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Optimization of Friction Stir Welding Parameters of AA5052-H32 Aluminium Alloy using Taguchi and Taguchi-Pareto Methods

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A B S T R A C T

It is difficult to improve the quality of friction stir welded joints of AA5052-H32 material because of scarce metrics on its concurrent optimization and prioritization. However, the objective of this article is to obtain optimal parametric values and identify important parameters using the Taguchi-Pareto method during the friction stir welding process of AA5052-H32 material. Then the ranks, delta values and optimal parameters are determined. The critical parameters identified for the friction stir welding process are the tool pin, rotational speed, welding speed and tool angle. When comparing the results of these parameters using the Taguchi method and Taguchi-Pareto method, the rotational speed retained its first position in both methods; the tool tilt angle gained the second position in the Taguchi-Pareto method from its third position when only the Taguchi method was considered. The welding speed became the third position in the Taguchi-Pareto method against the second position that it had in the Taguchi method. However, the tool pin profile retained its last position in both methods. Consequently, the rotational speed is the best parameter while the tool pin profile is the worst parameter. For the Taguchi-Pareto method, the optimal parametric setting is $TPP_2/TPP_4RS_1WS_4TTA_3$. This is interpreted as cylindrical tapered or square tapered for the tool profile, 40 rpm of rotational speed, 75 mm/min of welding speed and 1.5° of tool tilt angle. The novelty of this study is the scope of analysis of the AA5052-H32 material that extends beyond the Taguchi method to the Taguchi-Pareto method where the concurrent optimization and prioritization of friction welding parameters are achieved.

1. INTRODUCTION

Perhaps the most popular conventional optimization tool used in the welding research terrain is the Taguchi method for analyzing the weld quality of friction stir welding joints (Leuro et al., 2010; Lakshiminarayanan and Balasubramanian, 2011; Ahmach et al., 2012; Karthikeyan and Balasubramanian, 2013; Arya et al., 2022; Francis et al., 2022**)**. If the quantitative and qualitative attributes of the weld quality and fewer types of equipment are desired for the joint, it may be sufficient to deploy the Taguchi method for evaluation (Shunmugasundaram et al., 2020; Arya et al., 2022). However, with an increased commitment to add prioritization or the identification of the most important parameters to resource distribution prudence and conflict avoidance among welders, it may be misleading to deploy only the Taguchi method but using prioritization of parameters along with optimization may be very helpful (Francis et al., 2022). In this regard, it is essential to utilize the Taguchi method with the Pareto method.

In the past several years, many optimization studies have been conducted in friction stir welding (Siva et al., 2014; Shamsudeen and Dhas, 2018; Shanavas and Dhas, 2018; Jain and Kumar, 2021, Premraj et al., 2021). For instance, Shunmigasundaram et al. (2020) conducted the welding of AA6063 and AA5052 plates, which are dissimilar in material content, using friction stir welding and deploying the L9 Taguchi scheme for the optimization of the welded joints for high-quality outcomes. It was declared that welding speed has a superior rating than the feed and tilt angle parameters assessed during the weld quality development. In another study, Pradeep and Muthukumaran (2013) analyzed the outcomes of welding low alloy plates using friction stir welding and the Taguchi method with a tool conceal pin clearance of 0.4min, deploying the L9 orthogonal array of the Taguchi method to improve the weld quality. It was reported that the optimal tensile strength prediction using ANOVA yielded 472 MPa. Besides, Ahmadi et al. (2012) employed friction stir welding on polypropylene composites through a lapping joining method and analyzing the process parameters, which include the welding speed, tool pin geometry, tool rotational speed and tilt angle and their relationship with tensile shear strength, it was reported that the rotational speed, welding speed, tool pin geometry and tool tilt angle are respectively significant. The L16 orthogonal array of the Taguchi method was used to obtain the essential results in the work. Furthermore, Louro et al. (2012) described a procedure to use the Taguchi method in the friction stir welding of 4min thick aluminium alloy plates with the butt joint arrangement as the focal joint design. Welding speed was maximized concurrently with acceptable weld quality. The procedure was ascertained as effective.

Abd Elnabi et al. (2019) explored the behavioral studies of dissimilar joints involving the AA7075 and AA5454 after being worked on by the friction stir welding process. The differences between the article and the present work are many. While the authors considered the response surface method as a key optimization tool, the present article diverges from the use of this tool to the Taguchi and Taguchi-Pareto methods. Besides, the L16 orthogonal array was used in the work against the L25 considered in the present study. Furthermore, all the parameters considered in the present work are included in the reviewed work and it covers more aspects than considered in the present article. Out of the four parameters considered in the present study, the rotational speed and the welding speed were chosen as the first and second parameters, respectively with the greatest and next impact on the weld quantity while considering the Taguchi and Taguchi-Pareto methods. The results are in agreement with those revealed in Abd Elnabi et al. (2019) which placed the rotational speed and transverse sp ed (i.e equivalent to welding speed) as significant parameters that influenced the formation of a high property level regarding mechanical properties measured from the perspectives of ultimate tensile strength.

Raman et al. (2021) considered the friction stir welding process but uniquely done with a double side of the AA6082 material being considered. A key conclusion of the study is that the highest temperature at the advancing side exceeded that at the retreating side whether water or air is used as the cooling medium. Premraj et al. (2021) studied the friction stir welding process for the AA1100 material. The process parameters differ in that apart from the common parameters, welding speed was used in our work while feed was used in their study. Although optimization was done in both studies using orthogonal arrays, the L25 framework was used in our work while L20 orthogonal array was used in their work. Furthermore, Shine and Subbaiah (2020) analyzed the behavior of welded AA5083 material when scandium is added to it. Compared with our study the process parameters studied although common in some, are different in that tool tilt angle was considered in our work while absent in their work. Unfortunately, the Taguchi scheme that is promoted in such studies does not apply to such a situation where concurrent optimization and prioritization are required for the AA5052-H32 aluminium alloy, as a scheme that combines both optimization and prioritization, Ajibade et al. (2019) developed Taguchi-Pareto and Taguchi-ABC schemes for monitoring composites.

Although several studies have been conducted on the aluminium alloy 5000 series, it is rare to find any research applying the Taguchi-Pareto method related to the friction stir welding process. In this article, the Taguchi-Pareto method is considered, which is taken as a rare method. But first, the Taguchi method is used to establish the foundation for the computation of Taguchi-Pareto method. The Pareto scheme, a decision-making tool, has been useful to evaluate rival parameters in the welding process and predicting their influences in using them, permitting the process engineer to channel efforts and resources on parameters that will change the welding process most, as optimization is concurrently desired, the measurement metric does not fit the Pareto analysis anymore and the coupling of Taguchi method should be instituted. The procedure for this method is presented in the section on methods. Nevertheless, Francis et al. (2022) recently applied the Taguchi, Taguchi-Pareto and Taguchi-ABC methods to the friction stir welding process, only the AA6062-T6 alloy was studied. Besides, while Francis et al. (2022) considered the tool tilt angle, tool rotational speed and welding speed as parameters, the important influence of tool pin profile was ignored in the study. Therefore, interpreting and predicting the influence of the tool pin profile for the AA5052-H32 aluminium alloy from the experimental results and analysis, which excludes it may be confusing and deceptive until the proper analysis is conducted using the tool pin profit as an inclusive parameter in experiments and analysis. Consequently, to evaluate the weld quality of the friction-welded AA5052-H32 aluminium alloy, experimental data from Shamsudeen and Dhas (2018) was analyzed with the Taguchi and Taguchi-Pareto methods.

Furthermore, the scope of this study cut across analyzing the experimental data of Shamsudeen and Dhas (2018) to establish the optimal parametric settings among the following parameters: tool pin profile, rotational speed, welding speed and tool tilt angle. It was conducted on AA5052-H32 material using the friction stir welding process. The Taguchi experimental method was used where the four parameters are defined and five levels are established for the problem. Then the smaller-the-better criterion of the signal-to-noise ratios was implemented. Afterwards, the averages of this signal-to-noise ratio are presented in a response table that permits the computation of the data values and the ranking of parameters according to their order of importance. The interpretation of the signal-to-noise ratios in the response table is enabled by an organized set of level codes, which are labelled as codes 1, 2, 3, 4 and 5. The above process describes the Taguchi method proposed in the present work. A further scope is to introduce Taguchi Pareto into the analysis. In this case, the 80-20 Pareto principle is used to design the computational framework of the cumulative signal-to-noise ratios. In essence, after the signal-to-noise ratio has been developed, the cumulative signal-to-noise ratios are obtained and a cut-off is set at 80%. With 20% at a later value discarded. The 80% is marked to the orthogonal array omitting the unimportant values of 20%. This 80%, which is marked into levels is then computed by averages in the response table. Then, the optimal parametric setting of the Taguchi Pareto, the rank of the parameter and the data value is then computed.

Moreover, in the context of friction stir welding, the novelty of this study is the scope of analysis of the AA5052-H32 material that extends beyond the Taguchi method to the Taguchi-Pareto method where the concurrent optimization and prioritization of friction welding parameters are achieved. This provides new knowledge on the possibility of a joint optimization process together with a prioritization procedure that depends on the Pareto method. The uniqueness of this method is that it provides a platform through which the causal factors of poor performance of parameters could be investigated. The novel mechanism of the Pareto 80:20 rule discriminates experimental trials, which interacts with the signal-to-noise ratios to produce the average signal-to-noise ratios, ranking, delta values and optimal parametric settings. Thus, the objective of this study is to obtain optimal parametric values and identify important parameters using the Taguchi-Pareto method applied to the friction stir welding process where the primary material being processed is AA5052-H32.

2. LITERATURE REVIEW

2.1 General

This section contains references related to the friction stir welding process, which is a non-conventional welding process that welds materials that are difficult to weld through the conventional route (Gesella and Czechowski, 2017; Boitsov et al., 2018; Sekban et al., 2019). Surprisingly, in this solid-state joining process, the welding tool, described in pin profiles (i.e. hexagonal) and shoulder lengths, among others, is not consumed; unlike the electrodes in arc welding that get used up in the process. But through the tool's rotation and plunging into the interface of the workpieces the welding is conducted. The tool moves within the interface while the frictional heating is going on. Interestingly, the search space of the literature review is the friction stir welding process and the focus methods in the literature search are generally optimization methods that deploy various materials within the friction stir welding domain. These methods are mainly discussed as follows:

The first is the grey relational analysis. The principal concept displayed in the grey relational analysis is to position the geometric similarity of the reference data sequence against multiple proportional data sequences. However, the grey relational method achieves competence in defining circumstances where no information is available as black and when fall information abounds, the situation is defined as while. But the authors, Shamsudeen and Dhas (2018), in presenting the grey relational analysis as the tool for analyzing the AA5052-H32 material that was processed through the friction stir welding counted on the advantage of the grey relational analysis that imposes no specific limitation on the welded sample size and the normal spread of data while presenting a computationally straightforward method for evaluation.

The second set of methods used in the literature is under the Taguchi methods but could be broken into three aspects, namely the Taguchi method, the Taguchi-Pareto method and the Taguchi-ABC method. In the friction stir welding arena, the Taguchi method has been extensively deployed in the optimization of processes. The role of the Taguchi method in the analysis is to minimize the friction stir welding parametric variations before the optimization, aimed to reach mean target values for the process outputs. Accordingly, roughly between twelve years and now, several scholars have applied the Taguchi method to the friction stir welding process with a focus on process parametric optimization: Leuro et al. (2010), Lakshminarayanam and Balasubramanian (2011), Karthikeyan and Balasubramanian (2013), Ahmach et al. (2012), Pradeep and Muthukumaran (2013), and Silva et al. (2014). While it is common for these authors to use specific orthogonal arrays such as L9 (Pradeep and Muthukumaaaran, 2013), some authors complemented these orthogonal arrays with the ANOVA method to detect the significant parameters in the friction stir welding process. Furthermore, the range of materials used varies widely such as aluminium alloys (i.e. AA6082-T6, Silva et al., 2014; AA5083-H111, Leuro et al., 2010; AA7075, Karthikeyan and Balasubramanian, 2013), steel (i.e. IS 3039 plates, Pradeep and Muthukumaran, 2013; AISI 409M grade ferritic stainless steel, Lakshminarayanan and Balasubramanian, 2011, polypropylene composite (i.e. Ahmach et al., 2012).

At the beginning of this subsection, the Taguchi-Pareto was mentioned as another method, a variant of the Taguchi method that integrates the Pareto method to solve friction stir welding process parametric problems. The working mechanism of the Pareto method is to streamline activities to 80:20 rules where for a great number of process parameters, about 80% of the problem consequences are attributable to 20% of the causes. This principle is attached to the generated experimental trials from the orthogonal array and demonstrated by capturing the relevant cumulative signal-to-noise ratios. A thorough search of the friction stir welding literature reveals that only in one application can this new method be found within this reviewed area (Francis et al., 2022). Of particular interest was the use of AA6062-T6 alloy in demonstrating how the process parameters could be optimized. This limited application of the Taguchi-Pareto method raises the question of how much potential impact its use can make while planning based on the combined optimization and selection method. Prospective authors have a wide area to test the use of this method such as the joining of metals involving the AA5454-AA7075 (Abd Elnabi et al., 2019), AA5083-H111 and AA6061-T6 (Lakshmiknath and Subbaiah, 2020), and AA6063-AA5052 (Shunmugasundaram et al., 2020). Interestingly, the application is extended to the AA5052-H32 material and this article and the Taguchi-Pareto method are tested for its feasibility in friction stir welding.

Next, the Taguchi-ABC method is the third variant of the group of Taguchi methods; this combines the Taguchi method and the ABC analysis. The ABC analysis transforms the orthogonal array-originated signal-to-noise ratios into three groups – "A S/N ratio items having an extremely tight control and accurate information, "B S/N ratio items having lower tight controls and good information, and "C S/N ratio items having the least tight controls.

What follows is a brief review of other optimization methods that have been applied in friction stir welding. The use of particle swarm optimization in comparison with the response surface methodology was reported by Sahu et al. (2021). Consequently, a little change in joint strength efficiently was reported for ratio items having the least controls attainable and the least information. The ABC in this instance ranks the SN ratios along the experimental trials and classify item according to the mentioned A, B and C categories. Also, literature research was conducted on the friction stir welding process but only one case of application of the ABC analysis is reported as found in Francis et al. (2022). The focus materials were AA6062-T6 alloy. Thus, it is thought that the limited application of the Taguchi-ABC method could be expanded to some or all the joint combinations mentioned under the Taguchi-Pareto of the welded materials. Furthermore, the contribution of Yamin et al. (2020) includes the application of Box Behnken Design to optimize the refill friction stir spot welding similar to AA7075-T6 material. The optimal rotational speed, phage depth and speed yielded a tensile strength of roughly 660N. Besides Vijayan and Rao (2017) implemented the response surface method-oriented grey fuzzy method to optimize the friction stir welding outputs of ultimate tensile strength, and tensile elongation while the input parameters are the pin shape, welding speed, rotational speed and axial load while the joint considered are of the materials AA2024 and AA6061. It was stated that the results are effective and improved outcomes were noticed when compared with the grey relational analysis. Apart from the above methods, Rao et al. (2018), a new method called the grey relational analysis based on the Taguchi method was implemented and found suitable for the friction stir welding process parametric optimization of the AA6061-T6 and AA7075-T6 joint.

2.2 Literature observations and research gap

In this study, to implement experiments involving four parameters and five levels associated with the problem considered regarding the fiction stir welding problem where the AA5052-H32 aluminium is processed Shanavas and Dhas (2018) the requirement is $5^4 = 625$ experiments as needed in the classical experimental system. This is laborious, costly and time-consuming. But these experiments ought to be conducted in this examination while the results are examined further managerial decisions. Instead, however, the Taguchi optimization approach is adopted which provides a rare advantage of using an

L25 orthogonal array with a requirement of only twenty-five experiments, thus reducing the number of experiments by 96% presumably proportional to the cost and time savings also. Furthermore, in the study presented by Shamsudeen and Dhas (2018), the focus was primarily on the use of grey relational analysis on the AA5050-H32 aluminium alloy, which was implemented in a friction stir welding environment. The extension of the work was further noticed by Shanavas and Dhas (2018) where fuzzy logic was the predominant tool applied in the analysis. Besides, a comparative analysis was conducted by Shanavas and Dhas (2017) and the results were provided for the TIG welding process and the FSW process by still focusing on AA5050H32 aluminium alloy. However, in all these research endeavors, the economy of experimentation that is characteristic of the Taguchi method has not been exploited. Though some of the methods such as the fuzzy logic take advantage of the ability to generate and interpret qualitative information, surprisingly, this attribute is also present in the Taguchi method, making it a better edge over several competing methods such as grey relational analysis and fuzzy method as it combines economy of experimentation with quantitative information provision on the parameters being studied.

From the literature study, the following items of observations and literature research gaps were noted:

1. The present situation in the welding industry is an attempt to optimize activities and parameters of the process irrespective of the form of welding engaged (i.e. friction stir welding, spot welding, etc) and type of material used (i.e. metals or polypropylene composites) using optimized values indirectly conserve wasted and resources and assures target achievements and error avoidance.
2. The major advanced materials used in welding are of two types, namely metallic alloys and polypropylene composites. However, the most application tends to favor metallic material alloy usage while polypropylene is less used.
3. The Taguchi method was considered one of the most successful optimization methods in the friction stir welding domain. Notwithstanding, in the past few years, the inability of the Taguchi method to distinguish the importance of one parameter over the other has poured way for further research questions, which have identified the Taguchi-Pareto and Taguchi-ABC as possible challengers. But these options have not been applied in the friction stir welding domain to date.
4. There is no attempt to date to test the performance of the AA5052-H32 material with a combined Taguchi method and prioritization method. This may be considered and may be bridged by introducing combined Taguchi-Pareto and Taguchi-ABC methods.
5. A broad range of mathematical models is used in the friction stir welding process, namely the response surface methodology, and grey relational analysis.
6. A majority of friction stir welding processes have been conducted on single-sided schemes but a newly developed aspect is the double-sided friction stir welding process championed by AA6082 material.

3. METHODS

If experimental data associated with both optimization and prioritization attributes are being contemplated, a method to model the two attributes may be essential. An effective method to evaluate the optimization attribute concurrently with the prioritization concern of the weld quality for the friction stir welding of AA5052-H32 aluminium alloy is adopting the two variants of the Taguchi scheme, namely Taguchi and Taguchi-Pareto methods. The AA5052-H32 exhibits extraordinary attributes that make it suitable for wide usage, including good workability behavior. It is a superior corrosion resistance material and has an elevated fatigue strength. Other attributes of the AA5052-H32 material are its modest strength and workability. Based on these outstanding attributes, the AA5052-H32 material finds a broad application in sheet metal work, rivets, aircraft, fuel/oil lines, wire, fuel tanks, lighting and appliances. However, it is realized that improvements in the friction stir welding parameters from the sub-optimal values to optimality will touch many areas of engineering applications. Besides, by combining Taguchi's results based on optimal values with the Pareto tool of prioritization, there is a high potential to conserve waste and this is equally extended to the many application areas mentioned above. Furthermore, it translates to high planning efficiency since the information on the best and worst friction stir welding parameters may be useful in cost estimates for the next operating period. Therefore, in the article, the Taguchi method is first applied and the optimal parametric setting is determined, then, the Pareto method is integrated with the Taguchi method to form the Taguchi-Pareto method with which a significant contribution is made to the friction stir welding literature. Hence, the novelty of the present study is the unique development of a method that integrates the Taguchi method and the Pareto analysis, to aid a concurrent optimization of welding parameters in the friction stir welding process. In this article, the Taguchi method is applied to optimize the experimental data on the friction stir welding of AA5052-H32 material. The authors then proceeded to apply the Taguchi-Pareto method to the experimental data to ascertain the concurrent optimization and prioritization of parameters such that the best and worst parameters as they influence the friction stir welding process are identified.

3.1 Procedure for the Taguchi method

In this section, the Taguchi method (Fig. 1), which was studied in its performance application to the AA5052-H32 material (see also Arya et al., 2022) for the friction stir welding process at a later stage, has the following procedure.

Step 1: Obtain the factors and levels for the factors and set them up in a table. This is also referred to as factor selection and interaction assessment (Yang and Tang, 1998). Furthermore, it is known generally in management literature that decision-makers cannot control what cannot be measured and management cannot measure what is impossible to quantify. But control of the friction stir welding process is desired through the intervention of some quantitative metrics. Consequently, it is thought that the decision maker in the friction stir welding process should be able to study the system, understand where there is a heavy investment of energy and resources in the friction welding system and identify the key parameters that represent that system. These are the representative parameters of the system that best describes it and such are called factors. A good attribute of these factors is that they should be able to relate to one another and the goal of the friction stir welding process, which is to produce high-quality weld joints.

Step 2: Determine which of the orthogonal matrices will be suitable to solve the problem based on the information on the number of parameters (factors) and their levels characteristic of the problem. This is also the ascertainment of factor-level association and instituting a balanced design framework (Yang and Tang, 1998). For this step, the levels represented in each factor are defined. An appreciation of how levels are created may be made if the following illustration is understood. Suppose one hundred units of data concerning a factor were collected. The researcher needs to understand the spread of the data and represent them accordingly. One way of representing the data is to divide it in a manner such that frequency counts will represent the levels. Another approach is to divide it into four equal parts in averages and assign four levels to the work Here, there are standard orthogonal designs that are picked from a pool based on the factor-level combination. These designs have organized numbers running from the least values to the highest value in the level.

Step 3: Apply any or a combination of the three available signal-to-noise ratio criteria (Yang and Tang, 1998). This is the stage where the signal-to-noise ratios are determined based on any of the three possible ones: higher-the-better, lower-the-better and nominal-the-best. From the orthogonal arrays, the actual values are read from the factor-level table and translated into values. Then the signal-to-noise ratios are analyzed.

Step 4: Summarize the signal-to-noise ratio data into an average set of values that may be referred to as the response table for the signal-to-noise ratio considering the AA5052-H32 material.

Step 5: Obtain information regarding the delta values, optimal parametric settings and grades of the parameters in ranking.

For smaller the better (STB),

$$STB = -10\log(1/n)\sum Y^2 \quad (1)$$

Where n is the number of factors and Y is the factor value

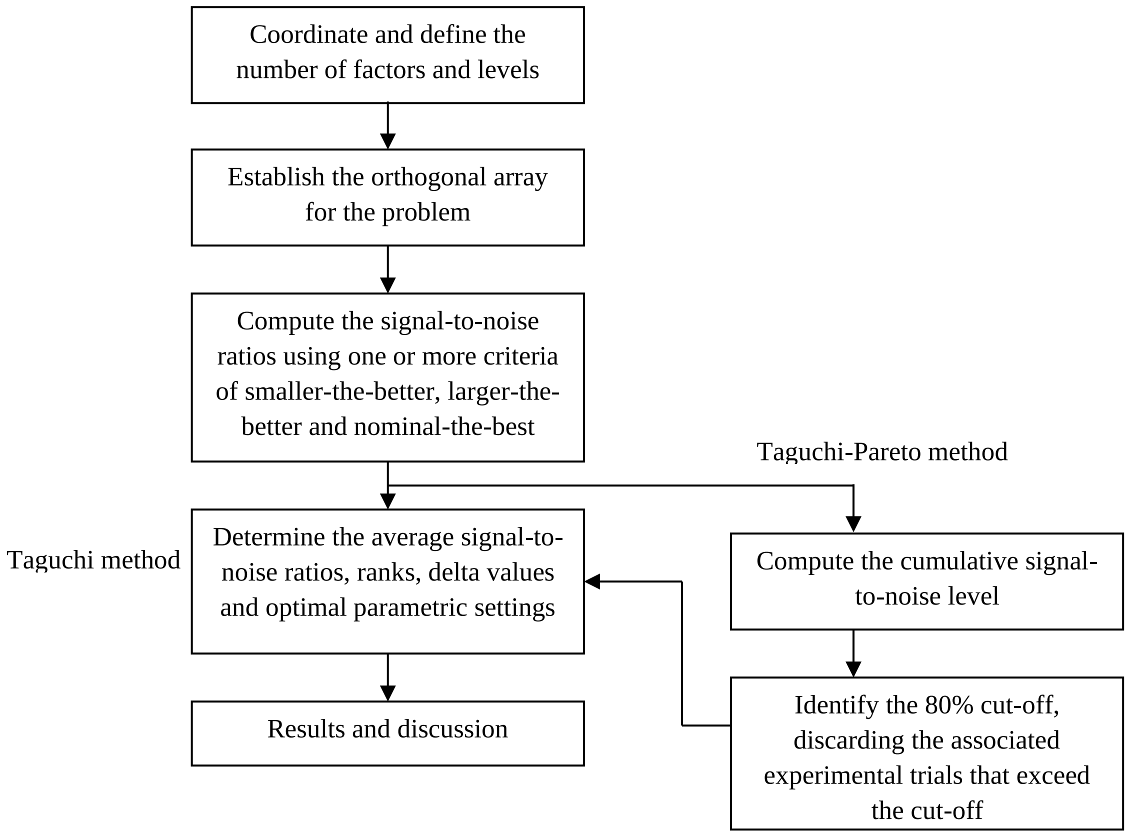

Fig. 1. Research scheme

3.2 Procedure for the Taguchi-Pareto method

From the above discussion, the various steps involved in implementing the Taguchi method have been described. However, since the two methods, namely the Taguchi method and the Taguchi-Pareto method (Figure 1) are analyzed in this article, and the Taguchi method has been introduced, what is next is to describe the Taguchi-Pareto method. Interestingly, many of the steps to implement the Taguchi method will be incorporated into the Taguchi-Pareto method. These steps are from the constitution of the factors (parameters) and levels to produce an orthogonal array with which the signal-to-noise ratios are computed. The common elements of the Taguchi method and Taguchi-Pareto method first end at the signal-to-noise ratio determination and then commences again at the determination of the summary table for the average of the signal-to-noise ratio, named the response table. The summary of the steps to implement the Taguchi-Pareto method is as follows:

Step 1: Follow Steps 1, 2 and 3 of the Taguchi method.

Step 2: Introduce an additional column after the signal-to-noise ratios to produce the cumulative values of the signal-to-noise ratios.

Step 3: Watch closely the values of the cumulative signal-to-noise ratios and determine the cutoff point, which is 80% if an exact cut-off point of 80% is not attainable, take approximate values. Note the relevant experimental trials covering the 80% or roughly 80% cumulative signal-to-noise ratios.

Step 4: Eliminate the experimental trials associated with 80% and more of the cumulative signal-to-noise ratios. Compute the average signal-to-noise ratios. Compute the average signal-to-noise ratios based on the remaining experimental trials.

Step 5: Determine the delta values, optimization parametric setting and the ranks of each parameter.

3.3 Parametric selection

In the prediction of the behavior of the friction stir welding process, heavy reliance is placed on the critical parameters in the process. However, process engineers in welding locations may not be aware of the strengths of one parameter over the other thereby putting the planner in a dilemma on what parameters to give utmost attention to and what parameters not to. In this context, parametric selection, which provides a good basis for achieving reliable process optimization results, is essential.

For the parameters used in the present study, obtained from Shamsudeen and Dhas (2018), the parameters chosen for investigation are the tool tilt angle, tool pin profile, welding speed and rotational speed. However, a similar work was conducted by Arya et al. (2022) that elaborated on the AA5052-H32 material and deployed the Taguchi method as done in the present study. The selected parameters by Arya et al. (2022) are the table (welding) speed, rotational speed, and shoulder speed. While Arya et al. (2022) limited their investigation to only three parameters, the present study considered four parameters and has the advantage of representing the complex process of friction stir welding much more with greater understanding and control than using fewer parameters. Furthermore, more dynamic user input to the analysis of the friction stir welding process is made with four parameters instead of the three showcased by Arya et al. (2022).

Besides, Arya et al. (2022) did not consider the tool tilt angle and the tool pin profile, which are important for the following reasons. First, while the tool conducts its functions such as blending the AA5052-H32 material, restraining the material within the bounds of the joints, producing heat of welding initiating and maintaining the forging pressure until the completion of the welding process, knowledge of the tool profile aids in planning for the energy utilization and the expected time of welding for the AA5052-H32 material. Second, ignoring the tool tilt angle as observed by Arya et al. (2022) puts the process engineer at risk of producing inferior weldments since the direct relationship between the tensile strength of the weldment produced and the tilting requirement of the tool is not known.

4. RESULTS AND DISCUSSION

4.1 Factor and level determination

Table 1 is an indicator of the factors and levels for the friction stir welding of the AA5052-H32 material as reported in Shamsudeen and Dhas (2018).

Table 1. Factor and level for friction stir welding problem

Sr. No.	Factors	Level 1	Level 2	Level 3	level 4	level 5
1	Tool pin profile	-2	-1	0	1	2
2	Rotational speed (rpm)	400	500	600	700	800
3	Welding speed (mm/min)	45	55	65	75	85
4	Tool tilt angle (degree)	0.5	1	1.5	2	2.5

(Source: Shamsudeen & Dhas 2018)

Key: -2 (cylindrical tapered), -1 (hexagon tapered), 0 (pentagon tapered), 1 (square tapered), 2 (triangular tapered)

The four parameters shown are the tool tilt angle, rotational speed, tool pin profile and welding speed. To understand what the tool pin profile stands for it is important to start explaining what a tool pin is. A tool pin is a physical metal object which aids the substantial flow of material during the friction stir welding process. The material flow is accompanied by a pulsating action in which the tool is driven discontinuously such that torque is applied in increments instead of in a continuous attempt. By such actions, the tool demonstrates a superior power-to-weight quotient. Apart, reaction forces are absent and this provides an opportunity to apply pulse. From this background, the tool pin profile is the nomenclature used to represent the shapes of tools i.e. hexagonal, square, etc. Irrespective of any of these mentioned configurations that the tool adopts, the choice of either being tapered or not is made by the process engineer.

The second parameter to explain is the rotational speed, which is described as the number of revolutions that the tool makes in a specified welding period. Next, the welding speed is the speed at which the welding activities take place. Also, the tool tilt angle helps to prevent the material in a flowing state from being ejected. Effectively, the tool tilt angle causes impacts on the mechanical properties of the AA5052-H32 material and such a mechanical property is the tensile-shear attribute of the material. In addition, the tool tilt angle influences the motion of materials, degree of heat generation and the merging of flowing AA5053H32 material after the tool pin. There is a positive correlation between the axial force applied by the tool as well as the climax temperature against the tool tilt angle. This implies that a high tool tilt angle is associated with a high applied force and climax temperature and vice-versa. Notwithstanding, as the tool tilt angle increases there is the possibility of having increased tool pin breaking arising from an increased wear rate.

4.2 Taguchi method

Table 1 displays four parameters and five levels. To proceed with the evaluation of the parameters using the Taguchi technique, an L25 orthogonal array is deployed (Table 2).

Table 2. An orthogonal array of the work

	Orthogonal array				Interpreted value for the orthogonal array						
Exp. trial	**TPP**	**RS**	**WS**	**TTA**	**TPP**	**RS**	**WS**	**TTA**	**SNR**	**Cum. SNR**	**Cum. SNR%**
1	1	1	1	1	-2	400	45	0.5	40507.31	40507.31	2
2	1	2	2	2	-2	500	55	1.0	63257.50	103764.8	4
3	1	3	3	3	-2	600	65	1.5	91057.81	194822.6	8
4	1	4	4	4	-2	700	75	2.0	123908.25	318730.9	13
5	1	5	5	5	-2	800	85	2.5	161808.81	480539.7	20
6	2	1	2	3	-1	400	55	1.5	40757.06	521296.7	22
7	2	2	3	4	-1	500	65	2.0	63557.50	584854.2	24
8	2	3	4	5	-1	600	75	2.5	91408.06	676262.3	28
9	2	4	5	1	-1	700	85	0.5	124306.56	800568.9	33
10	2	5	1	2	-1	800	45	1.0	160506.75	961075.6	40
11	3	1	3	5	0	400	65	2.5	41057.81	1002133	42
12	3	2	4	1	0	500	75	0.5	63906.31	1066040	44
13	3	3	5	2	0	600	85	1.0	91806.50	1157846	48
14	3	4	1	3	0	700	45	1.5	123006.81	1280853	53
15	3	5	2	4	0	800	55	2.0	160757.25	1441610	60
16	4	1	4	2	1	400	75	1.0	41406.75	1483017	62
17	4	2	5	3	1	500	85	1.5	64307.06	1547324	64
18	4	3	1	4	1	600	45	2.0	90507.50	1637832	68
19	4	4	2	5	1	700	55	2.5	123258.06	1761090	73
20	4	5	3	1	1	800	65	0.5	161056.56	1922146	80
21	5	1	5	4	2	400	85	2.0	41808.25	1963954	82
22	5	2	1	5	2	500	45	2.5	63008.81	2026963	84
23	5	3	2	1	2	600	55	0.5	90757.31	2117721	88
24	5	4	3	2	2	700	65	1.0	123557.50	2241278	93
25	5	5	4	3	2	800	75	1.5	161407.81	2402686	100

Key: Tool pin profile, TPP; Rotational speed (rpm), RS; Welding speed (mm/min), WS; Tool tilt angle (degree), TTA

This consists of twenty-five experimental trials and the matrix has randomly distributed members between 1 and 5 representing different levels of parameters in the process. The actual values represented by the actual values are interpreted from the factor-level table as where an intersection of a particular factor meets the level, Table 2. Recall that the objective of this study is to optimize the process parameters. But a choice among the smaller the better, larger the better and nominal the best needs to be made according to the needs of the process.

Thus, after careful consideration, the smaller-the-better criterion of the signal-to-noise ratio was chosen as the most suitable choice in the situation of welding the AA5052-H32 material. To use the smaller-the-better criterion, Equation (1) is recalled from the methods section. However, to implement this equation, each item of the experimental trial has to be squared considering each parameter. For instance, for experimental trial 1, the values of -2, 400, 45, and 0.5 units are attached to the parameters of tool pin profile, rotational speed, welding speed and tool tilt angle, respectively. But by squaring each parametric value and summing up their values regardless of their units, the logarithm of the product of the sum of factors and the inverse of the number of factors is obtained. This value is further multiplied by -10 to finally obtain 40507.31. By a similar computational activity, the experimental trial two results are 63257.50. Furthermore, all other values of experimental values three to twenty-five are obtained. Overall, the highest value obtained is 161808.81 (experimental trial 5) while the lowest value is 40507.31 (experimental trial 1).

The computation of the signal-to-noise response table is the next step in which the averages of the signal-to-noise ratios are computed as per each level and factor. In essence, each factor for a particular level will be traced to a previous table and the corresponding values to the choice of the levels are not noted and averaged (Table 3).

Table 3. Signal-to-noise response table for the Taguchi method

Levels	TPP	RS	WS	TTA
1	96107.94	41107.44	95507.44	96106.81
2	96107.19	63607.44	95757.44	96107.00
3	96106.94	91107.44	96057.44	96107.31
4	96107.19	123607.44	96407.44	96107.75
5	96107.94	161107.44	96807.44	96108.31
Delta	0.75	120000	1300	1.5
Rank	4th	1st	2nd	3rd

Key: Tool pin profile, TPP; Rotational speed (rpm), RS; Welding speed (mm/min), WS; Tool tilt angle (degree), TTA

For instance, consider the value of 96107.94 at the intersection of the tool pin profile and level 1 in the matrix containing the signal-to-noise response table, Table 3, the question of how to obtain it is interesting. To obtain this, Table 2 is considered. Recall that at the moment, the concern is the corresponding values to level 1 indicated by 1 along the column representing the tool pin profile of Table 2. These are located at experimental trials 1, 2, 3, 4 and 5 with the corresponding signal-to-noise ratio values traced in Table 2 as 40507.31, 63257.50, 91057.81, 123908.25 and 161808.81. By taking the average of these numbers, the values of 96107.94 are obtained as investigated. Furthermore, other values are obtained similarly as shown in Table 3. From Table 3, the optimal parametric setting of the friction stir welding process of AA5053H32 material is contemplated as $TPP_2/TPP_4RS_1WS_1TTA_1$, which is interpreted from Table 1 as the -2 or 1 of tool pin profile (tapered), 400rpm of rotational speed, 45mm/min of welding speed and 0.5 of tool tilt angle.

The mentioned optimal parametric settings are to optimize the friction stir welded joints of AA5052-H32 material by obtaining the optimal process parameters as specified, for the tool tilt angle, tool pin profile, rotational speed and welding speed to yield the desired tensile strength and hardness using the Taguchi method. Notwithstanding, the delta values are obtainable from Table 3 as the difference between the highest and lowest values of the average signal-to-noise ratios along the column representing the particular parameters. To understand how it is done, consider the tool pin profile, which occupies the second column of Table 3. The highest and lowest values are 96107.94 and 96107.19, respectively, and the difference is 0.75, which represents the delta value for the tool pin profile parameter. By following similar steps, the delta values of other parameters are computed. However, among all the delta values, rotational speed has the highest value of 120000, which is considered first in rank. This is followed by welding speed with a delta value of 1300 as second, tool tilt angle as third, and tool pin profile as fourth. The implication of these ranks is for resource distribution during the planning of the welding tasks. It means that more resources should be committed to enhancing the rotational speed and the least should be given to the tool tilt angle.

4.3 Taguchi-Pareto method

To commence with the Taguchi-Pareto method, the process of computing the Taguchi method was followed to the point of signal-to-noise generation. Then the cumulative SNR is introduced which is the cumulative value of the SNR for experimental trials from 1 through 25. Then these SNRS are converted into percentages in an additional column of Table 2. By tracing the values of the cumulative SNR %, it was noticed that 80% falls on experimental trial 20. Therefore, experimental trials 21 to 25 are discarded from further computations. The next stage is to interprete the spread of the orthogonal array and observes how the new cut-off point influences the computation of the optimal parametric setting, ranks and delta value of the parameters. Therefore, the next computation is regarding the response table. In the response table, there is a division per parameter per level. The starting point here is to compute the levels for parameters starting from level 1 for TPP. By taking note of all the codes named "1" in the orthogonal array under TPP, the associated experimental trials are 1, 2, 3, 4 and 5 while the associated SNRs are 40507.31, 63257.50, 91057.81, 123908.25 and 161 808.81. The sum of these SNRs is 480539.7 while the average is 96107.94. For level 2 of TPP, the associated code of "2" is with experimental trials 6 to 10. The corresponding values to experimental trials 6 to 10 are 40757.06, 63557.5, 91408.06, 124306.56 and 160506.75. But the average of the SNR is 96107.19. For level 3, the code "3" is associated with experimental trials 11 to 15 and the average of the associated SNRs is 96106.94. For level 4 of TPP, the code "4" for the orthogonal array is traced to experimental trails 16 to 20 and the corresponding SNRs are 41406.75, 64307.06, 90507.5, 123258.06 and 161056.56. The average of these numbers is 96107.19. However, by following this procedure a complete Table 4 is obtained.

Table 4. Signal-to-noise response table for the Taguchi-Pareto method

Levels	TPP	RS	WS	TTA
1	96107.94	32745.79	82905.67	77955.35
2	96107.19	51005.67	77605.97	71395.50
3	96106.94	72955.97	71345.94	63825.75
4	96107.19	98895.94	64125.87	87746.10
5	-	128825.87	88445.79	83506.55
Delta	1.00	96080.08	5549.12	23920.35
Rank	4th	1st	3rd	2nd

For the Taguchi-Pareto method, recall that experimental trails 21 to 25 are regarded as irrelevant to the goal of the friction welding process and discarded. Therefore the average value for level 5 of the TPP parameter does not exist. Then the cell is left blank as no value is recorded for it. It should be appreciated that when the Taguchi method was used for the analysis level 5 of the TPP parameter yielded 96107.94 but this is ignored using the Taguchi-Pareto method. However, when the delta values for the TPP, for the Taguchi-Pareto method, which is 1.00 was compared with what was previously obtained for the results using the Taguchi method alone (i.e. 0.75), there is a change of 0.25. Hence, the introduction of the Pareto method does not affect the Taguchi method significantly for TPP.

Next, the RS parameter is considered with only four values of the SN ratios considered since experimental trials 21 to 25 have been discarded. In this instance, only 40507.31, 40757.06, 41037.81 and 41406.75 are added up and the average is found. The average is obtained as 32745.79. However, by following the logic, for levels 2, 3, 4 and 5 of RS, the averages of the SN ratio obtained are 51005.67, 72955.67, 98895.94 and 128825.9, respectively. By following the same approach for levels 1,2,3,4 and 5 for WS, the averages of the SN ratios obtained are 82905.67, 77605.97, 71345.94, 64125.87 and 88445.79. Also for levels 1, 2, 3, 4 and 5 of TTA, the averages of the SN ratios are 77955.35, 71395.5, 63825.75, 87746.1 and 83506.55.

4.4 Comparison of the present results with the previous literature outcomes

This result is at variance with the suggestion of Shamsudeen and Dhas (2018) whose data has been used for analysis in this work. Compared with the present outcome, the choice of the tapered square pin was made by the previous article against the hexagonal shape recommended in the present report for the rotational speed, the previous article recommended 600rpm against 400rpm in the present article. Furthermore, 60mm/min and 1.9° were recommended by the previous article on the welding speed and tool tilt angle parameters against 45mm/min and 0.5° of welding speed and tool tilt angle parameters in the present article. Notice that the recommendations of the previous article are based on the grey relational analysis method while the present article considers the Taguchi method. Furthermore, by careful consideration of the tool rotational speed and the welding speed, which requires energy for their activation, it is the opinion of the present authors that setting the optimal parameters at lower values would require less energy and conserves the energy of the process. Accordingly, it is reasonable to prefer the results of the Taguchi method presented in the present article to the submission of Shansudeen and Dhas (2018) since it requires less energy for its actualization for the AA5052-H32 material.

However, further progress could be made by statistically comparing the outcomes of the Taguchi method with that of the grey relational analysis method. In this instance, the results from the Taguchi method are adopted as the observed values while those of the grey relational analysis is taken as the expected values in a chi-square statistical analysis using an online chi square calculated. To adapt the data to a form that could be processed by the calculator, remember the shapes of the tool are hexagonal, square, etc represented by -2, -1, 0, 1, 2. But for the Taguchi results, -2 is the result while the square shape is 0. But on attempting the computation using these values for the chi-square, the calculator displays an error function that explains that the calculator does not support zero as a cell value. To solve this problem, the negative sign is first ignored and an incremental step of 1 was made such that for the Taguchi method, the hexagonal shape is assigned a value of 3 while the square shape of the grey relational analysis method is given a value of 1. Further, the significant level is fixed as 0.05, with the set of values for the Taguchi method as 3, 400rpm, 45mm/min and 0.5° for the shape of the tool (tool pin profile), rotational shape, welding speed and tool tilt angle, respectively. Besides, the results reported for the grey relational analysis by Samsudeen and Dhas (2018) are 1, 600rpm, 60mm/min and 1.9° for tool pin profile, rotational speed, welding speed and tool tilt angle respectively. The chi-square statistic is then 2.3809 and the p-value is 0.4972, which means that the result is not significant. It suggests that there are no differences between the results of the two methods of Taguchi and grey relational analysis. The p-value is $p<0.05$.

Shamsudeen and Dhas (2018) deployed a combination of the response surface methodology and the grey relational analysis to improve the tensile strength and hardness of weldments from the AA5052-H32 material using the friction stir welding process. A feasible combination of the optimal process parameters involving the rotational speed, tool tilt angle, tool pin profile and welding speed was declared. Besides, Jain and Kumar (2021) also considered the tensile strength as a critical output of the friction stir welding where the candidate is the AA6061-T6 material. Being consistent with the choice of an optimal approach dissimilar to Shamsudeen and Dhas' choices, the authors declared the Taguchi method with an embedded grey relational analysis as the preferred quantitative tool. Also, while the welding speed tool rotation speed is common to both papers, the shoulder diameter was a different parameter considered in the work. The conclusion was that the Taguchi method appropriately established the optimum process parameters that substantially enhanced the friction stir welding possess of the AA6061 material.

Second comparison

The results of the grey relational analysis obtained by Shamsudeen and Dhas (2018) were compared with those obtained by the present tool, namely the Taguchi method according to the following analysis. To start with, the available information to the researcher from the present analysis is the averages of the signal-to-noise ratios, which were computed at five levels. However, to compare results, the present author looked at Equations (2) and (3) of Shamsudeen and Dhas (2018) to find the possibility of expressing the averages of the signal-to-noise ratios by levels in a similar relationship where the UTS and Hardness, represented as it could be developed as predictive equations with which the results of the grey relational analysis of Shamsudeen and Dhas (2018) and the Taguchi method in the present study may be compared. To achieve this, the present authors started with the UTS element. Here, the data in Table 4 of Shamsudeen and Dhas (2018), which expresses the computational results of the problem solved is examined by focusing on the UTS data in the second column of Table 4. Accordingly, the 31 data points were re-arranged as follows: 175.09, 175.69, 179.48, 182.56, 184.27, 184.97, 190.16, 190.21, 191.48, 191.81, 193.48, 193.99, 194.34, 194.72, 195.39, 195.39, 196.09, 196.62, 196.79, 196.84, 196.95, 197.58, 198.64, 198.64, 198.78, 198.80, 199.13, 199.43, 199.55, 200.03, 200.32, 201.42, and 202.04. Now, the dataset was divided into five categories each category representing levels 1 to 5 respectively. Since there are 31 data points there is no equal segregation that could be made with 6 data elements per group without having an extra data point. Consequently, it was decided to add this extra data to the first set since it has a low set of values compared to others. Thus, the first 7^{th} data point was taken as level 1 and the average was obtained to represent the UTS level 1. Also, the 8^{th} – 13^{th} data points were averaged as the representative of level 2. Accordingly, the averages of data from14^{th} to the 19^{th} represent level 3. For level 4, the averages of data points from the 20^{th} to 25^{th} were taken and for level 5, the averages of data points from the 26^{th} to 31^{st} were taken as the representatives of the group. The results for levels 1 to 5 are 179.42 MPa, 189.73MPa, 194.34MPa, 194.35MPa and 198.96MPa.

Besides, in Arya et al. (2022), the same material studied in the present article was analyzed under the Taguchi method. However, there are differences in results. First, while the rotational speed of the tool was ascertained as 400 rpm in the present study, it had a 150% increase in this value (i.e.100 rpm) when compared with Arya et al. (2022). Perhaps the difference in result was caused by the interactions of different parameters with the rotational speed of the tool. While the impact of the choice of tool profile as hexagonal, the welding speed and tilt angle drastically reduced the tool rational speed to 400 rpm, the impact of the choice of table movement and tool shoulder diameter on the tool rational speed drastically increased the value of the tool rational speed. Besides, in the present work, there are four factors considered whereas only three factors were considered by Arya et al. (2022) and more interactions become. Besides, there is no analysis concerning the combined optimization and prioritization in Arya et al. (2022) whereas it was explored and successful results were obtained in the present study.

5. CONCLUSIONS

In friction stir welding processes, studies are rare where optimization and prioritization are pursued. Although few methods address optimization such as the Taguchi method, grey relational analysis, grey wolf optimization and cuckoo search algorithm, and some prioritization schemes such as Pareto, ABC, etc., establishing the two issues of optimization and prioritization are sparsely noticed in the literature. In this article, the performance of weld quality of the AA5052-H32 aluminium alloy is analyzed and the Taguchi-Pareto method is used employing literature data from Shamsudeen and Dhas (2018). The chosen material is interesting being a material that contains 2.5% magnesium, is strain-hardened and steady through low-temperature heating and the material is one-quarter hard. It has a wide application to manufacture fuel tanks, and refrigerators among others. Specifically, the present study was conducted to tackle the problem of optimal parametric determination for the AA5052-H32 material using the Taguchi-Pareto method to obtain the optimal tensile strength of the joint.

However, the following conclusions are relevant to the study;

1. For the Taguchi-Pareto method, the greatest influence of the parameters on the tensile strength of the AA5052-H32 material was noticed with the rotational speed parameter which achieved first in rank. However, the least influence on the tensile strength outcome of the tool pin profile is with the fourth position.
2. The optimal parametric setting for the friction stir welding process of AA5052-H32 material using the Taguchi-Pareto methods is considered $TPP_2/TPP_4RS_1WS_4TTA_3$. This is interpreted as cylindrical tapered or square tapered for the tool profile, 40 rpm of rotational speed, 75 mm/min of welding speed and 1.5° of tool tilt angle.
3. When comparing the results of these parameters for the friction stir welding process using the Taguchi method and Taguchi-Pareto method, the following was observed. The rotational speed retained its first position in both methods; the tool tilt angle gained the second position in the Taguchi Pareto method from its third position when only the Taguchi method was considered. The welding speed became the third position in the Taguchi-Pareto method against the second position that it had in the Taguchi method. However, the tool pin profile retained its last position in both methods. Consequently, the rotational speed is the best parameter while the tool pin profile is the worst parameter.
4. The results showed the feasibility of applying the methods in a case situation. As no study was found regarding the use of the Taguchi-Pareto method concerning the friction stir welding of AA5052-H32 aluminium alloy.

Furthermore, in the literature on aluminium alloy processing, several types of aluminium have been analyzed, including the AA5454-AA775, the combination of AA6062-T6 and AA6061-T6. Others are the AA1100, AA6082, AA5083-H111, AA5050-H32, AA5083 and AA6063. However, only one type of aluminium alloy such as the AA5052-H32 was treated in this article. Therefore, the single treatment of an aluminium alloy is a limitation of the present study. Further work could extend the analysis proposed in this article to other aluminium types. Besides, enhancing the performance of the Taguchi-Pareto method by integrating artificial neural networks into it will be beneficial for future work. Moreover, in this article, the application of the Taguchi-Pareto method in solving the friction welding problem has been simplified using only four parameters. However, the reality is more complex than the case presented as the number of parameters could be several, running sometimes into tenths of parameters. In this case, it will be difficult to solve the problem using the presented approach. Then, in the future, the new complex model may be subjected to dimensionality reduction before optimization. The benefit is that the idea of dimensionality reduction will permit focusing on the important parameters at the outset (before optimization), improving the convergence rate and results. This is achieved as the search space is reduced, making the search effort more efficient.

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