Multi-Response Optimization of Weld-process variables for Micro-Friction Stir Welding of Al6061(T6) and Cu101 sheets using TOPSIS method

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Abstract. This work is an attempt to identify the optimum weld-process variables for micro-friction stir welding of Al6061(T6) and Cu101 sheets using multi-response optimization. The experiments were conducted according to L9 orthogonal array with selected input variables namely tool-rotational speed and tool-travel speed. The response variables considered in this study are ultimate tensile strength, micro-hardness and surface-roughness which determine the strength of the welded-joint. The multi-response optimization approach namely Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is used to determine the optimum process variables that provides the best value among all response variables. Finally, the optimal solution shows that multi-responses of micro-friction stir welds can be improved through TOPSIS method.

1. Introduction

Joining of aluminium and copper materials has gained significant scope in electrical and electronic industries due to their high corrosion-resistance and best conductivity properties. Among various joining techniques, Friction stir welding (FSW) has wide scope in joining dissimilar-materials without extending their melting zones [1]. The studies on FSW technique in present days is slowly focusing on thin sectioned materials joining with thickness of 1000 μm (1 mm) or low. This micro-level joining paved the way for the development of micro-friction stir welding (µFSW). Most of the research studies on FSW process were implemented on joining thick dimensioned plates in similar/dissimilar form and the work intended for joining thin dimensioned dissimilar materials in micro-level approach was identified to be less [2],[3].

Considering cost and time aspects, industries prefer easy and reliable operations to grasp optimization problems. In fact, Taguchi-approach is the basic designing concept generally used to optimize operational variables. But this approach focuses on single response criterion and does not give sufficient data about the remaining response variables involved. Generally performance of the product while manufacturing is examined by several responses. Hence Taguchi-approach turns out to be time consumption approach [4].

By overcoming the limitations observed by Taguchi-approach in solving multi-response problems, several techniques have been implemented to solve the multi-criteria decision making problems so that quality responses are simultaneously optimized and the solutions are evaluated for best levels. Several research studies were carried out to develop a mathematical relation between process variables and mechanical responses of welded-joint with different experimental design procedures. In general, multi-criteria decision making problems are usually subdivided into continuous and discrete types. In continuous type, response variables are determined in continuous domain having more number of alternative choices whereas in discrete type, response variables are determined randomly with limited number of pre-specified alternatives [5].
More research studies are focused on GRA-(Grey relational analysis) technique for solving multi-response optimization problems. This technique depends upon grey-system theory fitted for working out problems having intricate relationship between factors and levels. In similar manner, there is another method called Technique for order of preference by similarity to ideal solution (TOPSIS), which is simple and effective for solving multi-criteria decision making problems. Both GRA and TOPSIS methods are examined for several applications for selecting optimum parameters of process variables on multi-responses, hence those studies concludes that the solution achieved by TOPSIS method somewhat identified as better one when compared with GRA method [6],[7]. Very few works were carried out for optimizing multi-response problems in micro-FSW applications using TOPSIS method. With this intention, the present study has been reported to carry out TOPSIS optimization for weld-process variables effect on output responses such as Ultimate Tensile strength (UTS), Micro-Hardness (MH) and Surface Roughness (SR).

2. Design of Experiments

For conducting design of experiments, Taguchi-approach is selected to probe the effect of weld-process variables on output responses with limited experimental runs. In present study, two main weld-process variables such as tool-rotational speed and tool-travel speed were chosen based on several literature studies. Weld-process variables along with their levels are shown in Table 1. In Taguchi-method, relevant orthogonal array is selected based on degrees of freedom(DF). The total DF of process-parameters should be less than the DF of relevant orthogonal array. As per Table 1, total DF is calculated as four for two factors and three levels. Hence L9 orthogonal array was selected and this design is suitable for studying the effect of input process variables on output mechanical responses such as UTS, MH and SR.

| Weld-process variable | Unit | Level 1 | Level 2 | Level 3 | DF |
|-----------------------|------|--------|--------|--------|----|
| Tool-rotational speed | rpm  | 1100   | 1400   | 1800   | 2  |
| Tool-travel speed     | mm/min | 40    | 60    | 80    | 2  |
| Total DF              |      |        |        |        | 4  |

3. Materials and Methodology

Thin-gauge Al6061(T6) and Cu101 sheets of 0.8 mm thickness are selected for welding using µFSW technique. The complete welding process is operated on a semi-automated vertical milling machine using pinless tungsten-carbide tool. Weld-process variables are compiled for different tool-rotational speeds and tool-travel speeds by preserving three constant parameters such as tool plunge depth of 0.3 mm, tool tilt angle of 0.50 and tool dwell time of 5 seconds for all the levels [8]. After processing of all the weld-joints, quality of the weld-joint is determined by examining mechanical behaviours such as tensile test, micro-hardness test and surface roughness test.

Before proceeding to mechanical behaviour analysis, the weld-samples are cut as per ASTM E8M standard dimensions using Wire EDM technique as shown in Figure 1. Total three specimens were cut from each weld-sample. Finally nine samples were tested for tensile-behaviour for examining higher values at different levels using high precision computer control universal testing machine. Similarly micro-hardness test was carried out on all nine weld-samples using Vickers digital hardness machine for examining the intermetallic layers of Al/Cu mixture. In similar manner, surface roughness test was carried out on all nine weld-samples using Digital surface roughness tester for examining better surface finish at different levels.
Figure 1. Machines samples as per ASTM E8M standards

The measured responses for all the weld-samples are tabulated in Table 2 and their effects are plotted on Figure 2.

| Weld-Sample No. (WS) | Tool rotational speed – TRS | Tool traverse speed – TTS | Ultimate tensile strength – UTS | Micro Hardness – MH | Surface Roughness – SR |
|----------------------|----------------------------|---------------------------|-------------------------------|---------------------|------------------------|
| WS-1                 | 1100                       | 40                        | 83                            | 80                  | 3.364                  |
| WS-2                 | 1100                       | 60                        | 72                            | 71                  | 3.452                  |
| WS-3                 | 1100                       | 80                        | 80                            | 73                  | 3.380                  |
| WS-4                 | 1400                       | 40                        | 138                           | 55                  | 3.108                  |
| WS-5                 | 1400                       | 60                        | 162                           | 64                  | 3.024                  |
| WS-6                 | 1400                       | 80                        | 157                           | 59                  | 3.112                  |
| WS-7                 | 1800                       | 40                        | 175                           | 54                  | 1.841                  |
| WS-8                 | 1800                       | 60                        | 145                           | 58                  | 1.432                  |
| WS-9                 | 1800                       | 80                        | 191                           | 60                  | 1.172                  |

Figure 2. Graphical plots for measured response variables
4. Results and Discussions based on TOPSIS-method

Technique for order of preference by similarity to ideal solution (TOPSIS) method is a multi-response optimization tool for solving complex decision making problems in industrial applications. Initially this method was developed by Ching-Lai-Hwang & Yoon in 1981 [9] with further evolutions by K. Yoon in 1987 [10] and Hwang, Lai & Liu in 1993 [11]. The basic approach of this method is for choosing alternatives that have shortest distance from positive-ideal solution(PIS) and longest distance from negative-ideal solution(NIS). Finally ranks are created for alternatives based on the solutions obtained from multi-response problems. The classical TOPSIS algorithm [12] based on the experiment data is calculated in following steps,

Step 1: The initial step is to construct the decision-matrix which consists of 3 attributes (response variables) and 9 alternatives (experimental-runs) by removing all units. Now the decision matrix is normalized as per equation (1) and the computed values are shown in Table 3.

\[
v_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{9} x_{ij}^2}}
\]

for \(i = 1, 2, ..., 9\) and \(j = 1, 2, 3\)

Where \(v_{ij}\) = normalized value and \(x_{ij}\) = measure of \(j^{th}\) attribute to \(i^{th}\) alternative

**Table 3. Normalization**

| Weld-Sample No. | Normalized Response values |
|-----------------|---------------------------|
|                 | UTS | MH    | SR    |
| WS-1            | 0.19754 | 0.41449 | 0.40219 |
| WS-2            | 0.17136 | 0.36786 | 0.41271 |
| WS-3            | 0.19040 | 0.37822 | 0.40410 |
| WS-4            | 0.32844 | 0.28496 | 0.37158 |
| WS-5            | 0.38556 | 0.33159 | 0.36154 |
| WS-6            | 0.37366 | 0.30568 | 0.37206 |
| WS-7            | 0.41650 | 0.27978 | 0.22010 |
| WS-8            | 0.34510 | 0.30050 | 0.17120 |
| WS-9            | 0.45458 | 0.31086 | 0.14012 |

Step 2: In second step, relative-weights should be assigned to each of the attribute. In present study, all response variables are given equal significance and hence the relative-weight of 0.333 is considered. The weighted normalization is deliberated as per equation (2) and the computed values are shown in Table 4.

\[
V_{ij} = w_j x v_{ij}
\]

for \(i = 1, 2, ..., 9\) and \(j = 1, 2, 3\).

Where \(V_{ij}\) = weight-normalized value and \(w_j\) = weight of the \(j^{th}\) attribute
Table 4. Weighted-Normalization

| Weld-Sample No. | Weight-Normlized Response values |
|-----------------|----------------------------------|
|                 | UTS    | MH       | SR       |
| WS-1            | 0.06578 | 0.13802  | 0.13392  |
| WS-2            | 0.05706 | 0.12249  | 0.13743  |
| WS-3            | 0.06340 | 0.12594  | 0.13456  |
| WS-4            | 0.10937 | 0.09489  | 0.12373  |
| WS-5            | 0.12839 | 0.11042  | 0.12039  |
| WS-6            | 0.12442 | 0.10179  | 0.12389  |
| WS-7            | 0.13869 | 0.09316  | 0.07329  |
| WS-8            | 0.11491 | 0.10006  | 0.05701  |
| WS-9            | 0.15137 | 0.10351  | 0.04666  |

Step 3: In third step, the best (positive-ideal) and worst (negative-ideal) solutions are deliberated as per equation (3) and equation (4). The computed values are shown in Table 5.

\[ V^+ = \{(\max v_{ij} | j \in O), (\min v_{ij} | j \in P | i=1,2,\ldots,9)\} \]  \hspace{1cm} (3)

\[ V^- = \{(\min v_{ij} | j \in O), (\max v_{ij} | j \in P | i=1,2,\ldots,9)\} \]  \hspace{1cm} (4)

Where O = beneficial attribute, and P = non-beneficial attribute (if applicable)

Table 5. Best (PIS) and Worst (NIS) values

| Ideal-solution | Response values |
|----------------|-----------------|
|                | UTS  | MH       | SR       |
| \( V^+ \)      | 0.15137 | 0.13802 | 0.04666  |
| \( V^- \)      | 0.05706 | 0.09316 | 0.13743  |

Step 4: In fourth step, the separation measure for each alternative from PIS and NIS is deliberated as per equation (5) and equation (6). The computed values are shown in Table 6.

\[ S^+_i = \sqrt{\sum_{j=1}^{3}(v_{ij} - V^+)^2} \]  \hspace{1cm} (5)

\[ S^-_i = \sqrt{\sum_{j=1}^{3}(v_{ij} - V^-)^2} \]  \hspace{1cm} (6)

for \( i = 1,2,\ldots,9 \) and \( j = 1,2 \) and 3.

Step 5: In fifth step, closeness coefficient (CC) value for each alternative from the separation measure is deliberated as per equation (7) and the computed values are shown in Table 6.

\[ CC_i = \frac{S^-_i}{S^-_i + S^+_i} \]  \hspace{1cm} (7)

for \( i = 1,2,\ldots,9;\ 0 \leq CC_i \leq 1 \)
Step 6: In sixth step, ranking is given in preference order as shown in Table 6 that depends upon CC-values arranged in descending order,

WS-9>WS-7>WS-8>WS-5>WS-6>WS-4>WS-1>WS-3>WS-2

Based on the obtained ranks, WS-9 is considered as best-optimal solution and WS-2 is considered as worst-optimal solution among all alternatives(experimental-runs).

Table 6. Separation Measure and Closeness Coefficient Values

| Weld-Sample No. | Separation Measure | Closeness Coefficient - CC | Rank |
|-----------------|--------------------|-----------------------------|------|
| WS-1            | 0.12223            | 0.27269                     | 7    |
| WS-2            | 0.13181            | 0.18201                     | 9    |
| WS-3            | 0.12494            | 0.21148                     | 8    |
| WS-4            | 0.09780            | 0.35613                     | 6    |
| WS-5            | 0.08201            | 0.47877                     | 4    |
| WS-6            | 0.08946            | 0.43631                     | 5    |
| WS-7            | 0.05368            | 0.65912                     | 2    |
| WS-8            | 0.05363            | 0.64930                     | 3    |
| WS-9            | 0.03450            | 0.79189                     | 1    |

Finally, the average-CC value of each weld-process variable for all levels is deliberated and the computed values are shown in Table 7. By means of tabular data, a graph was plotted between average-CC value and levels of weld-process variables as shown in Figure 3.

Table 7. Average Closeness Coefficient Value (average-CC)

| Level | Weld-process parameter | TRS | TTS |
|-------|------------------------|-----|-----|
| 1     | 0.22206                | 0.42932 |
| 2     | 0.42374                | 0.43669 |
| 3     | **0.70011**            | **0.47989** |

Figure 3. Effect of weld-process variables on average-CC
5. Conclusion

Thin gauge Al6061(T6) and Cu101 sheets of 0.8 mm thickness were successfully welded using micro-friction stir welding approach. Weld-process variables such as tool-rotational speed and tool-travel speed were significantly influenced the output responses such as UTS, MH and SR.

Based on the Taguchi L9 orthogonal array design concept and Technique for order of preference by similarity to ideal solution (TOPSIS) approach, the optimum weld combination is observed as TRS3TTS3 (tool-rotational speed of 1800 rpm and tool-travel speed of 80 mm/min) that yields high closeness coefficient value of 0.79189 for producing high quality welded-joint.

6. Future Scope

Micro-Friction stir welding of Aluminium alloy and copper alloy sheets has been demonstrated successfully in the present work, but further work is required to improve the tool characteristics, and also to demonstrate the mechanical properties of the welds at different zones.

7. References

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Author Contributions

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