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Effects of Friction Stir Processing Parameters on the Tensile Strengths of Aluminum 6061 with Al_2O_3 Investigated Using the Taguchi Approach

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Abstract
This paper demonstrates how a multi-response orthogonal array of gray relational analysis enhanced parameters in friction stir processing (FSP) of Aluminum Alloy AA 6061 and Al_2O_3 powder. The L9 orthogonal sequence of Taguchi configuration is used to streamline the FSP process parameters on ultimate tensile strength, micro-hardness, and percentage elongation. The optimization process parameters are traverse speed , rotational speed, weight composition percentages of Al_2O_3 and tool geometry.The aim of this article is to decide the best parameters for achieving the maximum ultimate strength, micro-hardness, and percentage elongation. In GRG, optimum parameter levels were determined and the significant parameter contribution was measured with ANOVA. The confirmation run specifies and confirms the optimum method parameter amounts.

Keywords: *Gray relational analysis, Friction stir processing, Al_2O_3, L9 Orthogonal Array.*

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I. Introduction

Friction Stir Processing (FSP) is an evolution of FSW, developed by the United Kingdom in 1991. The Welding Institute (TWI) to alter local and surface properties at unique locations. FSP is a one-of-a-kind thermomechanical processing technique that modifies the material's micro structural and mechanical properties in a single phase to achieve maximum performance at the lowest possible cost and in the shortest amount of time [1]. Metal is nearly extruded into the joint line as the spinning instrument goes down it until it is forged by the massive down pressure (Fig. 1). The fluid flow during FSP is extremely unpredictable due to the instrument's composition, device parameters, and materials. This unpredictability can be adjusted and regulated by adjusting one parameter at a time while leaving the others alone. The ringing action and extrusion around the bolt are said to produce a secondary radial change around the longitudinal axis of the solder.Extreme plastic deformation around the instrument and friction between the tool and the piece during the FSP contribute to the temperature increase on the agitated region. In either case, due to intensive plastic deformation caused by rotation and translation of the part of the workpiece, the temperature measurements in the stirred region are difficult. The maximum temperature of various Al configurations in the stirred field during the FSP is between 0.6- and 0.9-times Tm depending upon the rate of rotation to the translation speed ratio (melting temperature) [7,8].

It is generally agreed that porosity, slag consideration, and hardening cracks are present in Al alloy fusion welding, and that these imperfections impair weld strength and joint properties [3]. FSW joints, on the other hand, are thought to be defect-free because the metal is not melted during the welding process, and the friction-induced heat and air flow produced by stirring activities joins it in a stable state. Pinholes, tunnel faults, piping defects, kissing bonds, and fractures, on the other hand, are common in FSW joints. As a result of poor plastic flow and a lack of metal mix in the FSP region [8,9]. Material property determination is a critical parameter in a wide range of modern applications, especially in automotive industries. Conversely, for those alloys that necessitate special treatment, such as high-strength confinements, and the time and difficulty in manufacturing, such as cost, regulation is given, and the price is needless. High strength combined with fine and homogeneous grain structures is a viable alternative for ductile metals like titanium [10, 11]. As a result, in the future, it would be important to create a manufacturing process for producing a product with a small grain structure that also possesses these characteristics. Despite advancements in conventional production methods like the Rockwell process and hydro-based metallurgy [hydrolytic metallurgy], modern processing techniques for 3D printing are being produced. Because of the advantages of other prior methods, FSP has recently been tested for use in a number of applications.

Aluminum oxide (Al_2O_3), also known as alumina, has a high ionic inter-atomic bonding degree, which leads to its appealing material properties [12,20]. It can be found in a number of crystalline configurations, all of which revert to the most stable hexagonal alpha state at high temperatures. Alpha stage alumina (–Al_2O3) is the most stable and rigid of oxide ceramics. It is the material of choice for a number of applications due to its high rigidity, excellent dielectric properties, refractoriness, and thermal properties. [21]. Because of its wide variety of applications, Al_2O_3 is used as reinforcements in our current work. In the aerospace and automotive industries, there has been no research into the use of Al-based metal matrix surface composites (MMSCs) sheet metals reinforced with nano Al_2O_3 as a surface modification technique. The primary aim of this paper is to investigate the feasibility of using the FSP technique to join Al6061-x wt% Al_2O_3– (5,10, and 15% wt%) surface composite sheets. Experimentally, the influence of various parameters and the percentage of nano Al_2O_3 reinforcement on mechanical properties and percentage elongation was investigated.

II. Materials And Methods

Material

Aluminum 6061 was chosen for this analysis because it possessed the following properties, as seen in Table 1. It has good mechanical properties and is readily welded. It is one of the most widely used general-purpose alloys. This is because magnesium and silicon materials are present, all of which are suitable for automotive applications.

Table 1. Aluminium alloy AA 6061 chemical properties

Fe	Si	Mn	Cu	Mg	Cr	Zn	Ti	Al
0.7	0.40	0.15	0.15	0.8	0.04	0.25	0.15	Balance

Design of Experiments

The four variables examined at three speeds are Traverse speed (mm/min), Rotational speed (rpm), Al_2O_3 composition (percent by weight), and Tool geometry. Grade (-1) values are based on changed criteria from previous studies [1,18-19], while levels (0) and (1) values are based on trial runs. Table 2 shows the complete experimental architecture, which included the L9 (33) Orthogonal array.

Table 2. Parameters and stages of processing

Symbol	Friction Stir processing parameter	Unit	Level 1	Level 2	Level 3
A	Traverse speed	mm/min	30	40	50
B	Rotational speed	rpm	710	900	1120
C	Composition of Al_2O_3	%Wt.	5	10	15
D	Tool geometry	Shape	Square	Conical	Circular

THE TAGUCHI METHOD

The Japanese quality engineer, Taguchi, who is commonly known as "father" of Performance Engineering[24], works in all fields of quality control: on-line and off-line. Both decisions on tasks to be completed in each of these fields are made from a cost-conscious mindset. Regulation of the output of a product or process as it progresses leads to improvement. The show manufacturing process to ensure that the quality levels produced are sufficient is what online quality control entails. [25]. The major difference between a conventional and Taguchi methods is the former approach is only dependent on the mean quality function, while the latter takes the fluctuation of the goal attribute into account. Despite the fact that the Taguchi method has received a lot of scrutiny due to a few significant shortcomings, It is possible to overcome single-answer problems successfully. The Taguchi technique aims to change a process or product
design in three phases:

1. Concept design;
2. Parameter design;
3. Tolerance design

In order to maximise function parameters, the following steps are taken: [26]:
Stage 1: Identify the standardised consistency characteristic;
Stage 2: Determine the sources of noise and test conditions.
Stage 3: Determine the sources of noise and their potential levels;
Stage 4: Create and describe the data analysis method for an experiment matrix.

Stage 5: Carry out the matrix testing;
Stage 6: Analyze data and calculate the best amount of control factor.
Stage 7: Predict how well these stages will do.

Figure 1. Friction Stir Processing Machine

SELECTION OF ORTHOGONAL ARRAY (OA)

In general, the importance of an orthogonal array is determined by its relationship to the other components.
the number of variables concerned, as well as their interdependence
the significance of the variables
A suitable cost constraint or an acceptable experimental resolution

GRAY RELATIONAL ANALYSIS

Gray relationship analysis is based on the theory of the gray method. Gray relational analysis [27] is a helpful method for the analysis of multiple responses. It has the ability to be used to overcome the perplexing interrelationships across multi-responses [27, 28]. The first step in gray relational processing is to normalise the data in the range of 0 to 1. After this, the coefficient of the gray relationship is determined using the standard data to show that the expected experial effects are linked to the real data. The gray relation rating is used to evaluate all aspects of the data.In most cases, analysing different complex performance characteristics is reduced to optimising a single relational gray grade. The optimum norm is determined by the function parameter with the highest gray relational score. ANOVA [29] is used to assess if the process parameters are statistically meaningful. Gray relational analysis and mathematical ANOVA can be used to estimate the optimal mix of process parameters. Finally, a validation procedure is passed out to ensure that the sample measured optimum process parameters are right. By optimizing process parameters, The Taguchi process can be used to increase the performance of the single process.

The experiments used the experimental Taguchi L9 orthogonal Array (OA) plan involving 9 rotational speed variations and traversing speeds., percentage composition by weight, and tool geometry. It is concerned with four process parameters that can be altered in three phases (without interactions). The aluminium plate samples were collected in an orthogonal array configuration. The dimensions of each plate were as follows: 130mm x 75mm x 6mm.

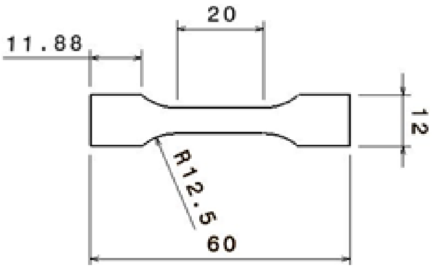

Figure 2. Tensile test sample as per ASTM E8/E8-M11

The HMT limited FN2EV vertical axis milling system is processed by friction mixing, as shown in Figure 1. The Taguchi L9 orthogon sequence was used for nine experiments. The tool was made of steel H13. The instrument profile was square, cylindrical and conical, and consisted of 20 mm of shoulder width, 3 mm pin diameter, and a 3 mm pin length with tools with rotary speeds of 710, 900, and 1100 rpm. The tool's pin was positioned just above the plate, with the pin's centre just above the groove section's centre. Al_2O_3 particles were inserted and processed into the job bit grooves.

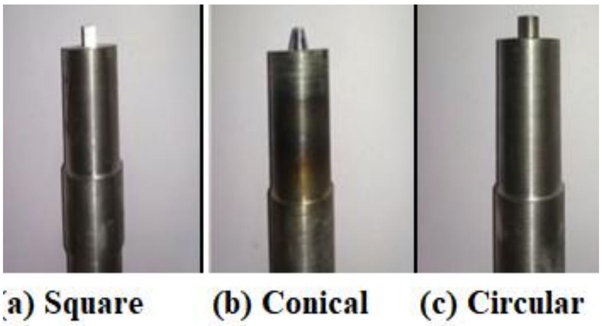
(a) Square (b) Conical (c) Circular

Figure 3. Different tool pin profile used for experimental work

In this step, the pieces are clamped rigidly to a support plate, preventing the adjoining joint faces from being forced apart. The tool shoulder should be in near contact with the work piece top, and the pin should be marginally shorter than the appropriate groove diameter. The pins were either pushing towards the work piece or the other way around at that time. Frictional heat is produced between the work piece material and the wear-resistant welding tool shoulder and pin. Along with mechanical mixing heat and adiabatic warming inside the substance, this heat will soften the stirred material without melting. The plasticized material is required to reverse the pin as the pin moves into the manufacturing, while the welded metal is consolidated with a significant welding power. Frictional stir treatment of a substance, including the complex recrystallization, is encouraged by intense plastic deformation in solid condition. The friction stir processed joints will be cut with a power hacksaw and machined according to the American Society for Testing Materials, the required measurements. (ASTM E8/E8M-11) rules for setting up the test specimens.

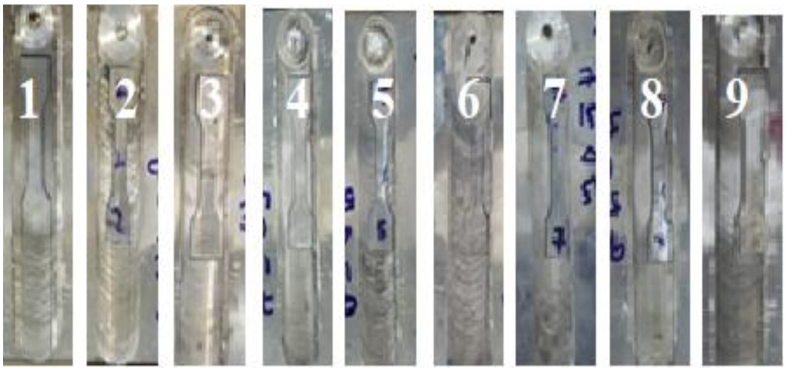

Figure 4. A sample photograph of Friction Stir Processed Aluminum 6061 Alloy after processing.

AA6061 aluminium alloy plates were used to machine the specimens, which were 130mm x 75mm x 6mm in dimension. Friction stir processing was used on nine AA6061 aluminium alloy plates using three different tool profiles made of H13 tool steel: cylindrical, circular, and conical. The instrument has a 20mm shoulder width, a 3mm pin diameter, and a 3mm pin length. It was operated on a vertical milling machine with the corresponding operation parameters: rotational speed of 710rpm, 900rpm, and 1100rpm, traverse speed of 30mm/min, 40mm/min, and 50mm/min, and percentage weight composition of Al_2O_3 of 5, 10, and 15 respectively.

Figure 5. Nano plug and play servo-hydraulic tensile testing machine

The tool's rotation stirred and mixed the tool's angular rotation shifted the front-to-back stirred fluid of the spinner. The pin vertical length was linked to the pin penetration depth into the job pieces. The pin's penetration depth defines how deep the tool shoulder approaches the work piece surface, resulting in inner channel and surface groove joints. These measurements were carried out on a vertical milling machine.

Figure 6. Tensile specimens as per ASTM E8/E8M-11.

MULTIOBJECTIVE OPTIMIZATION OF FSP PROCESS

Gray Relational Analysis of the Experimental Data

The Taguchi method is a method that is used in a systemic manner to optimising product quality through experimentation and analysis. The Taguchi method has proven to be a valuable tool for increasing research performance. The bulk of Taguchi evaluations are aimed at strengthening a certain accuracy criterion. The Taguchi technique, when paired with the gray relational system, will significantly accelerate Multi-performance method parameter refinement. For various process characteristics, gray relational analytic coefficients are estimated, and the average of these coefficients, known as the gray relational ranking, is used as a single response to Taguchi. Centered on a Taguchi method answer table, the gray relational analysis is then used to refine the requirements of current work. The FSP is made of the AA 6061 aluminum alloy, which combines the multi-response process's traction, microhardness, and percent elongation.

Data Pre-processing

Pre-processing of data is expected in gray relational analysis because the range and unit of one sequence of information differ between other. Pre-processing of the data is also required where the scope of succession is too wide or where the position of the target is uncommon. Data preprocessing is the act of moving the first grouping to a similar chain. As a result, experimental findings can be scaled from 0 to 1 [18, 19]. Ultimate tensile strength and nugget microhardness are the main reactions in FSP that determine the shape of the processed region under consideration. For "larger is bigger" The main standardized as follows, such as the final tensile strength and microhardness.

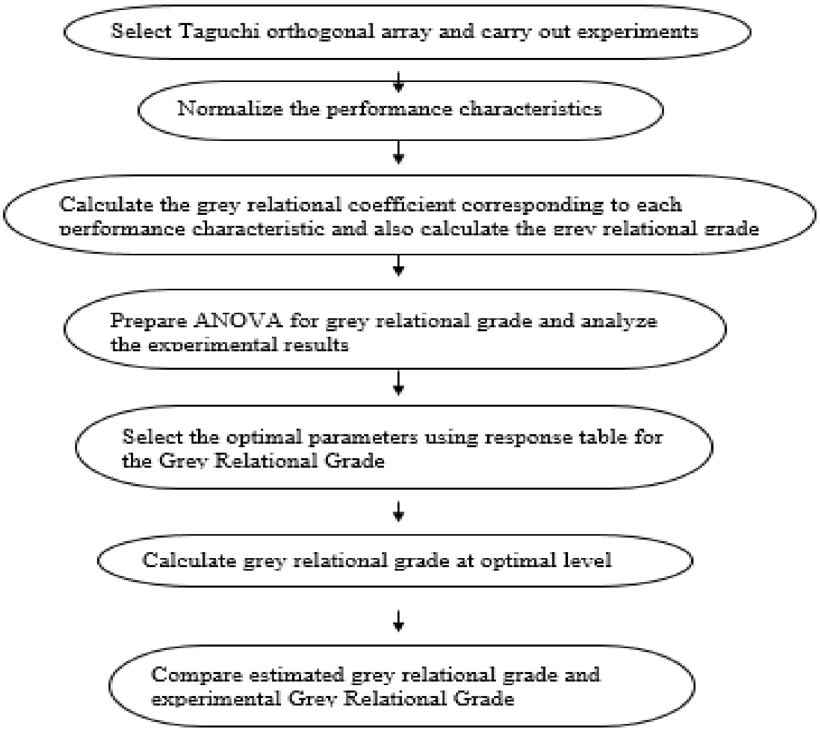

Figure 7. Gray relational analyzes to improve multi-performance processes [17]

Table 4 The impact of performance on the experimental design using a L9 orthogonal array

Exp. No.	Traverse speed (mm/min) (A)	Rotational speed (RPM) (B)	%Wt. Composition of Al_2O_3 (C)	Tool Geometry (D)	Tensile Strength (MPa)	Micro Hardness (Hv)	Percentage Elongation (%) (mm)
1	1	1	1	1	181	52	32.127
2	1	2	2	2	155	50	21.985
3	1	3	3	3	146	62	26.921
4	2	1	2	3	148	47	27.726
5	2	2	3	1	164	41	26.818
6	2	3	1	2	147	36	25.231
7	3	1	3	2	201	57	32.095
8	3	2	1	3	180	47	34.056
9	3	3	2	1	127	53	23.146

$$x_i^*(k) = \frac{x_i(k)-minx_i(k)}{maxx_i(k)-minx_i(k)} \quad (1)$$

where, after the preprocessing sequence and comparability sequence of the results, x i^* (k) and x i (k), where, k = 1 tensile, for microhard, 2; I = 1, 2, 3...,9 for 1 to 9 experimental numbers. [19].

Now, let's see that the deviation series is x 0^*(k)and x i^*(k), i.e., x i^*(k), respectively. Now the functional sequence (k) is the x 0^*(k) and x i^ (k) sequence of comparability, i.e.

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

The deviation categorization, $\Delta_{01}(k)$ can be used to measure
Eq. (3) as follows;

$$\Delta_{oi}(1) = |x_0^*(1) - x_i^*(1)| = |1.00 - 0.730| = 0.270$$
$$\Delta_{oi}(2)= |x_0^*(2) - x_i^*(2)| = |1.00 - 0.588| = 0.412$$
$$\Delta_{oi}(3)= |x_0^*(3) - x_i^*(3)| =|1.00 - 0.840| = 0.160$$

So, Δ_{01}= (0.270,0.412,0.160).
For I = 1–9 and all effects, similar calculations were carried outΔ_{oi} for i = 1–9 are listed in Table 6. Data in Table 6 was investigated, $\Delta_{max}(k)$ and $\Delta_{min}(k)$ the following character are given below.

$\Delta_{max}=\Delta_{07}(1)=\Delta_{03}(2)=\Delta_{08}(3)=1.00$

$\Delta_{min}=\Delta_{09}(1)=\Delta_{06}(2)=\Delta_{02}(3)=0.00$

Table 5 Each output sequence after data processing

Exp.no.	Tensile Strength (MPa)	Micro Hardness (Hv)	Percentage Elongation (%) (mm)
Reference sequence	1.000	1.000	1.000
1	0.270	0.412	0.160
2	0.622	0.491	1.000
3	0.743	0.000	0.591
4	0.716	0.564	0.524
5	0.500	0.789	0.600
6	0.730	1.000	0.731
7	0.000	0.198	0.162
8	0.284	0.561	0.000
9	1.000	0.359	0.904

3.2 Calculating the Gray Relational Grade and the Gray Relational Coefficient

A gray relationship coefficient for the preprocessed sequence has been determined following data preprocessing. It indicates the relation between idealized laboratory effects and real results. [18, 19] Formal paraphrase The following is the description of the gray relational coefficient:

$$\xi_i(k)=\frac{\Delta_{min}+\zeta.\Delta_{max}}{\Delta_{0i}(k)+\zeta.\Delta_{max}} \qquad (3)$$

where $\Delta_{0i}(k)$ is the variance Reference list sequence $x_0^*(k)$ which the equivalence sequence $x_i^*(k)$, ζ is the defining or Coefficient of recognition, which is set to 0.5 if all of the parameters are assigned equal weight.

Table 6 Sequences of deviation of each output feature

Deviation sequences	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$	$\Delta_{0i}(3)$
Exp. No. 1	0.730	0.588	0.840
Exp. No. 2	0.378	0.509	0
Exp. No. 3	0.257	1	0.409
Exp. No. 4	0.284	0.436	0.476
Exp. No. 5	0.500	0.211	0.400
Exp. No. 6	0.270	0	0.269
Exp. No. 7	1	0.802	0.838
Exp. No. 8	0.716	0.439	1
Exp. No. 9	0	0.641	0.096

For each experiment in the L9 orthogonal series, the grey relational coefficient was determined using Eq. (3), and the results are presented in Table 7.

The gray relation ranking was calculated by the multiplication of Gray relationship coefficients for each outcome's characteristic after the gray relation coefficient was obtained. The Gray Relational Grade is used to measure the importance of the following attributes of results:

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \qquad (4)$$

where γ_i is the ith experiment's gray relational score and n is the quantity of output features. The gray hierarchical classification of the orthogonal L9 for each experiment sequence is shown in Table 7. The closest the experimental result is to the idealised sense, the higher the gray qualitative grade. Experiment 9 has the best multiple output qualities as it has the highest gray ratio ranking of the nine measures, as seen in Table 7. The optimization of FSW's complicated multiple efficiencies of AA 6061 was, as can be seen in current research, turned into an optimization of a gray hierarchical classification.

Table 7 Gray relationship coefficient and gray association rating determined for the nine series of comparability

Exp. No.	Gray relational coefficient			Gray relational Grade
	Tensile Strength $\xi_i(1)$	Micro Hardness $\xi_i(2)$	Percentage Elongation $\xi_i(3)$	$\gamma_i = \frac{1}{3}(\xi_i(1) + \xi_i(2) + \xi_i(3))$
1	0.407	0.460	0.373	0.413
2	0.569	0.495	1	0.688
3	0.661	0.333	0.550	0.515
4	0.638	0.534	0.513	0.561
5	0.500	0.703	0.555	0.586
6	0.649	1	0.650	0.766
7	0.333	0.384	0.374	0.364
8	0.411	0.532	0.333	0.426
9	1	0.438	0.839	0.759

The results on the gray relation grade can be isolated from each processing parameter at various locations due to the orthogonality of the experimental design. For example, by comparing gray relational ratings with studies 1–3, 4–6 and 7–9, the mean gray relational rating for Tensile strength can be established at levels 1, 2 and 3. Table 8. The gray relationship grade mean was calculated in the same way as the other welding measurements,microhardness and percentage elongation. Table 8 provides the average mean for the nine studies in the grey sense grade. If the gray relation grade was higher, the result of the gray would be similar to the optimal rating.. As a consequence, the larger gray relational grade is chosen for best outcomes. As a result, as seen in Table 8, the best parameters for increasing tensile strength, microhardness, and percentage elongation are (A2B3C2D2). The optimum standard is the method The highest gray relational rating parameter index. ANOVA on a gray relation grade was also carried out to assess to the method parameter, which simultaneously influences the three process properties, which will be discussed in the following section.

The optimization of a gray relational grade has been converted from the optimization of the FSP of AA 6061's complicated multiple performance characteristics. Due to the orthogonality of the experimental architecture, At various points the influence of each machining parameter can be isolated on the gray contextual level. For example, by comparing gray relational ratings with studies 1–3, 4–6 and 7–9, the mean gray relational rating for It is possible to calculate tensile strength at stages 1, 2 and 3. Table 8.

The gray and mean relational rating, as well as microhardness and power supply, were all calculated in the same way. Performance index for multi-response Table 8 summarises at any point of welding parameters the mean of the grey connection grade. For the 9 studies shown in Table 8, the overall mean of the grey background grade. If the gray relation grade was higher, the product level would be similar to the grade of relation. As a consequence, the larger gray relational grade is chosen for best outcomes. Table 8 demonstrates the best criteria for increasing tensile power, microhardness, and percentage is ($A_2B_3C_2D_2$) as a result. The function parameter ranking with the highest gray relational rating is the best norm. Furthermore, A gray relational grade ANOVA was performed to determine the performance of the every parameter which simultaneously affects the main three process parameters, which will be addressed in the following section.

Table 8 Gray relational grade response table

Symbol	Machining parameter	Gray relational grade			Main effect
		Level 1	Level 2	Level 3	
A	Traverse Speed	0.540	0.638*	0.516	0.122
B	Rotational speed	0.446	0.566	0.680*	0.234
C	Percentage weight composition of Al_2O_3	0.535	0.669*	0.488	0.181
D	Tool geometry	0.586	0.606*	0.500	0.106

Total mean value of GRG =0.564
*Levels of optimum gray relational grade
The ideal environment for improved tensility and microhardening therefore, better percentage Wt. composition of Al_2O_3 and tool geometry is [$A_2B_3C_2D_2$].

III. Results and discussions

The objective of ANOVA is to find the statistically important part. It shows how the system parameters influence the response and the significance of the variable under consideration. Table 9 considers and mentions The gray relational category ANOVA table.Rotational speed and Al_2O_3 percentage wt. composition are Two important parameters affecting the gray link grade and, as a result, help to improve tensile power, microhardness, and percentage elongation, according to the ANOVA table. Aside from traverse and rotational speeds, the percentage weight composition of Al_2O_3 and tool geometry are critical factors to note. The optimum method parameters, based on the discussion above, are traverse speed at level 2, rotational speed at level 3, percentage weight composition of Al_2O_3 at level 2, and device geometry at level 2. In the FSP processed environment, heat input facilitates material movement and convergence, which is affected by rotational and traverse speeds. In the FSP field, defects such as pin holes or cracks occur at very low rotational speeds, Tensile strength is more reliable and durable. Turbulence increases rotational velocities, which decreases forging action and material consolidation in the friction stir processed part's trailing field. Higher heat intake causes grain growth at low traverse rates, and a larger heat affected area causes a decline efficiency and hardness of tensile. Higher traverse speeds restrict heat intake, resulting in pin holes and cracks, as well as lower tensile strength and hardness.

Table 9 ANOVA of gray relational grade

Welding parameter	DoF	SS	MS	Contribution
Traverse speed (mm/min)	2	0.02502	0.01251	13.98
Rotational speed(rpm)	2	0.08216	0.04108	45.91
Percentage Wt. composition of Al_2O_3	2	0.05298	0.02649	29.60
Tool geometry	2	0.01878	0.00939	10.50
Total	8	0.17894		

Table 10 Friction stir processing output at the original and optimal levels comparison below.

	Processing parameters in sixth trial	Optimal processing parameters	
		Prediction	Experiment
Setting level	$A_2B_3C_1D_2$	$A_2B_3C_2D_2$	$A_2B_3C_2D_2$
Tensile strength (MPa)	147		155
Microhardness (hv)	36		33.4
Percentage elongation	25.231		31.253
Gray relational grade	0.766	0.804	0.806

Improvement in the gray relational grade =0.038

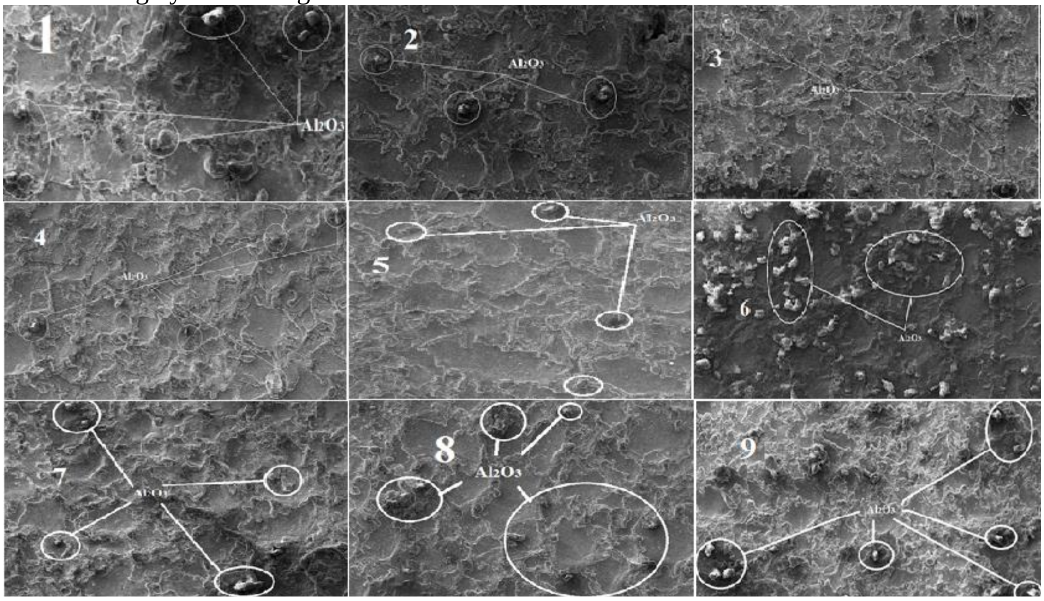

Figure 8: The microstructure of friction stir processed aluminium AA 6061 was investigated using multi-objective gray relation analysis at optimised parameters. Due to mechanical deformation and frictional heating, the microstructure is affected during the FSP.

3.4 Confirmation Test

A confirmation test has been performed to verify that AA 6061 is performing had increased when treated with aluminium oxide. As shown in Table 8 we have selected the best parameters for the confirmation test.The following equation can be calculated by means of approximate gray reference grade α* with the assistance of optimum machining parameters

$$\gamma^* = \gamma_m + \sum_{i=1}^{q} (\bar{\gamma}_i - \gamma_m) \qquad (5)$$

IV. Conclusions

The FSP manufacturing parameters for AA 6061 with multi-power aluminium oxide are optimized with Gray relational analysis such as ultimate stress pressure, microhardness, and elongation percentages. The experiment was using the L9 Taguchi orthogonal array. The ongoing work includes the following contributions.

1. The FSP amplitude tensile parameter, micro-hardness and elongation ratio are adjusted using grey relational analyses. The best method parameter speeds are 40 mm/min and a turning speed of 710 rpm, a percentage wt. composition of 5% Al_2O_3, and a conical instrument geometry. As a result, these are the suggested processing parameters for achieving higher tensile strength, microhardness, and percentage elongation all at the same time.
2. The gray relational grade ANOVA shows that the rotational speed is different in efficiency and Al_2O3 percentage wt. composition are the most influential parameters.
3. It is clear from the preceding discussion that the Taguchi method and gray relationship study will significantly simplify the optimization of complex multi-performance characteristics.
4. The optimal processing parameter assay results revealed an improvement in tensile strength, a small decrease in microhardness, and an increase in percentage elongation. Confirmation results revealed a 0.038 increase in Gray relation ranking.

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