Application of Taguchi, Taguchi-Pareto and Taguchi-ABC Methods for the Selection and Optimization Problem in Friction Stir Welding Process Parameters of AA6062-T6 Alloy

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Abstract. *In sharing friction stir welding input resources before working, several conflicting demands are made by welders in the system. However, there is no mechanism to distinguish the importance of the respective parameters. This article proposes two novel methods of Taguchi-Pareto and Taguchi-ABC, to concurrently optimize and prioritize process parameters while understanding the importance of parameters in the welding decision process. The input parameters are tool tilt angle, tool rotational speed and welding speed while the output is the tensile strength of the AA6063-T6 alloy. The Khan's specimen data, obtained from the literature is tensile specimens with a dimension of 350mm x 75mm employed in a Batliboi 10 HP milling machine operating at 2000 rpm during the friction stir welding experiments. The joints were made of EN31 die steel. The factor-level table is first formed for the response table development. Furthermore, the Pareto and ABC classification schemes were used to define the cut off points to distinguish the essential experimental trials from the rest. The tensile strength of the friction stirs welded joints of AA6062-T6 alloy are principally affected by the parameters of welding speed, tool tilt angle and rotational speed to yield the most favourable tensile strength. Taguchi Pareto showed the tool rotational speed (1400 rpm), tool tilt angle (2.5°) and welding speed (80 mm/min) as the 1st, 2nd and 3rd parameters respectively. Taguchi's ABC method (Part A) showed a tie between the tool tilt angle (2.5°) and welding speed (80mm/min) while the tool rotational speed (700 rpm) was the third. It is preferable to adopt the Taguchi-ABC method, Part A as the most suitable method with the least energy requirements. Previous literature has explored the Taguchi method but the present research introduces the prioritization idea into the methods to help process engineers in planning welding activities.*

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1. Introduction

Over the past several years, optimization evaluation using the Taguchi method has matured in the friction stirs welding research where the metal and alloy joining process prevails [1],[2],[3], [4], [5], [6], [7], [8]. Unfortunately, in sharing friction stir welding resources before the welding process, several conflicting demands are made by operators and other workers in the system [6], [9],[10],[11]. This puts the process engineers at risk of underestimating or overestimating the actual resource needs at parametric levels and a gross inadequacy in friction stir welding process effectiveness is expected. By introducing the Pareto analysis into the Taguchi method to establish the original basis of the resource sharing problem, the friction stir welding process will be capable of resolving the sharing problem with the uppermost procedure first. Also, using the ABC classification in the Taguchi method it is possible in friction stir welding to situate tighter control on pressing welding parameters. In sum, by examining both Taguchi-Pareto and Taguchi-ABC methods, an advanced and more realistic picture of the solution is obtained. Now, this concern is further convincing than previously since there is a very inspiring accuracy predictable from commencing the incorporation of Pareto and ABC analysis in the Taguchi scheme.

The principal objective of this paper is to examine the best possible parameters during the process activation of friction stir welding while manufacturing the AA6063-T6 Aluminum alloy on EN31 die steel welded joints using the unique dimension of 350 mm x 75 mm plates. Although several scholars have reported on the AA6000 series, no reports were found about the Taguchi-Pareto and Taguchi-ABC methods applied to the AA6063-T6 alloy. Examples are AA6082-T6 butt joints [1], AA6082/SiC/10p composites [12], aluminium alloy 6063-T6 [2], [13], aluminium alloy 6082-T6 [11], [14], AA6351 alloy [15], AA6062 T6 alloy [16], A16061-T651 [17] and AA6105 alloy [8].

Besides, to overpass the research opening stated earlier, this article examines the best possible parameters during the process activation of friction stir welding of

AA6063-T6 alloy [16], transforming the parameters into three quantitative methods and developing two principal kinds of concurrent optimization and prioritization schemes using the Taguchi-Pareto and Taguchi-ABC methods. The chief novelties of this article are as follows. Firstly, two efficient quantitative methods (i.e. Taguchi-Pareto and Taguchi-ABC) are established for the friction stir welding process of AA6063-T6 alloy. Secondly, two multi-phase methods are developed for the optimization and prioritization of parameters. These introduce an original basis for resource sharing by establishing the high priority parameters in friction stir welding (i.e. Taguchi-Pareto method) and the compelling need for tighter and regular control in high preference parameters (i.e. Taguchi-ABC method). Thirdly, the AA6063-T6 alloy is proved as a case to ascertain the effectiveness and superiority of the two optimization methods of Taguchi-Pareto and Taguchi-ABC over the Taguchi method.

Furthermore, this article develops the Taguchi-Pareto and Taguchi-ABC methods from the following advantages and disadvantages perspectives. Firstly, both methods exploit the full prospect of influencing the highest priority parameters and subsequently lower the operator's stress while welding and productivity enhancement are guaranteed. Secondly, while the welder is conducting multiple tasks, for instance, producing multi-featured components and incorporating a minimum quantity lubrication process for cooling, possible errors are checked. Thirdly, it provides a source of motivation for the welder as targets are met with accuracy. However, matching the Taguchi-Pareto against the failure modes effect analysis (FMEA) method exhibits a little weakness as follows. The FMEA method is known to contain three components in determining the risk priority number such as occurrence, severity and detection. But the only occurrence is contained in the Taguchi-Pareto method while elements of severity and detection are missing, which may inspire further studies on the present work. For the Taguchi-ABC method, the ABC classification scheme has been known to exhibit a conflict with the traditional accounting system which operates in a welding company.

Nevertheless, this study is designed from the quantitative perspective [9],[10],[12] aiming to understand the classification of friction stir welding process parameters according to an importance scale. Although various optimization methods in the friction stir welding research domain exist, such as simulated annealing, central composite design and Taguchi methods, the choice of the Taguchi, Taguchi Pareto and Taguchi ABC methods were made to examine the categorization of the parameters during the processing of the AA6063-T6 alloy [16]. The predefined factors, namely the tool tilt angle, welding speed and tool rotational speed were chosen while the output was streamlined to the tensile strength of the welded joints for the AA6063-T6 alloy [2], [16], [18], [19], [20], [21], [22]. In conjunction with the factors, the levels are defined and the orthogonal configuration, L27, is specified. This gives room to develop the optimal parametric setting of the process after the specification of the signal to noise criterion. The Taguchi method was first developed, and then the Pareto 80-20 rule and the ABC classification scheme were installed on the Taguchi scheme to translate into two concurrent optimization and prioritization mechanisms of the Taguchi-Pareto and Taguchi-ABC methods. By noting that the principal purpose of the orthogonal configuration is to provide information on the spread of the factors at the various levels in the formation of the signal to noise ratios, a properly designed orthogonal array was obtained from the Minitab software. Moreover, the average signal to noise ratios was computed to define the optimal parametric settings, ranks and delta values of the various parameters. This aid in finding out the relative positioning of the friction stirs welding parameters.

2. Literature Review

2.1 Literature Classifications

In this study, a literature survey was conducted to establish the research gap according to optimization in the friction welding process. Consequently, the following main divisions of the literature were established: (i) Studies associated with optimization of process parameters; (ii) Research related to the influence of friction stir welding process parameters; (iii) Studies linked to the mechanical properties of friction stir welding process; (iv) Research related to heat generated during the friction stir welding process; and (v) Optimization-based techniques applied to friction stir welding process. Hence, the review in this section is conducted accordingly.

(i) Studies associated with optimization of process parameters

In the research by Pradeep et al. [18] on an analysis to optimize the process parameter of friction stir welded low alloy steel plates, the tool tilt angle has the most remarkable effect of 63.83% among the parameters while travel feed has 32.83% and tool rotational speed has 2.81%. The tensile strength was also found to be improved. Ganapathy et al. [2] studied the process parameters optimization of friction stir welding in AA6063-T6 where the Taguchi method was used. The total rotational speed, welding speed and axial force were found as 1100rpm, 60mm/min and 12.5kN. In this research axial force played a very vital role in the total response carried out.

(ii) Research related to the influence of friction stir welding process parameters

Singh and Sidhu [23], tested lightweight alloys using the friction stir welding process in the fusion of magnesium alloy. They reported a positive influence of friction stir welding on hardness, welded zone's corrosion behaviour, tensile strength and toughness. Also, Prasad et al. [24] analyzed the influence of the geometry of the tool's shoulder on the AA2014-T6's microstructure and mechanical properties and reported that the concave shoulder has a radius of R.2.5 yielded superior grain from the standpoint of microstructural property evaluation. Besides**,** Raja et al. [19] studied the effect of rotational speed and welding speed on friction stir welding of AA1100 aluminium alloy. It was found that the hardness of the base metal was higher in the microhardness outcome of the different welds. Das and Toppo [25] stated that an increase in tool rotational speed increases the strength, and mechanical properties of AA6101-T6 and AA6351-T6 in friction stir welding.

Chandrashekar et al. [20] found the pin profile to have a high influence on the mechanical proportion and an increase in the motion conduct of the tensile strength more than the tool rotational speed and the transverse speed. In a study, Prabha et al. [21] showed that at the tool rotational speed of 1120rpm a quality weld was obtained and the mechanical properties and tensile strength of micro pattern were excellent compared to other rpm. Singh and Singh [8] concluded that for better tensile strength, quality weld and better grain structure for AA6105 joint weld, the tool rotational speed was at 1540rpm with a square pin profile.

Abd El-Hayez and El-Megharbel [26] discovered that for optimum strength, the welding speed and tool rotational speed has more effect on the weld joint of two different alloys AA2024-T365 AND AA5083-HIII and so does the square pin profile when compared with a prism and stepped profile**.** Mohamed and Manurung [5] noted that as the traverse speed and tool rotational speed rise the ultimate tensile strength, fatigue life cycle (FLC) and hardness get better. For a rise in fatigue, the life cycle resulted in a rise in the hardness of the joint weld.

(iii) Studies linked to the mechanical, corrosion properties and microstructural behaviour of friction stir welding process

Arab and Zemri [1] worked on the AA6082-T6 material and reported that the tool rotational speed exerted substantial influence at 1400rpm but the welding speed was 160mm/min. The authors further elaborated that tool rotational speed showed superior influence on the weld compared with the welding speed when studying the hardness property of AA6082-T6 material. Also, Goyal and Garg [22] worked on AA5086H 32 friction stir welded material and finalized that the least rate of corrosion was 3.2mg/cm^3 while 1296rpm, 79.4mm/min, 14, 9mm, 47.4HRC, 2.38° were obtained for the tool rotational speed, welding speed, tool shoulder diameter, tool hardness and tool tilt angle, respectively. Devanathan et al. [27] studied two dissimilar aluminium alloys A16061 and A16063 to find out that when spindle speed is varied while other parameters were kept fixed, from their experimental results that at a certain speed an optimum quality weld was obtained that gives a quality tensile strength and at the tool rotational speed any increase or decrease of it gave a poor weld. Hao et al. [28] reported that as the tool rotational speed decreases the yield strength and ultimate tensile strength increase and as the welding speed raises the yield strength and ultimate tensile strength rise also. Elatharasan and Kumar [29] examined the AA7075 aluminium alloy and discovered that the tool rotational speed of 800rpm and welding speed of 20mm/min has a greater influence on the tensile strength of the weld and also gave a fine grain to the microstructure.

Kumar et al. [30] examined the AA7075 alloy and reported that peak ageing and RRA gave the weld good hardness. Sadeesh et al. [31] considered welding two different aluminium alloys AA2024 and AA6061 and showed that TRS of 710rpm, welding speed of 28mm/min and D/d ratio of 3, for the cylindrical pin gave a quality joint and for the mechanical behaviour the TRS and 1000rpm, WS of 40mm/min and square pin of 6mm. for optimum weld the cylindrical threaded and square pin tool profile gave the best weld. Singh et al. [13] declared that friction stir welding gave a higher quality tensile strength than TIG welding.

(iv) Research related to heat generated during the friction stir welding process

Leon et al. [32] found that heat generated during friction stir welding affects the shoulder cone angle directly, likewise the pin taper angle, also the shape of the tool does not have any influence on the heat generated.

(v) Optimization-based techniques applied to friction stir welding process

Gopi and Nanonmani [14] studied the axial force exerted by conventional milling (CM) and that by friction stir welding. They declared that for an optimum result, the shoulder penetration of 0.15mm, spindle speed of 1100rpm, hexagonal pin profile of 3.2mm/s and shoulder taper of 10° is recommended. The most influential factor is spindle speed and the list factor is shoulder profile. Mohamed et al. [5] concluded that the welding speed has the most influential effect on the tensile strength and good welding joint with 71.8% while tool rotational speed has 28.2%. Raweni et al. [7] used the Taguchi method and discovered significant parameters during friction stir welding. The result shows that welding speed has the most significant influence doing the process while tool tilt angle followed, the tool rotational speed has the least effect.

Bhushan ad Sharma [12] worked on the welded joint of AA6082/SiC/10p composite. They declared that the UTS of the optimized process was 24.5% better than H's non-optimized process. Kumar et al. [3] optimized the input parameters affecting the mechanical properties of the welding joint and concluded that welding speed was the most significant variable. Kumar et al. [33] deployed the Taguchi method and ANOVA technique on the AA5083 alloy to reveal superior welded joints. They reported that a substantial effect of the tool to rotational speed was felt on the weld's quality and then the welding speed but minimum effect on the weld's quality was experienced by the tool tilt angle. Thilagham and Muthukumaran [11] declared that for maximum joint strength, the tool rotational speed and welding speed have a great influence on the mechanical and metallurgical properties as an increase in tool rotational speed and welding speed gave a rise to quality weld and better grains structure. Rathinasurigan and Kumar [34] used response surface methodology (RSM) and Grey relation analysis (GRA) to optimize submerged friction stir welding (SFSW) parameters of aluminium alloy. They found out that tool rotational speed was 1200rpm, welding speed of 30mm/min and water head of 10mm gave the best quality joint. The ANOVA analysis shows that tool rotational speed and welding speed were the most influential factors in GRG (grey rotational grade).

2.2 Observation Noted from the Literature Review

In this study, close observation of the literature has been made along the following lines of thought:

1. The influence of tool rotational speed, traverse feed, tool tilt angle and welding speed on the quality of weld in friction stir welding have been studied in several papers. However, the tool rotational speed (42.85% counts) followed the welding speed (40.82% counts) then the tool tilt angle 14.25% counts) and the transverse feed (2.05% counts).
2. Some techniques have been used in friction stir welding optimization processes, which are single or coupled methods. The list of these techniques includes Taguchi (56.25% counts), the ANOVA (25% counts), response surface methodology and grey relational analysis. Notwithstanding, the use of the Taguchi method was limited to the classical version but Taguchi Pareto and Taguchi ABC methods have not been used in the friction stir welding domain.
3. The tilt angle is often common to range between 1° and 3° for the friction stir welding operation
4. The pin structure (profile) of the tool has largely varied among three groups: hexagonal pin profile, a threaded pin and cylindrical profiles
5. The economic dimension of friction stir welding during process optimization has been completely ignored by researchers.
6. Sustainable friction stir welding is a promising issue in friction stir welding process optimization but yet ignored in research to date.
7. The following material categories have been studied with important documentation concerning their properties in the literature and additional studies on them are expected in the future. These are RDE-40 aluminium alloy [4], AA1100 [19]; AA2014 [6],[10],[24]; AA5083 [7],[21],[33]; AA5086 [22]; AA6061 [10]; AA6062 [16]; AA6063 [2],[13] AA6082 [11], [14]; AA6105 [8]; AA6351 [15]; AA7075 [3], [29], [30].
8. Various aspects of friction stir welding have been studied, including shoulder pin cone angles [32]; tool shoulder geometry [24]; tool rotational speed [21] and tool shape [23]

3. Methods

In this section, the optimization of the friction stir welding process parameters using the Taguchi techniques is exploited from a methodological perspective [35]. However, the fundamental definitions and briefs concerning these parameters are essential to understanding the structure of the Taguchi schemes and how it fits into the FSW domain. In this context, ideas concerning the Tool Tilt Angle (TTA), Tool Rotational Speed (TRS) and welding speed are discussed. First, the tool tilt angle indicates the degree of variance of the tool from the vertical position, often ranging from 0° to 3°. In a situation where the tool appears perpendicular to the AA6062-T6 alloy, a zero value for the tilt is assumed. In friction stir welding, the TTA is crucial in influencing the eventual joint quality. The TTA has also been found to significantly control material flow while welding the AA6062-T6 alloy. This means that it has an association with heat generation during friction stir welding (FSW). Furthermore, it is known that the TTA determines the microstructure and the welded joint properties using the FSW process. Nest, the tool rotational speed is the rate at which the tool revolves over the AA6062-T6 alloy. However, as friction serves as the source of heat generation for the FSW, the TRS influences the process' ultimate temperature, implying that a positive variation in the speed triggers a positive temperature change. In some experiments, for an average speed of 425 rpm, a temperature reading of roughly 910° has been reported in the literature. Furthermore, the welding speed is the speed for the parts which are rotated when the welding torch is in action. Often, it is described as the speed related to the tungsten surface. While it is conventional to use slow speed in parts having a huge thickness, it is also customary to utilize faster speed for parts exhibiting thinner walls

3.1 Taguchi Method

The signal to noise ratio is the “mean to the square deviation”, Khan [16]. The signal to noise ratio is used in determining the effect of each parameter on the welding operation. Prominent among the SNR are the following types:

Smaller-the-better

$$SN = -10\log\frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (1)$$

Larger-the-better

$$SN = -10\log\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2} \quad (2)$$

Where

y is the response for the factor level, *n* is the number of responses in the factor level, ∑ is the summation and *i* is the iteration.

The smaller the better and larger the better signal to noise criteria are two popular drivers of the Taguchi method, producing the response table, delta values, rank and optimal parametric settings. However, they are different in some respects. The smaller the better is used when the specific output that emerges from the system is not desirable such as energy wastage during the friction stir welding process (Equation (1)). However, the larger the better signal to noise criterion is used when there is a need to maximize a particular output (Equation (2)). In the friction stir welding domain, outputs such as the surface finish of the welded joints are desirable and the larger the better criterion is appropriate for this. Furthermore, there is a slight variation in the equations representing them. While the y_i, which represents the input values of all the various parameters of the friction stir welding process is squared before further processing for the smaller the better criterion, the reciprocals of the squares are needed to progress to evaluating the larger the better criterion of the signal to noise ratios.

Besides, the computational procedure for applying the signal to noise ratios for the friction stir welding process is indicated in Fig. 1. For smaller the better, the first step is to find the square of each of the parameters. This is followed by finding the sum of the squares. Furthermore, multiply the sum obtained by the inverse of the number of parameters. Then obtain the logarithm of the result obtained in the previous step. This is followed by multiplying this value by -10 (Fig. 1). For the larger the better, it is first required to find the squares of each of the parameters. Then obtain the inverse of these squared values. Then find the sum of the inverse obtained. Furthermore, multiply the sum by the inverse of the number of parameters. Then find the logarithm of the values obtained in the previous step and multiply the values obtained in the previous step by -10 (Fig. 1). These details in Fig. 1 apply to all the three methods of Taguchi, Taguchi-Pareto and Taguchi-ABC. However, the signal to noise ratio analysis is done from the output perspective.

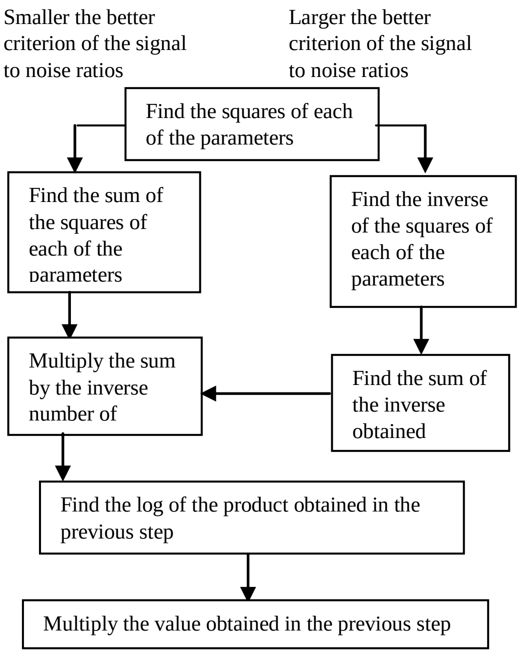

Fig. 1 Flowchart for the signal to noise ratio computation for the smaller the better criterion

3.2 Taguchi-Pareto Method

For the Taguchi-Pareto method [36], the following formula is used

$$\text{S/N} = -10\log_{10}(1/n\sum_{i=1}^{n} P_{80-20} y_i^2) \quad (3)$$

For this formula, y_i may be used to represent the smaller-the-better criterion, Equation (1). But to consider the larger the better criterion, th y_i^2 is is considered as a reciprocal, *n* shows the experimental counts. Also, the S/N (Equation (3) assesses the process using the $P_{\text{areto } 80-20}$ rule.

3.3 Taguchi-ABC method

By considering the Taguchi-ABC method [36], the following formula is used

$$\text{S/N} = -10\log_{10}(1/n(ABC)\sum_{i=1}^{n} y_i^2) \quad (4)$$

For this formula, y_i may be used to represent the smaller-the-better criterion, Equation (1). But to consider the larger the better criterion, the y_i^2 is considered as a reciprocal, n shows the experimental counts. Also, the S/N (Equation (3)) assesses the process using the ABC classification rule. Thus, to present a clear experimental method, an illustration of the experimental design is included in Fig. 2.

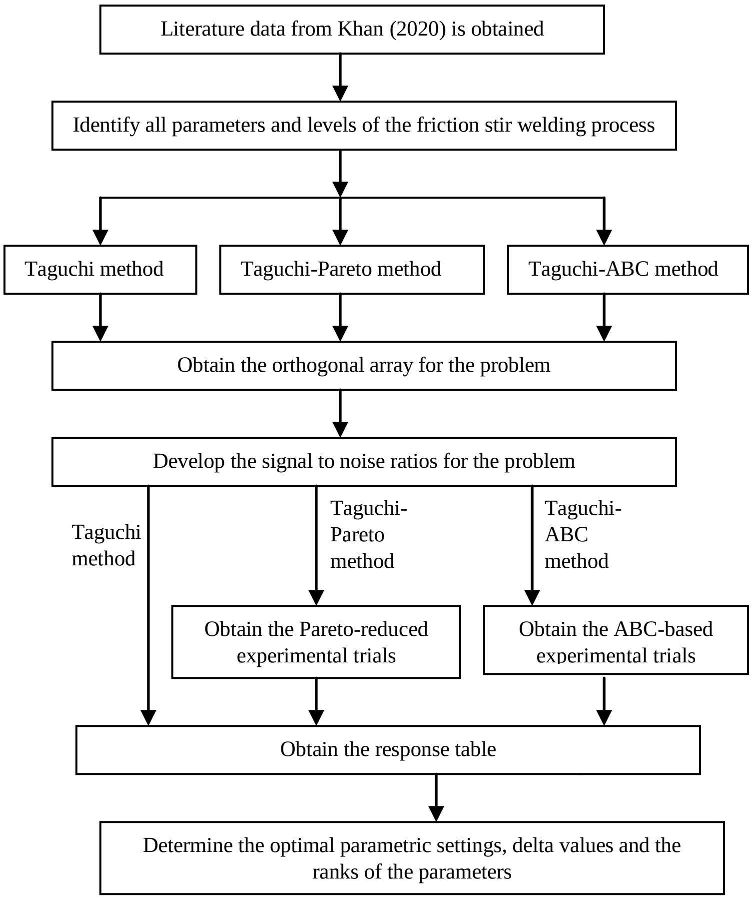

Fig. 2 An illustration of the experimental design for the friction stir welding of AA6063-T6 alloy

3.4 Procedures of Taguchi, Taguchi-Pareto and Taguchi-ABC methods

The Taguchi is a method used for the design of experiments. The first issue is to identify the factors and the levels. Then, the researcher makes use of the Minitab software as in the present case, to receive inputs from the configurations. The orthogonal array is for the combination of the factors and levels and this is called the formation of the design of experiments. In this context, the Taguchi methods crate a wide surface area for the experiments to take place. So, fundamentally, after the experiments have been designed, the researcher can conduct the experiments in several steps such that the study of the experiments can be achievable and in-depth. The Minitab software gives the researcher an orthogonal array after input of the number of factors and levels. The orthogonal array is a configuration of the factors in such a way that it makes different combinations for the user to experiment with. After this, the signal to noise ratios and computed and then the response table is prepared.

For the Taguchi-Pareto method, the first thing is to conduct the Taguchi method to obtain the orthogonal array. Then the Pareto analysis is implemented. The Pareto scheme is a computational method that helps to focus on the experimental sets for parameters that affects the results more. This set of parameters can be identified by their outputs. In Pareto analysis, as the researcher aims to maximize, the arrangement of the data can be made from the biggest to the smallest. Then the first 80% is obtained as the most relevant experimental sets for the parameters. However, if the researcher aims to minimize, the arrangement could be made from the smallest to the largest. But the smallest will be the most relevant in this care regarding the outputs. Then the first 80% can be taken to be the most relevant, which contains the choice behaviour being sought. Nonetheless, the Pareto scheme enhances the Taguchi method. The steps in conducting Taguchi-Pareto include the following. First, the output is sought out in a customs arrangement from the table containing the outputs and the set parameters. Then the cumulative addition of the output is pursued to identify the 80% mark so that the values that fall after the 80% can be eliminated.

The Taguchi-ABC method, in this case, is used for classifying the set of parameters in the case where the parameters are graded into C, which has percentages between 0 and 69%, B, which has values between 70% and 79% while A has values between 80% and 100%. This is also a way of classifying the parameters in terms of their relevance and importance.

3.5 Comparison among the Taguchi Methods

By employing the results obtained from the considered methods of Taguchi, Taguchi-Pareto and Taguchi-ABC, the comparison among these methods is discussed as follows to show the effectiveness of each method. The Taguchi method is effective because with few initial values there is a more expanded surface area to conduct the experiments. Taguchi method is also widely used in industries where the primary aim is to improve operations and minimize wastage and inaccuracies. The Taguchi-Pareto is an upgrade to Taguchi, capitalizing on the advantages, which are the strengths of the Taguchi method. It also introduces a more precise way of focusing on the parameters that have a real effect that is being sought after. The Taguchi-ABC method, simply while capitalizing on the advantages of the Taguchi method, helps to categorise the parameters. This is more like giving the user a more in-depth view of the parameters and their possible outputs.

4. Results and Discussion

4.1 Taguchi Method

In this section, computation analysis was introduced to determine the signal to noise ratios (SNRs). The effects of the operating parameters on the SNR are examined and discussed. These parameters are the tool tilt angle (TTA), tool rotational speed (TRS) and welding speed (WS). The Taguchi method is used to optimize the operation. The Taguchi is obtained by designing experiments as a means of investigating the effect of the various parameters, Khan [16]. These parameters and their levels are shown in Table 1. These parameters are the factors introduced into the Taguchi method to generate the L27 orthogonal array. The orthogonal array is generated by using the three factors with three levels aided by the Minitab 18version 2020, Table 2, and parameters are arranged with their levels. The array generated is used to compute the operating parameters accordingly. In this research, the larger the better will be used to determine which parameter has a greater effect on the welding process. Thus, in the computation of the signal to noise ratio, the y_i values are replaced with those of the tool tilt angle (TTA), tool rotational speed (TRS) and the welding speed (WS) based on the orthogonal array, Equation (2). The signal to noise ratio is calculated and tabulated as shown in Table 2. To simplify the computation, the Microsoft Excel software version 17 was used for analysis.

Level	TTA(°)	TRS(rpm)	WS(mm/min)
1	2.0	700	40
2	2.5	1000	80
3	3.0	1400	110

Table 1 Process parameter by Khan [16]

Exp.No.	A	B	C	TTA	TRS	WS	SNR	Exp.No.	A	B	C	TTA	TRS	WS	SNR
1	1	3	3	2	1400	110	61.7228	15	1	2	2	2	1000	80	65.2171
2	1	3	3	2	1400	110	61.7228	16	3	2	1	3	1000	40	65.2171
3	1	3	3	2	1400	110	67.7062	17	3	2	1	3	1000	40	65.2171
4	3	3	2	3	1400	80	67.7062	18	3	2	1	3	1000	40	65.2171
5	3	3	2	3	1400	80	65.2013	19	3	1	3	3	700	110	65.2171
6	3	3	2	3	1400	80	65.2013	20	3	1	3	3	700	110	65.2171
7	2	3	1	2.5	1400	40	65.2424	21	3	1	3	3	700	110	65.2171
8	2	3	1	2.5	1400	40	65.2424	22	2	1	2	2.5	700	80	65.2171
9	2	3	1	2.5	1400	40	61.6874	23	2	1	2	2.5	700	80	65.2171
10	2	2	3	2.5	1000	110	67.6973	24	2	1	2	2.5	700	80	65.2171
11	2	2	3	2.5	1000	110	61.7792	25	1	1	1	2	700	40	65.2171
12	2	2	3	2.5	1000	110	67.7205	26	1	1	1	2	700	40	65.2171
13	1	2	2	2	1000	80	65.2171	27	1	1	1	2	700	40	65.2171
14	1	2	2	2	1000	80	65.2171								

Note: A indicates the Part A, B shows the Part B and C reveals the Part C portions of the Taguchi-ABC method

Table 2 L27 Orthogonal array and SNR computation

Procedure for obtaining the SNR

On obtaining the L27 orthogonal array with its parameters and levels, you square this parameter to obtain the desired values and then sum each parameter row dividing one by the sum to obtain the values (Fig. 1). Then, multiply the value by (1/n), where n is the number of factors, 3. Then take the logarithm of this value and multiply it by (-10) to obtain the signal to noise ratio (SNR), Table 2. After calculating the SNR for each experiment, the average signal to noise SN value is calculated for each factor and level to obtain each parameter effect on the welding process, Table 3.

Level	TTA(°)	TRS(rpm)	WS(mm/min)
1	64.7356	61.7320	64.7210
2	64.7501	64.8002	64.7455
3	**64.7551**	**67.7086**	**64.7744**
Delta	0.0195	5.9765	0.05343
Ranking	3rd	1st	2nd

Table 3 Signal to noise response (SNR) table

The delta value of the SNR for each parameter is computed and this is calculated as the maximum value in the parameter minus the minimum value along the column. For the parameter TTA; the range is calculated, in Table 3. The delta value is also used to determine what the objective function will be considered. The larger the ranking value of a parameter, the more effect the parameter has on the operation. From Table 3 the first ranking is TRS with a value of 5.9765, followed by 0.0534 and lastly by 0.0195. It can be seen that tool rotational speed has a greater effect on the welding process followed by the welding speed while the tool tilt angle has the least effect on the process. For the optimal parametric setting, the highest values in each parameter are as follows:

- The highest value in parameter TTA in the three levels is 64.7551 at level 3
- The highest value in parameter TRS in the three levels is 67.7086 at level 3
- The highest value in parameter WS in the three levels is 64.7744 at level 3

Therefore the optimal parametric setting is $TTA_3TRS_3WS_3$

4.2 Taguchi Pareto Method

The Taguchi Pareto is a further study of the Taguchi method. The Taguchi Pareto principle is applied to the L27 experimental trials of the signal to noise ratio (SNR). The SNR is rearranged from the highest value to the lowest value and this rearrangement also affects the Taguchi orthogonal array for each parameter. This is obtained using the Microsoft Excel worksheet. Once this rearrangement is done, the cumulative SNR is computed. Then, by taking the first SNR of the rearranged value as the first cumulative value, Table 4, the first highest rearranged SNR value is 67.7205. This value now becomes the first cumulative value. The second value in the SNR row is added to the first rearranged value to obtain the second cumulative value. Table 6 shows the values of 67.7205+67.7205 as 135.4410. The next cumulative value is computed by adding 135.4410 to the third rearranged SNR value as 135.4410+67.7205to give203.1615, this process is carried out to the last value, Table 4.

Exp.No	A	B	C	TTA	TRS	WS	SNR	% Cumulative	Comment
1	1	3	3	2.0	1400	110	67.7205	4%	Ideal (1-79%)
2	1	3	3	2.0	1400	110	67.7205	8%	
3	1	3	3	2.0	1400	110	67.7205	12%	
4	3	3	2	3.0	1400	80	67.7080	15%	
5	3	3	2	3.0	1400	80	67.7080	19%	
6	3	3	2	3.0	1400	80	67.7080	23%	
7	2	3	1	2.5	1400	40	67.6973	27%	
8	2	3	1	2.5	1400	40	67.6973	31%	
9	2	3	1	2.5	1400	40	67.6973	35%	
10	2	2	3	2.5	1000	110	64.8235	39%	
11	2	2	3	2.5	1000	110	64.8235	42%	
12	2	2	3	2.5	1000	110	64.8235	46%	
13	1	2	2	2.0	1000	80	64.7989	50%	
14	1	2	2	2.0	1000	80	64.7989	53%	
15	1	2	2	2.0	1000	80	64.7989	57%	
16	3	2	1	3.0	1000	40	64.7782	61%	
17	3	2	1	3.0	1000	40	64.7782	65%	
18	3	2	1	3.0	1000	40	64.7782	68%	
19	3	1	3	3.0	700	110	61.7792	72%	
20	3	1	3	3.0	700	110	61.7792	75%	
21	3	1	3	3.0	700	110	61.7792	79%	
22	2	1	2	2.5	700	80	61.7296	82%	Cut off (80-100%)
23	2	1	2	2.5	700	80	61.7296	86%	
24	2	1	2	2.5	700	80	61.7296	89%	
25	1	1	1	2.0	700	40	61.6874	93%	
26	1	1	1	2.0	700	40	61.6874	96%	
27	1	1	1	2.0	700	40	61.6874	100%	

Note: A indicates the Part A, B shows the Part B and C reveals the Part C portions of the Taguchi-ABC method

Table 4 Cumulative values of the SNRs

The next computation is the percentage cumulative of the SNR. This is computed by dividing each of the computed cumulative values by the total cumulative value and multiplying this value by 100%. The first % cumulative is computed as (67.7205/1748.1676)*100=4%. The second is computed as (135.4410/1748.1676)*100=8%. This process is repeated from the 3rd to the 27th SNR value, Table 4. Applying the Taguchi Pareto principle to the experimental trials of the percentage cumulative of 1% to 79% is ideal and the 80% to 100% is cut off because it is not advantageous to the process. From Table 4 the table reduces from 27 to 21 experimental trials. This is used to obtain the signal to noise response for the ideal region. The signal to noise response table is then computed for each parameter at each level, Table 5. After calculating the SNR for each experiment, the average signal to noise SN value is calculated for each factor and level to obtain each parameter effect on the welding process, Table 5. From Table 4, we compute the signal to noise response table by averaging all the parameters in each level, Table 5; This is the average of each parameter in each level, For instance, The average of parameter TTA for level 1 is (67.7205+67.7205+67.7205+64.7989+64.7989+64.7989) /6=66.2597. Furthermore, the average parameter of TTA for level 2 is (64.8235 +64.8235 +64.8235 +67.6973+67.6973+67.6973)/6=66.2604.Also, that of level 3 is (67.7080 + 67.7080 + 67.7080 + 64.7782 +64.7782 +64.7782 +61.7792 +61.7792 +61.7792)/9=64.7551.

Repeat this same computation for parameters TRS and WS for each level as shown in Table 5.

Level	TTA(°)	TRS (rpm)	WS (mm/min)
1	66.2597	61.7792	66.2378
2	**66.2604**	64.8002	**66.2534**
3	64.7551	**67.7086**	64.7744
Delta	1.5053	5.9294	1.4791
Ranking	2nd	1st	3rd

Table 5 Signal to noise response for Taguchi Pareto

The delta value of the SNR for each parameter is computed and this is calculated as the maximum value in the parameter minus the minimum value along the column. For parameter TTA, the max (66.2604)-min(64.7551) yields 1.5053. Repeat the process for TRS and WS as shown in Table 5. The larger the ranking value of a parameter, the more effect the parameter has on the operation. And from Table 5, the first ranking is TRS with a value of 5.9294 followed by 1.5053 and lastly by 1.4791. It can be seen that tool rotational speed has a greater effect on the welding process followed by the tool tilt angle while the welding speed has the least effect on the process.

Optimal parametric setting

The optimal parametric setting is obtained by taking the highest value in each parameter, for instance; the highest value in parameter TTA in the three levels is 66.2604 at level 2, and the highest value in parameter TRS in the three levels is 67.7086 at level 3 and the highest value in parameter WS in the three levels is 66.2534 at level 2 ($TTA_2TRS_3WS_2$).

4.3 Taguchi-ABC Method

The Taguchi ABC is an advanced method of Taguchi. This is similar to the Taguchi Pareto except that the Taguchi ABC concept involves sectioning and it is segmented into three regions.

- Region A is between the percentages of 80-100
- Region B is between 70-79 percent
- Region C is between 1-69 percent.

Taguchi ABC concept is applied to the L27 experimental trials of the signal to noise ratio (SNR). The SNR is rearranged from the highest value to the lowest value and this rearrangement also affects the Taguchi orthogonal array for each parameter. This is obtained using the Microsoft Excel worksheet. Once this rearrangement is done, compute the cumulative of the SNR, by taking the first SNR of the rearranged value as the first cumulative value, for instance from Table 6, the first highest rearranged SNR value is 67.7205. This value now becomes the first cumulative value. The second value in the SNR roll is added to the first rearranged value to obtain the second cumulative value, 67.7205+67.7205=135.4402. The next cumulative value is computed by adding 135.4410 to the third rearranged SNR value, 135.4410+67.7205=203.1615. This process is carried out to the 27th experimental number. The next computation is the percentage cumulative of the SNR. This is computed by dividing each of the computed cumulative values by the total cumulative value and multiplying this value by 100%. The first % cumulative is computed as $(67.7205/1748.1676)\times 100$=4%. The second is computed as $(135.4410/1748.1676)\times 100$=8%. This process is repeated from the 3rd to the 27th SNR value as shown in Table 6.

	Orthogonal arrays			Translated values of parameters					
Exp. No.	TTA	TRS	WS	TTA	TRS	WS	Cumulative	SNR	% Cumulative
1	1	3	3	2.0	1400	110	67.7205	67.7205	4%
2	1	3	3	2.0	1400	110	135.4410	67.7205	8%
3	1	3	3	2.0	1400	110	203.1615	67.7205	12%
4	3	3	2	3.0	1400	80	270.8695	67.7080	15%
5	3	3	2	3.0	1400	80	338.5774	67.7080	19%
6	3	3	2	3.0	1400	80	406.2854	67.7080	23%
7	2	3	1	2.5	1400	40	473.9827	67.6973	27%
8	2	3	1	2.5	1400	40	541.6800	67.6973	31%
9	2	3	1	2.5	1400	40	609.3774	67.6973	35%
10	2	2	3	2.5	1000	110	674.2009	64.8235	39%
11	2	2	3	2.5	1000	110	739.0243	64.8235	42%
12	2	2	3	2.5	1000	110	803.8478	64.8235	46%
13	1	2	2	2.0	1000	80	868.6467	64.7989	50%
14	1	2	2	2.0	1000	80	933.4457	64.7989	53%
15	1	2	2	2.0	1000	80	998.2446	64.7989	57%
16	3	2	1	3.0	1000	40	1063.0228	64.7782	61%
17	3	2	1	3.0	1000	40	1127.8010	64.7782	65%
18	3	2	1	3.0	1000	40	1192.5792	64.7782	68%
19	3	1	3	3	700	110	1254.3600	61.7792	72%
20	3	1	3	3	700	110	1316.1400	61.7792	75%
21	3	1	3	3	700	110	1377.9200	61.7792	79%
22	2	1	2	2.5	700	80	1439.6464	61.7296	82%
23	2	1	2	2.5	700	80	1501.3759	61.7296	86%
24	2	1	2	2.5	700	80	1563.1055	61.7296	89%
25	1	1	1	2.0	700	40	1624.7929	61.6874	93%
26	1	1	1	2.0	700	40	1686.4803	61.6874	96%
27	1	1	1	2.0	700	40	1748.1676	61.6874	100%

Table 6 Percentage cumulative

The Taguchi ABC concept is applied to the computed cumulative percentage. From Table 7, the percentage between 4% and 68% are taken as region C and those between 72% and 79% as region B while those falling between 82% and 100% are taken as region A, Table 7.

Exp.No.	Cumulative	% Cumulative	Taguchi ABC
1	67.7205	4%	Region C
2	135.4410	8%	
3	203.1615	12%	
4	270.8695	15%	
5	338.5774	19%	
6	406.2854	23%	
7	473.9827	27%	
8	541.6800	31%	
9	609.3774	35%	
10	674.2009	39%	
11	739.0243	42%	
12	803.8477	46%	
13	868.6467	50%	
14	933.4457	53%	
15	998.2446	57%	
16	1063.0228	61%	
17	1127.8010	65%	
18	1192.5792	68%	
19	1254.3600	72%	Region B
20	1316.1400	75%	
21	1377.9200	79%	
22	1439.6464	82%	Region A
23	1501.3759	86%	
24	1563.1055	89%	
25	1624.7928	93%	
26	1686.4803	96%	
27	1748.1676	100%	

Table 7 Pareto ABC

The signal to noise response for each region is computed (Fig. 1).

Signal to noise response for Region C

The signal to noise response for region C is obtained by calculating the average SNR of each parameter on each level as shown in Table 8.

Level	TTA(°)	TRS (rpm)	WS (mm/min)
1	66.2597	Nil	66.2378
2	**66.2604**	64.8002	66.2535
3	66.2431	**67.7086**	**66.2720**
Delta	0.0173	2.9084	0.0343
Ranking	3rd	1st	2nd

Table 8 Signal to noise response for Region C

To obtain the response of each parameter on each level, the average of each parameter level is calculated. For example, the tool tilt angle is obtained by adding all the SNR values in level one. If Table 7 is considered as the source of data, then all the SNRs in level 1 within region C are:

(67.7205+67.7205+67.7205+64.7989+64.7989+64.7989) /6=66.2597.

Then, repeat this same process for other parameters. The delta value for each parameter is also computed by the highest value in each parameter and subtracted with the lowest value. For instance, for the parameter TTA, the value 66.2604-66.2431 will give the delta value of 0.0173. However, by repeating this process, the delta values for other parameters are obtained, Table 8. Furthermore, in ranking the parameters, from Table 8, the highest value from the delta row is 2.9084 and this will be the first ranking. It signifies that the tool rotational speed has more effect on the welding process followed by the welding speed while the tool tilt angle has less effect on the process. Besides, the optimal parametric setting is the parameter with the highest value in each parameter level. Thus, from Table 8, the highest value in the tool tilt angle column is in level two and for tool rotational speed it is in level three while for welding speed it is in level three ($TTA_2TRS_3WS_3$). The ranks of the parameters are 1^{st} to the tool rotational speed, 2^{nd} to the welding speed and 3^{rd} to the tool tilt angle.

Signal to noise response for Region B

To obtain the response table for region B we take the average value of the SNR for each level in each parameter. For instance, for the tool tilt angle, to obtain the value for level 1, the Microsoft Excel results used for the initial computation of the scores reveal the absence of signal to noise scores and nil is filled in Table 9 for this observation. A similar observation was made for level 2 under the tool tilt angle factor and nil was recorded as the outcome. Furthermore, still under the tool tilt angle and level 3, the computation shows a value of 61.7792. Repeat this process of computation for tool rotational speed and welding speed including their levels 1 to 3 and the average signal to noise response will be obtained for these two parameters as revealed in Table 9. The delta value and the ranking are also obtained as shown in Table 9. For instance, for the tool tilt angle, only an entry is available and since there is no comparison with other average values of the signal to noise ratio, a delta value of zero is recorded under the column of the tool tilt angle. The same is repeated for the tool rotational speed and the welding speed and all the delta values are zero in this instance. Then, the optimal parametric is also obtained as $TTA_3TRS_1WS_3$. The ranks of the parameters are 1^{st} to all the parameters of the tool rotational speed, welding speed and tool tilt angle.

Level	TTA(°)	TRS (rpm)	WS (mm/min)
1	Nil	**61.7792**	Nil
2	Nil	Nil	Nil
3	**61.7792**	Nil	**61.7792**
Delta	0	0	0
Ranking	1st	1st	1st

Table 9 signal to noise response region B

Signal to noise response for Region A

To obtain the signal to noise response table for region A we take the average of each SNR for each level in each parameter. For instance, for welding speed level 2, the average SNR is 61.7296, which was obtained from the calculations from The Microsoft Excel sheet that serves as the platform of calculation for the signal to noise ratios and their averages in this article. For level 3, the average SNR is nil. Then, it is required to repeat the same process for level 1 of the welding speed and other parameters. Accordingly, the delta value and the ranking are also obtained as shown in Table 10. But the optimal parametric value is also obtained as $TTA_2TRS_1WS_2$. The ranks of the parameters are 1^{st} to both the welding speed and to the tool tilt angle while 3^{rd} is allocated to the tool rotational speed,

Level	TTA(°)	TRS (rpm)	WS (mm/min)
1	61.6874	**61.7085**	61.6874
2	**61.7296**	Nil	**61.7296**
3	Nil	Nil	Nil
Delta	0.0422	0	0.0422
Ranking	1st	3rd	1st

Table 10 Signal to noise response region A

Besides, in this article, the interpretation of the linkage of the parameters with the ultimate tensile strength value is possible using the data from Khan [16], particularly in Table 3. In this table, the corresponding strengths of the welded joints of the optimal parameters are read from the table using various methods. For the Taguchi method, which was analyzed using the L27 orthogonal array as opposed to the L29 orthogonal array, the optimal parametric setting is $TTA_3TRS_3WS_3$ of TTA, 1400rpm of TRS and 110mm/min of WS. On finding the corresponding ultimate tensile strength, the occurrence of 1400rpm of TRS was not found in Table 3 of Khan [16]. Therefore, the interpretation of results is between experimental trials 7 and 9 with the corresponding ultimate tensile strengths of 138 and 197 MPa for the 700 and 1420rpm of TRS. By interpolation, the ultimate tensile strength of the optimal parametric setting of the Taguchi method's parameters is 195.36MPa. For the Taguchi-Pareto, the optimal parametric setting is $TTA_2TRS_3WS_2$ as 2.5 of TTA, 1400rpm of TRS and 110mm/min of WS. On reading from Table 3 of Khan [16], the value of 1400rpm of TRS does not exist in the Table, hence interpolated. But the experimental trials from which the interpolation could be made are 5 and 6. Similar to the procedure followed for the Taguchi method, the interpolated ultimate tensile strength at the optimal parametric setting for the Taguchi-Pareto method is 180.78MPa. For the Taguchi-ABC method, the ultimate tensile strengths for the A, B and C points are 134MPa, 138MPa and 180.78MPa respectively. Of all these ultimate tensile strength predictions, the highest is for the Taguchi method at 195.36MPa. However, this contradicts the results that promote part A of the Taguchi-ABC method as the best, which yields a lower tensile strength of 134MPa. Nevertheless, still, the results of the Taguchi-ABC method (Part A) could be relied upon as it incorporates prioritisation in addition to optimization of the parameters.

5. Conclusions

In this article, the optimization concerning the process parameters in a friction stir welding set-up was conducted. The process parameters were optimized through the Taguchi method and two other variants, namely the Taguchi-Pareto and Taguchi-ABC methods. In the Taguchi-Pareto method, the Pareto structure of the 80-20 rule was introduced to show that it is possible to reduce the experimental trials to the most important ones, and reveal that the idea of Pareto analysis is essentially useful in treating the problem of parametric ordering and elimination of unimportant parameters. Through the same type of idea, the Taguchi-ABC method was instituted to determine the critical concentration of the parameters, grouped as the A, B and C groups from the traditional ABC classification scheme in inventory analysis. From a summarized perspective, the following conclusions were drawn from the study.

1. The tensile strength of the friction stirs welded joints of AA6062-T6 alloy are principally influenced by the parameters of welding speed, tool tilt angle and rotational speed to yield the most favourable tensile strength.
2. From the Taguchi method, the tool rotational speed (1400rpm), welding speed (110mm/min) and tool tilt angle (3°) greatly influence the friction stir welding parameters in the order listed as 1st, 2nd and 3rd, respectively.
3. For the Taguchi-Pareto method, by concentrating on 80% of the experimental trials, tool rotational speed still maintained its lead as the first (preferred) parameter (1400rpm), while the tool tilt angle (2.5°) displaces the tool rotational speed to occupy the second position and the welding speed obtained the last position (80mm/min) as opposed to its previous positioning in the application of the Taguchi method to the problem.
4. For the Taguchi-ABC, segmentation was made according to 1 to 69%, 70-79% and 80-100% as C, B and A to capture the following results. For region C, to obtain the most favourable tensile strength, the system must operate at tool rotational speed (1400rpm) as the first parameter, welding speed (110mm/min) as the second parameter and tool tilt angle (2.5°) as the third parameter. However, for region B, the first result is shared among all the three parameters as the tool rotational speed (700rpm), welding speed (110mm/min) and the tool tilt angle (3°). Nonetheless, for region A, the tool rotational speed (700rpm) was the third position while the first position is shared between tool tilt angle (2.5°) and welding speed (80mm/min).
5. In all the methods, on average, the welding speed is preferred as first while the tool tilt angle and tool rotational speed had the same second position in the friction stir welding process.
6. The optimal process parameters are as indicated previously along with the ranks.
7. The developed methods of Taguchi, Taguchi-Pareto and Taguchi-ABC are reasonably accurate and presented as useful predictive tools for the setting of optimal parametric values with which welding plans may be accomplished.

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