Multi Response Optimization of Friction Stir Welding Process Variables using TOPSIS approach

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Abstract. Being a solid state welding process, the friction stir welding (FSW) is extensively used these days, to join difficulty-to-weld materials such as aluminium alloys and its composites. This study emphasizes on friction stir welding of aluminium matrix composite (AMC) reinforced with silicon carbide particle. The FSW tool geometry and process variables play a vital role in governing the joint strength. Size of the grain and the hardness at the weld region influences the joint strength. Process variables such as tool revolving speed, tool traverse speed and the tool pin profile are optimized with multiple responses such as % elongation, tensile strength and hardness. In the present study a technique for order preference by similarity to ideal solution (TOPSIS) approach is used to solve multiple response optimization problems. The optimal solution reveals that the multiple response characteristics of the FS welded AMCs can be improved through the TOPSIS approach.

1. Introduction

FSW is cogitated as a noteworthy development in welding of material in a decade. In FSW, a non-consuming revolving tool having shoulder and projected pin with different profile is plunged into the verges of the work piece to be joined and progressed along the weld line [1]. The friction at the rotating tool and the work piece interface generates enough heat to plasticize the material. The softened material along the weld line is moved around the periphery of the revolving tool, get solidified and a solid state weld is developed following the tool. Figure 1 shows the schematic representation of the FSW process.

To determine the thermo mechanical variations in the weld zone, it is necessary to understand the flow of material during FSW process. However the flow of material happens during the forward movement of the revolving tool is chaotic and scantily understood as reported in [2]. Lot of efforts have been made to realise the influence of process variables on the flow of material, development of grain structures and joint properties of FS welded joints. Influence of pin profiles and some of the major process variables such as revolving speed, speed of tool traverse and axial force on the joint strength is the main area for the study for many researchers. To understand the significance of process variables, many researchers usually adopt the conventional experiment methods, i.e. by varying single
variable at a time keeping all other variables constant [3]. However this approach is turns out to be time consuming and requires vast resources. To identify the major factor from many, one can utilize Taguchi statistical design approach, which drastically reduces the number of experiments. However, this technique basically does not account for the process variable interaction. Interaction among the variables are occasionally neglected to reduce the cost and time consumption. To get superior quality weld joints, it is essential to optimize the process variables by considering multiple responses. Various techniques utilized to optimize the variables are response surface methodology, grey relation analysis etc.

![Schematic representation of FSW process.](image)

Rajkumar and Balasubramanian [4] used RSM technique for multi-objective optimization of the FSW process and geometry of the tools in FSW of AA1100 aluminium alloy to get the higher strength and lesser corrosion rate. They suggested that revolving speed is more sensitive variable and other variables such as axial force, tool traverse speed, shoulder diameter, diameter of the protruded pin, and hardness of the tool follows it.

Vijyan et al. [5] carried out the optimization of FSW process variables for aluminium alloy AA 5083 with several outputs considering orthogonal array (O)A with GRA and revealed that tool the most significant process parameters is the revolving speed. Kasam [6] adopted TM with GRA method for FSW of dissimilar AA6082 and AA7075 Al alloys and found that traverse speed is highly important process variable.

Sanjay Kumar et al. [7] used Taguchi and Grey Relational Analysis (GRA) approach for multiple response optimizations of FSW process variables. Tool revolving speed, traverse speed, tool pin profile and tool tilt angle are considered as the process variables in the FSW of dissimilar aluminium alloys. Tensile strength, percentage of elongation was taken as responses. To ensure the heftiness of GRA technique a confirmation experiment is performed using a combination of optimum process variables. Senthil kuar et al. [8] performed multi response optimization of submerged friction stir welding process variables using TOPSIS approach. The optimum process parameter combinations derived from the TOPSIS method, gives higher closeness coefficient value.

Numerous studies reveal the various optimization techniques for obtaining the suitable variable selection when the diversified objective; however, those studies are not discussing about TOPSIS based optimization of FSW of aluminium composites. Hence in the present study, TOPSIS approach is used for multiple response optimization of FSW of AMCs. The number of experiment and combination of process variables are derived from Taguchi’s L9 orthogonal array and experiment is conducted. The effect of FSW process variables (tool traverse sped, tool revolving speed and pin geometry) on the chosen responses (tensile strength, hardness and percentage elongation) was studied. The optimal value of FSW process variable is tested by conducting confirmation experiments.
2. Experimentation

In the present study, aluminium matrix composite (Al6061-4.5Cu-5SiC) is prepared by stir casting process. AMC plates of size 100X50X6 mm are prepared from the stir cast composite by machining. These AMC plates are joined by FSW process on vertical milling machine. Figure 2 depicts the setup used for FSW. Range for the process variables are decided by conducting trial runs which yields defect free welds. According to Taguchi’s method, the degree of freedom of chosen OA should be equal or higher than the total degree of freedom needed for the experiment. L9 orthogonal array was adopted for carrying out the experiments [9].

![FSW setup](image)

Figure 2. FSW setup

Tool revolving speed, tool traverse speed and tool pin profile are selected as process variables to optimize the FSW of AMCs. In order to limit the study the other variables such as tool tilt angle of 3o, tool shoulder of 16 mm are kept constant. Trial experiments are carried out to get range of process variables which gives defect free welds. It has observed that the FSW of given AMC by using process variable value outside the selected range yields defects in the weld such as tunnel hole, crack etc. Process variables are chosen in 3 levels within the range as shown in Table 1.

Tool steel is used to fabricate the FSW tool and hardened up to 62 HRC. Three different tool pin profiles were used in the study including Square (SP), Cylindrical threaded (CTP) and Combination of square and cylindrical threaded (CSCTP) profile. Tool pin geometry is shown in figure 3.

Tensile test specimens are prepared from both the base metal and the FS welded part as per the ASTM E8 standard. From each FS welded joint three specimens were taken in a direction perpendicular to the joint line. Tests are conducted using universal testing machine and their UTS and % of elongation were measured. The geometry of the tensile test specimen is depicted in Figure 4.

| Factors | Process Variables | Level-1 | Level-2 | Level-3 |
|---------|-------------------|---------|---------|---------|
| A       | Tool Geometry     | CTP     | SP      | CSCTP   |
| B       | Revolving Speed   | 710     | 1000    | 1400    |
| C       | Traverse Speed    | 50      | 63      | 80      |

Table 1. Process variables and their levels
The hardness of the FS welded joint was measured using Vickers macro hardness tester with an indentation load of 5 kg for 15 sec. Test was carried out at the middle region across the weld at 3 mm interval on both side of the weld line. The table 2 summarizes the process variable values used in FSW and its output responses.

| Expt. No | Pin Geometry | Revolving Speed (RPM) | Tool Traverse Speed (mm/min) | UTS (MPa) | Vickers hardness (Hv) | % Elongation |
|----------|--------------|-----------------------|-----------------------------|-----------|-----------------------|--------------|
| 1        | CTP          | 710                   | 50                          | 115       | 103.5                 | 8.7          |
| 2        | CTP          | 1000                  | 63                          | 154       | 119                   | 7.3          |
| 3        | CTP          | 1400                  | 80                          | 139       | 109                   | 8.0          |
| 4        | SP           | 710                   | 63                          | 142       | 113                   | 8.7          |
| 5        | SP           | 1000                  | 80                          | 172       | 126                   | 7.7          |
| 6        | SP           | 1400                  | 50                          | 126       | 106                   | 9.2          |
| 7        | CSCTP        | 710                   | 80                          | 147       | 115                   | 8.3          |
| 8        | CSCTP        | 1000                  | 50                          | 149       | 117.5                 | 8.1          |
| 9        | CSCTP        | 1400                  | 63                          | 139       | 109                   | 8.7          |

3. TOPSIS

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was developed by Hwang and Yoon in the year 1995. TOPSIS approach is focussed on an alternative which has the shortest distance from the best/ positive ideal solution and on the other side have the longest distance from the worst/ negative ideal solution. A solution not only closer to the hypothetically best but also farther from the hypothetically worst is obtained from the TOPSIS. The various steps followed in this approach are given as follows.
STEP 1
Units of all the responses are removed and the responses are converted to normalized value by using the equation 1.

\[ n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{9} a_{ij}^2}} \]  

Where \( i = 1, 2, \ldots, 9 \) and \( j = 1, 2 \) and 3
\( i \) = number of alternatives, \( j \) = number of responses, \( a_{ij} \) = Actual value of the \( i^{th} \) value of \( j^{th} \) experimental run. The normalized values of the responses are shown in table 3.

STEP 2
Specific weights are assigned to each of the responses in order to rank the responses. These weights are multiplied with normalized value to get weighted normalized value as given in equation 2.

\[ r_{ij} = w_j \times n_{ij} \]  

In the present study equal weights (\( w_j = 0.33 \)) are assigned to all the three responses. The table 4 lists the weighted normalized values.

Table 3: Normalized Response value

| Expt. No. | UTS   | Hardness | % Elongation |
|-----------|-------|----------|--------------|
| 1         | 0.2674| 0.3045   | 0.3486       |
| 2         | 0.3580| 0.3501   | 0.2925       |
| 3         | 0.3232| 0.3207   | 0.3206       |
| 4         | 0.3301| 0.3324   | 0.3486       |
| 5         | 0.3999| 0.3707   | 0.3085       |
| 6         | 0.2929| 0.3118   | 0.3687       |
| 7         | 0.3418| 0.3383   | 0.3326       |
| 8         | 0.3464| 0.3457   | 0.3246       |
| 9         | 0.3232| 0.3207   | 0.3486       |

Table 4: Weighted Normalized value

| Expt. No. | UTS   | Hardness | % Elongation |
|-----------|-------|----------|--------------|
| 1         | 0.0891| 0.1015   | 0.1162       |
| 2         | 0.1193| 0.1167   | 0.0975       |
| 3         | 0.1077| 0.1069   | 0.1069       |
| 4         | 0.1100| 0.1108   | 0.1162       |
| 5         | 0.1333| 0.1236   | 0.1028       |
| 6         | 0.0976| 0.1039   | 0.1229       |
| 7         | 0.1139| 0.1128   | 0.1109       |
| 8         | 0.1155| 0.1152   | 0.1082       |
| 9         | 0.1077| 0.1069   | 0.1162       |

STEP 3
The best (R+) and worst (R-) ideal solution has been calculated using equation (3a) and (3b),

\[ R_+ = \{ \text{Max} (r_{ij}) \mid j \in J \mid i = 1, 2, \ldots, 9 \} \]  

\[ R_- = \{ \text{Min} (r_{ij}) \mid j \in J \mid i = 1, 2, \ldots, 9 \} \]

Where,
\( J \) is a set of beneficial attributes. Table 5 shows the R+ and R- values.
Table 5: Best (R+) and Worst (R-) ideal solution

| Solution | UTS  | Hardness | % Elongation |
|----------|------|----------|--------------|
| R+       | 0.1333 | 0.1236 | 0.1229 |
| R-       | 0.0891 | 0.1015 | 0.0975 |

STEP 4
The separation between alternative were computed using equations (4a) and (4b).

The separation of each alternative from best / positive solution is given by

$$S_i^+ = \sqrt{\sum_{j=1}^{9}(r_{ij} - R_j^+)^2}$$  \hspace{1cm} (4a)

The separation of each alternative from worst / negative solution is given by

$$S_i^- = \sqrt{\sum_{j=1}^{9}(r_{ij} - R_j^-)^2}$$  \hspace{1cm} (4b)

Where, i = 1, 2, 3 ... 9, and j = 1, 2, 3.

STEP 5
Relative closeness value of the particular alternative ($X_i$) to the ideal solution is measured, which is expressed as

$$X_i = \frac{S_i^-}{(S_i^- + S_i^+)}$$  \hspace{1cm} (5)

The closeness coefficient value was ranked in descending order to find the set of process variables having the most and least preferred solutions. Table 6 shows the closeness coefficient values and their rankings.

Table 6: Closeness Coefficient Value

| Expt No. | $S_i^+$ | $S_i^-$ | $X_i$ | Rank |
|----------|---------|---------|-------|------|
| 1        | 0.04983 | 0.01870 | 0.2729 | 9    |
| 2        | 0.02976 | 0.03383 | 0.5320 | 4    |
| 3        | 0.03448 | 0.02150 | 0.3841 | 8    |
| 4        | 0.02734 | 0.02957 | 0.5196 | 5    |
| 5        | 0.02004 | 0.04966 | 0.7125 | 1    |
| 6        | 0.04069 | 0.02688 | 0.3979 | 7    |
| 7        | 0.02522 | 0.03034 | 0.5460 | 3    |
| 8        | 0.02456 | 0.03157 | 0.5625 | 2    |
| 9        | 0.03125 | 0.02692 | 0.4628 | 6    |

STEP 6
Average closeness coefficient value for each level of process variables were computed as shown in table 7. From the table, the optimal combination of process variables is square pin profile with revolving speed of 1000 rpm and tool traverse speed of 80 mm/min.

Table 7: Average Closeness Coefficient Value

| Tool Geometry | Tool revolving Speed | Tool Traverse Speed |
|---------------|----------------------|---------------------|
| Level-1       | 0.3963               | 0.4462              | 0.4111              |
| Level-2       | **0.5433**           | **0.6023**          | 0.5048              |
| Level-3       | 0.5238               | 0.4149              | **0.5476**          |
4. Conclusion

In the present study, FSW of aluminium composite (Al 6061-4.5 Cu - 5 SiC) was performed. Influence of combined factor of various process variables and the tool pin profiles on the quality of joints are studied. In accordance with the L9 orthogonal array, set of experiments were performed and data obtained from the experiment were analysed using TOPSIS method. TOPSIS provides a solution which is not only closer to the hypothetically best but also farther from the hypothetically worst alternatives. Present study reveals that the optimum process variable combinations such as square pin profile, revolving speed of 1000 rpm and tool traverse speed of 80 mm/min gives better closeness coefficient value.

5. References

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