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Multi-Objective Optimization of Friction Stir Welding of Aluminium Alloy 6082-T6 Using hybrid Taguchi-Grey Relation Analysis- ANN Method

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Abstract

This paper aimed to multi-response optimization of friction stir welding (FSW) process for an optimal parametric combination to yield favourable tensile strength and impact strength using the Taguchi based Grey Relational Analysis (GRA) and the Artificial Neural Network (ANN). The objective functions have been selected in relation with FSW parameters; tool rotation speed, welding speed and tilt angle for newly developed composite pin profile tool. The experiments were planned using Taguchi's L27 orthogonal array for three different tools. The optimal tool and process parameters for friction stir welding were determined by simulating parameters using a well-trained ANN model with the help of grey relational grade obtained from the GRA. This study has also showed the application feasibility of the ANN-Grey relation analysis in combination with Taguchi technique for continuous improvement in welding quality.

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Keywords: friction stir welding; Taguchi method; grey relation analysis; analysis of variance; Artificial neural network.

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1. Introduction

Friction stir welding (FSW) is a machine tool welding process was design, developed and patented by Wayne Thomas at TWI (The Welding Institute) in the UK in December 1991. Friction stir welding is a solid state welding process, was firstly developed for the very high strength aluminium alloy (AA2xxx and AA7xxx) which are difficult to weld by using conventional welding processes. Initially, research in FSW, limited to laboratory experiments, but due to its several advantages over other welding processes it becomes popular in the welding of aluminium, copper, steel alloys etc. Due to its fine recrystallized microstructure, minimum heat affected zone (HAZ), good dimensional stability, low distortion, excellent mechanical properties in the joint area gaining popularity in the world [1,2].

As compared to other conventional welding processes like TIG, MIG and Laser welding, FSW gives improved material properties like tensile strength, fatigue strength, impact strength, corrosion resistance, residual stress etc.[3].

In the FSW, a non-consumable rotary tool with a circular shoulder and a specially designed pin is allowed to insert into the touching edges of plates to be joined, until the shoulder touches to the base material and subsequently moved along the joint line. Due to frictional heat generating between tool shoulder and parent material, re-circulating flow of plasticized material takes place near the tool surface. The material softened by stirring process is transferred from the leading edge of the pin to the trailing edge, due to the combined effect of the rotation of the tool and its traverse motion. The transferred material with the action of axial force then merged at the trailing edge of the tool. The tool pin rotational and its traverse movements causes an extrusion in softened plasticized material which leading to form a stir zone. Flow behavior the material under the action of the rotating tool affects the stir zone [2]. Under these circumstances, tool geometry and its dimensions plays a vital role since it is consider being the primary source of heat generation. From the literature review, various researchers has considered tool pin profile, tool rotation speed tool shoulder diameter, tool plunge depth, tool tilt angle, welding traverse speed, axial force etc. as the process parameters during experimentation [2]. The Friction stir welding can take place with the different joint configurations like edge butt, T-butt joint, lap joint, T-lap joint, Fillet joint.

Elangovan and Balasubramanian [4] investigated the influences of five different tool pin profiles (straight cylindrical, threaded cylindrical, tapered cylindrical, square and triangular) and welding speed on the formation of the friction stir processing zone in AA2219 aluminium alloy. The results indicated that the square pin profiled tool produces metallurgical defect free and mechanically sound welds out of all other tool pin profiles. Ugunder S et al. [5] found that butt joint AA 2014 fabricated with taper cylindrical pin profile gives improved joint mechanical properties compared to cylindrical pin profile. Vijayan D et al. [6] found that square pin profile gives significant mechanical properties over the taper cylindrical and straight cylindrical tool pin profile for Friction stir welding of AA2024 and AA6061 aluminum alloys. Ramanjaneyulu K et al. [7] found that hexagonal pin profile gives better mechanical properties as compared to conical, triangular, square an pentagon cross sectional truncated pin profile in the welding of Aluminum alloy AA 2014-T6 rolled plates.

Kumar SS et al. [8] investigates that square and conical tool pin profiles gives less power consumption with better tensile strength of AA 6063-T6 plates with 4 and 6 mm thicknesses. A. K. Lakshminarayanan et al. [9] applies Taguchi approach to design the number of experiments using L9 orthogonal array and Analysis of variance (ANOVA) test is used determine the most influential parameters out of rotational speed, axial load and transverse speed which affects mechanical strength of friction stir welded RDE-40 aluminium alloy joints. However, traditional Taguchi method have limitation to solve multi-response optimization problem. This problem is overcome by coupling Taguchi method with GRA has a wide range of application in field of manufacturing processes. Chong-Jyh Tzenga et al. [10] used Taguchi method and Grey relational analysis to get optimum setting of CNC turning input parameters such as cutting speed (m/min), the depth of cut (mm), the feed rate (mm/rev), and the cutting fluid mixture ratios (%) for the multi-response optimization of surface properties of roughness average, roundness and roughness of machined specimen of SKD 11 alloy tool steel. Sanjit Moshat et al. [11] proposed PCA-based Taguchi method for the multi-response optimization of CNC end milling process. Hakan Aydin et al. [12] and Sundaravel Vijayan et al. [13] followed Taguchi-Based Grey Relation Analysis for multi-objective optimization of friction stir welding process parameters followed by analysis of variance (ANOVA) to obtain most significant parameters which affects welding response. Saurav Datta et al. [14] has proposed RSM methodology coupled with

grey-Taguchi technique for parametric optimization of wire EDM process using L27 orthogonal array for performing the experiments.

The AA6082 aluminum alloy is a high-strength Al–Mg–Si alloy used in marine frames, storage tanks, pipelines and aircraft applications due to high corrosion resistance. Al–Mg–Si alloys are having good weldability, but they suffers severe softening in the HAZ due to dissolution of Mg_2Si precipitates they suffers severe softening in the HAZ during weld thermal cycle. Such type of mechanical weakening creates a major problem in engineering applications hence it is desire to control the HAZ softening to improve mechanical properties of welded joints.

However, although extensive research have been reported in published literature about different pin geometries and their effects, studies on double pin geometries with double shoulder in a single tool still appears to be undocumented. From the literature, it was observed that no work has been carried out on FSW using two different pin shapes in a single tool. Therefore, in this paper, on the basis of experimentation on the AA 6082-T6 5 mm thickness, the effect of tools with combined conical and square pyramidal pin geometries has been investigated on the mechanical properties of the joints. Hybrid Taguchi-Grey Relation Analysis- ANN Method is used to optimise FSW process parameters, followed by the study of influence of tool geometry, tool rotational speed, tool tilt angle and welding speed on mechanical properties (ultimate tensile strength and impact strength) of the welded joint.

1. Experimentation

The rolled plates of AA6082-T6 aluminium alloy, 5 mm thickness, have been considered as parent material for the experimentation. The chemical composition and mechanical properties of the base metal are presented in Table 1 and Table 2 respectively. Parent material cut into the required size (170x95 mm) by power hacksaw cutting and edges are finished by the milling process to make them parallel for the FSW machine clamping system.

Table 1. Chemical Composition of Aluminum Alloy 6082-T6 (all values are in %)

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	Sn	V	Zr	Sr	Al
0.75	0.18	0.01	0.4	0.42	0.01	<0.05	0.01	0.02	<0.05	0.01	0.01	<0.005	<0.01	98.1

Table 2. Mechanical properties of base metal Al 6082

Material	Vickers Hardness (HV)	UTS (MPa)	Density (kg/m ³)	% Elongation	Thermal Conductivity (W/m-K)
Al 6082 T6	100-110	290	2700	10	170

Table 3. Process parameters and their levels

FACTORS	LEVEL		
	1	2	3
A. Tools	TOOL1	TOOL2	TOOL3
B.Tool Rotation (TR) (RPM)	700	910	1035
C. Tilt Angle(TA) (in degrees)	1°	2°	3°
D.Welding Speed (WS) (Inch/sec)	1	1.5	2

Square butt joint configuration has been set to fabricate welded joints. The initial joint configuration is obtained by securing the plates in position using specially designed fixture. Single pass welding procedure has been followed to fabricate the joints (Fig. 1a). Non-consumable tools made of hot worked die steel of H13 grade have been used to fabricate the joints [16]. Three different tool pin profiles, as shown in Fig.2a have been used to fabricate the joints. The tool dimensions are 15 mm shoulder diameter, 5mm pin root diameter, 14° cone angle and 4.7 mm pin length are selected. A Berico made conventional vertical milling machine of power 10 HP, maximum speed up to 3000 rpm and applies load up 15KN has been used to fabricate the joints. The welded joints are cut to the required dimensions to prepare tensile specimens as per American Society for Testing of Materials (ASTM), E-8M-08 [ASTM-2008] guidelines. Electro-mechanical controlled UTM with 100 KN, capacity has been used to carry out tensile test. The specimen is loaded at the rate of 1.5 KN/min as per ASTM standards so that tensile specimen undergoes deformation. Specimens for impact testing were taken as per ASTM A370 standards shown in Fig 2b.

The Charpy ‘V’ notch impact test was conducted at room temperature using the pendulum type impact testing machine. The amount of energy absorbed in fracture was recorded and the absorbed energy is defined as the impact toughness of the material. Taguchi method to Plan the experiments has been used quite successfully in process optimization. Therefore, this study applied a Taguchi L27 orthogonal array to carry out the experiments on FSW welding process. Four controlling factors including tool pin profiles (Tool), tool rotation (TR), the tilt angle (TA) and welding speed (WS) were selected shown in Table 3. The Grey relational analysis is then applied to examine how the welding process factors influence the tensile strength (TS) and impact strength (IS). By analyzing the Grey relational grade matrix, optimal parameter combination was then obtained though, the most influential factors for individual quality targets of FSW welding process can be identified. Additionally, the analysis of variance (ANOVA) was also utilized to examine the most significant factors for the tensile strength and impact strength in FSW welding process.

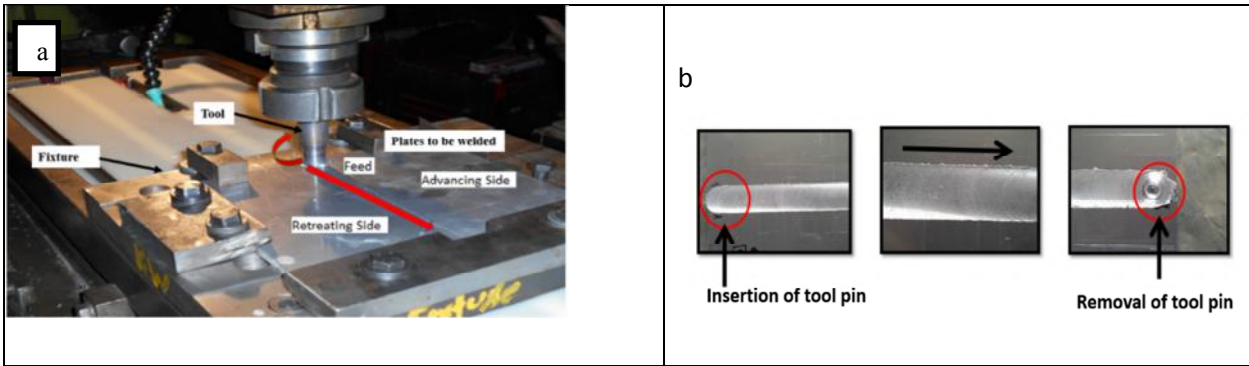


Fig. 1. (a) Friction stir welding setup; (b) welding procedure



Fig. 2. (a) Friction Stir welding tools; (b) FSW tensile strength tested samples.

2. Grey relation analysis

The Grey relational analysis is firstly attempted by Deng for solving multi-response characterisations. With the use of GRA inter-relationships among multiple responses is solved by converting several responses into an equivalent single grey relational grade function [15]. The GRA first begins with the data pre-processing with transferring a reference sequence to a comparable sequence. Initially, the experiment responses are normalized in the range between 0 and 1 according to three different performance characteristics nominal the better, smaller the better and larger the better are used [11].

For the maximisation of response, then normalization is done with the sequence “larger the better” performance characteristic normalized as by equation,

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

Where $x_i^*(k)$ is the sequence after the data pre-processing, $x_i^0(k)$ is the reference sequence, $\min x_i^0(k)$ is the smallest value in the reference sequence $\max x_i^0(k)$ is the largest value in the reference sequence, $i = 1, 2, \dots, m$; $k = 1, 2, \dots, n$; m is the number of experiment and n is the number of experimental data.

In this study, the aim is to maximize the reference sequence for each response. The data arrived after the pre-processing of the reference sequences are the comparability sequences. The comparability sequences for each experiment were calculated using equation (1). Grey relational coefficient (GRC) is used to explain the relationship between the comparability sequence and reference sequence [11] [12]. The GRC (ξ) is calculated from equations mentioned below

$$\Delta_{0i}(k) = \|x_0^*(k) - x_i^*(k)\| \quad (2)$$

$$\Delta_{\min}(k) = \min_{j \in i} \min_{\forall k} \|x_0^*(k) - x_j^*(k)\| \quad (3)$$

$$\Delta_{\max}(k) = \max_{j \in i} \max_{\forall k} \|x_0^*(k) - x_j^*(k)\| \quad (4)$$

$$\xi(x_0^*(k), x_i^*(k)) = \frac{\Delta_{\min}(k) + \zeta \Delta_{\max}(k)}{\Delta_{0i}(k) + \zeta \Delta_{\max}(k)} \xi \quad (5)$$

where $\Delta_{0i}(k)$ is the deviation sequence of the comparability sequence $x_i^*(k)$ and reference sequence $x_0^*(k)$ and ζ is the distinguishing coefficient having value between 0-1, and the value of 0.5 is generally used [11].

$$\gamma_i(x_0^*(k), x_i^*(k)) = \frac{1}{n} \sum_{i=1}^n w_i \xi(x_0^*(k), x_i^*(k)) \quad (6)$$

The GRCs were calculated using equation (3). For this study, 0.5 and 0.5 weights are given to ultimate tensile strength and impact strength respectively. In the final step grey relational grade (GRG) determined by taking mean sum of the GRC that is calculated using equation (7)

$$\gamma_i(x_0^*(k), x_i^*(k)) = \frac{1}{n} \sum_{i=1}^n w_i \xi(x_0^*(k), x_i^*(k)) \quad (7)$$

Where, w_i is the weighting value of the i^{th} performance characteristic, $\gamma_i(x_0^*(k), x_i^*(k))$ the GRG for an i^{th} experiment and n is the number of performance characteristics.

3. Parametric optimization of FSW process

Table 4 shows the Taguchi L27 orthogonal array consisting of 27 sets conditions and the experimental results for the responses of tensile strength test and impact strength. These data have been used to find optimum process parameters to get desired material properties.

3.1. By grey relation analysis

First, by using Eq. (1) experimental data have been normalized. Larger - the-better (LB) criterion has been selected for tensile strength and impact strength. By using Eq. (2). Grey relational coefficients of each performance characteristic are calculated with the weights of $w_1 = 0.5$ and $w_2 = 0.5$ [13]. The Grey relational coefficients for each response have been calculated by using Eq. (3) to evaluate Grey relational grade, which is the overall representative of all the features of FSW quality. Thus, the multi-response optimization problem has been transformed into a single equivalent objective function optimization problem using the combination of Taguchi approach and Grey relational analyses. Higher is the value of Grey relational grade, the corresponding factor combination is said to be close to the optimal. As indicated in Fig. 3a, the optimal condition for the FSW of aluminum alloy becomes Tool 2, too rotation 1035 rpm, tilt angle 2° and welding speed 2 inch/s. Table 6 shows the mean Grey relational grade ratio for each level of the process parameters.

Table 4. Grey relation analysis

Parameters					Testing Result		Grey relation analysis calculations							
Sr. No.	TOOL	TR	TA	WS	UTS MPa	IS Joule	Normalised		1-Normalised		GRC		GRG	RANK
1	1	700	1	1	173.3	12	0.5061	0.7778	0.4939	0.2222	0.5031	0.6923	0.2988	14
2	1	700	2	1.5	142.5	10	0.1913	0.5556	0.8087	0.4444	0.3821	0.5294	0.2279	21
3	1	700	3	2	123.7	6	0.0000	0.1111	1.0000	0.8889	0.3333	0.3600	0.1733	26
4	1	910	1	1.5	157.0	9	0.3391	0.4444	0.6609	0.5556	0.4307	0.4737	0.2261	23
5	1	910	2	2	204.7	9	0.8261	0.4444	0.1739	0.5556	0.7419	0.4737	0.3039	12
6	1	910	3	1	200.5	12	0.7826	0.7778	0.2174	0.2222	0.6970	0.6923	0.3473	7
7	1	1035	1	2	174.9	10	0.5217	0.5556	0.4783	0.4444	0.5111	0.5294	0.2601	16
8	1	1035	2	1	196.2	14	0.7391	1.0000	0.2609	0.0000	0.6571	1.0000	0.4143	2
9	1	1035	3	1.5	183.4	12	0.6087	0.7778	0.3913	0.2222	0.5610	0.6923	0.3133	9
10	2	700	1	1	173.2	10	0.5043	0.5556	0.4957	0.4444	0.5022	0.5294	0.2579	19
11	2	700	2	1.5	213.3	7	0.9130	0.2222	0.0870	0.7778	0.8519	0.3913	0.3108	11
12	2	700	3	2	190.2	8	0.6783	0.3333	0.3217	0.6667	0.6085	0.4286	0.2593	18
13	2	910	1	1.5	159.5	6	0.3652	0.1111	0.6348	0.8889	0.4406	0.3600	0.2002	25
14	2	910	2	2	189.4	5	0.6696	0.0000	0.3304	1.0000	0.6021	0.3333	0.2339	20
15	2	910	3	1	196.2	13	0.7391	0.8889	0.2609	0.1111	0.6571	0.8182	0.3688	5
16	2	1035	1	2	184.3	14	0.6174	1.0000	0.3826	0.0000	0.5665	1.0000	0.3916	4
17	2	1035	2	1	212.4	14	0.9043	1.0000	0.0957	0.0000	0.8394	1.0000	0.4599	1
18	2	1035	3	1.5	221.8	9	1.0000	0.4444	0.0000	0.5556	1.0000	0.4737	0.3684	6
19	3	700	1	1	173.3	12	0.5061	0.7778	0.4939	0.2222	0.5031	0.6923	0.2988	14
20	3	700	2	1.5	142.5	10	0.1913	0.5556	0.8087	0.4444	0.3821	0.5294	0.2279	21
21	3	700	3	2	123.7	6	0.0000	0.1111	1.0000	0.8889	0.3333	0.3600	0.1733	26
22	3	910	1	1.5	157.0	9	0.3391	0.4444	0.6609	0.5556	0.4307	0.4737	0.2261	23
23	3	910	2	2	204.7	9	0.8261	0.4444	0.1739	0.5556	0.7419	0.4737	0.3039	12
24	3	910	3	1	200.5	12	0.7826	0.7778	0.2174	0.2222	0.6970	0.6923	0.3473	7
25	3	1035	1	2	174.9	10	0.5217	0.5556	0.4783	0.4444	0.5111	0.5294	0.2601	16
26	3	1035	2	1	196.2	14	0.7391	1.0000	0.2609	0.0000	0.6571	1.0000	0.4143	2
27	3	1035	3	1.5	183.4	12	0.6087	0.7778	0.3913	0.2222	0.5610	0.6923	0.3133	9

Table 5. ANOVA results of FSW process

Source	DF	Adj SS	MS	F-Value	P-Value	% Contribution
TOOL	2	0.006041	0.003021	1.54	0.289	4%
TR	2	0.053748	0.026874	13.68	0.006	36%
TA	2	0.012633	0.006316	3.22	0.112	9%
WS	2	0.050066	0.025033	12.74	0.007	34%
TOOL*TR	4	0.010805	0.002701	1.38	0.346	7%
TOOL*TA	4	0.001516	0.000379	0.19	0.933	1%
TOOL*WS	4	0.001728	0.000432	0.22	0.918	1%
Error	6	0.011785	0.001964			6%
Total	26	0.148321	Means			100%

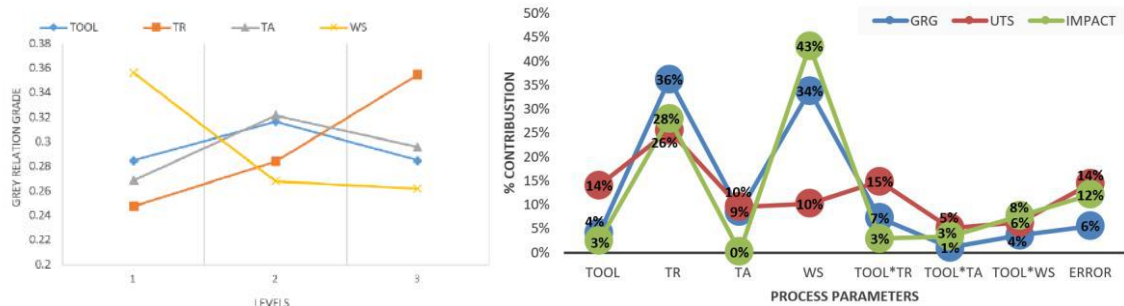


Fig. 3 (a) Main effect plots for mean for GRG; (b) % Contribution v/s Process parameters

3.2. The analysis of variance

The analysis of variance (ANOVA) is used to investigate which welding parameters significantly affects the performance characteristic. This can be done by separating the inconsistency of the GRG, which is measured by the sum of the squared deviations from the total mean of the GRG, into contributions by each welding parameters and the error. Thus

$$SS_T = SS_F + SS_e$$

Where $SS_T = \sum_{j=1}^{\rho} (\gamma_j - \gamma_m)^2$

And

- SS_T Total sum of squared deviations about the mean
- ρ Number of experiments in the orthogonal array
- γ_m Grand mean of the response
- γ_j Mean response for jth experiment
- SS_e Sum of squared deviations due to error
- SS_F Sum of squared deviations due to each factor

In addition, the F test was used to determine which welding process parameters have a significant impact on the response characteristic FSW. Generally, for large F value, performance characteristic is significantly influenced by process parameters as shown in Table 5. Fig 6(b) shows influence of process parameters on grey relation grade, tensile strength, and impact strength using ANOVA.

3.3. Artificial neural network

Artificial Neural Network (ANN) is an optimisation technique which mimics the human brain or neural system for the analysis of data to simulate information. The main advantage of ANN is to access larger input data and filter the incomplete and noisy data. According to the gradient descent method, to reduce error, the artificial neural network uses network training function that updates weights and bias values. Lakshminarayanan et al.[17] and V. D. Manvatkar et al. [18] has successfully developed an ANN model based on design of experiments to simulate the correlation between the Friction Stir Welding process parameters and mechanical properties of welded joint. The network is a multi-layer network consists of input layer (input parameters), output layer (response) and hidden layer (uses training function to processes input to yield output).

The developed neural networks consist of four inputs neurons for process parameters, 4 to 6 hidden layers consisting of 10 to 20 neurons in each layer for training the data and 1 to 3 neurons to predict the mechanical properties of welded joints. The feed forward four layered Levenberg-Marquardt (L-M) back propagation network architecture which provides nonlinear relationship between process parameters and grey relation grade [19] of UTS and impact strength as shown in the Fig.4. The input layer consist of four nodes which represents tool pin profile, tool rotational speed, welding speed and tilt angle which used to predict the response and the output layer consist of one nodes which represents response GRG. By training several networks, the number of hidden layer and neurons in the hidden layer has been determined. The number of hidden layer and neurons in the hidden layer has been determined by training several network, 4 hidden layers and 10 neurons in each hidden layer were chosen as optimum. In order to train the ANN model, 70% readings for training, 15% for validation and 15% for testing were

taken. The correlation coefficients for GRG at the training, validation and testing stages were 0.9989, 0.9999 and 0.9994 respectively.

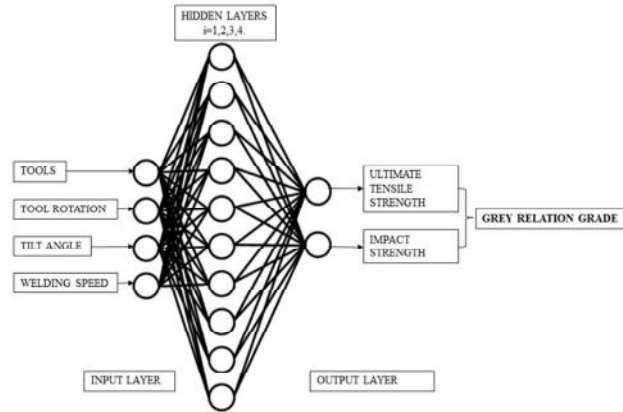


Fig.4 The architecture of ANN

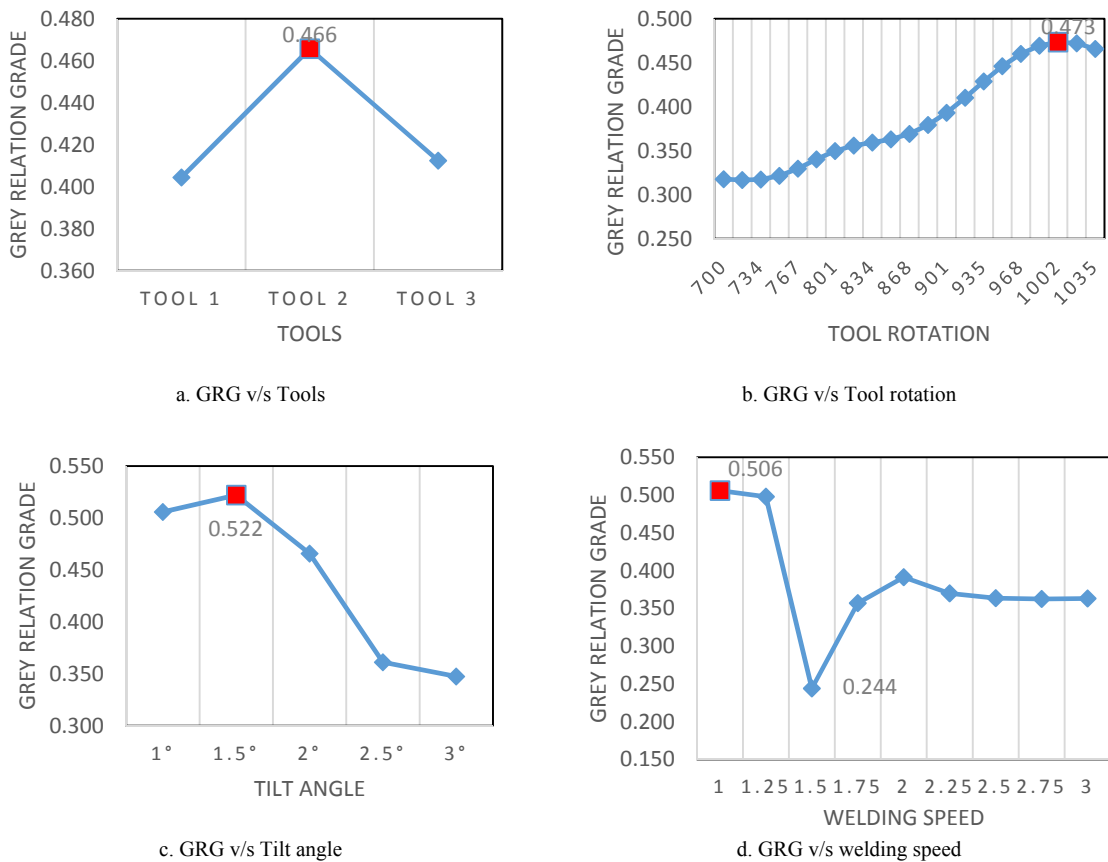


Fig. 5 Predicted response using ANN v/s Process parameters

It is seen that the response predictions of ANN model of process parameters follows the experimental results very closely and the developed ANN model can accurately predict the GRG. Therefore, it is possible to predict mechanical properties without carrying out the experiment. The lower value of the mean squared error indicates the neural network model developed will predict better result.

Fig. 5 a shows the simulating results via ANN using the different tools (Tool 1, Tool 2, and Tool 3), other conditions B1035RPM .C2° ,D 1 inch/sec from which it can be seen that the GRG is best for Tool 2. Fig.5 b shows the simulating results via ANN using, tool rotations (from the range between 700 to 1035 rpm) other conditions ATOOL 2 .C2° ,D 1 inch/sec from which it can be seen that the GRG is best for the setting 1002 rpm of tool rotation. Fig.5 c shows the simulating results via ANN using tilt angle(in the range between 1-3° with the interval of 0.5°), other conditions ATOOL 2 B1035RPM ,D 1 inch/sec from which it can be seen that the GRG is best for 1.5° of tilt angle setting. Last, Fig.5 d shows the of simulating results via ANN using different welding speeds (in the range between 1-3 inch/sec with the interval of 0.25 inch/sec), other conditions ATOOL 2 B1035RPM .C2° , from which it can be seen that the GRG is best 1 inch/sec setting of welding speed.

4. Comparison of optimisation performance and discussion

The final step is verifying the improvement in tensile strength and impact strength by conducting experiments using optimal conditions obtained by GRA-Taguchi method and Taguchi-GRA-ANN hybrid optimisation method. The predicted GRG $\hat{\gamma}$ using the optimal level of the process parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^O (\bar{\gamma}_j - \gamma_m)$$

Where γ_m is total mean grey relation grade, $\bar{\gamma}_j$ is the mean GRG at the optimal level and O is the number of the main design parameters. The tools with various tool pin profiles, rotational speed, tilt angle and welding speed were set at optimum levels and grey relation grade calculated using obtained average tensile strength and impact strength Table 8.

By using Taguchi method optimum parameters obtained were Tool 2, too rotation 1035 rpm, tilt angle 2° and welding speed 2 inch/s. Table 6 indicates the comparison of the actual GRG with that of pedicted by using the optimal welding parameters. Good agreement has been observed between the actual and predicted results. Grey relation grade obtained using proposed Taguchi-GRA-ANN approach was 0.508 with new revised optimum parameters Tool 2, too rotation 1002 rpm, tilt angle 1.5° and welding speed 1 inch/s gives 9.70% improvement as compared to conventional approach. The results show that adoption of the Taguchi-GRA-ANN hybrid optimisation method leads to significant improvement of mechanical properties in friction stir welding.

Table 6. Results of welding performance using the Taguchi-GRA and proposed method

Method	Optimum process conditions				Tensile Strength MPa	Impact strength Joules	GRG	% Improvement in GRG
	Tool	TR	TA	WS				
TAGUCHI-GRA	2	1035	2°	1	212.41	14	0.463	---
TAGUCHI-GRA-ANN(Pred)	2	1035	2°	1			0.492	5.90%
TAGUCHI-GRA-ANN (optimised parameters)	2	1002	1.5°	1			0.508	9.70%

From the Table 5 it is seen that tool show very negligible influence on mechanical properties of welded joint, due to their comparable static to dynamic volume ratio [4]. So all tools creates same kind modification in mechanical properties of welded joint. Tool rotation speed shows significant influence on mechanical properties of welded joint followed by welding speed, tilt angle and tool geometry. The mechanical properties of the welded joints prepared with different welding conditions shows that mechanical properties increases with increase in tool rotation speed up to 1002 rpm and again start decreasing. Tool rotation speed influences in the amount of rate of heat generation and thereby it influence the material flow in stir zone. For the welding speed or tool traverse, as welding speed increases which causes lower heat input in stir zone, resulted lack of stirring which deteriorate mechanical properties [4]. Fig 3(a) and 5 (d) shows that grey relation grade decrease as increase in welding speed, and gives maximum value at 1 inch/sec.

5. Conclusion

Following conclusions and salient observations have provided by conducting experiments, testing results and analysis on FSW butt joints:

- Well finished and defect-free butt type welded joint of Aluminium alloy AA6082 T6 have been produced by friction stir welding process.
- Tool rotation speed and welding speed shows significant influence on mechanical properties of welded joint as compared to tilt angle and tool geometry.
- The proposed approach hybrid Taguchi-Grey Relation Analysis- ANN Method gives the Friction Stir Welding parameters of 1002 rpm (tool rotational speed), 1.5° Tilt angle and 1 inch/sec (welding speed), with Tool 2 having conical and pyramidal cross sectional profile yielded higher grey relation grade of 0.508, which is 9.70% more than conventional Taguchi based grey relation analysis.
- The experimental results show that the performance characteristics of the Friction stir welding process using tool having composite profile with conical base are improved together by employing the proposed approach.

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References

- [1] Thomas WM, Nicholas ED, Watts ER, Staines DG, *8th International Conference on Aluminum Alloys* 2002; 1543–1548.
- [2] Mishra RS, Ma ZY, *Materials Science and Engineering R: Reports* 2005; **50** (2005): 1–78.
- [3] Yeni C, Sayer S, Pakdil M, *Kovove Mater* 2009; **47** (5): 341–347.
- [4] Elangovan K, Balasubramanian V, *Journal of Materials Processing Technology* 2008; **200** (1–3): 163–175.
- [5] Ugender S, Kumar A, Reddy a. S, *Procedia Materials Science* 2014; **5** : 824–831.
- [6] Vijayan D, Rao VS, *Journal of The Institution of Engineers (India): Series C* 2014; **95** (2): 127–141.
- [7] Ramanjaneyulu K, Madhusudhan Reddy G, Venugopal Rao A, Markandeya R, *Journal of Materials Engineering and Performance* 2013; **22** (8): 2224–2240.
- [8] Kumar SS, Ashok SD, Narayanan S, *Procedia Engineering* 2013; **64**: 915–925.
- [9] Lakshminarayanan a K, Balasubramanian V, *Transactions of Nonferrous Metals Society of China* 2008; **18** (3): 548–554.
- [10] Tzeng C-J, Lin Y-H, Yang Y-K, Jeng M-C, *Journal of Materials Processing Technology* 2009; **209** (6): 2753–2759.
- [11] Moshat S, Datta S, Bandyopadhyay A, Pal PK, *International Journal of Engineering, Science and Technology* 2010; **2** (1): 92–102.
- [12] Aydin H, Bayram a, Esme U, Kazancoglu Y, Guven O, *Materiali in Tehnologije* 2010; **44** (4): 205–211.
- [13] Vijayan S, Raju R, Rao SRK, *Materials and Manufacturing Processes* 2010; **25** (11): 1206–1212.
- [14] Datta S, Mahapatra SS, *MultiCraft International Journal of Engineering, Science and Technology Extension* 2010; **2** (5): 162–183.
- [15] Sudeepan J, Kumar K, Barman TK, Sahoo P, *Journal of The Institution of Engineers (India): Series C* 2015; **97** (1): 41–53.
- [16] Kumar K, Kailas S V., Srivatsan TS, *Materials and Manufacturing Processes* 2011; **26** (7): 915–921.
- [17] LAKSHMINARAYANAN AK, BALASUBRAMANIAN V, *Transactions of Nonferrous Metals Society of China (English Edition)* 2009; **19** (1): 9–18.
- [18] Manvatkar VD, Arora A, Debroy T, *Science and Technology of Welding and Joining* 2012; **17** (6): 460–466.
- [19] Lin HL, *Journal of Intelligent Manufacturing* 2012; **23** (5): 1671–1680.