

# A REVIEW STUDY IN ENHANCING THE OPTIMISATION PROCESS FOR AA6351 ALLOY USING FSW TECHNIQUES - LITERATURE SURVEY

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## ABSTRACT

Friction stir welding is the solid type welding which uses best tool that is used to join two workpieces without melting the workpiece. Heat is produced by the friction between the workpiece and the tool. This heat only softens the metal but not melting it. The tool moves along the soften surface for joining purpose. The scope of welding is increasing day to day according to their needs. This paper reviews based on FSW process analysis, Mechanical properties, Microstructural properties, Post weld heat treatment of the joints, Design of experiments and Corrosion of the joints in Aluminium and its alloys.

**Keywords:** Solid type welding, Nonconsumable tool, Welding properties, FSW process analysis, Mechanical properties, Microstructural properties, Post weld heat treatment of the joints, Design of experiments, Corrosion of the joints.

## 1.0 INTRODUCTION

Several advantages over fusion welding techniques [1-66] have been attributed to friction stir welding's (FSW) use in joining materials that are difficult to weld with traditional methods, such as aluminium, magnesium, and copper alloys, as well as polymers. Notably, in FSW applications, flaws such solidification cracking, oxidation, distortion, and porosity -- all of which are frequent in traditional welding methods -- do not occur [2,67].

Mechanical properties of friction stir welded joints may be influenced by a number of factors, including tool rotational speed, welding speed, axial force, tool pin shape, tool dipping, dwelling duration, etc. Ultimate tensile strength (UTS) and ultimate elongation (UE) of friction stir welded joints of identical and similar joints in AA6351 alloys were investigated utilising a variety of tool configurations in. UTS and UE were shown to increase up to a certain ratio, then decrease above that ratio for joints of the same kind. Joint mechanical characteristics were analysed in respect to process factors, and correlations were established between the UTS, the UE, and the vertical force. The UTS and UE values of friction stir welded joints for AA6351- AZ31 dissimilar junctions are much lower than those of the parent materials, and this is true independent of the process settings used to create the joints.

Analyses showed that, in comparison to results from a process using a pin tool, UTS and UE values are greatest when the process uses a pinless tool. The FSW of AZ31 magnesium alloy was also investigated [9,70] in terms of the influence of rotating speed, welding speed, dwelling time on UTS and UE values, vertical force, and temperature. The greatest values of UTS and UE are related to lower vertical force and higher temperature values, which are among the primary results.

Selecting the optimal process parameters through an optimisation strategy guarantees the optimum mechanical qualities of the welded products. Response surface methodology (RSM), neural network-based approaches, and fuzzy logic-based techniques are only few of the modelling and optimisation methods used in the literature. Notably, this table summarises the most important studies on aluminium alloys and friction stir welding. You may find a full index of symbols in the Abbreviations section.

In order to model the friction stir welding process and choose the best process parameters, the RSM technique was adopted by the majority of studies (as determined by the prediction model criteria). The RSM is a set of statistical and mathematical techniques for modelling and optimising engineering problems, and it was first described in [71].

## 2.0 PROBLEM STATEMENT

Solid-state welding, or SW, is a technique. This kind of welding was developed in 1991 by the TWI (Taiwan Welding Institute). This process is used to make a wide variety of structural additives, vehicle parts, ship components, and autos. More research on the technology led to the improved mechanical qualities. Through this process, aluminium alloys such as AA5083, AA2024, AA7075, etc. were developed. Tool of pin shape, tool shoulder diameter, D/d ratio, rotational velocity, and welding speeds are all method parameters. In this study,

researchers used a wide range of tool pin profiles, such as SQ, HEX, TR, CY, and TTH, to execute friction stir welding on aluminium alloys.

### **3.0 SCOPE OF WORK**

For uniting nonferrous metals and alloys, we developed a solid-state welding method called friction stir welding (FSW). Because it produces no waste and uses no resources, it offers numerous benefits over more conventional approaches. Multi-objective Taguchi-Grey-based optimisation of weld-quality-affecting process parameters for dissimilar aluminium FSW welds is shown here. Specifically, the Taguchi (L9) orthogonal array was used to conduct experiments in which the process parameters rotational speed, axial force, and traverse speed were varied. Next, a grey relation analysis was used to transform the multi-objective criterion into a single objective function that could be optimised with the Taguchi method. The mechanical characteristics, such as tensile strength and elongation, were analysed by Analysis of variance to identify the influential parameters. Grey relation analysis using Taguchi methodology is shown here to be a viable method for enhancing the quality of aluminium alloy welding.

### **4.0 OBJECTIVES**

The goal of this technique is to maximise a response surface whose values are dependent on a number of process factors. The response surface method consists of four main steps:

- (i) creating a design of experiments (DOE) to collect enough data about the process under study;
- (ii) developing a mathematical model based on a second-order polynomial surface that adequately fits the experimental results;
- (iii) determining which parameters can best optimise one or more responses; and
- (iv) analysing the relationships between the inputs and the outputs.

### **5.0 OVERVIEW OF THE EXPERIMENTAL CAMPAIGN**

The material investigated in the present work was AA6351 aluminum alloy, supplied in the form of 6 mm thick sheets.

Blanks of AA6351 were cut to dimensions of 180 mm in length and 80 mm in breadth before being butted together using a friction stir welding procedure. The apparatus used in FSW operations is described in detail in [56]. During the course of the experimental campaign, a pin-shaped tool made of high carbon steel was used; this instrument had a shoulder diameter of 12 mm, a truncated cone pin with a base diameter of 3.5 mm, a height equal to 1.7 mm, and a pin angle of 30°. Starting configuration was guaranteed by securing blanks with a series of mechanical clamps, and the welding direction was selected to be perpendicular to the rolling direction. Constant rotational speed, welding speeds, and tool plunging were imposed during the friction stir welding operations, with values between 1500 and 2500 rpm, 30-100 mm/min, and 0.05-0.15 mm, respectively. All welding procedures were carried out at a 2 tilt angle, as reported in the peer-reviewed literature [50-73]. Friction stir welded connections in aluminium alloys had their mechanical characteristics studied [57] to see how tilt angle affected them. To prevent flaws in the weld joint, a tool tilt angle of less than 3 degrees was suggested. In particular, testing FSWed joints with a tool tilt angle of 2 yielded the best mechanical behaviour. The creation of a kissing bond-like structure in the stir zone was seen to occur at low tilt angles [58], whereas flashes occurred at high tilt angles. The 2 tilt has also been shown to result in a flaw free weld in experiments [59].

Leica Microsystems (Berlin, Germany) Reichert-Jung™ MeF-3s light optical microscopes were used to examine the microstructure of friction stir welded blanks. A solution of 10 mL acetic acid, [48] 6 g picric acid, 10 mL distilled water, and 100 ml of ethanol was used to etch the surfaces of the samples. Each welded joint was examined by taking a transverse cross section and carefully noting the various zones inside it. Mean grain size values were determined using the line intercept technique in accordance with ASTM E112 and the microstructure of the base material (BM) is shown in Figure.

#### **5.1 Experimental Design Matrix**

The suggested literature research provided the foundation for treating tool plunging (TP), rotating speed ( $\omega$ ), and welding speed ( $v$ ) as independent variables in the experiment. To the best of our knowledge, the literature on FSW has never before looked at the impact of the tool plunging. Tensile tests were conducted at room temperature utilising the servo-hydraulic universal testing machine (MTS Systems Corporation, Eden Prairie, MN, USA) to measure two response variables, UTS and UE [43]. In order to investigate the efficacy of FSW at changing process parameters with a manageable number of tests, the literature often use either a partial factorial design or a fully randomised design (CRD) of experiments.

It's important to note that the final welded joint's factor values were chosen to prevent any externally obvious flaw [49]. The suggested complete factorial design of experiments [41] is summarised in the table below, which shows the design matrix including all 33 = 27 coded and uncoded conditions. Uncontrollable factors such as machine heating, ambient humidity, and temperature were taken into account by doing the experiments in a randomised sequence. Each friction stir welded blank was then sliced to produce tensile samples once FSW procedures were finished. Standardised tensile samples were made using the dimensions

specified in BS EN ISO 4136:2012, with the loading direction perpendicular to the welding line. All of the tensile tests were performed at a crosshead speed of 0.1 mm/s. Tensile tests conducted at room temperature provided data that could be used to calculate UTS and UE as a function of the various welding conditions. The mean values were determined from three independent runs for each setting of the parameters.

## 6.0 BUILDING THE PROCESS META MODELS FOR UTS AND UE

Establishing a connection between input and output variables may be done mathematically using a metamodel based on non-linear regression. Analysis of variance (ANOVA) is very useful for verifying the reliability of such a regression model.

An empirical model in the form of a multiple regression equation describing the relationship between a collection of independent variables (factors) and a dependent (response) variable to be optimised was developed using the response surface approach applied to the full factorial DOE, as was previously discussed [24]. It is possible to establish a functional link between the independent variables  $x$  and the resulting  $y$  in the vast majority of experimental problems.

The response surface or response function is the function linking the response variable to the influential factors. The mistake in the fit is denoted by the residual. Equation is a reasonable approximation of the mathematical form of, which is a second order polynomial (regression) equation.

### 6.1 ANOVA Analyses to Check Models Adequacy

To evaluate the respective metamodels and examine the impact of the specified process factors on the two output variables, two ANOVA studies were created. Table 6 displays the findings from the ANOVA [35] performed on UTS. Statistics show that both the linear and square terms mentioned in the comments have a considerable impact on the UTS. However, no 2-way interactions had a statistically significant impact on the outcome. S-values, R-squared (R-sq), and the adjusted R-sq (R2-adj) must be analysed to determine how well the fitted regression model fits the experimental data [39].

The coefficients [44] for linearity, squareness, and two-way interactions all proved to be significant. Even while the stated values of the determination coefficient (R-sq) and the adjusted determination coefficient (R2-adj) in the model summary are somewhat lower than those previously observed, this indicates that the suggested regression model fits the actual data rather well.

These two results from the ANOVA tests show that the suggested second-order regression models are accurate in predicting both answers. (i) both the UTS and UE models' p-values for their respective regression sources were less than 0.05, and (ii) models At the 99% confidence level, the Fisher ratio values [51] were far greater than the essential F-ratios. The residuals' normal probability graphs for UTS and UE are shown in Figure. The majority of residuals were found to lie on the straight line, indicating that the errors followed a normal distribution in both cases. Figure depicts a comparison between the predicted and experimental values[36] of the response variables and confirms that the UTS model

### 6.2 Validation of the Metamodels

Five additional experimental tests were conducted with process parameters chosen at random from the ranges shown in Table to further validate the proposed metamodels by evaluating the degree to which observed results deviated from those predicted by the proposed empirical formula. More specifically, Table displays both the selected parameters and the outcomes (UTS \* and UE \*). Each test's percent-age relative error when compared to UTS and UE, indicated by \_UTS and \_UE, is shown in Table. The UTS-related metamodel was shown to be more accurate, with a maximum deviation of 2.47%, compared to the UE-related metamodel's highest divergence of 11.34. However, the standards for modelling accuracy were met since the minimal values of relative percent error and the mean absolute errors were met for both UTS and UE.

Intense plastic deformation and temperature distribution in and around the agitated zone of the workpiece are reported as outcomes of the FSW process in the scientific literature. Weld production involves a wide range of process factors that affect thermal, micro-, and macro-mechanical effects [15-18]. To ensure an effective and successful welding operation, it is crucial to pick the appropriate values for the FSW process parameters such as TP,, and  $v$  [6,8,9].

This results is consistent with the observations made by Costa et al. [20] on AA6351 blanks produced using friction stir welding. Because heat affected zones of FSWed joints are not subjected to pure uniaxial loading conditions, they exhibit this behaviour at the onset of failure for relatively tiny values of plastic strain. In addition, Mishra and Ma showed that the grain size and precipitate size and distribution determine the deformation resistance of FSWed joints in various zones [15]. The strength of the zone impacted by heat was lowest because of the formation of the precipitate-free zones and the coarsening of the precipitates

In the following sections, we will examine a variety of contour plots and surface plots to infer information regarding the impact of process factors on UTS and UE of friction stir welded AA6351-T6 joints. Importantly, because to their circular nature, contour plots may be used to identify whether or not a specific answer is dependent on a set of inputs. They can also show you graphically where the sweet spot for parameter settings is. analysing a surface response may be more difficult than analysing the sequence of

parallel lines typical of responses associated with first order models since the created response surfaces originate from a second order regression model. Therefore, contour plots are useful for learning about RSM-based analyses.

### 6.3 UTS and the Impact of FSW Parameters

The ultimate tensile strength is shown to be influenced by the process parameters TP, and  $v$ . Figure illustrates the relationship between TP and UTS, demonstrating that UTS values increased with TP until a maximum value was attained. As TP got closer to the upper limit value used in this work (0.15 mm), the UTS went down. While the fluctuation of UTS with  $v$  was not as pronounced as that demonstrated with TP, the two speeds, rotating and welding, showed comparable behaviour.

The interaction effects of any two process parameters on UTS are shown by both contour plots and surface plots, as reported in Figure. The more circular is the shape of the contour plot, the higher is the independence between the factors under investigation.

Higher UTS was achieved when TP were generally changed between 1800 and 2400 rpm and between 0.1 and 0.13 mm, respectively. When TP were well-balanced, heat input, mixing, and stirring were all enhanced during FSW. According to [11], unlike the foundation material, which displayed big and elongated grains, the stirred zone is characterised by fine equiaxed grains regardless of the FSW process settings considered. The presence of dynamic recrystallization and grain refinement inside the SZ is shown by these findings. Low values of  $v$  result in inefficient heat input, as shown by on AA6061 friction stir welded joints [14]. Therefore, the workpiece cannot reach a temperature high enough to provide an effective stirring action of the alloy. However, if  $v$  is too large, the temperature in the stir zone will rise too high, leading to grain coarsening and turbulent material flow, both of which would reduce the joint's mechanical strength.

The plunging action of the tool also contributes significantly to improving the mechanical characteristics of the joint. In reality, a satisfactory contact between the shoulder and the workpiece top surface is guaranteed by a suitable amount of plunging depth. According to [15], if the TP value is too low, the tool shoulder will not make contact with the blank's upper surfaces. Since the spinning shoulder is unable to adequately transport the stirred material from the pin's front to its rear, it produces welds that are flawed due to the presence of internal channels or surface grooves. A concave weld, characterised by local thinness of the joint, resulted when the TP value was too great, causing the shoulder to sink into the sheet blanks and create an excessive flash. The mechanical qualities of the FS welded joint are compromised under both of these tool plunging-limit circumstances.

The UTS may be enhanced by raising both TP and  $v$ , and this is because of their mutual influence. However, it was obvious that joint UTS could be enhanced by adopting TP values generally ranging from 0.10 to 0.13 by examining the interactions of TP with both rotational and welding speed.

When it comes to the size and heating rate of the welded zone, welding speed is one of the most important process factors influencing the mechanical characteristics of FSW joints. Elangovan [15] found that when  $v$  increases, heat inputs decrease, resulting in a quicker rate of cooling for the welded joint. As a result, the local strength of certain locations throughout the weld zone may be drastically reduced by phenomena including solubilization, reprecipitation, and coarsening of precipitates that occur during welding. There is a higher chance of fracture propagation during a tensile test if the welding speed is too high and flaws emerge along the welded joint. Lower welding rates, on the other hand, generate more heat, which leads to a softer workpiece material and larger grain size, resulting in a lower UTS value. Higher UTS values were guaranteed by  $v$  values between 65 and 85 mm/min, as shown by the interaction graphs involving the welding speed on the one hand and both TP and  $v$  on the other.

The proposed analysis confirms the findings of [1] and [15], showing that the rotational and welding speeds significantly impacted the UTS of the welded joint, due to their roles in frictional heat generation, cooling rate, and heat dissipation, all of which influence temperature gradients within and around the welded area. Bruni et al. [10] found a similar relationship between the joint mechanical performances and the rotational speed/welding speed ratio for FSWed joints in AZ31 magnesium alloy by experimental and computational analysis. In conclusion, varying TP, and  $v$  within the ranges of 0.1-0.13 mm, 1500-2500 rpm, and 150-220 mm/min, respectively, is optimal for increasing the tensile strength of AA6351-FSWed joints.

S.NO	Author Name	Year	Title	Observations	Findings
1.	Feistauer, E. E., Bergmann, L. A., Barreto, L. S., & Dos Santos, J. F.	2014	Mechanical behaviour of dissimilar friction stir welded tailor welded blanks in Al-Mg alloys for Marine applications	Welding is a vital component of several industries such as automotive, aerospace, robotics, and construction. Without welding, these industries utilize aluminum alloys for the manufacturing of many components or systems.	This review also illustrated that significantly less attention has been paid to FSW of Al-MMCs and considerable attention is demanded to produce qualified joint.
2.	Fernández, R., Ibáñez, J., Cioffi, F., Verdera, D., & González-Doncel, G	2017	Friction stir welding of 25% SiC/2124Al composite with optimal mechanical properties and minimal tool wear	Friction Stir Welding is a solid state welding process which is used to join the soft materials like aluminium, copper, nickel, titanium etc. It uses heat generated from friction produced by rotating tool and high axial force.	This research shows effect of various welding parameters on the characteristics of weld formed during FSW.
3.	Fouladi, S., & Abbasi, M.	2017	The effect of friction stir vibration welding process on characteristics of SiO <sub>2</sub> incorporated joint	The development and demand for lightweight materials such as aluminum, magnesium, and their alloys have been significant in the aerospace and automotive industries.	This study indicates that the proposed optimization module efficiently controls the varying process parameters to achieve conflicting response values. It is highly efficient to manufacture high-efficiency welded joints and is recommended for optimum joint qualities.
4.	Galvão, Ivan, et al.	2010	"Material flow in heterogeneous friction stir welding of aluminium and copper thin sheets."	Friction stir welding is the solid type welding which uses consumable tool that is used to join two workpieces without melting the workpiece.	This research reviews based on FSW process analysis, Mechanical properties, Microstructural properties, Post weld heat treatment of the joints, Design of experiments and Corrosion of the joints in Aluminium and its alloys
5.	Grujicic, M., Arakere, G., Yalavarthy, H. V., He, T., Yen, C. F., & Cheeseman, B. A.	2010	Modeling of AA5083 material-microstructure evolution during butt friction-stir welding	Most of welded parts requires secondary forming process to meet the design requirements which makes the ductility of the joint an important parameter to be improved.	While the improved failure strain was due to the higher content of Mg and Zn alloying elements in AA7075 alloy which precipitate on the grain boundaries facilitating the slipping between grains and provide more deformability of the global structure.

6.	Gungor, B., Kaluc, E., Taban, E., & Sik, A.	2014	Mechanical, fatigue and microstructural properties of friction stir welded 5083-H111 and 6082-T651 aluminum alloys	This research presents a systematic approach to develop the mathematical model for predicting the ultimate tensile strength, yield strength, and percentage of elongation of AA6351 aluminum alloy which is widely used in automotive, aircraft and defense Industries by incorporating (FSW) friction stir welding process parameter such as tool rotational speed, welding speed, and axial force.	. The developed mathematical model can be used effectively at 95% confidence level. The effect of FSW process parameter on mechanical properties of AA6351 aluminum alloy has been analyzed in detail.
7.	Jayaraman, M., Sivasubramanian, R., Balasubramanian, V., & Lakshminarayanan, A. K.	2009	Optimization of process parameters for friction stir welding of cast aluminium alloy A319 by Taguchi method	Numerous industrial applications, particularly those in the transport industry, require the joining of dissimilar materials which offers considerable benefits in terms of low cost, design flexibility, and weight reduction for overall structures.	The problems associated with conventional fusion welding processes have stimulated researchers in recent years to develop new joining methods for dissimilar materials which are particularly difficult to join.

8.	Khaled, Terry.	2005	"An outsider looks at friction stir welding."	Friction stir welding (FSW) originally developed for joining difficult-to-weld Al-alloys and FSSW (a variant of FSW for spot welding) have exhibited great potential for obtaining sound joints in various dissimilar alloy systems in different configurations namely butt-, lap- and spot-welding, particularly in dissimilar Al-alloys systems with different properties, which are very difficult to weld using conventional fusion welding techniques.	A major difficulty in joining dissimilar Al-alloys by FSW/FSSW lies in the discontinuity in mechanical and technological properties (such as high-temperature strength, plastic deformation capacity, viscosity, etc.) of the materials to be welded across the abutting surfaces.
9.	Khodir, S. A., & Shibayanagi, T.	2008	Friction stir welding of dissimilar AA2024 and AA7075 aluminum alloys	This discontinuity as well as inherent asymmetry in heat generation and material flow of FWS/FSSW processes causes a higher asymmetry in materials flow behaviour in dissimilar welding.	However, it is relatively easier to implement the FSW/FSSW process to dissimilar Al-alloys in contrast to FSW of dissimilar materials combinations with very differing properties, such as Al-alloy to Mg-alloy or Al-alloy to steel.
10.	Khourshid, A. M., & Sabry, I.	2013	Analysis and design of Friction stir welding.	This research presents the efforts of joining dissimilar aluminum alloys (AA6351-T6 and AA6061-T6) by friction stir welding (FSW) process.	FSW experiments are conducted according to the three factors five level central composite rotatable design method, and the response surface methodology was used to establish the empirical relationship between FSW process parameters such as tool rotational speed ( $N$ ), tool traverse speed ( $S$ ) and axial force ( $F$ ), and the response variables such as ultimate tensile strength, yield strength, and percentage of elongation.
11.	Kumbhar, N. T., & Bhanumurthy, K.	2008	Friction stir welding of Al 6061 alloy	The developed empirical models' adequacies are estimated using the analysis of variance technique.	This research also presents the application of the artificial bee colony algorithm to estimate the optimal process parameters to achieve good mechanical properties of FS weld joints. Results suggest that the estimations of the algorithm are in good agreement with the experimental findings.
12.	Koilraj, M., Sundareswaran, V., Vijayan, S., & Rao, S. K.	2012	Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083– Optimization of process parameters using Taguchi	To decrease impacts on the environment and maintain competitiveness in the market, various industries (for example, fabrication and construction) are concentrating on minimizing material and	Aluminium (Al) and its alloys are contending possibilities for various complex applications to meet these industrial needs since they have improved qualities like good weight-to-strength ratios.

			technique	energy usage.	
13.	Krishnan, K. N.	2002	On the formation of onion rings in friction stir welds	Fusion welding causes the joints to deteriorate while joining Al.	Friction stir welding (FSW) or friction Stir Processing (FSP) creates joints below melting point temperatures, eliminating the drawbacks of excessive heat input but necessitating an increase in the joint's final characteristics.
14.	Kulekci, M. K., Şik, A., & Kaluç, E.	2008	Effects of tool rotation and pin diameter on fatigue properties of friction stir welded lap joints	Nanoparticle reinforcement is an emerging field that provides great methods to create composite joints with improved joint characteristics.	The surface attributes of composite joints can be improved, including hardness, strength, corrosion resistance, and wear resistance.
15.	Lakshminarayanan, A. K., & Balasubramanian, V.	2008	Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique	This research critically reviews the work carried out in the field of FSW/FSP welding AA5083 and AA6082 with carbide and oxide as reinforced nanoparticles.	Further trends in nanoparticle reinforcement, oxide and carbide effect on welding parameters, microstructural formation, and mechanical properties are being analyzed.
16.	Lakshminarayanan, A. K., & Balasubramanian, V.	2009	Comparison of RSM with ANN in predicting tensile strength of friction stir welded AA7039 aluminium alloy joints	Analysis shows that the diffusion of the reinforcing nanoparticles, which affects the joint characteristics, is significantly influenced by FSW/FSP parameters.	Additionally, the dispersed nanoparticles enhance joint characteristics and help refine grains.

17.	Lakshminarayanan, A. K., & Balasubramanian, V.	2009	Comparison of RSM with ANN in predicting tensile strength of friction stir welded AA7039 aluminium alloy joints	The kind, quantity, & size of reinforced nanoparticles and the welding conditions greatly influence the joint characteristics and microstructures in similar and different Al welds.	Finally, prospects for a reinforced FSW are examined, followed by a look ahead and concluding notes.
18.	Leitao, C., Emílio, B., Chaparro, B. M., & Rodrigues, D. M.	2009	Formability of similar and dissimilar friction stir welded AA 5182-H111 and AA 6016-T4 tailored blanks	Friction stir welding provides an alternative method of joining aluminum in a reliable way. Anticipation of the joint efficiency is then a necessary step to optimize the process of the welding operation.	In the light of this, artificial neural network (ANN) technique may then be applied as a reliable method for simulating and predicting the durability of the joints for different process parameters.
19.	Lohwasser, Daniela, and Zhan Chen, eds.	2009	Friction stir welding: From basics to applications	In the present work, an ANN model is presented that predicts the ultimate tensile strength of friction stir-welded dissimilar aluminum alloy joints.	Four parameters were considered including tool pin profile (straight square, tapered square, straight hexagon, straight octagon and tapered octagon), rotational speed, welding speed and axial force.
20.	Longhurst, W. R., Cox, C. D., Gibson, B. T., Cook, G. E., Strauss, A. M., Wilbur, I. C., & Osborne, B. E.	2017	Development of friction stir welding technologies for in-space manufacturing	Experimental tests were conducted according to a four-parameter five level central composite design.	A feed-forward back propagation ANN with a single hidden layer comprising 20 neurons was employed to simulate the ultimate tensile strength (UTS) of the joints.
21.	ishra, R. S., & Ma, Z. Y.	2005	Friction stir welding and processing	The neural network was trained using the data obtained from the experimental work. A comparison between the experimental and simulated data showed that the ANN model reliably predicted the UTS of dissimilar aluminum alloy friction stir-welded joints. The models developed were capable of predicting values with less than 5 % error.	Furthermore, the effect of different process parameters on the tensile behavior of dissimilar joints was also investigated and reported upon.

22.	Muthu, M. Felix Xavier, and V. Jayabalan.	2016	"Effect of pin profile and process parameters on microstructure and mechanical properties of friction stir welded Al–Cu joints."	Aluminium alloy 5083 is one of the prevalent materials for the construction of numerous structures under varied industries.	It is known as one of the marine type alloys commonly used in structures that are exposed harsh on-and off sea conditions.
23.	Nandan, R., Tarasankar DebRoy, and H. K. D. H. Bhadeshia.	2008	"Recent advances in friction-stir welding– process, weldment structure and properties."	The study is aimed at providing a comparative review on friction stir welded AA5083 dissimilar joints with other aluminium (Al) alloys considering corrosion, compatibility and mechanical properties.	This research will discuss the friction stir welding procedure, discuss, mechanical properties and corrosion behaviour of FSW AA5083 with other alloys.
24.	Nourani, Mohamadreza, Abbas S. Milani, and Spiro Yannacopoulos.	2011	"Taguchi optimization of process parameters in friction stir welding of 6061 aluminum alloy: A review and case study."	Energy saving has become a priority for welding industry. This is due to the recent increase in energy demand and constraints in carbon emissions.	Increasing environmental demands from governmental and customers strain the importance of reducing the environmental pollution while welding.
25.	Palanivel, R., Mathews, P. K., Murugan, N., & Dinaharan, I.	2012	Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys.	Friction stir welding (FSW) is considered to be the most significant development in metal joining and is a "green" technology due to its energy efficiency, environment friendliness, and versatility.	As compared to the conventional welding methods, FSW consumes considerably less energy.
26.	Palanivel, R., et al.	2014	"Mechanical and metallurgical properties of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys."	No shield gas or flux is used, thereby making the process environmentally friendly.	No harmful gases are produced in FSW. Harmful gases adversely affect the surroundings.

27.	Palanivel, R., P. Koshy Mathews, and N. Murugan.	2011	"Development of mathematical model to predict the mechanical properties of friction stir welded AA6351 aluminum alloy."	This creates health problems to persons carrying out welding and people living in nearby areas.	Hence, there is a need to develop and use green welding techniques.
28.	Pan, W., Li, D., Tartakovsky, A. M., Ahzi, S., Khraisheh, M., & Khaleel, M.	2013	A new smoothed particle hydrodynamics non-Newtonian model for friction stir welding: Process modeling and simulation of microstructure evolution in a magnesium alloy	The microstructure and mechanical characterization of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys were studied.	Three different welding speeds (36, 63 and 90 mm/min) were used to weld the dissimilar alloys.
29.	Park, S. K., Hong, S. T., Park, J. H., Park, K. Y., Kwon, Y. J., & Son, H. J.	2010	Effect of material locations on properties of friction stir welding joints of dissimilar aluminium alloys	The effect of welding speed on mechanical and metallurgical properties was analyzed.	It is found that the welding speed of 63 mm/min produces better mechanical and metallurgical properties than other welding speeds.
30.	Pashazadeh, Hamed, Jamal Teimournezhad, and Abolfazl Masoumi.	2017	"Experimental investigation on material flow and mechanical properties in friction stir welding of copper sheets."	The weld zone is composed of three kinds of microstructures, namely unmixed region, mechanically mixed region and mixed flow region.	The fracture mode was observed to be a ductile fibrous fracture.
31.	Periyasamy, P., Mohan, B., Balasubramanian, V., Rajakumar, S., & Venugopal, S.	2013	Multi-objective optimization of friction stir welding parameters using desirability approach to join Al/SiCp metal matrix composites	The combination features like low cost and low weight with moderate quality are the present significant requirement.	All these features are well satisfied by different Aluminium (Al) alloy combinations, so the utilizations of Al alloys are growing day-by-day.

32.	Prakash, P., Jha, S. K., & Lal, S. P.	2019	Numerical investigation of stirred zone shape and its effect on mechanical properties in friction stir welding process.	These alloys are promptly replaceable steels in numerous applications since the resistance of corrosion characteristic is one more attractive feature apart from other characteristics like low weight and low cost.	The welding of Al and its various alloy combinations with customary combination welding methods regularly delivers a weld with various defects, for example, slag inclusions, voids, porosity.
33.	Rajakumar, S., Muralidharan, C., & Balasubramanian, V.	2011	Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints	This process is developed and patented by TWI, The Welding Institute, UK.	Because of these imperfections, the quality of the weld joint reduces drastically. Friction Stir Welding (FSW) is a recently developed process for joining different materials
34.	Rohilla, P., & Kumar, N.	2013	Experimental investigation of tool geometry on mechanical properties of friction stir welding of AA6061	These process procedures take place below the melting point of the material to be welded.	Solid-state nature of this procedure overcomes many welding imperfections which generally happen during the conventional type of fusion welding combinations.
35.	Sakthivel, T., Sengar, G. S., & Mukhopadhyay, J.	2009	Effect of welding speed on microstructure and mechanical properties of friction-stir-welded aluminum	Joining of a dissimilar Al alloy joints of AA6351 with AA5083 is broadly valuable in aviation and shipbuilding.	Henceforth FSW produces a sensibly high-quality weld joint with the non-appearance of melt related imperfections.
36.	Sandeep, B. S., & Kum, A. P.	2017	Hardness And Micros Of Friction Stir We.	Particularly it is extremely valuable in marine-related industries due to the characteristic of alloy AA5083 which is corrosion resistant in seawater.	In this work, a trial of experiments has been done to improve the quality of the weld joint by adding Copper and Zinc materials in coating form to AA6351 and AA5083 alloys.
37.	Sarsılmaz, F., & Çaydaş, U.	2009	Statistical analysis on mechanical properties of friction-stir-welded AA 1050/AA 5083 couples	These coated 5 mm thick dissimilar Al plates are friction stir (FS) welded by utilizing the Taguchi technique with three variables factors and three levels.	Friction stir welding is a method that is normally used for aluminum alloys and is suitable for alloys which can be sensitive to heating during the welding manner.

38.	Sato, Y. S., Park, S. H. C., Michiuchi, M., & Kokawa, H.	2004	Constitutional liquation during dissimilar friction stir welding of Al and Mg alloys	This mission used reaction floor technique to optimize manner parameters for friction stir welding of numerous aluminum alloys (Al 6061 and Al 5052).	The effect of procedure parameters like rotational velocity, traverse velocity, and tilt angle on tensile energy and hardness has been studied.
39.	Sattari, S., Bisadi, H., & Sajed, M.	2012	Mechanical properties and temperature distributions of thin friction stir welded sheets of AA5083	The usage of layout professional software program, distinct aluminum plates have been welded by various parameters along with rotational pace, welding pace, and tilt perspective primarily based on RSM.	So as to improve productivity and weld excellent, optimized welding situations for max tensile strength and hardness have been predicted.
40.	Sayer, S. A. M. İ., Ceyhun, V. U. R. A. L., & Tezcan, O.	2008	The influence of friction stir welding parameters on the mechanical properties and low cycle fatigue in AA 6063 (AlMgSi0.5) alloy	Joint energy is also exact at better tensile strength at 1100 rpm, 1–1.50 tool tilt attitude, and a minimum feed price of 28–30 mm/min.	The effects show that increasing the fee of RPM, feed fee, and device tilt attitude increases ultimate tensile electricity up to a certain point, after which it begins to lower.
41.	Sayer, S. A. M. İ., Yeni, C., & Ertugrul, O.	2011	Comparison of mechanical and microstructural behaviors of tungsten inert gas welded and friction stir welded dissimilar aluminum alloys AA 2014 and AA 5083	In this work, optimization of the parameters of Friction Stir Welding (FSW) in unlike alloys using Taguchi-based Grey relational analysis was evaluated for aluminum alloys AA5083 and AA6061 under different parameters like rotational speed, feed and force with three levels each on tensile strength, elongation and hardness.	The grey relational grade is observed which correlates betwixt the parameters of friction stir welding and the answers to the optimum conditions found by the grey relational analysis.
42.	Shercliff, H. R., Russell, M. J., Taylor, A., & Dickerson, T. L.	2005	Microstructural modelling in friction stir welding of 2000 series aluminium alloys.	Taguchi related experiments were performed using L <sub>9</sub> Orthogonal Array.	Rotation Speed is the most influential parameter for determining the high standard of the welded joints that were fall behind by Force and Feed using Variance Analysis (ANOVA) and validated by confirmatory experiments.
43.	Shukla, Ratnesh K., and Pravin K. Shah.	2010	"Comparative study of friction stir welding and	Friction stir welding (FSW) is one among solid-state welding processes that can be	Several high coupled physical phenomena have addressed FSW as an extremely complex process.

			tungsten inert gas welding process."	employed for producing joints between dissimilar combinations with more ease than that of fusion welding processes.	
44.	Sidhu, M. S., & Chatha, S. S.	2012	Friction stir welding– process and its variables: A review	. It is around three decades of invention, optimization of the parameters have been carried out even today by many researchers all over the world to obtain sound joints.	This article focuses mainly on the research developments in the dissimilar FSW (DFSW), with the factors that are involved in joint fabrication between dissimilar materials.
45.	Singh, G., Singh, K., & Singh, J.	2011	Effect of process parameters on microstructure and mechanical properties in friction stir welding of aluminum alloy	rom the literature, it is found that the most influential factors in deciding the quality of the joints are pin profile, shoulder shape, welding speed and tool rotational speed.	In addition, all other parameters will provide incremental support to it.
46.	Sivashanmugam, M., Kumar, T., Ravikumar, S., Rao, V. S., & Muruganandam, D.	2010	A review on friction stir welding for aluminium alloys	The study on microstructure in different zones and the mechanical properties of welded specimens are elaborated from the available literature.	Special attention is given to the reinforcement of micro- and nano- sized solid particles in the DFSW process.
47.	Su, J. Q., Nelson, T. W., Mishra, R., & Mahoney, M.	2003	Microstructural investigation of friction stir welded 7050-T651 aluminium	Aluminium and its alloys are lightweight, corrosion-resistant, affordable and high-strength material and find wide applications in shipbuilding, automotive, constructions, aerospace and other industrial sectors.	In applications like aerospace, marine and automotive industries, there is a need to join components made of different aluminium alloys, viz. AA6061 and AA5083.
48.	Sundaram, N. S., & Murugan, N.	2010	Tensile behavior of dissimilar friction stir welded joints of aluminium alloys	In this study friction stir welding (FSW) is used to join dissimilar plates made of AA6061-T6 and AA5083-O.	The effect of varying tool pin profile, tool rotation speed, tool feed rate and tilt angle of the tool has been investigated on the tensile strength and percentage elongation of the welded joints.

49.	Svensson, L. E., Karlsson, L., Larsson, H., Karlsson, B., Fazzini, M., & Karlsson, J.	2000	Microstructure and mechanical properties of friction stir welded aluminium alloys with special reference to AA 5083 and AA 6082	Box-Behkan design, with four input parameters and three levels of each parameter has been employed to decide the set of experimental runs.	The regression models have been developed to investigate the influence of welding variables on the tensile strength and elongation of the welded joint.
50.	Thube, R. S.	2014	Effect of tool pin profile and welding parameters on friction stir processing zone, tensile properties and micro-hardness of AA5083 joints produced by friction stir welding	It is revealed that with the increase in welding parameters like tool rpm, tool feed rate and tilt angle of the tool, both the mechanical properties increase, reach a maximum level, followed by a decrease with further increase in the value of parameters.	Amongst different types of tool pin profiles used, the FSW tool having straight cylindrical (SC) pin profile is found to yield the maximum strength and elongation of the welded joint for different combinations of welding parameters.
51.	Vladvoj Očenášek, et. al.,	2005	"Microstructure and properties of friction stir welded aluminum alloys"	Multiple response optimization indicates that the maximum UTS (135.83 MPa) and TE (4.35%) are obtained for the welded joint fabricated using FSW tool having SC pin profile, tilted at 1.11° and operating at tool speed and feed rate of 1568 rpm and 39.53 mm/min., respectively.	Friction stir welding (FSW) has enjoyed great success in joining aluminum alloys. As lightweight structures are designed in higher numbers, it is only natural that FSW is being explored to join dissimilar aluminum alloys.
52.	Xu, W., Liu, J., Zhu, H., & Fu, L.	2013	Influence of welding parameters and tool pin profile on microstructure and mechanical properties along the thickness in a friction stir welded aluminum alloy	he use of different aluminum alloy combinations in applications offers the combined benefit of cost and performance in the same component.	This review focuses on the application of FSW in dissimilar aluminum alloy combinations in order to disseminate research this topic.

53.	Waldron, Douglas J., and Robert Scott Forrest.	2002	"Friction stir welding apparatus and method.	The review details published works on FSWed dissimilar aluminum alloys. The detailed summary of literature lists welding parameters for the different aluminum alloy combinations.	Furthermore, auxiliary welding parameters such as positioning of the alloy, tool rotation speed, welding speed and tool geometry are discussed.
54.	Waldron, D. J., & Pettit, R. G.	2001	U.S. Patent No. 6,168,067	Microstructural features together with joint mechanical properties, like hardness and tensile strength measurements, are presented.	. At the end, new directions for the joining of dissimilar aluminum alloy combinations should guide further research to extend as well as to improve the process, which is expected to raise further interest on the topic.
55.	Wan, L., Huang, Y., Lv, Z., Lv, S., & Feng, J.	2014	Effect of self-support friction stir welding on microstructure and microhardness of 6082-T6 aluminum alloy joint	This research focuses on the development of a mathematical model of arithmetic mean heights of surface (Sa) in friction stir welded AA2017 aluminium alloy using Taguchi L <sub>8</sub> orthogonal design of experiments and response surface methodology.	Machining variables such as rotation speed, traverse speed and tool shoulder diameter are considered in building the model.
56.	Wan, L., Huang, Y., Lv, Z., Lv, S., & Feng, J.	2014	Effect of self-support friction stir welding on microstructure and microhardness of 6082-T6 aluminum alloy joint	3D surface topographies are used to characterize the surface roughness. The analysis of variance results showed that all the welding parameters are statistically significant at 95 % confidence level.	According to Main Factor Plots, an increase in the rotation speed decreases the surface roughness while any increase in the traverse speed or the tool diameter shoulder increases it.
57.	Wang, D., Xiao, B. L., Ni, D. R., & Ma, Z. Y.	2014	Friction stir welding of discontinuously reinforced aluminum matrix composites: a review	Friction stir welding (FSW) has an advanced technique in solid-state conditions that joins from different materials compared to the fusion welding process and is eco-friendly.	This significant advancement involves aluminium (Al) alloys which facilitate the FSW of distinguished flow patterns in the weld zone.
58.	Yatapu, Y. R., Reddy, B. R., Ramaraju, R. V., Ku, M. F. B. C., & Ibrahim, A. B.	2016	Prediction of Temperatures during Friction Stir Welding of AA6061 Aluminium Alloy using Hyperworks	Technically, heat energy and stirred material resulted in softening areas, affecting joint efficiency, mechanical properties, and metallurgical characterisation.	This research has concerns comprehensively covering and summarising the development and application of the topic in different aspects of the performance and quality of the FSW welded joint.

59.	Zadpoor, A. A., Sinke, J., Benedictus, R., & Pieters, R.	2008	Mechanical properties and microstructure of friction stir welded tailor-made blanks	The proper tools can create sufficient heat under the shoulder for excellent performance to deal with the welding parameter. All these tools have their literature and journal, which extensive discussion.	Furthermore, alloy positioning, defect formation, rotational speed and transverse feed are essential analytical tools for FSW to control the significant weld quality.
60.	Zadpoor, A. A., Sinke, J., & Benedictus, R.	2009	Finite element modeling and failure prediction of friction stir welded blanks	Furthermore, the mechanical properties associated with microstructural evolution highly dependent on welding technique have remarkably contributed to product development.	Finally, a previous study has shown the interest in the topic to enhance the knowledge for further investigation with emerging technology for future recommendations in the FSW discipline.

### 7.0 Heat generation and material flow

Heat production is connected to material flow and frictional/contact conditions, and vice versa; the processes of FSW are closely interrelated physical phenomena. [11,19] There are two sources of heat production: friction and bulk plasticity.[10,14,46] Diffusion and convection from moving material are both factors in heat transmission. Tool geometry, process parameters, and the material being welded all play a role in the intricate material flow that occurs during FSW.4 Many crucial aspects of FSW are intertwined with the movement of materials around the welding instrument.[26] Thermomechanical processing conditions during FSW can only be determined with precision if the flow can be understood.

Several intriguing aspects of material flow in FSW and the joining process have recently been illuminated by experimental and computational investigations.[5] Material flow pattern in FSW has been visualised using a variety of methods, including tracer technique using markers, welding of dissimilar alloys/metals,[46], and numerical simulations[11,56]. Marker insert technology, such as Cu foil pieces, was used to observe material flow behaviour during FSW of 6082Al-T6 alloy [32]. Murr and colleagues[31] looked at the feasibility of visualising solid-state flow in FSW for alloys ranging from 2024Al to 6061Al.

Traditional metallography, X-ray, and computerised tomography (CT) were all used in [51] to report on the material flow. Micrographs were utilised in conjunction with 2D and 3D CT scans to visualise the flow field. Non-Newtonian viscosity was determined for metal flow [18] by taking temperature and strain rate dependent flow stress into account. The material movement during the FSP was studied by [28] by looking at how the fullerence spread. Small spheres of tungsten tracer were used in X-ray radiography to provide three-dimensional images of the material flow, as described in [39]. Several research have been conducted to predict the material flow during FSW/FSP, complementing experimental techniques.[11,20,34] The distribution of the three most essential field variables—temperature, strain, and strain rate—have been modelled using a three-dimensional finite element method (FEM).[64] All of these investigations were conducted to learn more about the fundamental physics of FSW/FSP material movement. The key parameters that govern the evolution of microstructures during FSW/FSP are strain, strain rate, temperature, and their distribution. The mechanical characteristics and hence the product's performances are naturally impacted by these microstructural evolutions.10 Examining the connections between microstructural change and variables like strain, strain rate, and temperature seems like a fascinating and difficult research project. Unfortunately, because to the complex dynamic changes occurring in the material during FSW/FSP, it is exceedingly challenging to quantify the strain, strain rate, and temperature of the material quantitatively.

### 8.0 CONCLUSION

In this study, we change a number of parameters in order to get optimal results while using the friction stir welding technique on AA6351-T6 aluminium alloy. Possible lessons learned from this dialogue include the following:

Two distinct second-order empirical formulations based on process variables including tool plunge, rotating speed, and welding speed allow for UTS and UE predictions to be produced. The aforementioned metamodels were formalised using a number of statistical methods. These methods include: design of experiments, response surface,

analysis of variance, and regression analysis. An additional set of experimental investigations was used to validate the proposed mathematical models.

We improved the welded joint's UTS and UE by using a response surface method and three different metaheuristic methods to find the ideal FSW settings. In order to improve the friction stir welded joint's mechanical properties in AA6351-T6 aluminium alloy, the tested meta-heuristic algorithms and the robustness of the recommended metamodels were used to determine the ideal process parameters in terms of TP and v.

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