints*"Trans. Non ferrousMet. Soc.ChinaVol. 23,pp.616-624.

[16]Z. Zhang and H.W. Zhang: J. Mater. Process Technol., 2009,vol. 209 (1), pp. 241–70.

[17]Takehiko Watanabe, Hirofumi Takayama and yanagisawa,*joining of aluminium alloy to steel by friction stir welding*, Journals of material processing technology, Vol. 178, pp. 342-349,2006.

[18]Manoj Kumar Shivaraj, Vijay Dinakaran and VenkateshMahadevan, *Frictional stirwelding on aluminium alloys AA2024-T4 and AA 7075-T6,* 2nd International Conference on Computer Engineering and Technology, vol. 5, 2012.

[19]S. Rajakimar, C. Muralidharan and V. balasubramanian, *Predicting tensile strength, hardness and corrosion rate offriction stir welded AA 6061-T6 aluminium alloy joints*, Materials and Design, vol. 32, pp. 2878-2890, 2011.

[20]Jayaraman,VBalasubramanian, *Effect of process parameters on tensile strength of friction stir welded cast A356 aluminium alloy joints,* Trans. Nonferrous Met. Soc. China, Vol. 23,pp.605-615,2013.

[21]Y J Kwon, I Shigematsu, N Saito, *Dissimilar friction stir welding between magnesium and aluminum alloys* Materials Letters, Vol. 62, pp. 3827-3829, 2008.

[22]M.Simoncini, A. Forcellese, *Effect of welding parameters and tool configuration on micro- and macro- mechanical properties on similar and dissimilar FSW ed joints in AA5754 and AZ31thin sheets,* Materials and Design, Vol. 41, pp. 50-60, 2012.

[23]Ming- Der Jean, Wei-Jen Chen, Jeng-Der, Lin, *Joint properties of tilted angles of spin for 6061 AA aluminium alloys in friction stir welded experiments*, IEEE, Vol. 12, pp. 978-1-4577-1415-3,2012.

[24]Y S Sato, T W Nelson, C J Sterling, R J Steel and C.O.Pettersson,*Microstructureandmechanicalpropertiesoffrictionstir welded SAF 2507 super duplex stainless steel*, Materials Science and Engineering A, Vol. 397, pp. 376-384, 2005.

[25]B F Chenelle, D A Lados, Frictio*n Stir Welding in 6061Aluminum Alloys: Microstructure, Residual Stress and FatigueCrackGrowthMechanisms*,IntegrativeMaterialsDesignCente*r*Internal Report, Worcester Polytechnic Institute, June 2010.

[26]M A Sutton, B Yang, A P Reynolds, R Taylor, *Micro structural studies of friction stir welds in 2024-T3 aluminum*, Materials Science and Engineering, Vol. 325, pp. 160-166, 2002.

[27]Mustafa Boz, Adam Kurt, *The influence of stirrer geometry onbonding and mechanical properties*

in friction stir welding process, Material and Design, Vol. 25, pp. 343-347, 2004.

[28]AK Lakshminarayanan, VBalasubramanian andM Salahuddin, *Microstructure, Tensile and Impact Properties of Friction Stir Welded Mild Steel*, J. Iron and Steel Research, International,Vol. 17 (10), pp. 68-74, 2010.

[29]T. Saeid, A. Abdollah-zadeh, H. Assadi and F. Malek Ghaini, *Effect of friction stir welding speed on the microstructure and mechanical properties of a duplex stainless steel*, Materials Science and Engineering A, Vol. 496, pp. 262-268, 2008.

[30]R.beygi, M. kazeminezhad, A.H. Kokabi, *Butt joining of Al-Cubilayer sheet through friction stir welding*, Trans. Non ferrousMet, Soc. China, Vol. 22, pp. 2925-2929, 2012.

[31]IDinaharan, KKalaiselvan, S J Vijay, P Raja, *Effectof material location and tool rotational speed on microstructure and tensile strength of dissimilar friction stir welded aluminium alloys*, Archives of Civil and Mechanical Engineering, pp. 446-454,2012.

[32]ESAB Welding Automation: *Friction Stir Welding Handbook*,LAZA, Sweden, Chap. SE 695-81, 2009.

[33]YSSato, MEnomoto, and RKate, *Application of Aluminum Extrusions to Suspension Arms*, SAE International ,SAE Technical Paper 982331, 1998.

[34]K.H.Song,H.FujiiandK.Nakata,Mater.Des,2009,vol.30(10), pp. 3972 78.

[35] Lockheed Martin Corporation*: Friction Stir Welding Experience*