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Optimization of friction stir welding AA6082-T6 parameters using analysis of variance and grey relational analysis

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Abstract. Friction stir welding (FSW) is a solid-state welding process, which has a significant role in solid-state welding processes for nonferrous alloys. Conventional arc welding processes for aluminum alloys such as metal inert gas (MIG) and tungsten inert gas (TIG) are replaced by FSW. The effect of FSW parameters such as rotational and traverse speeds, tool geometry, plunge depth, tilt angle, etc., on weld quality were considered in several optimization studies. Hence, the effect of fixture position is included in this study. Multi-criteria decision-making (MDCM) techniques such as grey relational analysis (GRA) were used to determine the optimal condition among experimental runs designed by response surface methodology (RSM). The Taguchi method was widely applied with MCDM techniques. Therefore, the experiments were conducted according to response surface methodology. Input parameters were (14, 16 and 18) mm for shoulder diameter (SD), (0.0, 0.2 and 0.4) mm for plunge depth (PD), and (30, 60 and 90) mm for fixture position (FP), which is the distance between fixture bolts used to fix the welded plate. The results obtained by GRA were similar to the ANOVA optimizer, and the optimum process conditions are shoulder diameter of 14 mm, plunge depth of 0.2 mm, and fixture position of 60 mm.

1. Introduction

Four decades ago in the United Kingdom, the welding institute (TWI) developed the friction stir welding (FSW) process, solid-state welding, that overcomes many problems of conventional welding methods. Welding of workpieces by FSW can be performed without melting the workpiece material or using filler wires. Due to friction between the workpiece and the rotating tool, frictional heat is generated, causing a soft area around the tool. When the tool moves transversely, it mechanically mixes the softened metal and forges it by mechanical pressure applied by the tool [1]. Particularly, it can be used for welding aerospace aluminum alloys and other materials such as stainless steel, titanium, and high-strength steel, which are difficult to weld by conventional fusion welding processes. FSW prevents melting, cast microstructure formation, and solidifying weld shrink zone found in traditional fusion welding [2]. The FSW process schematic diagram is shown in figure 1.

FSW process is attractive, unique, and reliable due to its advantages such as lower power consumption, good quality joint without defects, no gas shielding required, improved mechanical properties, reduced distortion, cracks elimination, and reduced residual stresses [3]. The solid-state FSW technique can successfully join various aluminum alloy grades [4]. FSW process still has some defects such as pinholes, tunnel defects, voids, etc., that affect welding quality. figure 2 shows FSW defects, [5], [6] provide more information on these defects. Tensile strength, surface roughness, hardness, microstructure, impact strength, etc., all influence the quality of a weld. As a result, it is critical to evaluate the parameters' influence on weld quality attributes [2].

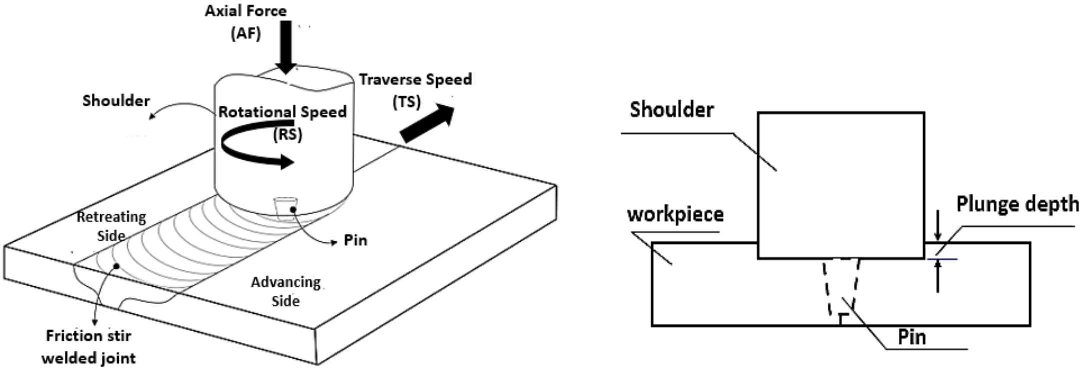

Figure 1. FSW process schematic diagram

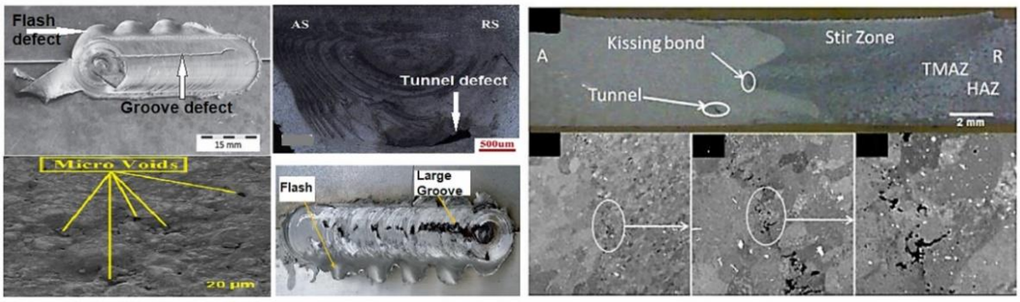

Figure 2. FSW common defects

Sabry et al. [7] investigated the FSW parameters' influence on nugget zone hardness, UTS, and temperature distribution of welded T-joints of AA6063-T6. The axial force, tool rotational speed, and traverse speed were all input parameters utilized in this process. High rotational speed and fixed axial force were found to yield the most elevated peak temperature. The nugget zone's hardness and ultimate tensile strength were increased by raising the axial force to 2 KN and the rotational speed to 1800 rpm. Internal cavities were avoided, and high tensile strength was achieved at a moderate traverse speed. Rotational speed and pipe wall thickness, mechanical qualities increased, such as the joint hardness and tensile strength.

Sabry[8]optimized the FSW of the AA6061 pipe using fuzzy logic analysis. The pipe wall thickness, rotational, and traverse speeds were employed as inputs. By applying the Six-Sigma technique to the process, it was found that decreasing traverse speed, and increasing thickness of the pipe wall and rotational speed increased hardness and tensile strength. Using a taper tool pin profile, Shahabuddin and Dwivedi [9] reported that the flash defect quantity was low during friction stir welding of AA7075. This result is in line with [10]. Furthermore, the material flow velocity near the welding surface is affected by the shoulder diameter, and the material inside the weldment is affected by the pin diameter. Mahany et al. [11] observed that increasing rotating speed and axial force increases both the hardness of the stirred zone and the tensile strength during friction stir welding of AA7075-T6 and AA2024-T3. Khan et al. [12] The influence of FSW tool plunge depth and pin offset on the development of defects such as kissing bond (KB) and tunneling defect during welding of AA6063-T6 and AA5083-H116 was investigated. It was discovered that increasing plunge depth resulted in acceptable heat quantity generation and mixing of different materials, which limited defect development and enhanced tensile strength, while higher plunge depth resulted in weak mechanical qualities.

As a result, the mechanical qualities of welded joints can be enhanced at high rotational tool speed, and slow tool travel speed. Plunge depth and shoulder diameter critically influence the FSW process's weld quality. Thus, shoulder diameter, taper pin profile, and plunge depth all affect the quality of FSW welds. However, few studies have examined the interaction between tool shoulder diameter and plunge depth, and none have examined the effect of welded plate fixture position on welded joint quality.

Periyasamy et al. [13] used friction stir welding to weld butt joints of AA7075-T651 and AA6061. Tool offset, tilt angle, and tool pin diameter were all input parameters with five levels each. RSM and ANOVA were used to create the experiments and assess the derived model's adequacy. They discovered that pin diameter and tool offset influenced joint tensile strength and microhardness. Tensile strength R2 was 0.9855, and microhardness R2 was 0.9872. El-Kassas and Sabry [14] predicted the ultimate tensile strength of AA1050 friction stir welded pipes underwater using a hybrid model of RSM-Fuzzy. This investigation used three levels of shoulder diameter, tool traverse, and rotational speeds. They discovered that the RSM-Fuzzy hybrid model outperformed both fuzzy and response surface technique models separately. Dinaharan et al. [15] used an ANN model to forecast the wear rate of FSW AA6082 plates with B4C, SiC, Al2O3, TiC, and WC ceramic particles. Traverse speed, groove width, rotational speed, and ceramic particle types were input parameters. To test the ANN's prediction ability, one and two hidden layers were tried. They found a positive correlation between the experimental and ANN data. Babu [16] used a feedforward neural network model with three levels of input parameters (traverse speed, tilt angle, and rotational speed) to define the relationship between inputs and outputs of FSW of AA2219 depending on the L9 orthogonal array data. Then a genetic algorithm was employed to optimize parameter values. Vijayan and Rao [17] used ANFIS and RSM to optimize axial force, pin profile, tool traverse, and rotational speeds for FSW of AA6061 and AA2024.

As previously stated, the mechanical properties of welded joints determine FSW joint quality. Selecting the best FSW parameters requires examining numerous quality characteristics [18]. Several techniques, such as response surface methodology, Taguchi method, adaptive neuro-fuzzy inference system, and artificial neural network, can optimize single objective problems [19]. Thus, Grey Relational Analysis (GRA) can handle various objective issues. GRA is based on grey system theory and is useful for resolving problems involving multiple variables. GRA can be used to solve a variety of multi-attribute decision-making problems, including power distribution, quality improvement, and industrial resource utilization. GRA solves the multi-attribute problem by merging all of the attribute values into a single value, therefore converting the multi-objective problem into a single-objective problem. As a result, the GRA technique decreases the complexity of decision-making and enhances the system's efficiency [20].

Sabry et al. [21] used GRA and ANOVA to optimize gas metal arc welding parameters of AA6061 pipes, such as current, voltage, and travel speed. Outputs included corrosion rate and tensile strength. Kasman [22] used GRA to choose optimal FSW conditions for AA6082 and AA5754. It was designed using tool shoulder to pin ratio, traverse and rotational speeds as inputs, and tensile strength and elongation as outputs. The experiments were designed using L9 orthogonal array. Also, [23] and [24] incorporated Grey Relational Analysis (GRA) with the Taguchi method to optimize the FSW process. El-Kassas and Sabry [25] used MCDM approaches, namely GRA and TOPSIS, to find the best settings for friction stir welding AA6061 pipes. The input parameters were tool rotational speed, pin diameter, and tool traverse speed, while the outputs were welded joint ultimate tensile strength and hardness. Sudhagar et al. [26] used MCDM approaches such as TOPSIS and Grey Relational Analysis to identify optimal friction stir welding parameters for AA2024. The tests were designed by L9 orthogonal array for impact toughness, ultimate tensile strength, and hardness. Both techniques had the same optimum conditions

According to the literature review, numerous studies have optimized a single objective problem in friction stir welding. Only a few studies have concentrated on multiple mechanical properties. In Multi criteria decision making techniques(MCDM), there are numerous decision making approaches available, such as grey relation analysis (GRA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), FUZZY TOPSIS, VIKOR, COPRAS (Complex Proportional Assessment), , and SAW (Simple Additive Weighting) are all techniques used to solve engineering problems. GRA have been proven to be particularly effective in solving MCDM problems because it provides a simple computation that takes less time and produces results that are near to the process parameters.

While the Taguchi approach has been widely employed with MCDM techniques, RSM has been mentioned in FSW rarely. The present study used GRA approaches based on RSM to determine the optimal parameters for AA6082's FSW. We study the effect of FSW parameters on surface roughness, nugget zone hardness, and ultimate tensile strength. Additionally, the GRA approach combines the FSW process's three outputs into a single objective. The best solution to a single objective is considered to have the optimal parameter conditions.

2. Experimental work

2.1. Material and the Experiment setup

Friction stir welding of two pieces of AA6082-T6 butt joint -with chemical structure and mechanical properties presented in Table 1- starts by placing a tapered pin in the line between the two plated then applying downward movement until shoulder touches plates' surfaces.

Table 1. AA6082-T6 chemical composition and mechanical properties [27]

Chemical composition

Element	Mn	Fe	Mg	Si	Cu	Zn	Ti	Cr	Al	Others
(%)	0.8	0.5	1	1.2	0.1	0.2	0.1	0.25	98.3	0.15

Mechanical Properties of AA6082-T6

Property	Tensile strength	Yield Strength	Elongation	Hardness
Unit	MPa	MPa	%	VH
Value	290	240	10	95

The experiment is constructed utilizing the central composite design method developed by RSM (DESIGN EXPERT 11). Table 2 contains a list of the process parameters values.

Table 2. Process parameters

Parameter	Shoulder Diameter (mm)	Plunge Depth (mm)	Fixture Position (mm)
Symbols	SD	PD	FP
Low level	14	0.0	30
High level	18	0.4	90

2.2. Methods

For friction stir welding process, a CME milling machine type FU1S was equipped with a 3-horsepower spindle motor, and a tool made of K110 with a tapered pin profile as presented in figure 3 were used during welding. A steady 1800 rpm and 2mm/min rotation and traverse speeds were maintained. K110 tool Chemical composition is presented in Table 3.

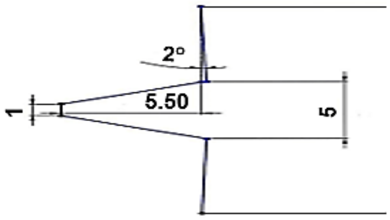

Figure 3. FSW tool pin profile

Table 3. K110 Chemical composition [28]

Element	C	Si	Mn	Cr	Mo	V	Fe
%	1.55	0.30	0.30	11.30	0.75	0.75	85.05

In order to hold the workpiece securely from the sides, a standard vise is utilized, and a specially constructed fixture is used to control the workpiece in various positions of fastening bolts, as illustrated in figure 4.

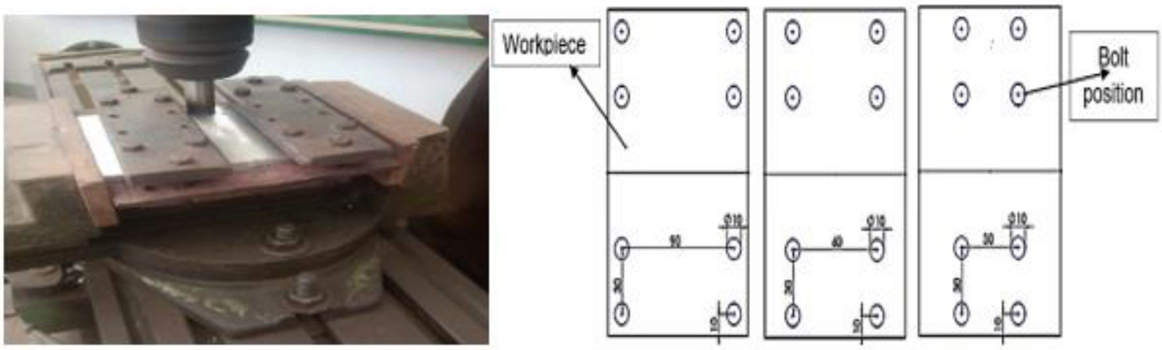

Figure 4. a) FSW fixture used in experimental work. b) schematic drawing of fixture positions

2.3. *The design matrix*

A set of 20 runs were designed using CCD method developed by RSM for three input parameters with three levels. Surface roughness, nugget zone hardness, and ultimate tensile strength were measured as output. RSM design with experimental results is presented in Table 4.

Table 4. RSM design with experimental results.

Run No.	Shoulder diameter (mm)	Plunge Depth (mm)	Fixture Position (mm)	Surface Roughness, Ra (µm)	Hardness (HV)	Ultimate tensile strength (MPa)
1	14	0	30	13.52	57.4	210.1
2	18	0	30	7.8	51	171.9
3	14	0.4	30	14.9	54.4	153.2
4	18	0.4	30	8.75	52.78	173
5	14	0	90	8.66	51.8	185.8
6	18	0	90	8.11	50.93	148.9
7	14	0.4	90	16.15	53.7	157.7
8	18	0.4	90	13.56	55.6	183.3
9	14	0.2	60	16.33	59.1	208.6
10	18	0.2	60	11.53	57.9	195.4
11	16	0	60	14.34	51.4	168.5
12	16	0.4	60	17.69	53.54	164.8
13	16	0.2	30	12.96	58.98	196.1
14	16	0.2	90	12.6	57.4	184.3
15	16	0.2	60	15.13	57.86	189.9
16	16	0.2	60	14.98	57.9	196.7
17	16	0.2	60	16.5	58.85	193.3
18	16	0.2	60	15.77	59	191.2
19	16	0.2	60	15.9	57.6	189.9
20	16	0.2	60	16.18	58.6	188.2

2.4. Grey Relational Analysis (GRA)

Deng developed GRA in 1982 to analyze structures' uncertainties and systems interaction, etc. [29]. Output values in GRA are normalized, between 0 and 1. The Grey relational coefficient (GRC) is estimated from normalized outputs values. Then, the grade of grey relational (GRG) γ_i is calculated for each run by summing the grey relational coefficients average. Greater GRG obtains the optimum solution. GRA steps are presented in figure 5, where $x_i(k)$ is the normalized output value, $max\, y_i(k)\ and\ \min y_i(k)$ are the highest and least values of $y_i(k)$ for k$_{th}$ response, respectively, $\Delta_{oi}(k) = |x_0(k) - x_i(k)|$, ɷ lies between 0 and 1 and expands or compresses the GRC range. But the rank of $\zeta_i(k)$ will always be the same whatever the ɷ value. 0.5 is a preferable value of ɷ [29]. Δ_{max} and Δ_{min} are maximum and minimum values of $\Delta_{oi}(k)$, respectively, and n is the output number.

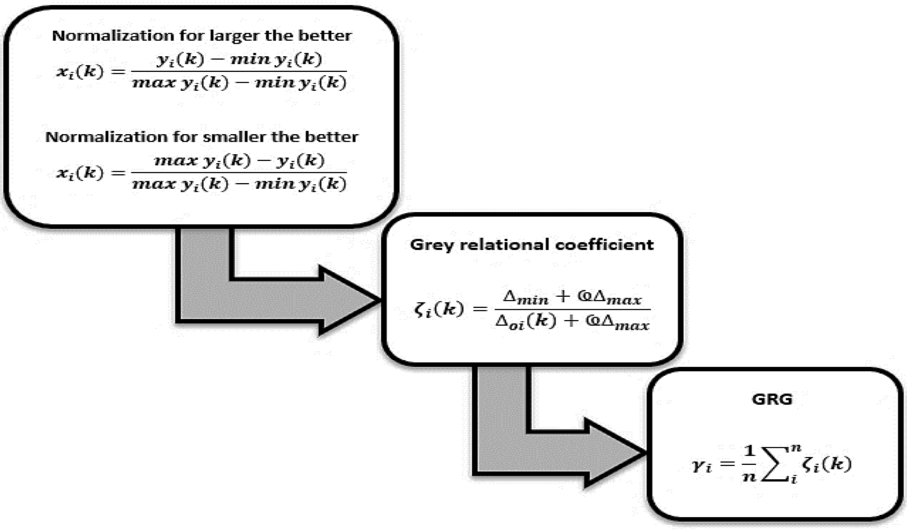

Figure 5. Grey Relational Analysis steps

3. Results and discussion

Effects of FSW parameters such as plunge depth (PD), shoulder diameter (SD), and position of the fixture (FP) on surface roughness (Ra), nugget zone hardness, and ultimate tensile strength are shown in figure 6 using Minitab 17 software.

The surface finish contributes to the surface's integrity since material failure begins at the surface. Additionally, the surface finish has a significant impact on corrosion resistance. As illustrated in figure 6-a, the welded joint surface roughness increases as the diameter of the shoulder increases and subsequently reduces to its minimum value at the maximum shoulder diameter. The generated heat increases as the diameter of the shoulder increases, allowing more softened material around the weldment surfaces to refill the advancing side's opening (AS) [30]. figures 6-b and 6-c indicate that UTS and hardness decrease to the lowest as shoulder diameter increases. With a wider tool shoulder diameter, more heat is dissipated to the workpiece, causing coarse grain development in the weld zone, reducing UTS and hardness. This result agrees with [26], [31].

The plunge depth affects the generated heat during the FSW process and regulates the forging action and welding thrust. [32]. Surface roughness, hardness, and ultimate tensile strength peak at 0.2 mm plunge depth and decline with rising and decreasing plunge depth values, as illustrated in figure 6. Increased plunge depth results in excessive heating, resulting in an intermetallic compound formation, resulting in decreased joint strength. At a lower plunge depth, a lack of bonding between welded components and insufficient material flow occurs, resulting in a loss of strength. [12]. This result is supported by [33], [34] At the fixture position value of 60 mm, the welded joint has a high surface roughness, which reduces by decreasing the fixture position, as illustrated in figure 6-a. UTS and hardness are at the highest value at 60 mm fixture position, but both decrease at lower and higher fixture positions, as illustrated in figures 6-c and 6-b, respectively.

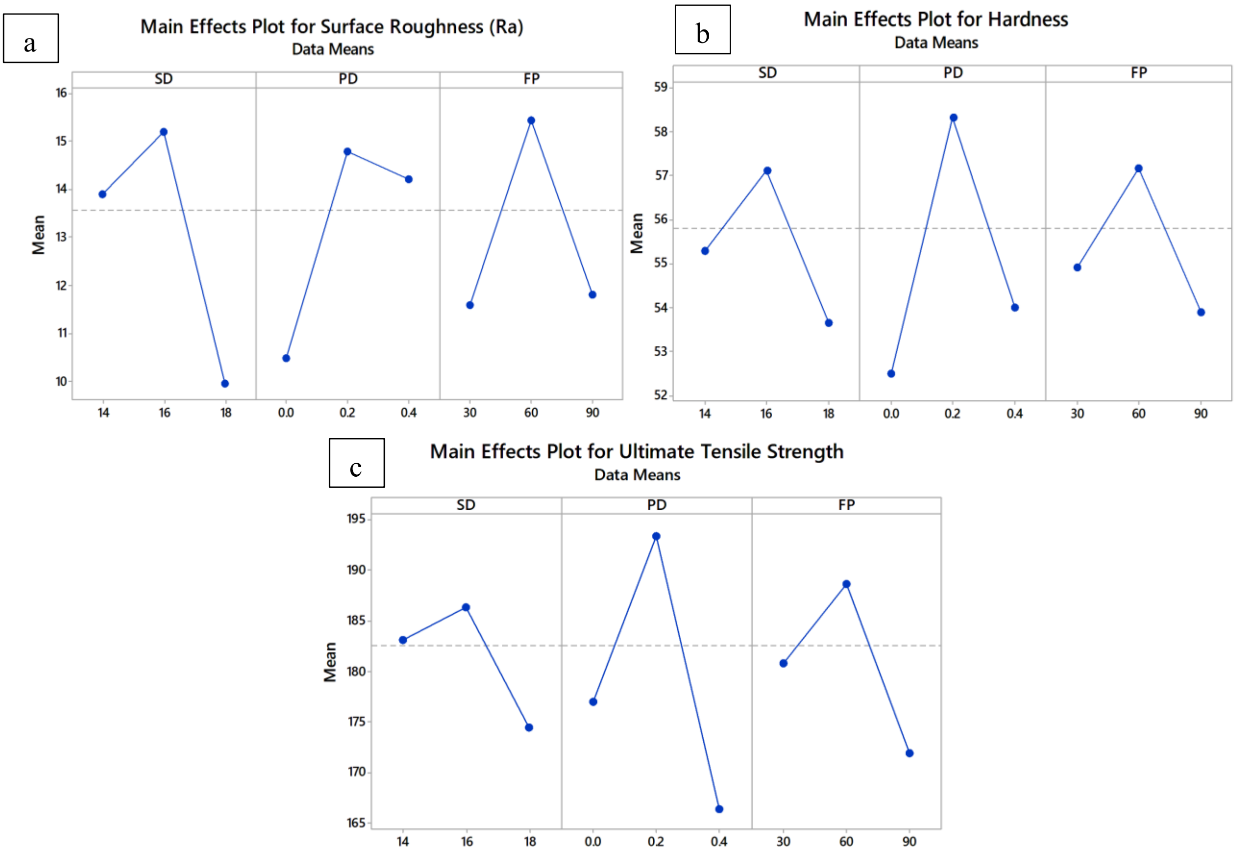

Figure 6. input parameters effects on (a) Surface roughness, (b) nugget zone hardness, and (c) UTS.

3.1. Grey Relational Analysis (GRA)

The purpose of our study is to increase the welded joint's strength and quality, which indicates outputs such as UTS and hardness should be enhanced. At the same time, surface roughness should be minimized using the normalization equations presented in figure 5. Table 5 contains the normalized values, the grey relational coefficient, and the GRG derived using the equations in figure 5.

According to the literature review, distinctive coefficient is taken to be 0.5. In GRA, the ideal solution is determined by the degree to which the grey relational grade approaches one. Among the 20 experiments, the closest value to one is recorded at the experimental run 9 with a 0.9125 value of GRG. 14 mm diameter of the shoulder, 0.2 mm of plunge depth, and 60 mm for the fixture position (30 mm between the welded plate center and bolts) are considered the optimal experimental run parameters.

3.2. ANOVA optimizer

As illustrated in figure 7, an ANOVA optimizer was used to optimize the inputs and outputs of FSW. The response optimizer by ANOVA is capable of determining the optimal parameters condition for a single or a group of outputs. GRA produced optimized parameters that are identical to those produced by the ANOVA optimizer, This result agrees with the results of [21]. The diameter of the shoulder, plunge depth, and fixture position optimized were 14 mm, 0.2 mm, and 60 mm, respectively.

Table 5. GRA

	Normalized Values			Grey relational coefficient			
Run No.	Surface Roughness (Ra)	Hardness	Ultimate tensile strength	Surface Roughness (Ra)	Hardness	Ultimate tensile strength	GRG
1	0.5784	0.7919	1	0.5425	0.7061	1	0.7495
2	0	0.0086	0.3758	0.333333	0.3352	0.4448	0.3711
3	0.7179	0.4247	0.0703	0.6393	0.4650	0.3497	0.4847
4	0.0961	0.2264	0.3938	0.3561	0.3926	0.4520	0.4002
5	0.0870	0.1065	0.6029	0.3538	0.3588	0.5574	0.4233
6	0.0313	0	0	0.3404	0.3333	0.3333	0.3357
7	0.8443	0.3390	0.1438	0.7625	0.4307	0.3687	0.5206
8	0.5824	0.5716	0.5621	0.5449	0.5386	0.5331	0.5389
9	0.8625	1	0.9755	0.7843	1	0.9533	0.9125
10	0.3771	0.8531	0.7598	0.4453	0.7729	0.6755	0.6312
11	0.6613	0.0575	0.3203	0.5961	0.3466	0.4238	0.4555
12	1	0.3195	0.2598	1.0000	0.4235	0.4032	0.6089
13	0.5217	0.9853	0.7712	0.5111	0.9715	0.6861	0.7229
14	0.4853	0.7919	0.5784	0.4928	0.7061	0.5426	0.5805
15	0.7412	0.8482	0.6699	0.6589	0.7671	0.6024	0.6761
16	0.7260	0.8531	0.7810	0.6460	0.7729	0.6955	0.7048
17	0.8797	0.9694	0.7255	0.8060	0.9423	0.6456	0.7980
18	0.8059	0.9878	0.6912	0.7203	0.9761	0.6182	0.7715
19	0.8190	0.8164	0.6699	0.7342	0.7314	0.6024	0.6893
20	0.8473	0.9388	0.6422	0.7661	0.8909	0.5829	0.7466

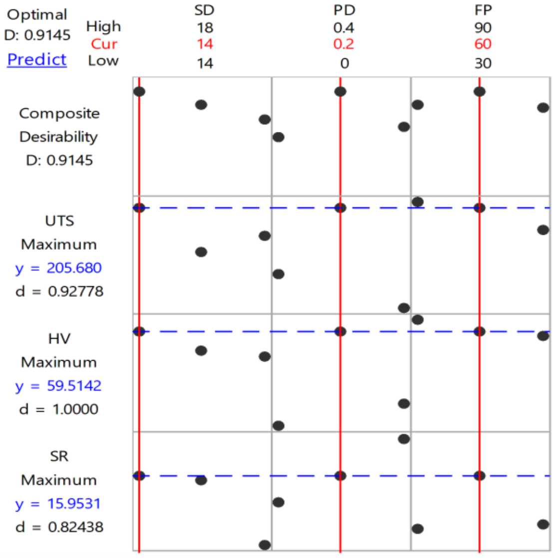

Figure 7. Results of ANOVA optimizer

4. Conclusion

This study's objective is to use a MCDM technique such as GRA to select the optimum parameter condition for FSW of AA6082-T6 from a group of twenty experimental runs designed using RSM. Shoulder diameter, plunge depth, and fixture position are inputs, and outputs are surface roughness, hardness, and ultimate tensile strength.

The following conclusions are obtained:

i. According to GRA, the best welded joint quality is obtained by 14 mm shoulder diameter and 0.2 mm plunge depth and fixture location of 60 mm.
ii. The GRA results are comparable to those obtained using the ANOVA optimizer.
iii. MCDM approaches such as GRA and ANOVA effectively optimize process parameters.

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