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FSW tool design using TRIZ and parameter optimization using Grey Relational Analysis

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Abstract

In this work, a new tool geometry was designed which combines the geometry features of both conical and square pin profiled tool. The tool pin profile is made based on theory of inventive problem solving technique where the tool pin has four grooves on the conical pin. Effect of this tool design on mechanical properties of friction stir weldments of AA 2014-T6 aluminium alloy was studied. The process parameters were optimized using grey based Taguchi method. Experimental results have shown that optimal process parameters can be determined effectively so as to improve multiple weld quality characteristics through this approach.

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Keywords: Friction Stir Welding; Mechanical property; TRIZ; Tool Geometry; Taguchi Method; Grey Relational Analysis.

1. Introduction

AA2014 is a heat treatable aluminium alloy; possesses good combinations of high strength (especially at elevated temperatures), toughness and is widely used in aircraft primary structure, heavy-duty forgings, plate, extrusions for aircraft fittings, wheels, major structural components, space booster tankage, truck frame and suspension components [1]. However, this particular alloys hard to weld by fusion welding due to porosity formation, oxide

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inclusions, hot cracking, hydrogen pick-up during melting and re-solidification process, and dendrite structure formed in fusion welding which can affect the weld properties seriously [2]. It is agree that the hardness in the weld zone (WZ) and heat affected zone (HAZ) of friction stir welded (FSW) joints is lower than the base metal which results in lower joint efficiency thereby failure at the WZ. To improve the joint efficiency as well as strength/mechanical properties newer, techniques/method/processes must require initiative steps. FSW is a relatively new solid state localized thermo-mechanical process which is used for butt and lap joints, and it is presently attracting considerable interest and has been extensively developed for alloys of Al, Mg, Cu, Ti, Steel as well as dissimilar materials. In the last two and half decade, significant developments have been achieved in FSW process concerning welding tools, shoulders and tool pin profiles. The tool design plays a vital role in material flow, temperature history, grain size, and mechanical properties in the FSW process. The plastic deformation and the frictional heating of the workpiece are necessary for friction stirring and are influenced by the FSW tool design [3]. The shoulder and pin diameter; tool pin profile and pin length; and shoulder pattern are critical parameters in determining the quality of welds [4]. The tool pin disrupts the contact surfaces of the workpieces to be welded, to shearing of the material in its front and movement of the material behind the tool.

As far as FSW process is concern, the process is started from almost two and half decade ago. It is reported that the FSW technology is not yet fully developed, and it is anticipated that significant developments in tool design, tool materials, process control, etc., will continue [5]. TRIZ which is an acronym for the theory of inventive problem solving in Russian. TRIZ method is an effective tool, especially when used for solving problems of product/process development [6]. Following reported literature applied TRIZ methodology for product design problems: Total Knee Prosthesis [7], deburring tools for intersecting holes [8], metal seated ball valve mechanism [9], automotive headlight [10], CAD/CAM systems [11], automated manufacturing system [12], and friction stir welding process[13]. Concerning these literatures an attempt is made to employ TRIZ approach for the innovative solution to the FSW tool design and later with this FSW tool the microstructure and mechanical properties was studied using Taguchi's orthogonal array design of experiment method. The TRIZ principle states that first transforms the ordinary problems into TRIZ problems, and then takes advantage of tools such as Inventive Principles, Standard Techniques to find the similar solution. The specific process is shown in Fig. 1.

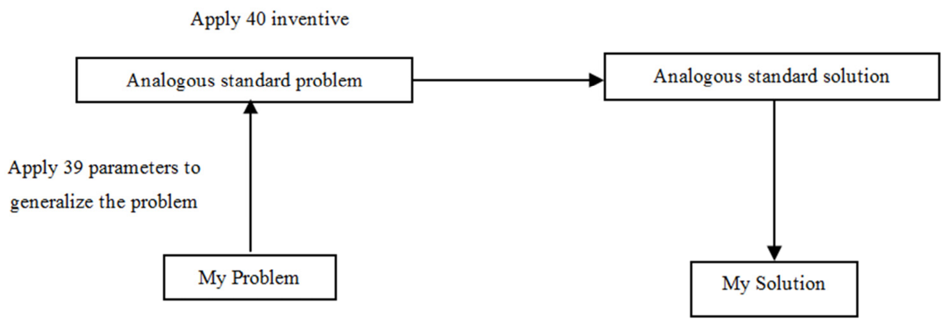

Fig. 1. TRIZ approach.

2. Development of FSW tool pin geometry using classical TRIZ method

Table 1 shows 39 TRIZ parameters which are concepts from numerous physical parameters of real-world problems. In the present work, the physical parameter of FSW tool is pin geometry, which is the single most influential parameter on the joint strength in comparison to other parameters such as pin height and pin diameter. The tool pin is mainly responsible for controlling the weld speed and deformation depth [4]. Also, its geometry influences the plasticized flow of material and joint performance [14–17]. So, the present situation may be stated as "The FSW tool pin profile needs to be modified such that joint strength will improve without affecting the hardness at the WZ." This is a clear contradiction between the need for modification of the tool geometry. TRIZ contradiction analysis suggests solution guidelines for the given problem. In the TRIZ contradiction analysis, the real world solution strategies are classified into 40 solution principles [18]. The 39-by-39 contradiction matrix [19] for TRIZ analysis enlists solution principles for each combination of "feature to improve" from 39 rows and "worsening feature" from 39 columns. In the current problem, the "feature to improve" is the strength of the joint, which may correspond to the 14th parameter "strength." The "worsening feature" is the loss of hardness at the weld zone, which can be correlated with the 23rd parameter "Loss of substance" or the 31st parameter "Object generated harmful." For each combination of the "feature to improve" and the "worsening feature," the TRIZ contradiction matrix [19] suggests several candidates from the 40 generalized solution principles, shown in Table 1. The principles of dynamics (15), Blessing in Disguise (22), Taking out (2), mechanics substitution (28), porous materials (31) and composite materials (40) seems to be irrelevant to the current problem. Concerning parameter changes (35) principle, i.e. change an object's physical state. Hence, change in tool pin profile is essential for the joint strength improvement.

Table 1. Contradiction matrix for the joint strength improvement

Feature to improve ↓	Worsening feature →	
	Loss of substance	Object generated harmful
Strength	35,28,31,40	15,35,22,2

From the reported literature it is evident that conical pin profiled tool gives better results than cylindrical pin profiled tool and square pin tool gives the better result than non-cylindrical tools [20]. In this work, a new tool geometry was designed which combines the geometry features of both conical and square tool pin profile. Based on this concept, the two tool pin geometries were design and manufactured using theory of inventive problem solving (TRIZ) concept (Fig. 1). Figure 2 (a-b) shows the new tool pin geometries designed in a similar way as household lassi/curd making stirrer Fig. 2 (c-d). The stirrer's useful function is to mix the curd/lassi thoroughly in a similar way as FSW tool.

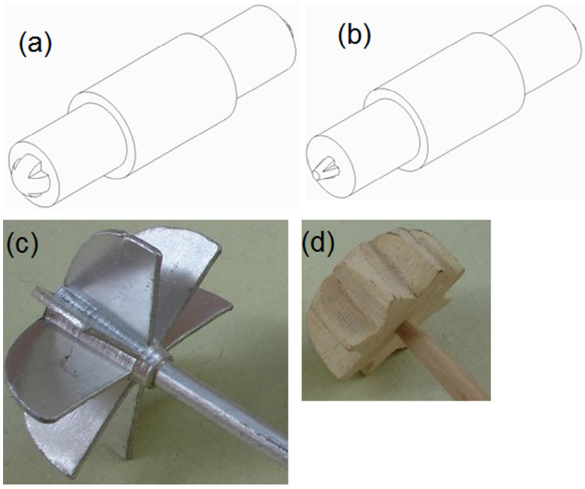

Fig. 2. Schematic diagram of FSW tool (a) Hemispherical Square Plus; (b) Conical square plus; (c) Lassi/Curd making aluminium stirrer; (d) Wooden Lassi/ Curd making stirrer.

In this paper, the use of the grey-based Taguchi method to optimize the FSW process parameters with considerations of multiple weld quality characteristics such as ultimate tensile strength, percentage elongation, impact strength and hardness is reported. The Taguchi method is a systematic application of design and analysis of experiments for the purpose of developing and improving product quality. In the following, an overview of the optimization of the multiple performance characteristics by the grey-based Taguchi method is given first. Then, the selection of FSW process parameters and the evaluation of FSW weld qualities are discussed. Optimization of the FSW process parameters based on the grey-based Taguchi method is described in detail. Finally, the paper concludes with a summary of this study.

3. Grey-Based Taguchi Method

The grey system theory proposed by Deng [21] has been proven to be useful for dealing with inadequate, incomplete, and uncertain information. The grey relational analysis (GRA) based on the grey system theory can be used to solve complicated inter-relationships among multiple performance characteristics effectively. Through the GRA, a Grey relational grade (GRG) is obtained to evaluate the multiple performance characteristics. As a result, optimization of the complicated multiple performance characteristics can be converted into optimization of a single GRG. It is shown by this study that the use of the Taguchi method with the GRA can significantly simplify the optimization procedure for determining the optimal welding parameters with the multiple performance characteristics in the FSW process. Optimization of process parameters is the key step in the Taguchi method in achieving high quality without increasing the cost. This is because optimization of process parameters can improve performance characteristics and the optimal process parameters obtained from the Taguchi method are insensitive to the variation of environmental conditions and other noise factors. To solve this task, the Taguchi method uses a particular design of orthogonal arrays to study the entire process parameter space with a small number of experiments only.

Then, the GRG is computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple performance characteristics is based on the GRG. As a result, optimization of complicated multiple performance characteristics can be converted into the optimization of a single GRG. The optimal level of the process parameters is the level with the highest GRG. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the grey relational analysis and statistical ANOVA, an optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the process parameter design.

4. Experimental Procedure

In this study, the number of process parameters considered were three, and the level of each parameter was three as shown in Table 2. The degrees of freedom of all three parameters were two (i.e. number of levels-1) and the total degrees of freedom of all the factor is 6 (i.e. 3×2 = 6). The selected orthogonal arrays (OA) degrees of freedom (DOF) (i.e. number of experiments – 1= 9 – 1 = 8) must be greater than the total DOF of all the factors (6). Hence, L_9 (3^4) OA is considered for the present study. Based on the preliminary experimentation, there is no interaction between the selected process parameters. Hence, interaction is not considered for the present study. The working range of process parameters was decided by exploring the different process parameters within the range of machine's capabilities using Taguchi's one parameter at one time approach. It was observed that, out of two tool geometries, one of the tool pin geometry was failed to perform FSW i.e. Fig. 2 (a). This tool pin created a slot instead of welding which is attributed due to large surface area of the tool pin. Then experiments were performed using second tool pin (Fig. 2 b) i.e. Conical bottom plus.

Table 2. Weld Parameters and Their Levels.

Sr. No.	Welding parameter	Unit	Level 1	Level 2	Level 3
1	Tool Rotational Speed (TRS)	rpm	710	900	1180
2	Weld Speed (WS)	mm/min	49	83	108
3	Tilt Angle (TA)	degree	2	3	4

Experiments were conducted under different welding conditions to estimate the weld properties. The workpiece material selected for the experiments was AA 2014-T6 Aluminium alloy. AISI H13 tool steel is chosen as a tool material for conducting the FSW of AA2014-T6 Aluminium alloy. The FSW process was carried out on a vertical milling machine (Make: G. Dufour Montrenil, 7.5 HP, 1500 rpm). The workpiece of 300 mm × 80 mm size and 5 mm thickness was selected. After machining the tool of required dimension and then subjected to heat treatment process and final hardness obtained for AISI H13 tool steel was ~53 HRC.

Specimens for transverse tensile testing were prepared as per ASTM A 370: 2012 standards and conducted using a computer controlled universal testing machine (Make: Shimadzu, Model: AGIS Autograph) with a crosshead speed of 0.5 mm/min. The process parameters levels and the experimental values are shown in Table 3. Sub size Charpy V-notch impact specimens were prepared and tested using impact testing machine (Make: F.I.E. Ichalkaranji, Model: IT-30) according to ASTM E23: 2008. A nominal striking energy of pendulum 300 J was used with 8 mm dimension of striker tip. The microstructural analysis of FSWed joints was carried out using inverted optical electron microscope (Make: Metavis) with image analyzing software (Make: Biovismat, Model: MetImage Lx). The microstructure at different locations of the weld was examined after preparation of sample using conventional metallographic techniques (For rough grinding grade 160 emery paper was used, further grinding using emery paper of grades 600, 800, 1000, and 1200) and etching with Keller’s reagent (2 ml HF, 3 ml HCL, 5 ml HNO_3, 190 ml H_2O). In order to characterize the FSWed surface, hardness test was performed by using Vickers digital micro-hardness tester (Make: Chennai Metco Pvt. Ltd, Chennai, Model: Economet VH-1).

Table 3. Experimental layout using L_9 orthogonal array.

Exp. No.	Welding process parameter			TS (MPa)		PE		IT (J)		
	TRS	WS	TA							
1	710	49	2	332.92	330.88	5.3	5.80	4	4	4
2	710	83	3	101.46	155.2	0.04	0.1	4	4	4
3	710	108	4	184.22	142.70	0.24	0.12	4	4	4
4	900	49	3	265.45	226.62	2.80	1.6	4	4	4
5	900	83	4	127.19	99.64	0.3	0.2	4	2	2
6	900	108	2	130.72	58.57	0.2	0.06	2	2	2
7	1180	49	4	93.33	125.94	0.1	0.12	2	4	2
8	1180	83	2	260.6	216.24	3.5	1.9	2	2	2
9	1180	108	3	113.22	69.4	0.04	0.14	2	2	2

5. Results and discussions

5.1. Microstructure

The macrostructures at different conditions including base material, WZ, thermo-mechanically affected zone (TMAZ) and HAZ along with nature of defects of nine FSW experiments at different process parameter combination is shown in Fig. 3. It is observed that the WZ is approximately symmetric about the weld centerline, it is typically similar in diameter of the tool pin and it is most projecting feature of the WZ. In this region much smaller and equi-axed grains are observed compare to the base metal microstructure is as shown in Fig. 3. The region followed by the WZ is TMAZ, which is clearly identified by the comparing the grain structure between TMAZ and WZ. In the TMAZ flow lines are altered by plastic deformation. Grain structure observed in the TMAZ are coarser due to less heat generation and stirring action as shown in Fig. 3. In this region, the FSW tool plastically deforms the material and the heat from the process will also exert some influence on the material. It is possible to obtain significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone and the deformed zones of the TMAZ. The region followed by the TMAZ is HAZ, which is clearly identified by the comparing grain structure between them. In this region, which lies closer to the weld-center, the material experiences a thermal cycle that has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occur in this area.

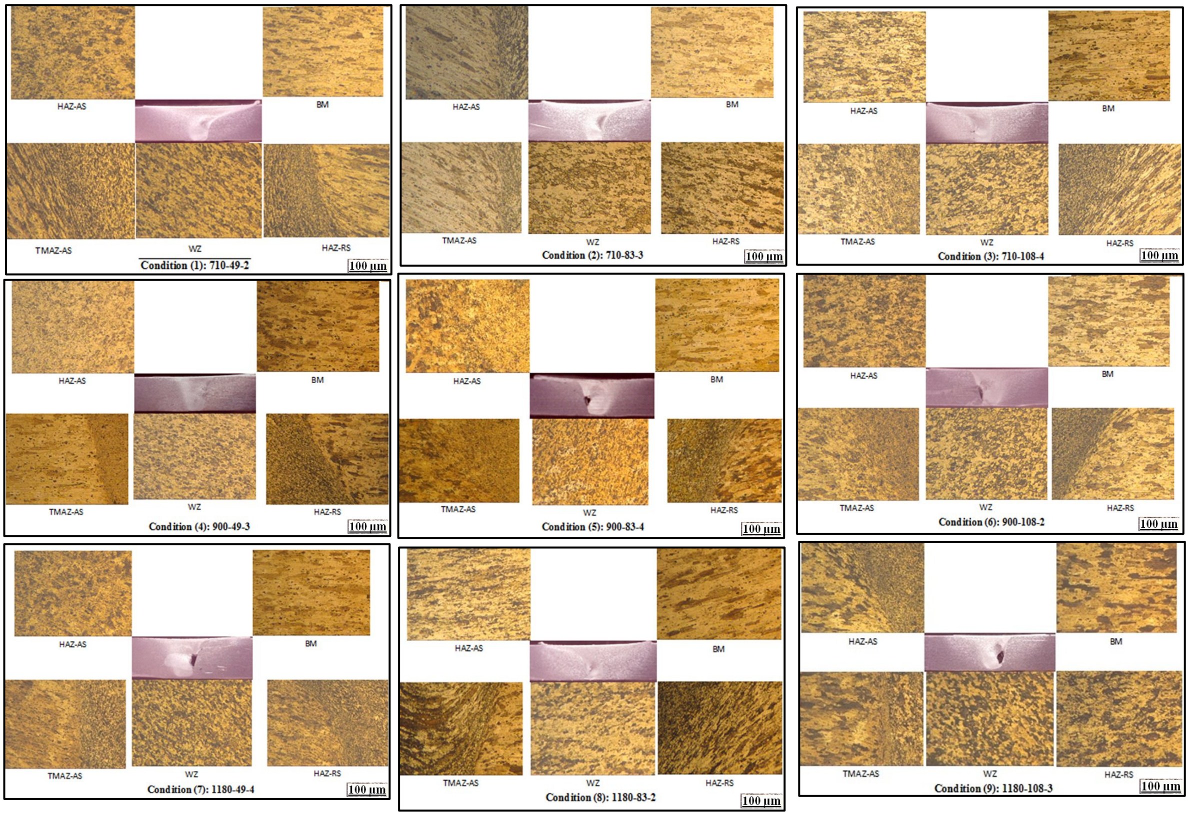

Fig. 3. Effect of process parameters on microstructures at different regions of the WZ of the joints fabricated by Conical square plus tool pin profile

5.2. Microhardness

The micro-hardness graph at different process parameter combinations is shown in Fig. 4. At constant tool rotational speed (710 rpm) and increasing weld speed and tilt angle hardness decreases as shown in Fig. 4. This is due to less heat is generated at higher weld speed which affects the process of recrystallization i.e. microstructure shows elongated grain structure as shown in condition (2) and (3) compared to condition (1) in Fig. 3. Similarly increasing tilt angle widens the gap between the tool shoulder and base material which causes more material will flash out and due to which defect like tunnel and pin hole are observed. Macrostructure of the weldment of condition (1) and (2) shows the defect-free surface of weldment and macrostructure of condition (3) shows defect like pin hole due to insufficient heat developed which unable to produce dynamic recrystallization. From the above study it is observed that condition (1) i.e. (710-49-2) shows highest value of hardness i.e. 173 Hv.

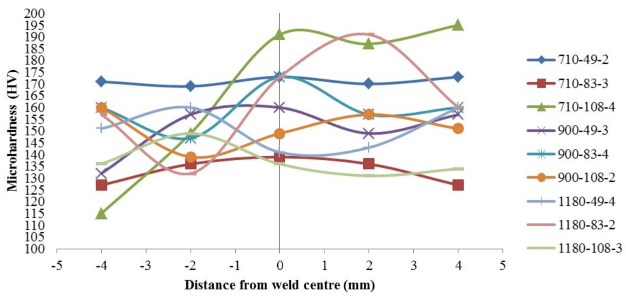

Fig. 4. Microhardness distribution of the FSWed joints in as welded condition carried out using different process condition

If the joints are defective, then the failure takes place along the defects. If the joints are defect-free, then the failure takes place along the lowest hardness region. In Fig. 3, it is observed that the macrostructure of the condition (5 and 6) shows defect like pin hole and tunnel defect. Hardness value recorded in the condition (4 and 6) is lower in the WZ compared to condition (5). The lowest hardness value in the WZ region was observed in condition (8) due to improper consolidation of material on advancing side. On the contrary, condition (7 and 9) shows lower hardness values when compared with condition (8) due to defect observed in the macrostructures. Macrostructure result of the condition (8) shows defect free weld region. From condition (7 and 9), it is observed that at higher constant value of tool rotational speed and increasing the weld speed and tilt angle exhibits lower value of hardness.

5.3. Grey Relational Analysis

The first step in GRA is normalization. Experimental data is normalized in the range between zero and one. In order to express the relationship between the ideal (best) and the actual experimental data, the grey relational coefficient is calculated from the normalized experimental data. GRG is calculated by averaging the grey relational coefficients corresponding to each performance measure. The experimental data of the multi-response characteristics is evaluated by using GRG. The optimum level of the process parameters is the level with the highest GRG.

The data sequence for tensile strength (larger-the-better performance characteristic), is normalized as follows:

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{1}$$

Where, k = 1 to n, i = 1 to 9, n is the performance characteristic, and i is the trial number. The normalized values are shown in Table 4. The grey relational coefficient [$\xi_i(k)$] is calculated as follows:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta\Delta_{\min}}{\Delta_{0i}(k) + \zeta\Delta_{\max}} \tag{2}$$

Note that larger-the-better is achieved when xi(k) = x_0(k), i.e., when x = reference.

Table 4. Normalized values of the response

Exp. No.	TS		PE		IT		
	Trail 1	Trail 2	Trail 1	Trail 2	Trail 1	Trail 2	Trail 3
1	1	1	1	1	1	1	1
2	0.0339	0.354853	0	0.0273	1	1	1
3	0.3794	0.308949	0.0380	0.0307	1	1	1
4	0.7184	0.617128	0.5247	0.2833	1	1	1
5	0.1413	0.150821	0.0494	0.0444	1	0	0
6	0.1561	0	0.0304	0.0205	0	0	0
7	0	0.247402	0.0114	0.0307	0	1	0
8	0.6982	0.579009	0.6578	0.3345	0	0	0
9	0.0830	0.20069	0	0.0341	0	0	0

Here, $x_0^*(k)$ denotes the reference sequence $x_j^*(k)$ indicates the comparability sequence, $\zeta \in [0-1]$ is the distinguishing coefficient; 0.5 is widely accepted, $\Delta_{0i} = \left\| x_0^*(k) - x_i^*(k) \right\|$ is the difference in absolute value between $x_0^*(k)$ and $x_i^*(k)$,

$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall j \in k} \left\| x_0^*(k) - x_i^*(k) \right\|$ is the smallest value of Δ_{0i}, $\Delta_{\max} = \max_{\forall j \in i} \max n_{\forall j \in k} \left\| x_0^*(k) - x_i^*(k) \right\|$ is the largest value of Δ_{0i} .After calculating Grey relational coefficients, the GRG is obtained as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \tag{3}$$

Where γ_i the GRG and 'n' is is the number of performance measures. The grey relational coefficients and corresponding GRG for each experiment are calculated and shown in Table 5. The higher value of GRG indicates optimum process parameters.

Table 5. Grey relational coefficient, grade and rank

Sr. No.	Grey Relational Coefficient							Grey Relational Grade	Rank
	TS		PE		IT				
1	1	1	1	1	1	1	1	0.3214	1
2	0.3410	0.4366	0.3333	0.3395	1	1	1	0.1867	4
3	0.4462	0.4198	0.3420	0.3403	1	1	1	0.1934	3
4	0.6397	0.5663	0.5127	0.4109	1	1	1	0.2263	2
5	0.3680	0.3706	0.3447	0.3435	1	0.3333	0.3333	0.1369	6
6	0.3720	0.3333	0.3402	0.3379	0.3333	0.3333	0.3333	0.1103	9
7	0.3333	0.3992	0.3359	0.3403	0.3333	1	0.3333	0.1360	7
8	0.6236	0.5429	0.5937	0.4290	0.3333	0.3333	0.3333	0.1556	5
9	0.3529	0.3848	0.3333	0.3411	0.3333	0.3333	0.3333	0.1125	8

5.4. Optimum Levels of the Factor

For each level of the factor the average GRG is calculated. The higher the GRG indicates the better quality measures. The optimum level of the each controllable factor is determined based on the higher GRG. The average GRG and the optimum levels of the factors are shown in Table 6. TRS1WS1TA1 are the optimum levels of the process parameters based on the GRG.

Table 6. The average GRG at each level

Process Parameter	Average GRG			Max-Min
	Level 1	Level 2	Level 3	
TRS	0.2338*	0.1578	0.1347	0.0992
WS	0.2279*	0.1597	0.1387	0.0892
TA	0.1958*	0.1752	0.1554	0.0404

*Indicates the optimum level of the factor.

5.5. Analysis of variance

ANOVA is to investigate which welding process parameters significantly affect the performance characteristic. This is accomplished by separating the total variability of the GRGs, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each welding process parameter and the error. The percentage contribution by each of the process parameter in the total sum of the squared deviations can be used to estimate the importance of the process parameter change on the performance measure. The F-test is used to determine which weld process parameters have a significant effect on the performance measure. Usually, the change of the weld process parameter has a significant effect on the performance characteristic when the F value is large. Results of ANOVA (Table 7) indicate that TRS and WS are the significant weld process parameters affecting the multiple quality characteristics. Moreover, TRS is the most important weld process parameter due to highest percentage contribution.

Table 7. ANOVA for means

Source	DoF	Adj SS	Adj MS	F	% Contribution
TRS	2	0.01615	0.00807	3.71	44.8663
WS	2	0.01304	0.00652	2.99	36.2392
TA	2	0.00244	0.00122	0.56	6.7908
Residual error	2	0.00436	0.00218		12.1037
Total	8	0.03599			100

DoF = Degrees of freedom; Adj SS = Adjusted sum of square; Adj MS = Adjusted mean square; F = Fisher ratio.

5.6. Prediction of optimum condition

Based on the experiments, the optimum level setting is TRS1WS1TA1. The average GRG values of the factors at their levels are taken from Table 6 and the predicted GRG given below:

Grey Relational Grade (predicted)

$= TRS_1+WS_1+TA_1-2T$

$= 0.2338+0.2279+0.1958-2\times0.1754$

$= 0.3066$

Where, TRS1: Average GRG value of tool rotational speed at the 1st level WS1: Average GRG value of weld speed at the 1st level TA1: Average GRG value of tilt angle at the 1st level T: Overall average GRG.

5.7. Confirmation tests

The confirmation experiments were carried out by setting the process parameter at optimum levels. By setting parameters as tool rotational speed 710 rpm, weld speed of 49 mm/min and tilt angle as 2°, the achieved mean tensile strength, percentage elongation, and impact strength are 341.29 MPa, 5.65, and 4 J, respectively. The confirmation experimental results with GRG values are shown in Table 8.

Table 8. Grey relation grade values.

Setting level	Initial data	Optimal machining parameter	
		Prediction	Experiment
TS	331.90		341.29
PE	5.55		5.65
IT	4.00		4.00
Grey relational grade	0.3214	0.3066	0.3453

Improvement in the GRG is 0.0239.

6. Conclusion

The use of the grey-based Taguchi method to determine the FSW process parameters using newly design tool geometry with consideration of multiple quality characteristics has been reported in this paper. The mechanical properties and microstructure of FSWed butt joints of AA2014-T6 aluminium alloy using newly design tool geometry was studied and following conclusions are drawn:

- Taguchi's design of experimental technique was used to find the optimum levels of process parameters in FSW. The optimum levels of the tool rotational speed, tile angle and weld speed are 710 rpm, 2° and 49 mm/min respectively.
- In this investigation tool rotational speed plays a vital role and contributes ~70% to the overall contribution.
- Maximum ultimate tensile strength (331.19 N/mm^2), percentage elongation (5), impact toughness (4 J) and joint efficiency (68.71 %) is observed at tool rotational speed (710 rpm), weld speed (49 mm/min) and tilt angle (2˚) due to fine and equi-axed grain structure.
- Maximum ultimate tensile strength (246.04 N/mm^2) is observed at tool rotational speed (900 rpm), weld speed (49 mm/min) and tilt angle (3˚).
- Maximum joint efficiency was achieved using tool rotational speed (710 rpm), weld speed (49 mm/min) and tilt angle (2˚).
- Increasing the rotational speed and tilt angle of the tool at constant weld speed (49 mm/min) resulted in decrease in mechanical properties and hardness values.
- The performance measures of the FSW process such as tensile strength, percentage elongation, and impact strength are improved together by using the method proposed by this study.

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