Multi Objective Optimization of Friction Stir Welding Process

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***Abstract*:- Friction Stir Welding (FSW) a solid-state welding technique developed by twi used primarily for joining non-ferrous metals and alloys. It has many advantages when compared to traditional methods, as it is pollution free and no consumable materials are involved. This Work Presents multi objective optimization of process parameters affecting weld quality of dissimilar aluminium FSW welds using Taguchi Grey based approach. For this experiments were conducted by varying the process parameters such as rotational speed, axial force, traverse speed using the Taguchi (L27) orthogonal array and a grey relation analysis has been adopted to convert this multi-objective criterion into an equivalent single objective function, which has been optimized by using Taguchi technique. The Analysis of variance was used to find out the significant parameter that affects the mechanical properties i.e tensile strength and elongation. This work shows the feasibility of the grey relation analysis with Taguchi technique for improvement in welding quality of aluminium alloy.**

Keywords: AA2024-T6 and AA6351-T6 dissimilar alloy, friction stir welding, rotational speed, axial force, traverse speed and Taguchi grey analysis.

1. INTRODUCTION

Friction stir welding (FSW), an innovative solid state welding technique, is finding greater use in defense and aerospace applications [1].This environment-friendly and energy-efficient technique can be used to join high strength aluminum alloys and other metallic materials that are difficult to join using conventional fusion welding processes. In FSW, a rotating tool is forced down into the joint line under conditions where the frictional heating is sufficient to cause a local increase in the temperature of the material to the range where it is readily deformed plastically [2]. Despite the evolution of numerous models and investigations, the flow of material is not fully understood [3]. The tool used in FSW has two distinct parts, the shoulder and the pin, and is designed to serve three functions (i) generate frictional or deformational heat that softens the work material around and ahead of the pin (ii) control the material flow to produce a defect-free joint and (iii) confine the hot material under the shoulder. Despite the fact that friction stir welded joints are now employed in a wide range of applications [4-10] many of the factors that control their microstructure and properties are still poorly understood, due to the complex nature of the metal-flow during welding. In addition to the process parameters, effectiveness of the weld joint is strongly dependent on geometric features of the tool. For instance, the height and shape of the pin [11-13], together with the shoulder diameter, exercise substantial influence on both the material-flow and heat generation caused by friction as well as rapid plastic deformation [14-17].

Taguchi method is a power full tool which can upgrade/improve the performance of the product, process, design and system with a significant slash in experimental time and cost (Montgomery, 2006). It appears that the optimization of FSW process parameters of dissimilar aluminum alloy using Taguchi and grey analysis [20-31] has not been reported yet. Considering the above fact, the Taguchi method is adopted to analyze the effect of process parameters [18-19] i.e. rotational speed (RS), traverse speed (TS) and axial force (AF)) for optimizing FS Welds of dissimilar aluminum alloys.

Grey relational analysis is an impacting measurement method in grey system theory that analyses uncertain relations between one main factor and all other factors in a given system. When the experiments are ambiguous or when the experimental method cannot be carried out exactly, grey analysis helps for the shortcomings in statistical regression. Grey relational analysis is actually a measurement of the absolute value of data difference between sequences, and it could be used to measure the approximate correlation between the sequences.

2. EXPERIMENTAL DETAILS

2.1. Material and methods

A Friction stir welding machine was used, which was primarily developed for joining different aluminium alloys and other soft materials like magnesium alloys. Rolled plates of material AA2024-T6 and AA6351-T6, 5mm thick plates were cut into work pieces of size 70 x 200 mm as shown in fig. 1 Plate edges to be weld are prepared so that they are fully parallel to each other. This is to ensure that there was no uneven gap between the plates. Surface preparation is done so that the surfaces of both the plates are equal level and footing. The plates were cleaned by rotary wire brushing containing stainless steel bristles followed by acetone cleaning in order to remove grits.

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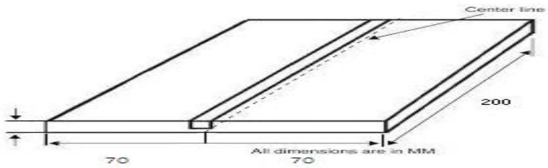

Fig. 1: Arrangement of plates to be weld

A butt joint is the most common type of weld obtained through the FSW process. For this type of joint the work pieces are held tight with adjoining edges against each other. The rotating tool at a constant rotational and traverse speed with sufficient downward axial force is moved across the work piece surface. The friction between the shoulder and the work piece surface of the weld metal generates enough heat required to create the weld. Fig. 2 shows the schematic representation of FSW of a butt joint.

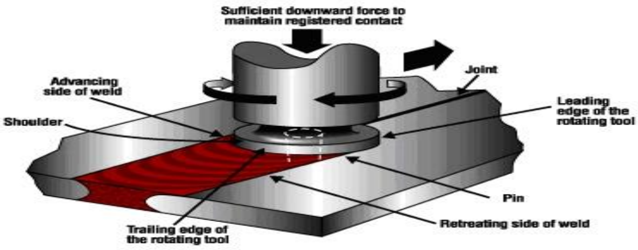

Fig. 2: schematic representation of FSW

The test plates to be welded were clamped firmly on the rigid back plate as shown on fig.3. The clamping prevents the work pieces from spreading apart or lifting during welding. The welding tool, consisting of shank, shoulder and pin is then rotated to a prescribed speed and placed normal with respected to the work piece. The tool is slowly that plunged into the work piece material at the butt line, until the shoulder of the tool forcibly contacts the upper surface of the material and the pin is a short distance from the back plate. A downward force is applied to maintain the contact and a short dwell time is observed to allow for the development of the thermal fields for preheating and softening the material along the joint line. At this point, a lateral force is applied in the direction of welding and the tool is forcibly traversed along the butt line.

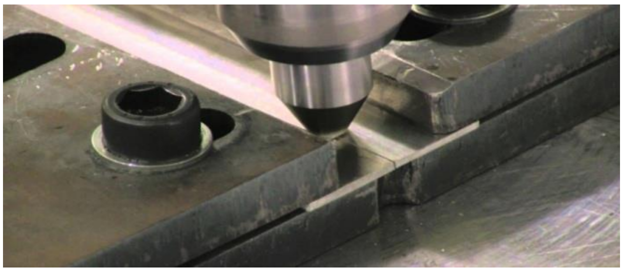

Fig. 3: clamped plates of FSW

2.2 Selection of Process Parameters

Selection of right combination of process parameters and setting the range of the process parameters is very important step in the process. Small variation in process parameters will effect the strength and % elongation. In the present work process parameters are taken in two types.

The three control factors are:

1. Rotational Speed 2. Traverse Speed 3. Axial Force

The uncontrolled factors are:

1. Humidity 2. Operator change

2.2.1 Selection of Rotational Speed

Beyond open circuit of rotational speed there will be excessive turbulence resulting in defects. At a higher rotational speed the temperature increases were so excessive that the magnesium in the aluminum alloy oxidized and the resulted in an unsound joint. Rotational speed below lower end of circuit, there will be insufficient heat generation and insufficient metal transportation, resulting in defects in stirred zone. A lower rotation spped gave rise to an insufficient increase in temperature at the weld, so that the pin worked out in a short time. Hence suitable speeds between 800 rpm and 1600 rpm are selected.

2.2.2 Selection of Traverse Speed

When the Traverse (weld) speed is low, pin hole type of defect was observed due to excess heat input/unit length. When the weld speed is high, defective weld was found due to insufficient heat input caused by inadequate flow of material. Hence in the work the welding speed between 0.35 mm/sec and 1.2 mm/sec are selected.

2.2.3 Selection of Axial Force

Axial force is one of the influencing parameter on the response of friction stir welding welded specimens in decreasing order from rotational speed, axial force traverse speed. In this work axial force between 3000N and 7000N are selected. From the brainstorming session the following possible levels were taken for constructing the experimental runs.

Table. 1: Process Parameters with their Control factors and their levels

S.No	Process Parameters	Units	Level 1	Level 2	Level 3
1	Rotational speed (RS)	rpm	800	1200	1600
2	Traverse Speed (TS)	rpm	0.35	0.7	1.2
3	Axial Force (AF)	N	3000	5000	7000

2.3. Taguchi Method

Taguchi techniques are statistical methods developed by Genichi Taguchi to improve the Quality of manufacturing goods. Basically, classical experimental design methods are to complex and not easy to use. A large number of experiments have to be carried out when the number of the process parameter increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. From the preliminary experimental results, three levels of the cutting parameters have been selected as shown in table 1. In this study, L27 orthogonal array were used, shown in Table 2.

Table. 2: Taguchi Design L27 Orthogonal Array

Exp. No	RS	TS	AF	UTS (Mpa)	% Elongation
1	1	1	1	210	6.1
2	1	1	2	215	6.25
3	1	1	3	223	6.45
4	1	2	1	212	6.2
5	1	2	2	220.5	6.4
6	1	2	3	226	7.1
7	1	3	1	211	5.53
8	1	3	2	213.4	5.78
9	1	3	3	216	5.69
10	2	1	1	245	7.3
11	2	1	2	250	7.53
12	2	1	3	254	8
13	2	2	1	243	7.98
14	2	2	2	256	8.11
15	2	2	3	263	7.64
16	2	3	1	226	5.48
17	2	3	2	238	5.69
18	2	3	3	243	6.7
19	3	1	1	228	4.48
20	3	1	2	232	4.24
21	3	1	3	241	5.13
22	3	2	1	231	5.08
23	3	2	2	240	5.1
24	3	2	3	251	5.3
25	3	3	1	217	4.21
26	3	3	2	225	4.72
27	3	3	3	232	4.8

3. RESULT AND DISCUSSION

From the experimental results, it is found that the joints fabricated using a rotational speed of 1200 RPM, a traverse speed of 0.7 mm/s and an axial force of 7000 N exhibited more Ultimate Tensile strength and % Elongation properties.

3.1 GREY RELATIONAL ANALYSIS

Taguchi analysis method can optimize single objective function; it cannot solve multi-objective optimization problem. So, Tensile strength and %Elongation can be optimized individually by using this Taguchi technique. But it may so happen that, the optimal setting for a response variable cannot ensure other response variables within acceptable limits. So, one should go for such an optimal parameter setting so that all the objectives should fulfill simultaneously. These will be achieved using grey based Taguchi method as discussed below. This method can convert several objective functions into an equivalent single objective function (representative of all desired response characteristics of the product/process), which would be maximized.

The use of Taguchi method with grey relational analysis to optimize the Welding operation with multiple processes responses characteristics includes the following steps:

1. Identify the performance characteristics and Welding parameters to be evaluated.
2. Determine the number of levels for the process parameters.
3. Select the appropriate orthogonal array and assign the Welding parameters to the orthogonal array.
4. Conduct the experiments based on the arrangement of the orthogonal array.
5. Normalize the experiment results.
6. Perform the grey relational generating and calculate the grey relational coefficient.
7. Calculate the grey relational grade by averaging the grey relational coefficient.
8. Analyze the experimental results using the grey relational grade and statistical ANOVA.
9. Select the optimal levels of Welding parameters.

Table 3 shows the process responses of experiment trails. The table shows the process responses considering the experimental trail number with process responses of Ultimate tensile strength and % Elongation. It takes 27 trails to get the process responses.

Table. 3: Process Responses

Experiment No	Process Responses	
	UTS	%EL
1	210	6.1
2	215	6.25
3	223	6.45
4	212	6.2
5	220.5	6.4
6	226	7.1
7	211	5.53
8	213.4	5.78
9	216	5.69
10	245	7.3
11	250	7.53
12	254	8
13	243	7.98
14	256	8.11
15	263	7.64
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17	238	5.69
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19	228	4.48
20	232	4.24
21	241	5.13
22	231	5.08
23	240	5.1
24	251	5.3
25	217	4.21
26	225	4.72
27	232	4.8

3.1.1 Grey Relational Analysis

Step 1: Pre-processing data: The obtained process responses are preprocesses in the first step. The Pre-processing data for each individual response using the formula for larger the better type $x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$.

Step 2: Sequencing Deviation (Δ_{0i}): Deviation sequencing is calculated for the obtained pre-processing data by considering ideal value 1. Results of sequencing deviation are obtain by using the formula $\Delta_{0i} = 1 - x_i(k)$.

Step 3: Grey Relational Coefficient: In this step coefficient ξi is calculated for all the obtained deviational sequencing data individually, Grey relational coefficient $\xi_i(k)$ is calculated by using $\xi_i(k)=\frac{\Delta_{min}+\psi\,\Delta_{max}}{\Delta_{oi}(k)+\psi\,\Delta_{max}}$ Where ψ is the distinguishing coefficient $0 \le \psi \le 1$, therefore ψ is take as 0.5.

Step 4: Grey Relation Grade: Grey relational grade is calculated by using $\gamma_i = 1/n \sum_{k=1}^{n} \xi_i(k)$. Table 4 shows the Grey relational Grade value.

Table. 4: Grey relation Grades

S.No	Grey Relational Grade	Ranking
1	0.412878788	20
2	0.433757861	15
3	0.469331223	12
4	0.423558416	16
5	0.458422428	14
6	0.538053309	9
7	0.384021597	26
8	0.401916748	22
9	0.403384237	21
10	0.651013679	16
11	0.720818532	5
12	0.846540407	3
13	0.753696237	4
14	0.895522388	2
15	**0.902892562**	**1**
16	0.421543513	18
17	0.480393682	10
18	0.575124808	7
19	0.390178337	24
20	0.397960556	23
21	0.470964639	11
22	0.422278859	17
23	0.464249348	13
24	0.548987777	8
25	0.349425287	27
26	0.388010626	25
27	0.415795999	19

From the table 4 it is clearly noticed that experiment number 15 is the optimum level, so optimum parameters are Rotational speed 1200 rpm, Traverse speed 0.7 mm/s and Axial force 7000 N.

Step 5: ANOVA for Grey Relational Grade:

In the final step the obtained Grey relational grade has been analyzed by using Taguchi AVOVA to obtain the optimal process parameter level shown in table 7

Table. 5: Response Table for Signal to Noise Ratios Larger is better

Level	RS	TS	AF
1	0.4361	0.5326	0.4676
2	**0.6942**	**0.6009**	0.5157
3	0.4275	0.4244	**0.5746**
Delta	0.2666	0.1764	0.1069
Rank	1	2	3

Optimal parameters from the table 6 by Taguchi design for Grey relational grade are Rotational speed = 1200 rpm, Traverse speed = 0.7 mm/s, Axial force = 7000 N. The corresponding levels and optimal process parameters and responses are shown in table 8

Table. 6: Optimal Process Parameters levels

Parameters	Level	Level Description	Units
Rotational Speed	2	1200	rpm
Axial Force	3	7000	N
Traverse Speed	2	0.7	rpm

3.1.2 Analysis of variance for Grey Relation Grade

From the ANOVA the most significant factors that affect the both Ultimate Tensile Strength and % Elongation are Rotational speed, Traverse speed, axial force, respectively based on the percentage of contribution they are providing for the response Ultimate Tensile Strength and % Elongation. The following graph below shows the Taguchi optimal parameters Ultimate Tensile Strength and % Elongation. The Fig 4 shows the effect of each parameter on the process response

Table 7 Analysis of Variance for Grey

Source	DF	Seq SS	Adj SS	Adj MS	F	P
RS	2	91.73	91.73	45.8645	63.38	0
TS	2	34.11	34.11	17.0542	23.57	0
AF	2	13.56	13.56	6.7800	9.37	0.001
Error	20	14.47	14.47	0.7236		
Total	26	153.87				

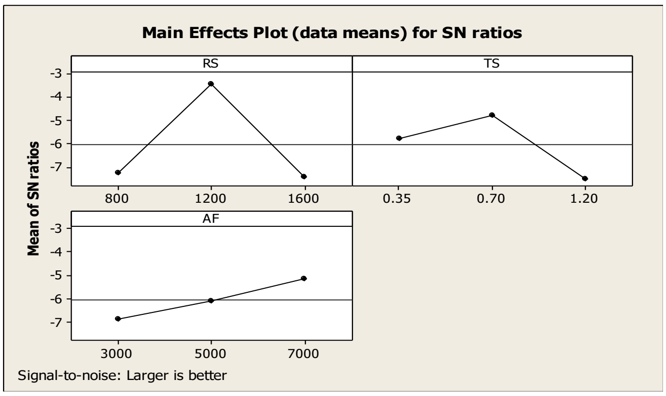

Fig. 4: showing the main effect plot for Grey relation Grade

3.2 Determination of Optimal Conditions

The optimal settings are those which provide the best performance based on the data obtained from the experiment. In this case, the setting of significant design parameters based on main effect is selected by making use of Taguchi, ANOVA, and Grey analysis. The optimal condition was determined and given rankings as:

Table. 8: Optimal Conditions

Parameters	level	UTS	% Elongation control
Rotational Speed (rpm)	1200	**263**	**7.64**
Traverse speed (mm/s)	0.7		
Axial Force (N)	7000		

3.3 Metallurgical Studies

Base material presents elongated grain as result of the rolling of the plates observed in the Fig.5 Due to the concentration of small precipitates in grain boundaries the grains are well defined can be seen in Fig .6.

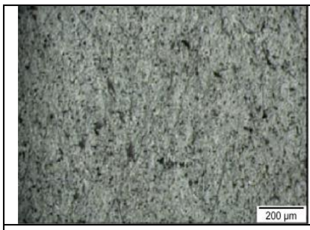

Fig.5: Optical Microstructure of Base material (AA2024-T6 and AA6351-T6)

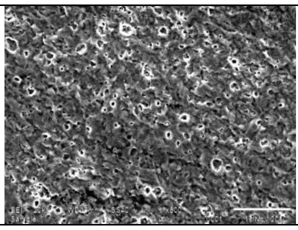

Fig.6: SEM image of Base metal AA2024-T6 and AA6351-T6

Results of the metallurgical analysis for the optimized Friction Stir Welded AA2024-T6 and AA6351-T6 can be analyzed the grain morphology observed in the Fig. 7 and precipitates.

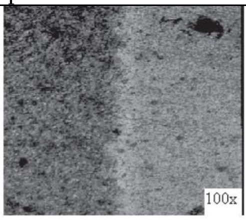

Fig. 7: Optical Microstructure of FSWed (AA2024-T6 and AA6351-T6)

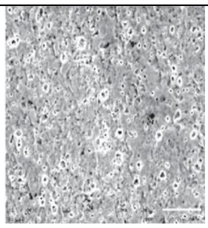

Fig. 8: SEM image of FSWed AA2024-T6 and AA6351-T6

Fig. 9 (a), (b) shows the Typical SEM micrograph of AA2024-T6 and AA6351-T6 base metal showing Al–Mg–Cu rich particles in the Metal matrix

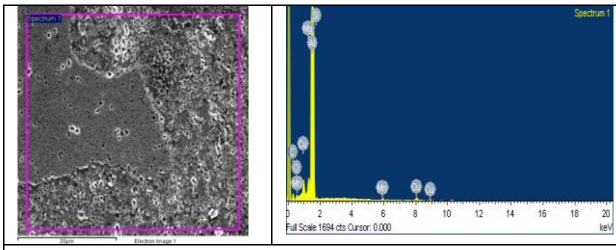

Fig. 9 (a): Typical SEM micrograph of AA2024-T6 and AA6351-T6 showing Al–Mg–Mn-rich particles in the Metal matrix, (b): SEM EDAX spectra of Al–Mg–Cu rich particles shows energy in (KeV) and Intensity in (counts) x 1000

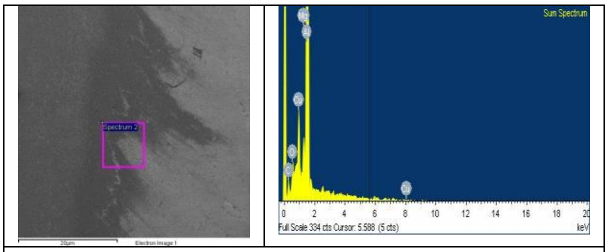

Fig. 10(a): Typical SEM micrograph of FSWed AA2024-T6 and AA6351-T6 (optimal conditions) showing Al–Mg–Mn-rich particles in the Metal matrix, (b): SEM EDAX spectra of Al–Mg–Cu rich particles shows energy in (KeV) and Intensity in (counts) x 1000

3.6 Factrography

Fig. 11(a) and (b) shows the fractured tensile specimen of the base metal and FSW weld respectively. Dimple like patterns are observed in the fractured tensile specimen of the base metal, while the FSW weld specimen shows a river like pattern. It denotes that base metal failure is ductile in nature and the FSW weld brittle in nature.

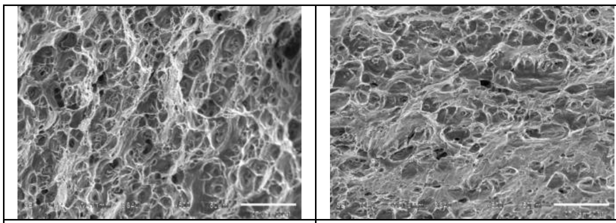

Fig. 11(a): Base material (b) FSWed (optimal conditions)

5. CONCLUSIONS

To optimize the welding process parameters of two different aluminum alloys, Taguchi grey relational analysis was applied in this work. The following conclusions can be drawn

1. Observations concludes that the optimized process parameters are Rotational speed at 1200 rpm, Traverse speed at 0.7 mm/sec, Axial force at 7000 N for both Tensile strength and % Elongation.
2. The ANOVA results show that the most effective process parameters that effect the Tensile strength and % Elongation are Rotational speed, Traverse speed and axial force, which are in ascending order.
3. It is apparent from the ANOVA results that the two factors interactions play a significant role in the weld quality
4. In this present work grey-Taguchi technique was successfully implemented for converting multi objective criterion into a single objective function and the results obtained by grey-Taguchi analysis showed better Tensile strength and % Elongation.

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