

Optimization of Sustainable Process Parameters of Friction-Stir Welding of Aluminium Alloy by Taguchi Method

Sandeep Kumar¹, Kaushal Kumar¹, Jarnail Singh^{2}, Puja Acharya³, Prabhakar Bhandari¹, Musheer Vaqur⁴, Ram Subbiah⁵, Namita Kaur⁶ and D. Baloji⁷*

¹Department of Mechanical Engineering, K R Mangalam University, Gurguram-122103, Haryana

²Department of Mechanical Engineering, University Centre for Research and Development, Chandigarh University, Mohali- 1404133, Chandigarh

³School of Engineering and Technology, K R Mangalam University, Gurguram-122103, Haryana

⁴Division of Research & Innovation, Uttaranchal University, Dehradun, Uttaranchal

⁵Department of Civil Engineering, GRIET, Bachupally, Hyderabad, Telangana

⁶Lovely Professional University, Phagwara, 144001, Punjab

⁷KG Reddy College of Engineering & Technology, Moinabad, Hyderabad, Telangana

Abstract. In the current paper, AA6101-T6 aluminium alloy was subjected to friction stir welding (FSW) utilizing a vertical milling machine. Alloy plates were welded in butt position to provide a virtually flat interface, using a tool shape that was carefully selected. Because of the excessive generation of heat via the tool and workpieces during friction stir welding, substantial deformation in the nugget zone is seen. The mechanical attributes of the base metal at the joint are significantly impacted by an excessive variation in temperature at the weld. In this experiment, mechanical properties-related changes through the FSW process are kept to a minimum to achieve high tensile strength. The tool's rotating speed (measured in rpm), the workpieces' traverse speed (measured in mm/min), and the tool tilt angle were chosen as the parameters to regulate the weld quality. As a result of its 44% contribution, the rotating speed parameter is shown to be the most beneficial one for stir welding. The metric determining transverse speed contributes the least, at 19%. For effective stir welding, such as high strength welds, defect-free welds, short welding times, low welding costs, etc., it is preferred that the tool rotational speed parameter be concentrated. By using sustainable Taguchi approach to optimize the chosen process parameter, high tensile strength is achieved at the welded connection.

* Corresponding author: jarnailnith@gmail.com

Keywords: Friction stir welding, Sustainability, Tensile strength, Microstructure, ANOVA

1 Introduction

The future of aluminium alloys in industrial sectors like automotive, aerospace, construction, rail transportation, and marine is bright because of their intriguing properties like low density and mechanical properties, good corrosion resistance, and good thermal and electrical conductivity [1, 2]. Unfortunately, due to their poor weldability when using the traditional ways of welding fusion, some aluminium alloys cannot be used. Weld solidification cracking occurs when joining heterogeneous aluminium alloys because their constituent constituents produce low melting eutectics. (hot cracking) [3]. The composition of metal being weld is determined by the filler metal composition, base metal composition, and degree of dilution; this is especially important when welding aluminium alloys. Careful consideration of contents of filler followed by parameters of welding, is required to avoid cracking from solidification in the finished weld composition. When fusion welding equivalent aluminium alloys, this can be done without too many issues. For each category and subtype of aluminium alloy, there is a set of guidelines for selecting the appropriate filler metal [4]. However, when fusion welding different aluminium alloys, solidification cracking might be difficult to control. For the wide variety of incompatible aluminium alloys, there is no filler metal that can provide welding without cracks. Even if a suitable substitute filler metal exists, it is still impossible to achieve acceptable joint efficiency. Because of these issues, fusion welding is rarely used for joining dissimilar aluminium alloys in practical applications. Welding solidification cracking is not an issue when using these techniques, making them ideal for welding a variety of aluminium alloys. The number of pores, discrimination, inflexible quasi expansion, and heat-impacted region liquid cracking are only some of the challenges that can be avoided when using solid-state welding procedures for aluminium alloy fusion welding. As a result, highly strong aluminium alloys or alloys that have been molded are typically assembled mechanically using bolts or rivets. Friction stir welding, which completes the welding process totally in solid phase, offers a remedy in this case of alloys. This method of welding permits an assembly due to its solid nature, which eliminates conduit faults caused by solidification, as well as defects caused by internal stresses that are weaker than those in conventional methods of welding [5-7].

Friction stir welding, another solid-state welding technology, is extremely attractive for joining incompatible aluminium alloys because it can provide welding with a range of joint configurations, together with butt joints. The FSW of heterogeneous alloys and metals has attracted a lot of researcher's interest because of the possibility of technological significance. FSW has been used to combine several incompatible aluminium alloy combinations with high joint efficiency [8-10]. Mechanical mixing of the heterogeneous alloys was observed in the weld nugget or stir zone in most of these tests, with complicated whirl, quasi and swirling structures indicative of chaotic-dynamic mixing. The material's flow arrangement and the overall performance of the final weld were also shown to be significantly affected by the relative placements of two distinct alloys [11]. Many researchers argued that the more advanced side should use the tougher of both materials. Lee et al. [12] studied the friction stir welding of forged A356 material to hammer aluminium alloy AA6061 and found that a significant portion of the stir zone consisted of material on the retreating side. During conducting the FSW of aluminium alloys, Priya et al. [13] found that alloy deposited on the approaching edge controlled the stir zone.

Nevertheless, various studies [7,11,12] focused on material flow visualization rather than finding optimal FSW parameters or tool shape.

Thus, this method is particularly suited to aluminium alloys that are very closely related yet are not easily weldable. Within the context of the lightweight frameworks for land, sea, and air transportation, the coupling alloy with high mechanical assembly qualities is particularly intriguing [3-5]. A cylindrical or conical stem, ideally threaded or striated, is used in friction stir welding. It rotates at a very high speed (200 to 2000 rpm) and plunges through (plunges through) the joint between the two pieces to weld. The material becomes softer due to friction at the shoulder, and metal engagement is prevented by sufficient force being applied to the plate edges [6]. The plates' edges exhibit plastic deformation.

1.1 FSW parameters

The consumable rotational tool having distinctively intended shoulder and pin is used to move across the connection line once the outermost edges between the sheets or plates being joined have been placed into one another. The major roles of the tool are to preheat the workpiece and drive the material to form the junction. Friction amongst the workpiece and device generates heat by making the workpiece flex plastically. Specific ablation loosens the material adjacent to the pin, and as the tool spins and travels, the material travels from the front to the back of the pin. Using this technology, a solid-state joint is created. Because of the pin's multiple geometrical features, the material movement around it may be exceedingly complicated [14]. High-temperature FSW results in substantial plastic distortion of the material, resulting in the creation of tiny, reconciled recrystallized grains [9-15]. Friction stir welds provide exceptional mechanical properties due to their exact microstructure. Welding parameters, tool geometric shapes, and joint designs all have an impact on how to distribute material movement and temperature [16]. The rotational speed, N (in rpm), transverse velocity, S , tool tilt, the diameter of the tool's shoulder, the diameter of the needle's tip, and shoulder insertion on the workpiece are the FSW process parameters. (in mm).

According to the literature that is currently available [17–20], FSW factors including tool geometry, transverse speed, and rotational speed, have a substantial impact on the procedure and are crucial in determining the weld quality. Transverse speed, tool tilt angle, and rotational speed optimization lead to produce defect-free welds in dissimilar materials of Al alloys. Furthermore, rotating or welding speed increases tensile strength to a peak level and then decreases as an effect of the void defect [21–26]. The fracture is obvious in the weld nugget's zone at moderate welding speeds due to the significant softening in these spots and the emergence of occasional, oddly shaped cavities adjacent to the separation among the base alloy and weld area on the advancing side. Furthermore, the bulk of weld failures observed are for high rotation speeds. Baeslack et al. [27, 28-33] revealed that the yield strength of AA8009 was 60-70% of the base metal when working at elevated revolving rates of 1200 rpm and 90% at modest speeds of rotation of 428 rpm in their investigation on friction stir welding. per Parket et al.'s experiment [28], adequate material blending appeared in the nugget region when the more robust base substance was placed on the advancing side. Faux material on the approaching side, resulting in narrower weld nuggets and insufficient mixing. As previously stated, the performance of dissimilar friction stir welding is dependent on precise material location, tool layout, and process parameters that are dependent on the physical characteristics of the materials to be welded. Aluminium alloy is mostly used in the aircraft industry. (AA6101). Because the Mg is brought together in a liquid state, fusing these alloys would result in low melting point eutectic and solidification cracking. Several researchers have investigated friction stir welding for connecting incompatible metals and alloys. The technique of friction stir welding is being

utilised successfully to join a wide range of mismatched aluminium alloy a mix with good joint efficiency. Magnesium is the major alloying element in the 6000 series. Magnesium at a concentration of about 6% in sea water provides good strength and corrosion resistance. In the available literature, there is very little details regarding friction stir welding of this specific material combination[34-35].

Elements	Mn	Si	Zi	Cu	Cr	Al
Percentage	0.600	0.50 0	0.02 1	0.074	0.015	98.79

Consequently, a study of FSW of AA6101 is attempted here. The three parameters used in this investigation—rotational and transverse speed, and tilt angle of tool. To demonstrate the significance of various parameters, an experimental work has been conducted in the present work. The goals of the current study are to assess the optimum percentage impact of the process that was selected variables for friction stir welding and to optimize the tool rotational speed (N), tool’s tilt angle (Ø), and transverse welding speed of the work pieces (S) on a specified aluminium alloy (AA6101-T6) for exceptionally strong friction stir welding.

2 Experimental Details

The aluminium alloy AA 6101-T6 was selected for this experiment. The flat rectangular bar with a cross-sectional area of 35×6 mm2 and a length of 610 mm is what is purchased when the aluminium alloy AA6101-T6 is chosen. Table 1 provides the chemical make-up of this aluminium alloy. The alloy's physical characteristics are as follows: Poisson's ratio is 0.33, the density is 2700 kg/m3, the elastic modulus is between 70 and 80 GPa, the tensile strength is 250 MPa, the yield strength is 210 MPa, and the thermal conductivity is 218 W/m-K at 250 °C. The alloy AA 6101 is heated to about 530 °C, quenched in water, and aged at about 180 °C for about 8 hours to achieve the T6 temper.

Table 1. Chemical composition of alloy AA 6101-T6.

3 Characterization techniques

Mechanical qualities including tensile strength, tensile strength, shear strength, yield strength, fracture point, etc. are evaluated using universal testing machines. The servo controlled Universal Testing Machine (Make: A.S.I Sales Private Limited, ISO 9001:2000 CO) is used to determine the tensile strength of the friction stir welded specimen and has a maximum load capacity of 400 kN. According to ASTM E8M-04, tensile test specimens were created. The specimen is built of 6 mm thick, 35 mm broad, and 60 mm long plates of aluminium alloy AA6101-T6. These parts' surfaces are filed and rubbed with sandpaper to prepare them for welding. With the aid of a milling machine fixture that was specially made, two plates were held in the butt position for the friction stir welding, and the plate was then welded with a welding tool. According to figure 1, the welding is visually evaluated; if there are no defects, it is accepted.



Fig. 1. Specimens for tensile testing

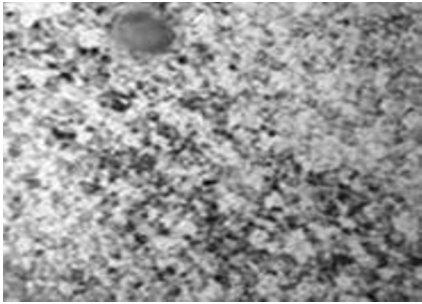
4 Results and Discussion

4.1 Microstructural Analysis

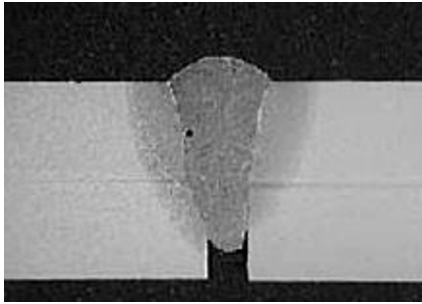
The selection of the level of all process parameters is the main issue in the current work. To determine the practicable working limit of these process settings, numerous experiments have been carried out on flats of AA6101-T6 aluminium alloy measuring 6 mm in thickness and 35 mm in width. As seen in figure 2, macrostructure inspection determines each parameter's operating level. The following observations are drawn from the inspection:

(a) Tunnel defects are seen when tool rotation speeds are lower than 800 rpm. These defects are caused by insufficient heat generation and metal transportation. Due to excessive turbulence brought on by high tool rotation speed, pipe defects are visible when rotational speed of tool > 1250 rpm.

(b) A tunnel flaw is seen when tool transverse speed is less than 16 mm/min, which is caused by an excessive amount of heat input per unit length. A tunnel flaw is seen when the tool transverse speed is more than 25 mm/min because the material is not flowing properly due to insufficient heat input.



(a)



(b)

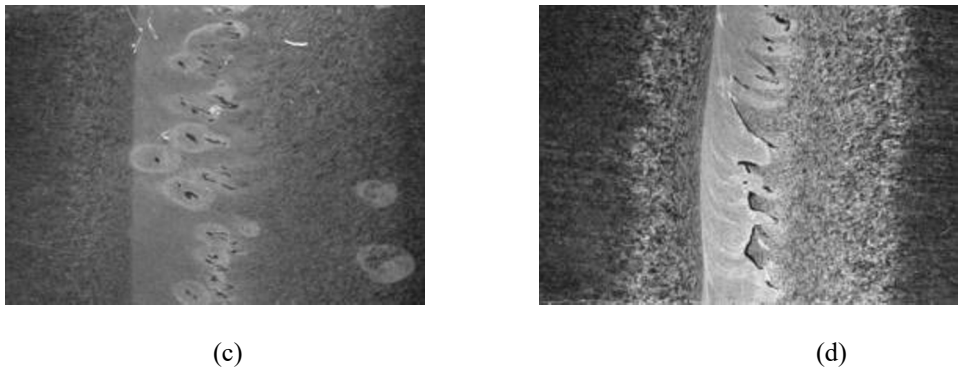


Fig. 2. Microstructure of FSW joints at (a) 700 rpm, (b) 1300 rpm, (c) 14 mm/min, (d) 30 mm/min

For the current investigation, which is shown in table 3, the following parameter levels and tool design dimensions are considered based on the preceding observations. Table 2 provides a full description of the arranged selected characteristics and their level (low, medium, and high level).

Table 2. Process Parameter and its level.

S. No.	Level	Rotation speed, N (rpm)	Transverse speed, S (mm/min)	Tilt angle, Ø (degree)
1	Low	800	16	0
2	Medium	1000	20	1
3	High	1250	25	2

In order to assess the effect of different parameters, it is necessary to calculate both the average and S/N relation for each controlling component. The input factors (N, S, and Ø) that were selected in compliance with the array's orthogonal selector are shown in Table 3, along with the compressible test material findings per each trial.

Table 3. Experimental values of the specimens tested on universal testing machine.

Experiment	Input parameters			Load on UTM (KN)		
	N	S	φ	Trial 1	Trial 2	Trial 3
1	800	16	0	30.8	32.4	31.4
2	800	20	1	41.6	41.4	38.6
3	800	25	2	34.8	33.6	30.2
4	1000	16	1	45.2	42.8	44.4
5	1000	20	2	41.4	44.2	41.4
6	1000	25	0	34.8	43.5	44.8
7	1250	16	2	37.2	33.6	35.4
8	1250	20	0	46.4	44.2	47.4
9	1250	25	1	41.8	46.6	50.8

4.2 Signal to noise (S/N) ratio

The S/N ratio is determined depending on the degree of the target attributes. Since goal of this investigation is to maximize tensile strength, a higher SN ratio provides more reliable estimates. Below is the formula for determining the signal-to-noise ratio:

$$\frac{S}{N} \text{ ratio} = -10 \log_{10} \sum_{i=1}^n \frac{1}{z_i^2}$$

(1)

The tensile property of the FSW joints is evaluated to determine the influence of parameters of the friction stir welding technique. From the experimental data, we can determine the mean and the S/N ratio. Table 4 displays the projected S/N ratio and average values, where n is the number of trials, N is the rotational speed of the tool in rpm per minute, S is the transverse speed in millimetres per minute, "Ø" is the angle of tilt in degrees, and "zi" is the tensile strength in megapascals. Tables 5 provide the calculated average mean and S/N ratio values for all attributes. Better quality attributes are correlated with a higher S/N Ratio [18–21].

4.3 Analysis of variance (ANOVA)

Statistically important factors can be isolated with the use of analysis of variance. It shows the extent to which the process parameter influences the answer and how important the component is. The average and signal-to-noise ratio ANOVA table is displayed in Tables 6; the columns labelled DOF (for "Degree of Freedom"), SS ("Sum of Squares"), V ("Variance"), SS* ("Pure Sum of Squares"), and P% ("Percentage Contribution") contain the results of the analysis. The main primary effects are shown for the average and SN ratio in figures 3 and 4, respectively.

4.4 Estimation of tensile strength

The anticipated tensile strength is evaluated using an additive model developed from the literature [24-26,41]. In Table 4, we can see the mean, S/N ratio, and tensile strength from each experiment. The mean and S/N Ratio of the process parameters listed in Table 5 were calculated. A higher signal-to-noise ratio was shown to be indicative of better quality. The best value for a process parameter is the one that maximizes the signal-to-noise ratio. Level 3 rotating speed (1250 rpm), Level 2 transverse speed (20 mm/min), and Level 2 tilt angle (1 degree) are found to maximize the strength of tensile and signal-to-noise ratio, respectively. (Table 5). The order is established by the delta value, the disparity between the largest and lowest numbers.

Table 4. Tensile strength (Mean) and S/N ratio values (determined experimentally).

Experiment	Input parameter			Response (Z _i in MPa)			Mean Value	S/N ratio
	N	S	φ	Trial 1	Trial 2	Trial 3		
1	800	16	0	146.67	154.29	149.52	150.16	43.53
2	800	20	1	198.10	197.14	183.81	193.02	45.70

3	800	25	2	165.71	160.00	143.81	156.51	43.84
4	1000	16	1	215.24	203.81	211.43	210.16	46.44
5	1000	20	2	197.14	210.48	197.14	201.59	46.08
6	1000	25	0	165.71	207.14	213.33	195.40	45.65
7	1250	16	2	177.14	160.00	168.57	168.57	44.51
8	1250	20	0	220.95	210.48	225.71	219.05	46.80
9	1250	25	1	199.05	221.90	241.90	220.95	46.80
Total							1715.41	409.35

Table 5. The average and S/N ratios of tensile strength.

Source	Average			Delta	S/N Ratio			Delta
Level	1	2	3		1	2	3	
N	166.56	202.38	202.86	35.82	44.36	46.06	46.04	1.70
S	176.30	204.55	190.95	28.25	44.83	46.19	45.43	1.36
Ø	188.20	208.04	175.56	19.84	45.33	46.31	44.81	0.98

Table 6. Values of means and S/N ratios using ANOVA.

Source	DOF	SS		V		SS*		P%	
		S/N Ratio	Mean	S/N Ratio	Mean	S/N Ratio	Mean	S/N Ratio	Mean
N	2	5.71	2600.99	2.86	1300.49	5.42	2462.34	44.14	44.40
S	2	2.79	1197.65	1.39	598.83	2.50	1059.00	20.36	19.10
Ø	2	3.48	1608.35	1.74	804.18	3.19	1469.70	25.98	26.50
Error	2	0.29	138.65			1.17	554.60	9.53	10.00
Total	8	12.28	5545.64					100	100

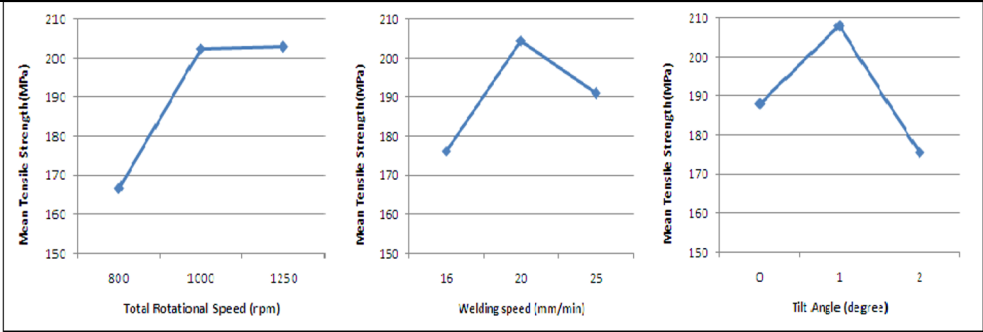


Figure 3. The average value of tensile strength with process parameters variation.

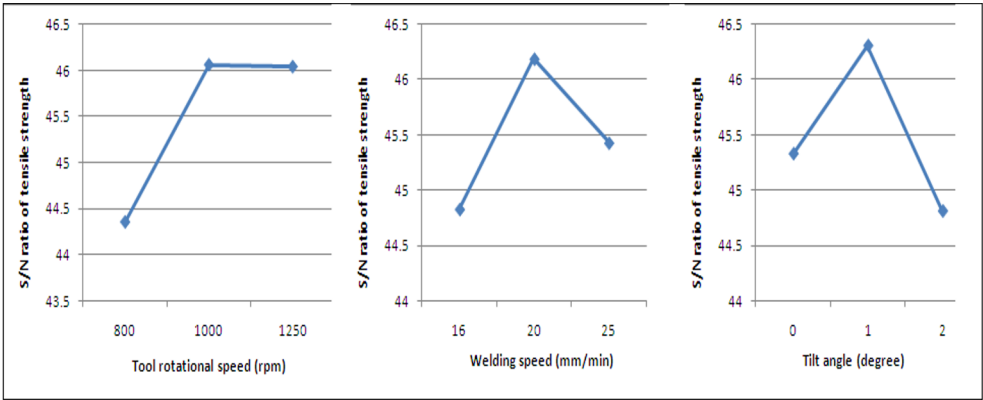


Figure 4. Illustration of S/N ratio with variation of process parameters.

Experimental results indicate that a tool rotational speed of 1250 rpm, a rate of welding of 20 mm/min, and a tilt angle of 1° produce the best results when stir-welding tensile specimens. The tensile specimen findings shown in Table 7 show that the source metal's tensile strength is virtually reached if welding is performed under ideal conditions

Table 7. Experimental values of tensile strength for optimized parameters.

Experiment	Input parameter			Response (Z _i in MPa)			Mean Value	S/N ratio
	N	S	φ	Trial 1	Trial 2	Trial 3		
1	1250	20	1	204.56	208.44	206.52	206.51	46.29

5 Conclusion

Since optimizing the friction stirring welding process variables is the primary goal of this study, three crucial process factors are considered. In this case, the process variables at hand were the rotational (N) and transverse (S) tool speeds and the angular (Ø) tool tilt. All of these factors increase heat production and reduce the tensile strength with friction stir welded joints made from aluminium alloy. The following are the major takeaways from this experimental study.

- i. Aluminum alloy AA6101 friction stir welded joints have strength nearly comparable to that of the original material because melting does not take place during this operation. FSW uses far lower temperatures than traditional welding methods, allowing grains to maintain their natural characteristics.
- ii. The relative importance of the FSW parameters for the process was calculated. The tensile strength of joints that are welded is found to be affected by three different variables : the welding speed, the rotational speed, and the tilt angle.
- iii. The welding strength is best achieved at rotational speed of 1250 rpm, welding speed of 20 mm/min, and tilt angle of 1°, with tensile strength highest at rotating speed having level 3 and welding rate and tilt angle at level 2.

References

- [1] Yong-Jai Kwon, Seong-Beom Shim, Dong-Hwan Park, “Friction stir welding of 5052 aluminum alloy plates”, *Trans. Nonferrous Met. Soc. China* 19 s23–s27 (2009).
- [2] J. Adamowski , C. Gambaro, E. Lertora, M. Ponte, M. Szkodo, “analysis of FSW welds made of Aluminium alloy AW 6082-T6”, *Archives of Materials Science and Engineering*, Volume 28, Issue 8(2007).
- [3] Shigematsu I, Kwon Y J, Suzuki K, Imai T, Saito N., Joining of 5083 and 6061 aluminum alloys by friction stir welding, *J Mater Sci Lett*, 22(5): 353–356 (2003).
- [4] Shigematsu I, Suzuki K, Imai T, Kwon Y J, Saito N., Friction stir welding of recycled A6061 aluminum plates fabricated by hot-extrusion of machined chips. *J Mater Sci*, 40(11): 2971–2974 (2005).
- [5] Kannan M B, Dietzel W, Zeng R, Zettler R, Santos J F D., A study on the SCC susceptibility of friction stir welded AZ31 Mg sheet. *Mater Sci Eng A*, 460/461: 243–250 (2007).
- [6] Darras B M, Khraisheh M K, Abu-Farha F K, Omar M A. Friction stir processing of commercial AZ31 magnesium alloy. *J Mater Proc Tech*, 191(1/3): 77–81 (2007).
- [7] R. Nandan, T. DebRoy, H.K.D.H. Bhadeshia; “Recent Advances in Friction Stir Welding – Process”, *Weldment Structure and Properties*, *Progress in Materials Science* 53 (2008) 980-1023.
- [8] Mohamed Merzoug, Mohamed Mazari, Lahcene Berrahal, Abdellatif Imad, “Parametric studies of the process of friction spot stir welding of Aluminium 6060-T5 alloys”, *Materials and Design* 31 (2010) 3023–3028.
- [9] S. G. Arul, S. F. Miller, G. H. Kruger, T.-Y. Pan, P. K. Mallick and A. J. Shih. “Experimental study of joint performance in spot friction welding of 6111-T4 Aluminium alloy”, *Science and Technology of Welding and Joining* 2008 Volume 13 issue 7 (2008) 629-637.
- [10] M. Koilraj, V. Sundareswaran, S. Vijayan, S.R. Koteswara Rao, “Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083-Optimization of process parameters using Taguchi technique”, *Materials and Design*, Vol 42, pp1-7 (2012).
- [11] Yahya Bozkurt, “The optimization of friction stir welding process parameters to achieve maximum tensile strength in polyethylene sheets”, *Material and Design*, Vol 35, pp 440-445 (2012).
- [12] Lee WB, Lee CY, Chang WS, Yeon YM, Jung SB. Microstructural investigation of friction stir welded pure titanium. *Mater Lett* 59:3315–8 (2005).
- [13] Priya R, Subramanya Sarma V, Prasad Rao K. Effect of post weld heat treatment on the microstructure and tensile properties of dissimilar friction stir welded AA 2219 and AA 6061 alloys. *Trans Indian Inst Met* 62:11–9 (2009).
- [14] Shigematsu I, Kwon YJ, Suzuki K, Imai T, Satio N. Joining of 5083 and 6061 aluminum alloys by friction stir welding. *J Mater Sci Lett* 22:353–6 (2003).
- [15] Ouyang JH, Kovacevic R. Material flow during friction stir welding (FSW) of the same and dissimilar aluminum alloys. *J Mater Eng Perform* 11(1):51–63 (2002).
- [16] G. Elatharasan, V.S. Senthil Kumar, “An experimental analysis and optimization of process parameters on friction stir welding of AA6061-T6 aluminum alloy using RSM”, *Procedia Engineering*, Vol 64, pp 1227-1234 (2013).
- [17] Cho JH, Boyce DE, Dawson PR. Modeling strain hardening and texture evolution in friction stir welding of stainless steel. *Mater Sci Eng A* 398:146–63 (2005).
- [18] Liu H, Fulii H, Maeda M, Nogi K. Tensile properties and fracture locations of friction-stir welded joints of 6061-T6 aluminium alloy. *J Mater Sci Lett*; 22:1061–3 (2003).

- [19] Lapasset G, Denquin A. Midling. Metall Mater Trans A 32A:1189 (2001).
- [20] K. Kumar, S. Kumar, M. Gupta and H.C. Garg, Ind. Lubr. Tribol. 70, 1721-1728 (2018)
- [21] K. Kumar, S. Kumar, G.Singh, J. P. Singh, J.Singh, Coatings 7, 54(2017).
- [22] K. Kumar, Int. J. Appl. Mech. 25, 202-210 (2020).
- [23] Bala Srinivasan P, Dietzel W, Zettler R, dos Santos JF, Sivan V. Stress corrosion cracking susceptibility of friction stir welded AA7075–AA6056 dissimilar joint. Mater Sci Eng A 392:292–300 (2005).
- [24] Amancio-Filho ST, Sheikhi S, dos Santos JF, Bolfarini C. Preliminary study on the microstructure and mechanical properties of dissimilar friction stir welds in aircraft aluminium alloys 2024-T351 and 6056-T4. J Mater Process Technol 206:132–42 (2008).
- [24] Khodir SA, Shibayanagi T. Friction stir welding of dissimilar AA2024 and AA7075 aluminum alloys. Mater Sci Eng B 148:82–7 (2008).
- [26] Cavaliere P, De Santis A, Panella F, Squillace A. Effect of welding parameters on mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding. Mater Des 30:609–16 (2009).
- [27] H. J. Liu, H. Fujii, K. Nogi, Friction stir welding characteristics of 2017-T351 aluminum alloy sheet, Journal of materials science 40, 3297 – 3299 (2005).
- [28] Lee WB, Yeon YM, Jung SB. The joint properties of dissimilar formed Al alloys by friction stir welding according to the fixed location of materials. Scripta Mater 49:423–8 (2003).
- [29] D. Aghimien, N. Ngcobo, C. Aigbavboa, S. Dixit, N. I. Vatin, S. Kampani, and G. S. Khera, Buildings 12, (2022)
- [30] S. Bhardwaj, P. Singh, and S. Dixit, in Mater Today Proc (2022), pp. 499–507
- [31] Y. Kuppusamy, R. Jayaseelan, G. Pandulu, V. S. Kumar, G. Murali, S. Dixit, and N. I. Vatin, Materials 15, (2022)
- [32] R. P. Singh, G. Manchanda, I. K. Maurya, N. K. Maheshwari, P. K. Tiwari, and A. R. Rai, Biocatal Agric Biotechnol 17, 507 (2019)
- [33] V. Kumar, R. Kumar, D. Rawat, and M. Nanda, Appl Biol Chem 61, 7 (2018)
- [34] Pande, P. Gairola, P. Sambyal, S. P. Gairola, V. Kumar, K. Singh, and S. K. Dhawan, Mater Chem Phys 189, 22 (2017)
- [34] C. Chandana Priya, M. V Seshagiri Rao, and V. Srinivasa Reddy, International Journal of Civil Engineering and Technology 9, 2218 (2018)
- [35] K. S. S. T. Naidu, M. V. S. Rao, and V. S. Reddy, International Journal of Innovative Technology and Exploring Engineering 8, 641 (2019)