Investigating weld strength of AA8011-6062 alloys joined via friction-stir welding using the RSM approach

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Abstract. In this study, an effort has been made for analyzing the results of the weld strength of aluminum composites AA6061 and 8011 which were developed by friction stir welding (FSW), via response surface methodology (RSM). The RSM approach was adopted considering rotational speed (RS) of 1200, 1300 and 1400 rpm, welding speed (WS) of 75,100 and 125 mm/min and axial force (AF) 5, 6 and 7 KN as the process parameters and output weld characteristic was obtained in terms of the weld strength. Design-Expert software version 11 was used in this paper to plan the survey and generate response surface plots. This investigation revealed that the best welding strength of AA6061 and 8011 aluminum amalgams obtained was 127 MPA, in run no. eight which had parameters RS 1400 RPM, WS 100 mm/min, and AF 7 KN. The obtained values of results were further analyzed through ANNOVA statistical analysis for obtaining the percentage contribution of selected variable parameters towards strength enhancement. The AF contributed significantly around 90%, RS contributed 10 % and contribution of WS was minimal for selected ranges to enhance the strength quality of the weld joint.

Keywords: Welding, strength, joining, RSM, analysis of variance.

1. Introduction
The FSW itself is breakthrough advancement in the history of metal joining and, at the same time, it is a green technology as it increases energy efficiency [1]. If the friction stir welding is compared to the conventional method of welding, it has been seen that friction stir welding consumes very less energy as compared to the conventional method [2]. Aluminum became the first substance to be welded by FSW. This was invented in 1991 by the Welding Institute in the United Kingdom. The process is also known as solid-state welding and is used now for welding/manufacturing a variety of similar and dissimilar engineering materials [3]. The basic concept of using it is very easy. In this process, a rotating tool is utilized that is non-consumable, as well as a special design pin and solder is used which is inserted in the corners of plates and sheets which are to be joined along the line [4]. One of the best things about the FSW is that it does not use any filler metal to join so it is a great relief from the fusion welding or hardfacing in which is another material is applied to a base metal [5]. Aluminum alloy or any other metal which are reinforced with any by-product as fly ash can be practiced by joining it with friction stir welding [6]. The addition of fly ash in aluminum increases the strength of aluminum which is formed through casting [7,8], Traditional friction welding was previously used for small axisymmetric parts in which parts could be pushed or rotate in the opposite direction, but the same friction stir welding can be used on any kind of joints. These are butt joints, lap joints, T butt joints, and fillet joints, on which FSW can be performed [9]. Aluminum alloy can be used for developing wind turbines which is light in weight [10,11]. There is no shielding gas used in this process, which makes the process atmospheric friendly. In this welding, process object is welded before it reaches its
melting point, only then its name is solid-state welding the tool (probe) used is usually a cylindrical shoulder with which the profiled pin and the size of the probe are smaller than the thickness of the welding plate [12].

![Figure 1. Schematic of friction stir welding.](image)

Rotational speed in this welding means that the angular velocity with which the tool rotates in a revolution per minute. The translation speed in which the tool travels along with the welding line is called feed rate or welding speed, which is given in millimeters per second (mm/s) [13]. The progressing and driving side of the welding is the side where the angular velocity and forward velocity of the pin tool are additives and the opposite side where angular velocity and translation velocity are in inverse ways these are called retreating or trailing or side [14]. The probe or tool pin is then traveled in the opposite direction of the clamped workpiece. The primary purpose of doing the study is to get aluminum joined by FSW and to investigate whether it is better than conventional welding. For that tensile strength and hardness are measured as per the standards. Here, a universal testing machine to utilize to measure the strength and a Rockwell hardness testing machine has been used to measure hardness [15]. To analyze the parameter RSM (response surface methodology) is used in which there are 3 levels and 3 factors that make a total of 9 orthogonal arrays.

Friction stir welding finds wide applications in the following engineering fields like railways, Shipbuilding and marine industries. The structures from aluminum expulsions can be joined with the help of friction stir welding [16]. Shipbuilding and marine industries are also the two sectors are to be named, which contributes to enhancing the business application of FSW, it is the marine industries and the shipbuilding industry [17]. The procedure is appropriate for the platforms for landing Helicopter, panels for decks, sides, bulkheads, and floors. Also, in central air conditioning the ducts are made of aluminum and can be successfully joined via welding. Air conditioning is another important sector, people nowadays spend lot of time in indoor dwellings due to coronavirus pandemic [18] and these swellings are installed with air conditioners with lightweight aluminum ducting channels connected via welding. Also in aerospace industry, the avionic business at present is the welding model and delivering fabricated parts made of aluminium prepared through optimized techniques [19,20]. The eclipse airship has bolts that are supplanted by this welding [21]. This offers considerable advantages contrasted with riveting and machining, for example, decreased assembling expenses and weight investment funds.

2. Materials

There are a large number of materials that can be joined through the FSW technique and also have some combinations that cannot be joined by the convectional technique if they are as follows, Aluminum, Brass, Aluminum Alloys, Ceramic, Copper, Bronze, Steel Alloys, Tungsten, Magnesium
Alloys, Manganese, and many more [22].

3. Literature Review
According to G. Elatharasana and V.S. Senthil Kumar (2013) [23], the ultimate tensile strength and yield strength of the joint developed by friction stir welding have increased due to tool RS, WS, and tool AF up to a maximum value, and then reduced. Tensile elongation (TE) of the joint rises with the rise of rotational speed and axial force but reduces due to a continuous rise in WS. According to C. Elanchezhian et.al (2014) [24], the Taguchi method has been used to analyze the most favorable condition, for FSW for Aluminium alloy 8011-16062. For this, an ANOVA table has been used to analyze the outcomes. It has been observed that the major effect on impact strength is due to tool RS and on the other hand, WS has a negligible effect on tensile strength. According to Deepak Kumar and Jatinder Kumar (2020) [25], the tensile strength of the joint rises with the rises in rotational speed which is in the range of 710-1000 RPM, and the maximum value is achieved at 1000 RPM. After that, the strength reduces with the rise in RS.

4. Plan of Investigation
Response surface methodology (RSM), which is also known as RSM, is used for modeling and analyzing, through mathematical and statistical methods. Optimization of advanced engineering materials is done on basis of process parameters [26,27]. So that the input and output variables in R.S.M. can be detected so that the most appropriate and relevant relationship can be determined and studied further. A total of 3 factors have been made for the study, and the labels have also been made, which has led to a total of 9 orthogonal arrays. Therefore, an L9 (3^3) orthogonal array is decided for the experimentation because in L9 (3^3) in 9 combinations of experiments, 3 factors with 3 levels can be analyzed.

| Sr. No | Parameters                  | Level 1 | Level 2 | Level 3 |
|--------|-----------------------------|---------|---------|---------|
| 1.     | Rotation speed (RPM)        | 1200    | 1300    | 1400    |
| 2.     | Welding speed (mm/min)      | 75      | 100     | 125     |
| 3.     | Axial Force (KN)            | 5       | 6       | 7       |

5. Experimental set-up and procedure
FSW was invented in the UK in the Welding Institute (TWI) in 1991. This technique has been used in the early stages of aluminum alloys. This technique has been patented by W.M Thomas. This technique is relatively new in the welding field and is also known as the solid-state fabrication process. Aluminium metal has been a core area of interest for research as is most abundantly used metal in the aviation industry [30]. This technology is an environmentally friendly and single-phase process used to join almost all types of aluminum alloy, which is extensively used in the aviation industry. The rotating tool used in it is non-consumable, with a specially designed pin and shoulders that are inserted into the edges of sheets or plates that have to be joined. This tool has two major functions are to heat the work-piece and movement of material to produce the joint.

6. Result and Discussion
ANOVA technology has been used to test the adequacy relationship for the response surface tensile strength. The study has been carried out by taking the parameters into account experiments friction stir welding, and their levels are mentioned in Table 2. The summary reveals the linear model that is made up of these parameters which are sufficient to analyze the response variable. The regression equation generated is as follows:
Tensile Strength = 97.616 + 7.4535 * A - 1.84729 * B + 22.0884 * C - 0.00245432 * AB - 0.0668121 * AC + 0.152713 * BC

Analysis of Variance is known as ANOVA in shot form, which is a static method that can use to discuss the control factor and find out which parameters have been most contributing [28,29]. F test that has been applied through Fisher, which is an additional tool used for analyzing the values. Finally, it shows that if the reading of the f-test is higher, then that parameter will be more prominent.

| Run | Factor 1 (RPM) | Factor 2 (mm/min) | Factor 3 (KN) | Response 1 (MPA) |
|-----|----------------|------------------|---------------|-----------------|
| 1.  | 1200           | 75               | 7             | 114             |
| 2.  | 1400           | 75               | 5             | 85              |
| 3.  | 1200           | 100              | 6             | 90              |
| 4.  | 1300           | 100              | 6             | 98              |
| 5.  | 1200           | 75               | 5             | 70              |
| 6.  | 1400           | 125              | 5             | 81              |
| 7.  | 1200           | 125              | 5             | 66              |
| 8.  | 1400           | 100              | 7             | 127             |
| 9.  | 1300           | 125              | 7             | 118             |

Table 2. Experimental results

The extent to which any material can endure stress which is applied by stretching or pulling until it breaks or fails is called Tensile strength and ultimate strength. Table 3 below demonstrates the ANOVA table for the tensile strength. From Table 3, it is seen that the highest contribution in this study is of a parameter, the AF, and then the RS is there.

| Source      | Sum of Squares | df | Mean Square | F-value | p-value  | Contribution % |
|-------------|----------------|----|-------------|---------|----------|----------------|
| Model       | 3705.71        | 3  | 1235.24     | 21093.51| < 0.0001 |                |
| A-Rotation speed | 378.59        | 1  | 378.59      | 6464.97 | < 0.0001 | 10%            |
| B-Welding speed   | 21.53         | 1  | 21.53       | 367.64  | < 0.0001 | 0.5%           |
| C-Axial Force   | 3360.30        | 1  | 3360.30     | 57382.12| < 0.0001 | 90%            |
| Residual       | 0.2928         | 5  | 0.0586      |         |          | 0.0%           |
| Cor Total      | 3706.00        | 8  |             |         |          |                |

Table 3. Demonstrates the ANOVA table for tensile strength.

Table 2 shows that when tensile strength is maximum which is 127 MPA is achieved only when the rotation speed is 1400 RPM, and the axial force is 7 KN, and last the welding speed which is 100 mm/min this will not impact much on the workpiece. This analysis for the contribution through the axial force, then the rotation speed, and last but not least the welding force in this FSW is demonstrated in Figure 2 which is a response plot that has been investigated above for the tensile strength in this study. This response plot provides the change in the tensile strength after FSW on each parameter.
Figure 2 (a). Plot between RS and WS for the tensile strength

Figure 2 (b). Plot between WS and RS for the tensile strength

Figure 2 (c). Plot between RS and AF for the tensile strength
The parameters used for analyzing are shown in Figure 3 in the form of a response plot. As a result, as the rotational speed and the axial strength of the tool increases, the tensile strength of the FSW joints is increased up to a certain amount whereas weld speed decreases the tensile strength. Figure 4 is the contour plot between the factor which are RS, WS, and tool AF and the tensile strength. The contour plot, which is presented below in Figure 3 (a) in which the plot is in between RS and WS in which the output is the tensile strength.

![Figure 3 (a). Contour plot RS and WS](image)

Figure 3 (b) in which the plot is constructed in between RS and WS along that the output is the tensile strength.

![Figure 3 (b). Contour plot between WS and RS](image)

Figure 3 (c) shows that the plot is in between RS and AF in which the output is the tensile strength. So, an investigation can be done more transparently. This shows that as the tool rotation speed increases its impact will ultimately increase the value of the tensile strength, but when it comes to maximum, the value starts falling.
Figure 3 (c). Contour plot between AF and RS

But when the rotational speed is lower, it may be because of insufficient heat or material flow that causes the defect between the joints occurs, which may lead to the reduction of tensile strength in the future.

Figure 4. Percentage contribution for the obtained tensile strength

Figure 4 is a graphical representation of percentage contribution and table 3 which is an ANOVA table showcases the major role is of axial force which is 90% and then rotation speed which is 10% and other factors have a negligible role in the tensile strength of aluminum alloy 8011-6062 alloys through friction stir welding.

7. Conclusions
Through this study, tensile strength for the FSW process was simulated and analyzed via response surface methodology. Herein, three variables that are taken into attention were RS, WS, and AF. These parameters are taken into account for the investigation:

- The results of RSM reveal that strength of the FSW joint increases when the rotational speed of the tool, WS, and AF rises to an optimum level after which it varies.
The highest contribution in FSW welding is of AF and RS, but welding speed’s contribution is not much.

The maximum tensile strength is 127 (MPA) at the rotation speed of 1400 rpm in which the axial force is 7 KN.

WS has the least influence on tensile strength for the joints prepared by FSW for selected aluminum alloys.

The major role is of AF which is 90% and then RS which is 10% and other factors have a negligible role in the tensile strength of aluminum alloy 8011-6062 alloys through FSW.

The tool rotation speed increases its impact will ultimately increase the value of the tensile strength, but when it comes to maximum, the value starts decreasing.

Based on the above study, it can be seen that similar works can be performed for other industrial materials manufactured in the same manner. The parameters and Levels taken into account in the study can also be further expanded for their ranges in the future for this friction stir welding to create a welding process by which the strength of any material can be increased. There is yet to be a lot more work done in this direction in the future because so far, the work has been done in a fixed lobby, research should be done as to what could be the impact of friction stir welding on other metals.

References
[1] Hema, P., Sai Kumar Naik, K., & Ravindranath, K. (2017). Prediction of Effect of Process Parameters on Friction Stir Welded Joints of dissimilar Aluminium Alloy AA2014 & AA6061 Using Taper Pin Profile. Materials Today: Proceedings, 4(2), 2174–2183. https://doi.org/10.1016/j.matpr.2017.02.064.

[2] Haghshenas, M., & Gerlich, A. P. (2018). Joining of automotive sheet materials by friction-based welding methods: A review. In Engineering Science and Technology, an International Journal (Vol. 21, Issue 1, pp. 130–148). Elsevier B.V. https://doi.org/10.1016/j.jestch.2018.02.008.

[3] Aminzadeh, A., Parvizi, A., & Moradi, M. (2020). Multi-objective topology optimization of deep drawing dissimilar tailor laser welded blanks; experimental and finite element investigation. Optics and Laser Technology, 125. https://doi.org/10.1016/j.optlastec.2019.106029.

[4] Rambabu, G., Balaji Naik, D., Venkata Rao, C. H., Srinivasa Rao, K., & Madhusudan Reddy, G. (2015). Optimization of friction stir welding parameters for improved corrosion resistance of AA2219 aluminum alloy joints. Defence Technology, 11(4), 330–337. https://doi.org/10.1016/j.dt.2015.05.003.

[5] Arora, N., & Akhai, S. (2015). Reclaiming EN-14b steel grade implements by hardfacing. International journal of scientific research, 4(10), 14-16.

[6] Sharma, V., & Akhai, S. (2019). Trends in Utilization of Coal Fly Ash in India: A Review. Journal of Engineering Design and Analysis, 2(1), 12-16.

[7] Sharma, V., & Akhai, S. (2019). Mechanical Behaviour of Fly Ash Reinforced Aluminum Composite Prepared by Casting. Journal of Advanced Research in Mechanical Engineering and Technology, 6(1&2), 23-26.

[8] Thareja, P., & Akhai, S. (2017). Processing Parameters of Powder Aluminium-Fly Ash P/M Composites. Journal of advanced research in manufacturing, material science & metallurgical engineering 2017; 4 (3&4): 24, 35.

[9] Abd Elaziz, M., Shehabeldeen, T. A., Elsheikh, A. H., Zhou, J., Ewees, A. A., & Al-qaness, M. A. A. (2020). Utilization of Random Vector Functional Link integrated with Marine Predators Algorithm for tensile behavior prediction of dissimilar friction stir welded aluminum alloy joints. Journal of Materials Research and Technology, 9(5), 11370–11381. https://doi.org/10.1016/j.jmrt.2020.08.022.

[10] Elanchezhian, C., Ramnath, B. V., Venkatesan, P., Sathish, S., Vignesh, T., Siddharth, R. V., ... & Gopinath, K. (2014). Parameter optimization of friction stir welding of AA8011-6062 using mathematical method. Procedia Eng, 97, 775-782.

[11] Akhai, S., Srivastava, P., & Sharma, S. (2020). Developments in Horizontal Axis Wind Turbines - A Brief Review. Journal of Critical Reviews, 7(19), 255-260.

[12] Shanavas, S., & Dhas, J. E. R. (2018). Quality Prediction of Friction Stir Weld Joints on Aa 5052 H32 Aluminium Alloy Using Fuzzy Logic Technique. Materials Today: Proceedings, 5(5), 12124–12132. https://doi.org/10.1016/j.matpr.2018.02.190.

[13] Sahu, P. K., & Pal, S. (2015). Multi-response optimization of process parameters in friction stir welded AM20 magnesium alloy by Taguchi grey relational analysis. Journal of Magnesium and Alloys, 3(1), 36–46. https://doi.org/10.1016/j.jma.2014.12.002.

[14] Choudhury, B., & Chandrasekaran, M. (2020). Electron beam welding of aerospace alloy (Inconel 825): A comparative study of RSM and ANN modeling to predict weld bead area. Optik, 219. https://doi.org/10.1016/j.ijleo.2020.165206.

[15] Wadhwa, A. S., & Dhaliwal, H. S. (2008). A Textbook of Engineering Material and Metallurgy. Firewall Media.
[16] Wakchaure, K. N., Thakur, A. G., Gadakh, V., & Kumar, A. (2018). Multi-Objective Optimization of Friction Stir Welding of Aluminium Alloy 6082-T6 Using hybrid Taguchi-Grey Relation Analysis- ANN Method. Materials Today: Proceedings, 5(2), 7150–7159.

[17] Ugrasen, G., Bharath, G., Kumar, G. K., Sagar, R., Shivu, P. R., & Keshavamurthy, R. (2018). Optimization of Process Parameters for Al6061–Al7075 alloys in Friction Stir Welding using Taguchi’s Technique. Materials Today: Proceedings, 5(1), 3027–3035.

[18] Akhai, S., Mala, S., & Jerin, A. A. (2020). Apprehending Air Conditioning Systems in Context to COVID-19 and Human Health: A Brief Communication. International Journal of Healthcare Education & Medical Informatics (ISSN: 2455-9199), 7(1&2).

[19] Awasthi, A., Panwar, N., Wadhwa, A. S., & Chauhan, A. (2018). Mechanical Characterization of hybrid aluminium composite-a review. Materials Today: Proceedings, 5(14), 27840-27844.

[20] Thareja, P., & Akhai, S. (2016). Processing Aluminum Fly Ash Composites via Parametric Analysis of Stir Casting. Journal of Advanced Research in Manufacturing, Material Science & Metallurgical Engineering, 3(3&4), 21-28.

[21] He, X., Gu, F., & Ball, A. (2014). A review of numerical analysis of friction stir welding. In Progress in Materials Science (Vol. 65, pp. 1–66). Elsevier Ltd. https://doi.org/10.1016/j.pmatsci.2014.03.003.

[22] Heidarzadeh, A. (2019). Tensile behavior, microstructure, and substructure of the friction stir welded 70/30 brass joints: RSM, EBSD, and TEM study. Archives of Civil and Mechanical Engineering, 19(1), 137–146. https://doi.org/10.1016/j.acme.2018.09.009.

[23] Elatharasan, G., & Kumar, V. S. (2013). An experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy using RSM. Procedia Engineering, 64, 1227-1234.

[24] Elanchezhian, C., Ramnath, B. V., Venkatesan, P., Sathish, S., Vignesh, T., Siddharth, R. V., … & Gopinath, K. (2014). Parameter optimization of fraction stir welding of AA8011-6062 using mathematical method. Procedia Eng, 97, 775-782.

[25] Kumar, D., & Kumar, J. (2020). Optimization of Parameters in Friction Stir Welding of AA6101-T6 by Taguchi Approach. In Advanced Engineering Optimization Through Intelligent Techniques (pp. 361-370). Springer, Singapore.

[26] Singh, G., & Akhai, S. (2015). Experimental study and optimisation of MRR in CNC plasma arc cutting. International Journal of Engineering Research and Applications, 5(6), 96-99.

[27] Wadhwa, A. S., & Chauhan, A. (2020). An overview of the controllable process parameters in mechanical characterization of developed hybrid metal matrix composites and their optimization for advanced engineering applications. Materials Today: Proceedings, 28, 1295-1301.

[28] Singh, S. (2016). Study the drilling behaviour of aluminium 6061 metal matrix composites using Taguchi's methodology. International journal of machining and machinability of materials, 18(4), 327-340.

[29] Singh, S., Singh, I., & Dwivedi, A. (2013). Multi objective optimization in drilling of Al6063/10% SiC metal matrix composite based on grey relational analysis. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 227(12), 1767-1776.

[30] Awasthi, A., Panwar, N., Wadhwa, A. S., & Chauhan, A. (2018, December). Friction Characteristics of Hybrid Aluminium 6061 Composite Reinforced With Silicon Carbide and Red-Mud. In Proceedings of TRIBOINDIA-2018 An International Conference on Tribology.