

Multi-attribute Optimization of Weld Parameters for Micro-friction Stir Welded Al6061/SS304 Sheets Using TOPSIS Approach

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Abstract

Friction stir welding (FSW) is a solid-state welding approach that can produce high quality joints in a fast and reliable manner. The present study is focused on optimization of multi-responses for micro-friction stir welded Al6061-T6 and SS304 sheets. Weld-parameters such as tool-rotational speed (TRS) and tool-traverse speed (TTS) influenced the mechanical responses of dissimilar welded joints significantly. In order to determine the effect of optimum process parameters on mechanical responses such as ultimate-tensile strength (UTS), micro-hardness (MHV) and surface-roughness (Ra) of dissimilar welded joints, an attempt has been made to find out the best possible set of process variables through multi-attribute optimization using technique for order of preference by similarity to ideal solution (TOPSIS) approach. Finally, the optimal solution shows that multi-responses of micro-friction stir welds can be improved through TOPSIS approach.

Keywords

dissimilar welded joints, micro-friction stir welding (μ FSW), multi-attribute optimization, TOPSIS approach

1 Introduction

Friction stir welding (FSW) is a solid-state joining method developed by The Welding Institute in 1991 to join different dissimilar materials, especially aluminum and steel alloys which are otherwise difficult to join using conventional-joining techniques [1]. Joining of aluminum and stainless-steel alloys through FSW technique has been employed for many applications in the field of nuclear and automotive industries due to enhanced mechanical properties and improved quality joints when compared with fusion (conventional) welding techniques [2, 3]. Recent developments in micro-level friction stir joining process gained significant scope in welding of thin-sectioned sheet materials with thickness 1mm or less [4]. Micro-friction stir welding (μ FSW), extends FSW applications to many areas such as copper electrical-contacts, tailor-welded blanks and composites joining [5, 6]. In the view of any μ FSW application, manufacture of defect free and better quality weld is necessary, so one should assume optimum process parameters by selecting multiple responses during welding. Therefore, it is necessary to study the effect of

weld-process parameters on multiple output responses to achieve high quality weld-joints [7].

Several studies were carried out to develop a mathematical-connection between the weld-parameters and mechanical-characteristics of the weld-joint by theoretical and experimental design procedures. In most of the manufacturing applications, Taguchi's robust design concept is extensively used for optimizing the process variables. This experimental study is focused on optimizing the process parameters in view of a single quality criterion which does not give sufficient thinking about the influence on other concert attributes involved [8]. The performance of the manufactured product is evaluated by several response variables. However, this concept turns out to be time consumption technique. Hence this technique fails to solve a multi-criteria optimization problem. To overcome this limitation, multi-attribute optimization techniques are implemented so that the quality attributes are simultaneously optimized, and the results are computed to select the best levels [9, 10].

In-general, for solving multi-objective optimization problems, several approaches are available such as Grey Relational Analysis (GRA), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), etc. GRA depends on grey-system theory, suitable for solving problems with intricate relationship between several factors and levels. Therefore, GRA reduces intricacy and can be used for solving various types of multi-attribute decision-making problems [11, 12]. In a similar way TOPSIS-approach is also a simple and effective method for multi-attribute decision making problems used in several applications mainly in selecting the process-parameters in manufacturing studies [13].

Both GRA and TOPSIS approaches are examined by most researchers in various applications for selecting optimal process parameters effect on multiple output responses and those research studies concludes the solution achieved by TOPSIS-approach seems to be the best selection when compared with GRA-approach solution. Moreover, optimal solutions obtained from TOPSIS-approach gives higher closeness-coefficient value [14, 15].

Based on the above literature review studies several researchers have focused on optimizing single-objective problems in solid state welding concepts. Very few works have been carried out in optimizing multi-objective problems by considering multi-responses and moreover GRA-approach has been used to solve those multi-objective problems in many FSW case-studies. But the TOPSIS-approach utilization for selecting best weld-process parameter in FSW-applications reported to be less. With this intention, the research has been carried out to optimize the weld-parameters effect on multiple responses such as ultimate-tensile strength, micro-hardness and surface-roughness using TOPSIS-approach.

2 Design-of-Experiments

For conducting the design-of-experiments, Taguchi design concept is mostly used to probe the consequence of each input-response on output-response in a partial number of experiments. The method for selecting a partial number of experiments by producing more information is known as a partial-factorial experiment. Hence Taguchi-orthogonal array design is said to be partial-factorial design that can save both time and cost while optimizing the process variables. In this study, two significant factors such as tool-rotational speed and tool-traverse speed were considered based on several research studies. Weld-process parameters along with their levels are shown in Table 1. In Taguchi Design, relevant orthogonal array is to be selected based on degrees-of-freedom (DoF). The total DoF of input responses should be low when compared with the DoF of selected orthogonal array. The DoF of each weld-process parameter is calculated by subtracting one from number of levels of input-responses. The entire DoF is calculated as four in this study for two factors and three levels. Hence L9 orthogonal array is selected. Since DoF of L9 orthogonal array is eight, which is greater than the total DoF, this design can be suitable for studying the effect of weld-process parameters on individual output responses such as ultimate-tensile strength, micro-hardness and surface-roughness of the weld-joint.

3 Materials and methodology

In this study, thin gauge AA6061-T6 aluminum alloy and SS304 austenitic stainless steel sheets of dimensions 150 mm length × 75 mm width × 0.8 mm thickness are considered for joining using friction stir welding process. The chemical-composition and mechanical-properties of the base materials are shown in Table 2.

Table 1 Weld-process parameters and their levels with DoF

Weld-process parameter	Unit	Level			DoF
		I	II	III	
Tool-rotational speed	rpm	1800	2800	3800	2
Tool-traverse speed	mm/min	60	80	100	2
Total DoF					4

Table 2 Chemical composition and mechanical properties of base materials

Base materials	Chemical composition							Mechanical properties			
	Mg	Si	Cu	Fe	Mn	Cr	Zn	Al	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Micro-Hardness (HV)
AA 6061-T6	1.02	0.66	0.29	0.48	0.15	0.2	0.05	Balance	310	276	90
SS304	C	Mn	Si	Cr	Ni	P	S	Fe	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Micro-Hardness (HV)
	0.08	2	0.75	18.80	8.46	0.045	0.03	Balance	505	215	220

The complete welding process is carried out on a semi-automated vertical milling machine with butt-joint configuration using a zero-pin length tungsten-carbide tool. The selection of zero-pin length tool is found to be more effective and better in improving the mechanical properties for micro-level joining approaches when compared with pin type tools. The workpieces are accurately clamped on backing plate made up of mild steel material which is designed for the fixture mechanism. This fixture should be attached firmly on milling machine bed as shown in Fig. 1. In this methodology, tool rotation produces thermo-mechanical force to join the materials without any fusion normally that occurs in conventional welding techniques.

Weld-process parameters are mainly studied on tool-rotational speed and tool-traverse speed by maintaining the constant tool plunge depth of 0.3 mm, tilt angle of 0.5° and tool dwell time of 3 seconds for all levels.

After processing of all weld-joints, the weld-quality is determined by conducting several mechanical response tests such as tensile-test, micro-hardness test and surface-roughness test. Before proceeding to analyze tensile response, all the welded samples were cut into standard dimensions as per ASTM-E8M standards using Wire-cut EDM technique as shown in Fig. 2. For each weld-joint



Fig. 1 Fixture set-up on milling machine



Fig. 2 Machined samples as per ASTM standards for TRS, (a) 1800 rpm, (b) 2800 rpm and (c) 3800 rpm

three tensile specimens were cut for testing at different levels. Totally nine samples were tested for tensile behavior under high precision computer controlled universal testing machine with a measuring load capacity of 100 KN having an accuracy of $\pm 0.5\%$. Similarly Micro-hardness test was carried out on all the nine samples for observing intermetallic phases along the weld-path. Digital-Vickers hardness equipment is considered for testing the weld samples as per ASTM E384 standards. The tool indenter profile is diamond-pyramid shape with a square base having an angle of 136° and the measurements were carried out along the traverse path of welded joint. Finally, surface-roughness test was carried out on all the nine weld samples to define surface integrity. Digital-Surface roughness equipment is considered for testing the weld samples as per IS-3073:1967 (R2006) assessment to observe better surface finish at different levels.

The measured values for the entire weld samples based on their mechanical responses were shown in Table 3 and the graphical plot for attributes is shown in Fig. 3.

3.1 TOPSIS-approach

Technique for order of preference by similarity to ideal solution (TOPSIS) approach is a multi-attribute tool of optimization for solving intricate decision-making problems in manufacturing field. This approach was developed initially by Hwang and Yoon [16] in 1981 for the measurement to the extent of closeness for an ideal solution. This approach involves in determining optimum solution among alternatives which is having shortest distance from positive(best) ideal solution and largest distance from negative(worst) ideal solution. The basic concept of this approach is used to rank the alternatives obtained by solutions from multi-objective problems. The classical TOPSIS approach algorithm is expressed in the following series of steps:

Table 3 Taguchi L9 Orthogonal array design with mechanical responses

Weld-Sample No. (WS) ↓	Tool rotational speed – TRS	Tool traverse speed – TTS	Ultimate tensile strength – UTS	Micro Hardness – MHV	Surface Roughness – Ra
	Weld-process parameters		Mechanical responses		
Units ⇒	rpm	mm/min	MPa	HV	μm
WS1	1800	60	209	71	3.591
WS2	1800	80	188	70	3.642
WS3	1800	100	155	68	3.761
WS4	2800	60	120	82	3.416
WS5	2800	80	130	87	3.268
WS6	2800	100	118	84	3.353
WS7	3800	60	102	89	3.101
WS8	3800	80	104	83	2.934
WS9	3800	100	111	93	2.808

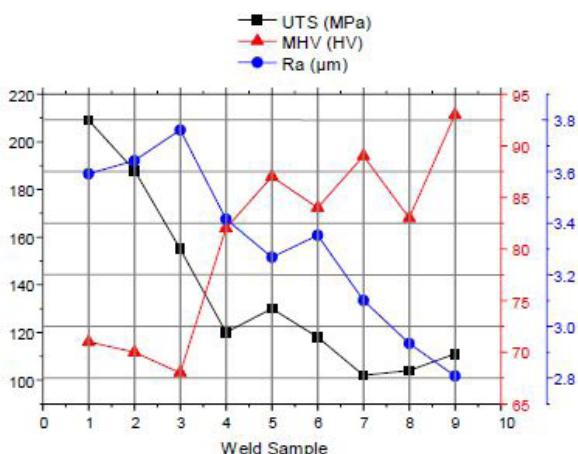


Fig. 3 Graphical plots of mechanical responses for weld samples

- Step 1:** Based on the obtained experimental data, initial decision matrix (D_m) should be constructed as per Eq. (1):

$$D_m = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \dots & \dots & x_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & x_{m3} & \dots & \dots & x_{mn} \end{bmatrix}, \quad (1)$$

where x_{ij} is the measure of j^{th} attribute to i^{th} alternative. D_m consists of " n "-attributes and " m "-alternatives. In present study, mechanical responses are attributes and experimental-trail runs are alternatives.

- Step 2:** The normalized value v_{ij} is calculated from the decision matrix as per Eq. (2):

$$v_{ij} = (x_{ij}) / \sqrt{\sum_{i=1}^m x_{ij}^2} \quad (2)$$

for $i = 1, 2, \dots, m$ and $j = 1, 2 \dots n$.

- Step 3:** In this step, the weights for each attribute was assigned and their sum should be equal to one. The weighted normalized value V_{ij} is calculated from the normalized decision matrix as per Eq. (3):

$$V_{ij} = w_j \times v_{ij}, \quad (3)$$

for $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$, where w_j is the weight of the j^{th} attribute, and

$$\sum_{j=1}^n w_j = 1.$$

- Step 4:** The positive-ideal solution (V^+) and negative-ideal solution (V^-) is determined by Eq. (4) and Eq. (5):

$$V^+ = \left\{ (v_1^+, v_2^+, \dots, v_n^+) \right\} \\ = \left\{ (\max v_{ij} | j \in O), (\min v_{ij} | j \in I | i = 1, 2, \dots, m) \right\} \quad (4)$$

$$V^- = \left\{ (v_1^-, v_2^-, \dots, v_n^-) \right\} \\ = \left\{ (\min v_{ij} | j \in O), (\max v_{ij} | j \in I | i = 1, 2, \dots, m) \right\}, \quad (5)$$

where O is associated with beneficial attribute, and I is associated with non-beneficial attribute (if applicable).

- Step 5:** The measure of separation between alternatives from positive (best) ideal solution (V^+) and negative (worst) ideal solution (V^-) is determined by Eq. (6) and Eq. (7):

$$S_i^+ = \sqrt{\sum_{i=1}^m (v_{ij} - V_j^+)^2} \quad (6)$$

$$S_i^- = \sqrt{\sum_{i=1}^m (V_{ij} - V_j)^2} \quad (7)$$

for $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$.

- **Step 6:** The relative closeness coefficient value of each alternative to the ideal solution is calculated using Eq. (8):

$$RCC_i = \frac{S_i^-}{S_i^- + S_i^+} \quad (8)$$

for $i = 1, 2, \dots, m$; $0 \leq RCC_i \leq 1$

- **Step 7:** Rank the preference order by means of relative closeness coefficient value. The best experimental run is selected based on high closeness coefficient value, which is close to the ideal solution.

4 Results and discussion

4.1 Effect of weld-process parameters on attributes

The effect of weld-process parameters (TRS and TTS) on mechanical responses (UTS, MHV and Ra) was shown in Figs. 4 to 6. The UTS of weld-joints decreases with increase in TRS and TTS. Higher value of UTS is observed

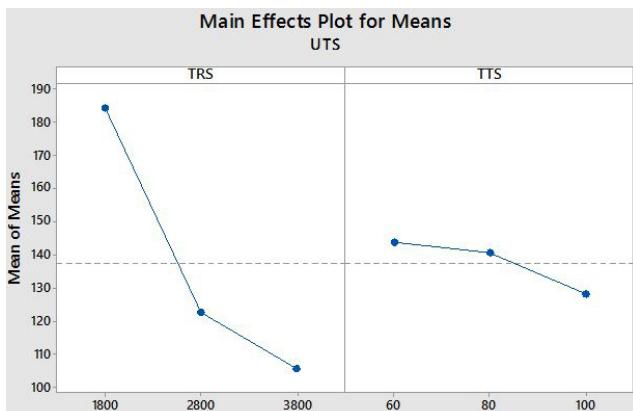


Fig. 4 Effect of weld-process parameters on UTS (MPa)

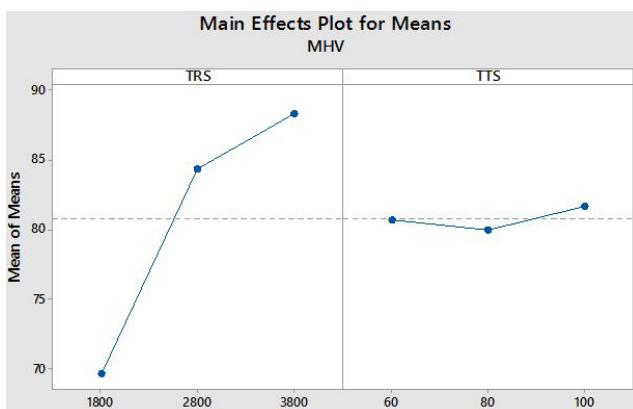


Fig. 5 Effect of weld-process parameters on MHV (HV)

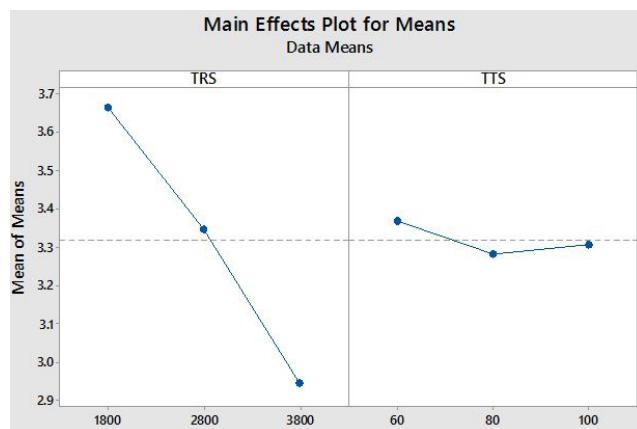


Fig. 6 Effect of weld-process parameters on Ra (μm)

for lower TRS due to the proper amount of heat input generation on weld-nugget zone location that can be greatly influenced on grain size. Moreover, the study on tensile strength of weld-joint is approximately found to be 25% lower when compared with their parent metal. Due to the presence of intermetallic phases of iron and aluminum at weld-nugget zone location, MHV increases for higher TRS and decreases when TTS increases from 60 mm/min to 80 mm/min. The principle of surface roughness is to define the surface integrity of material or workpiece. From the studies of Ra, it is found that TRS is significantly influenced on roughness values for better surface finish. Lower value of Ra is predicted at higher TRS within the weld-nugget zone location. At higher TRS, heat dissipation will be high that results in smooth surface finish of weld-zone.

4.2 TOPSIS analysis

In this approach, firstly the experimental results are transformed into decision matrix consisting of alternatives (in rows) and attributes (in columns) as per Eq. (1). The experimental runs conducted are said to be alternatives and the tested mechanical responses are said to be attributes.

Now, the decision matrix is normalized (for $i = 1, 2, \dots, 9$ and $j = 1, 2$ and 3) as per Eq. (2) and the computed values are shown in Table 4. After normalization, relative weights should be assigned to each attribute. In present work, all attributes were given equal importance. Hence relative weight of 0.333 is assigned to each response. Weighted normalization is calculated as per Eq. (3) and the computed values are shown in Table 5. Now from the results of weighted normalization, positive (best) ideal solution and negative (worst) ideal solution are selected as per Eq. (4) and Eq. (5). Since all the attributes are beneficial, positive-ideal solutions consists of best value from weighted normalization data ($V_{\text{UTS}}^+ = 0.1632209$, $V_{\text{MHV}}^+ = 0.127096$, $V_{\text{Ra}}^+ = 0.09350$)

Table 4 Normalization

Weld-Sample No.	Response values of Normalization		
	UTS	MHV	Ra
WS1	0.49015	0.29138	0.35909
WS2	0.44090	0.28727	0.36419
WS3	0.36351	0.27907	0.37609
WS4	0.28142	0.33652	0.34159
WS5	0.30487	0.35704	0.32679
WS6	0.27673	0.34473	0.33529
WS7	0.23921	0.36525	0.31009
WS8	0.24390	0.34063	0.29339
WS9	0.26032	0.38167	0.28079

Table 5 Weighted-Normalization

Weld-Sample No.	Response values of Weighted-Normalization		
	UTS	MHV	Ra
WS1	0.16322	0.09703	0.11958
WS2	0.14682	0.09566	0.12128
WS3	0.12104	0.09293	0.12524
WS4	0.09371	0.11206	0.11375
WS5	0.10152	0.11889	0.10882
WS6	0.09215	0.11479	0.11165
WS7	0.07965	0.12163	0.10326
WS8	0.08121	0.11343	0.09770
WS9	0.08668	0.12709	0.09350

and negative-ideal solutions consists of worst value from weighted normalization data ($V_{\text{UTS}}^- = 0.079658$, $V_{\text{MHV}}^- = 0.092931$, $V_{\text{Ra}}^- = 0.12524$). The separation measures or Euclidian distance of positive (best) ideal solution and negative (worst) ideal solution are calculated as per Eq. (6) and Eq. (7). From the separation measured values, relative closeness coefficient value for each individual alternative is determined by Eq. (8) and the computed values are shown in Table 6. Finally ranking is given in preference order based upon higher closeness coefficient values.

Table 6 Separation Measure and Relative Closeness Coefficient

Weld-Sample No.	Separation Measure		Relative Closeness Coefficient – RCC	Rank
	S^+	S^-		
WS1	0.03979	0.08385	0.67815	1
WS2	0.04503	0.06733	0.59922	2
WS3	0.06287	0.04139	0.39699	3
WS4	0.07393	0.02638	0.26293	9
WS5	0.06409	0.03771	0.37040	5
WS6	0.07437	0.02862	0.27785	8
WS7	0.08430	0.03615	0.30009	6
WS8	0.08323	0.03437	0.29222	7
WS9	0.07653	0.04716	0.38125	4

4.3 Effect of weld-process parameters on RCC values

From the tested experimental trail runs, alternative WS1 has maximum relative closeness coefficient of 0.67815 and the ranks are preferred from higher to lower as WS1 > WS2 > WS3 > WS9 > WS5 > WS7 > WS8 > WS6 > WS4. Based on the obtained ranks, WS1 is considered as best optimal solution and WS4 as worst optimal solution. The mean-RCC of each weld-process parameter is computed and shown in Table 7. By means of the tabular data, a graph was plotted for the mean RCC values and weld-process parameters as shown in Fig. 7.

Finally, considering the highest RCC value from Table 6 and the mean values from Table 7, the determined optimal combination for achieving high quality weld-joint is TRS1TTS2 (tool-rotational speed of 1800 rpm and tool-traverse speed of 80 mm/min).

5 Conclusion

The present study is mainly focused on the quality of the weld-joint through multi-attribute optimization approach. Thin gauge Al6061 and SS304 sheets were successfully welded using micro-friction stir welding technique. Weld-process parameters such as tool-rotational speed and tool-traverse speed have greatly influenced the mechanical responses such as ultimate-tensile strength, micro-hardness, and surface-roughness.

Based on the Taguchi-L₉ orthogonal array design concept, an experimental plan was conducted, and the data

Table 7 Mean RCC Value

Level	Weld-process parameter	
	TRS	TTS
I	0.55812	0.41373
II	0.30373	0.42062
III	0.32452	0.35203

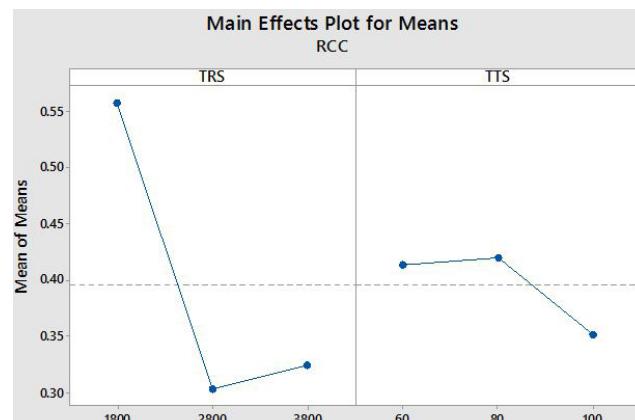


Fig. 7 Effect of weld-process parameters on mean RCC

considered from the experiment trail runs were analyzed using Technique for order of preference by similarity to ideal solution (TOPSIS) approach. From this approach, the optimum weld-process parameter combinations such as

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tool-rotational speed of 1800 rpm and tool-traverse speed of 80 mm/min yield high relative closeness coefficient value of 0.67815 for achieving better quality weld-joint.