Optimization of arc brazing process parameters for exhaust system parts using box-behnken design of experiment

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Abstract

Stainless steel is used in automobile muffler and exhaust systems. However, in comparison with other steels it has a high thermal expansion rate and low thermal conductivity, and undergoes excessive thermal deformation after welding. To address this problem, we evaluated the use of arc brazing in place of welding for the processing of an exhaust system, and investigated the parameters that affect the joint characteristics. Muffler parts STS439 and hot-dipped Al coated steel were used as test specimens, and CuAl brazing wire was used as the filler metal for the cold metal transfer (CMT) welding machine, which is a low heat input arc welder. In addition, a Box-Behnken design of experiment was used, which is a response surface methodology. The main process parameters (current, speed, and torch angle) were used to determine the appropriate welding quality and the mechanical properties of the brazing part was evaluated at the optimal welding condition. The optimal processing condition for arc brazing was 135A current, 51cm/min speed and 74° torch angle. The process was applied to an actual exhaust system muffler and the prototype was validated by thermal fatigue, thermal shock, and endurance limit tests.

Key Words : Arc brazing process, Muffler, Design of Experiment, Box-Behnken, Composite desirability

1. Introduction

Casting steel and aluminum coated steel have been previously used in exhaust systems, but demand for eco-friendly and lightweight materials has led to a complete conversion to corrosion-resistant stainless steel. However, stainless steel has a high thermal expansion rate and low thermal conductivity compared to other steels. As a result, the final product undergoes excessive thermal deformation after welding. The arc brazing process may be used to solve this problem, and also reduce spatter, fume, and welding smut. Arc brazing uses a low melting point wire and a metal inert gas (MIG) power source. This not only minimizes the effect of heat input on the base metal, but also results in higher productivity than a conventional brazing process, as well as enabling digital quality control. Due to these advantages, arc brazing is widely used in the automobile industry, despite the cost of the expensive wire. However, the arc brazing process has some drawbacks, such as production costs and weak mechanical strength (e.g. tensile strength). Furthermore, it is difficult to determine the initial conditions because of the use of filler metals with low melting points, unlike those in traditional welding, and the process was developed only recently. In addition, it is difficult to achieve high joint quality, because the joint quality depends on various factors. Therefore, it is important to determine the process conditions that obtain an optimal joint quality with a minimal number of experiments.

For this reason, Box-Behnken design methodology was used in this study to find the optimal parameters. The final conditions were then applied to manufacture a prototype exhaust muffler. Finally, the prototype was validated using thermal fatigue, thermal shock, salt spray, and endurance limit tests.
2. Experimental Methods and Design

2.1 Materials and Methods

The location of the exhaust muffler and its shape are shown in Fig. 1. The outer two layers of the muffler case are made from hot-dipped aluminum coated steel (SACD) and the inner two layers are formed from STS439 pipes. In order to reproduce the joint, geometry of the specimen was prepared as shown in Fig. 2. The specimen was fixed using toggle clamp and to measure deformation, a section from the center of the specimen was cut down as shown in Fig. 2. CuAl-A2 wire was used as the brazing filler metal and its diameter was 1.2mm. A low heat input MIG pulse arc welding power source was used in this study. The chemical compositions of the base metal and the brazing wire used in the experiment are given in Tables 1 to 3.

2.2 Box-Behnken Design

In this study, we used a Box-Behnken (B-B) design of experiment (DOE) at the specimen level, to optimize the arc braze welding of exhaust muffler parts and to determine optimal processing condition. The B-B DOE, which was first proposed by Box and Behnken in 1961, does not use any experimental points at the vertices as shown in Fig. 3. If the factors are quantitative with the three levels, then the DOE produces a second-order regression equation to yield the optimal condition. For k factors, this DOE has fewer experimental points than a 3^k factorial design, allows facile orthogonal blocking, and produces a second-order regression equation. Due to these advantages, a B-B DOE is used in the surface response methodology. For k=3 factors, a B-B DOE is more economical than 3^3 factorial design (which requires 27 experiments), does not require experiments at very high or low levels, and conducts experiments at the center of the edges of a polyhedron and at the center of the whole experimental region.

Response surface methodology, such as B-B design, is used to identify a relationship between one or more response variables and a quantitative experimental variable or a group of factors, and its goal is to determine the condition for the factor that optimizes response variable. Several applications of the response surface methodology are as follows:

(1) To determine the condition for optimal response
(2) To determine the condition for the factor that satisfies a given work condition or process specification
(3) To model the relationship between the quantitative factor and the response variable
(4) To confirm a new condition for improved quality
2.3 Process Parameters and Regions of Interest

For a complex phenomenon governed by multiple variables, it is necessary to conduct experiments for different combinations of the variables in order to examine the effect of each variable on the whole. During this process, the variable combination must be carefully selected in order to guarantee the reliability of the analysis\(^5\)\(^\text{-}^9\). A welding process involves multiple inputs and outputs, and involves coupled interactions of input variables. Therefore, adjusting a welding process parameters by trial and error would result in using up a great deal of time and resources. To avoid this problem, it is necessary to build a model for the input and output variables of the welding process, and then use the model to determine the optimal welding process parameters\(^5\).

The process parameters for the arc brazing of the exhaust muffler studied in this research are as follows:

1. Current (A)
2. Brazing speed (cm/min)
3. Torch angle (degree)

First, a pilot study was conducted to select the region of interest for the process parameters of the B-B DOE. From this study, it was shown that for currents below 120 A heat input was too low and the bead deposit was insufficient, whereas for current above 160 A heat input was too high and the bead became excessively large. Furthermore, the optimal brazing speed and torch angles were expected to be within 40–60 cm/min and 45–75°, respectively. Based on the pilot study, we divided each process parameter into three levels, as shown in Table 4, and used the B-B design to construct an experimental design with a total of 15 experiments, as shown in Table 5. The lap joint arc brazing was performed using the conditions of the experiment design.

3. Results and Discussion

3.1 Desirability Function Setting

As a result of the tensile shear test at room temperature and at high temperatures (450°C, and 600°C) after accomplishing arc-brazing with a total of 15 experiments using the plan created by the B-B design, fracture did not occur from the joint in all conditions as in Fig. 4, but occurred from the base material of STS439.

The reason why fracture of base material occurred in all the conditions was that brazing was done within the range, selected through preliminary experiments, that forms appropriate beads and also the tensile strength (560 MPa) of Cu-Al filler metal was not only higher than base metal (400 MPa) but also larger in the adhesive joint area (leg length) than in the cross-section area of the base material.

Also, although the heat input variation was higher in the experiment based on the experiment designs, burn through of base material did not occur unlike in general arc welding. Instead, at the center of the specimen that was not fixed by toggle clamp as shown in Fig. 3, a huge deformation of the base material occurred as shown in Fig. 5(b). This is because the brazing process has a great gap bridging ability and since the melting point of the brazing wire is lower than the base material, although heat input varia-

![Fig. 4 Result of tensile strength test](image)

![Fig. 5 Measurements for bead geometry](image)
tion is high, the molten pool permeates into the gaps in the sheets of the base materials due to capillary action, instead of the base material being melted. Therefore, response variables were set for conditions where all the adhesive strengths are satisfied with regard to appropriate area, height of beads and minimized deformation of the specimen. Finally, optimization of process condition was accomplished through the following stages.

(1) Individual desirability “di” deduced for each response variables (bead area, height and deformation)
(2) Composite desirability “D” value deduced by combining individual desirability
(3) Deduction of optimal design solution by maximizing composite desirability

Fig. 5 explains the measurement methods for each particular value of the response variables. First, the bead area and height was measured in the parts without deformation (fixed with toggle clamp). However, deformation was measured from the center of the specimen and it was calculated after deducting 3.6mm, which is the thickness of 4 layers of raw materials, from the final deformed height.

Individual desirability is a function designed to indicate the level of desirability regarding the response variable in values between [0, 1]. The values that express individual desirability, including T, L, U and w, are chosen by the users and in case of w, it indicates the importance of each response variable. Individual desirability is closer to “1” if the desirability of the response is higher and it is closer to “0” if the desirability is lower. The range of individual desirability was set based on the standard of the ISO 5817 and the result of the preliminary experiment. Firstly, it was defined as ‘larger-the-better’ in case of individual desirability for bead areas. Usually, there are problems of with deformation from welding in under high temperatures when the bead area is larger, but since it is the function controlled by ‘deformation’, another individual desirability, it was not considered in the bead area. Therefore, the lowest limit was L: 3.6 considering the total thickness of the specimen, 3.6mm. The target was set as T:5.4, which was 1.5 times bigger than the thickness of the specimen, considering the difference existing between the filler metal and the interface, and all the above was set to have an individual desirability of 1.

The bead height has the feature of nominal-the-best, and its lowest limit was set as L:2.6, target as T:3.25, and highest limit as U:3.9. The lowest limit was set according to the height of the specimen, 2.6mm, excluding the lower valve, as the standard and the highest limit was set below 3.9mm, according to the ISO 5817 regulation that the height of the weld reinforcement should not exceed 50% of the thickness. Therefore, the target was set as the median value of the highest and the lowest value. Weight values of both bead area and height were set as 1.

Meanwhile, deformation has the feature of smaller-the-better. Therefore, there is no L, the lowest limit, and the target was set as T:0 and the highest limit as U:5.2. The highest limit was set twice the thickness of base material to limit the deformation to twice the thickness of the higher value material. Also, because it is the best with no deformation, the weight was given to the deformation closer to 0, and its value was set as w:3. In Table 5, forms according to each response variable and ranges of individual desirability are set.
Table 6 Experimental design and the results of Box-Behnken method

<table>
<thead>
<tr>
<th>No.</th>
<th>Current (A)</th>
<th>Brazing speed (cm/min)</th>
<th>Torch angle (°)</th>
<th>Bead shape (mm)</th>
<th>Deformation size (mm)</th>
<th>Geometric mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>width</td>
<td>height</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>160</td>
<td>30</td>
<td>60</td>
<td>8.18</td>
<td>3.38</td>
<td>4.50</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>45</td>
<td>75</td>
<td>5.00</td>
<td>2.99</td>
<td>0.88</td>
</tr>
<tr>
<td>3</td>
<td>160</td>
<td>60</td>
<td>60</td>
<td>5.74</td>
<td>2.78</td>
<td>1.52</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
<td>45</td>
<td>60</td>
<td>5.87</td>
<td>2.87</td>
<td>0.87</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>60</td>
<td>60</td>
<td>4.09</td>
<td>2.73</td>
<td>0.35</td>
</tr>
<tr>
<td>6</td>
<td>140</td>
<td>45</td>
<td>60</td>
<td>5.12</td>
<td>2.89</td>
<td>1.86</td>
</tr>
<tr>
<td>7</td>
<td>160</td>
<td>45</td>
<td>45</td>
<td>7.40</td>
<td>3.10</td>
<td>3.57</td>
</tr>
<tr>
<td>8</td>
<td>140</td>
<td>45</td>
<td>60</td>
<td>6.21</td>
<td>2.83</td>
<td>1.34</td>
</tr>
<tr>
<td>9</td>
<td>140</td>
<td>30</td>
<td>45</td>
<td>8.15</td>
<td>3.00</td>
<td>3.13</td>
</tr>
<tr>
<td>10</td>
<td>120</td>
<td>45</td>
<td>45</td>
<td>5.10</td>
<td>2.91</td>
<td>1.58</td>
</tr>
<tr>
<td>11</td>
<td>140</td>
<td>60</td>
<td>45</td>
<td>5.04</td>
<td>2.91</td>
<td>0.56</td>
</tr>
<tr>
<td>12</td>
<td>140</td>
<td>60</td>
<td>45</td>
<td>4.89</td>
<td>2.87</td>
<td>0.36</td>
</tr>
<tr>
<td>13</td>
<td>120</td>
<td>30</td>
<td>60</td>
<td>6.24</td>
<td>2.91</td>
<td>2.66</td>
</tr>
<tr>
<td>14</td>
<td>140</td>
<td>30</td>
<td>75</td>
<td>6.73</td>
<td>3.25</td>
<td>3.03</td>
</tr>
<tr>
<td>15</td>
<td>160</td>
<td>45</td>
<td>75</td>
<td>6.24</td>
<td>3.07</td>
<td>2.27</td>
</tr>
</tbody>
</table>

desirability are expressed.
The value of composite desirability was deduced by combining the weighted geometric mean as shown in equation (1) with each calculated individual desirability.

\[ D = \left( d_1 \times d_2 \times \ldots \times d_n \right)^{\frac{1}{m}} \] (1)

### 3.2 Results of B-B DOE

The weld bead shape, deformation size, and response variable from the arc brazing experiment are given in Table 6. Fig. 6 shows the cross-sectional shape for each experimental condition, and the cross-section and bead shape for the deformed part. As can be seen from figure, deformation was observed along the specimen’s height for the high heat input condition.

### 3.3 Regression Analysis

A regression analysis examines the relationship between variables. It involves building a regression model, estimating coefficient of regression from the observed samples, and producing a regression equation that describes the relationship between the variables. Based on the arc brazing experiments chosen by the B-B DOE, we determined a regression equation for the response variable bead shape and the process parameters (current, brazing speed, and torch angle). Eq. (2) is the second-order regression equation that describes the relationship between the response variable and the process parameters.

\[
y = -2.5463 + 0.05767x_1 + 0.00537x_2 \\
- 0.03728x_3 + 0.00030x_1 x_2 \\
+ 0.00007x_1x_3 - 0.00006x_2x_3 \\
- 0.00028x_1^2 - 0.00042x_2^2 \\
+ 0.00028x_3^2
\] (2)

Table 7 shows the results of analysis of variance (ANOVA) that was used to validate the regression equation. The validity of the regression equation may be tested by the F-test. An F-test compares the residual sum of squares (RSS) from the unrestricted original model to the RSS of the null hypothesis model. In the ANOVA table, the \( F_0 \) statistic is the ratio of the sum of mean squares from regression (MSR) to the sum of mean squares from the residual (MSE). A large \( F_0 \) signifies that the MSR is larger than the MSE, implying that relationship between input and output is significant. Critical values (\( \phi_R, \phi_E; \alpha \)) can be obtained for a given significance level and degree of freedom (\( \phi_R, \phi_E \)), and the regression equation is considered to be significant when \( F_0 > F (\phi_R, \phi_E; \alpha) \). In this regression analysis, test statistic of \( F_0 = \frac{MSR}{MSE} = 4.90 \), which is bigger than the critical value of (critical value) \( F (9, 5; 0.05) = 0.047 \), thereby rejecting the null hypothesis that regression does not exist. Therefore, regression reduced from Eq. (2)
Table 7 NOVA (analysis of variance) of bead geometry

<table>
<thead>
<tr>
<th>Source of variance</th>
<th>Degree of freedom</th>
<th>Sum of squares</th>
<th>mean squares</th>
<th>F0</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>9</td>
<td>0.275</td>
<td>0.031</td>
<td>4.90</td>
<td>0.047</td>
</tr>
<tr>
<td>Residual (error)</td>
<td>5</td>
<td>0.031</td>
<td>0.006</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>0.306</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>3</td>
<td>0.019</td>
<td>0.006</td>
<td>0.98</td>
<td>0.54</td>
</tr>
</tbody>
</table>

denoted by $R^2$. $R^2$ is equal to the sum of squares from regression (SSR) divided by the total sum of squares (SST). When $R^2=1$, all observations are on the regression line, and the estimated regression line completely describes the relationship between the variables. Conversely, when $R^2=0$ the regression line does not describe the relationship between variables. From the ANOVA of the experimental results, $R^2=SSR(0.27513)/SST(0.30630)=0.8982$, implying that the regression equation is valid with about 89% confidence level.

3.4 Response Surface Analysis

Response surface analysis is used to identify the relationship between the response variable and a quantitative experimental variable or a group of factors. In this study, this analysis was used to determine the factor conditions that would optimize bead shape as the response variable. The results of the analysis are given in Figs. 7 to 9.

Fig. 7 shows the response surfaces of the current and brazing speed for fixed torch angles. The response variable was high when the current was at 130–140 A and the brazing speed was above 55 cm/min. Fig. 8 shows the response surfaces of the current and torch angle for fixed brazing speeds. The response variable was high when the current was approximately 130-140 A and the torch angle was above 70°.

Fig. 9 shows the response surfaces of brazing speeds and torch angles for fixed currents. The response variable was high when the brazing speed was approximately 55–60 cm/min and the torch angle was above 70°. The results of response surface analysis were combined for the optimization of the response variable, which determined that the optimal condition for arc brazing was 135 A, 51 cm/min, and 74° as shown in Fig. 10.

Fig. 11 shows the bead and cross-section shapes after a specimen had been treated by arc brazing with the optimized processing condition of 135 A, 51 cm/min and 74°. As seen in the bead shapes, the optimized arc brazing did not result in deformation after processing. Table 8 shows the result of measuring bead size of optimal brazing joint and scale of deformation, and a stable shape of bead al-

![Fig. 6 Results of bead and cross section shape depending on Box-Behnken design](image)

as a result of experiment could be considered as the similar shape in significant level $\alpha=0.05$.

The coefficient of determination describes the extent to which the regression line estimated from the samples can explain the observation. In other words, the coefficient of determination measures how well the regression line represents the actual observed values, and the coefficient has a value between 0 and 1. The coefficient of determination is equivalent to the square of correlation coefficient, and is
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Fig. 7 Response surface of current and speed

(a) Torch angle 45°
(b) Torch angle 60°
(c) Torch angle 75°

Fig. 8 Response surface of current and torch angle

(a) Brazing speed 30cm/min
(b) Brazing speed 45cm/min
(c) Brazing speed 60cm/min

Fig. 9 Response surface of speed and torch angle

Fig. 10 Optimal condition of arc brazing process

<table>
<thead>
<tr>
<th>Optimum</th>
<th>Hi</th>
<th>Lo</th>
<th>Current</th>
<th>Welding</th>
<th>Torch Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Cur</td>
<td>0.39665</td>
<td>135.4135</td>
<td>120.0</td>
<td>75.0</td>
</tr>
<tr>
<td>Bead Geo</td>
<td>Max</td>
<td>y = 0.6682</td>
<td>d = 0.39665</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8 Result of optimal condition

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Brazing speed (cm/min)</th>
<th>Torch angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>135</td>
<td>51</td>
<td>74</td>
</tr>
<tr>
<td>Bead shape (mm)</td>
<td>Deformation size (mm)</td>
<td>Geometric mean</td>
</tr>
<tr>
<td>Width</td>
<td>Height</td>
<td>0.26</td>
</tr>
</tbody>
</table>
most without any deformation was found.

3.5 Evaluation of Prototype Reliability

After conducting arc brazing on an actual exhaust muffler under optimized conditions, various reliability tests were performed. The tests consisted of a salt spray test, thermal fatigue and shock tests, and endurance limit test. The passing standard was determined as the Hyundai Motor Company (HMC) quality standards. All of the reliability tests for the exhaust muffler prototype produced by arc brazing were conducted using HMC standard ES28600-09. Fig. 12 shows the results of the salt spray test, comparing the corrosion resistance of parts welded by MIG welding or arc brazing after 72 h exposure to 5% NaCl. The MIG welded part experienced significant corrosion, whereas the arc brazed part did not show any corrosion. This is due to the copper component of the brazing wire, which has strong corrosion resistance. The test demonstrated that arc brazing provides excellent corrosion resistance.

Fig. 13 describes the thermal fatigue and thermal shock tests that were conducted with the exhaust muffler treated by arc brazing. For the tests, 200 cycles were conducted at a muffler surface temperature of 450 °C. Fig. 14 and 15 show the muffler after the thermal fatigue test. The brazed part did not exhibit any cracks from thermal fatigue and shock tests, and did not undergo harmful deformation or oxidation, thereby satisfying the reliability standards.

4. Conclusion

In this study, we used a Box-Behnken design of experiment in order to apply arc brazing to a stainless steel muffler of an exhaust system. An optimized processing condition and joint quality were obtained, and the following conclusions were drawn:
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1) The Box-Behnken design was used to develop a regression model, with the bead shape as the response variable, and the current, brazing speed, and torch angle as the process parameters of the arc brazing.

2) In order to minimize the deformation of the specimen after arc brazing and to obtain a stable bead shape, a regression equation between the process parameters and the response variable was produced, and its validity was confirmed by ANOVA.

3) Correlations between the process parameters were analyzed by response surface analysis. An optimization of the response variable determined that optimal processing conditions for arc brazing were 135A, 51cm/min and 74°.

4) After conducting the arc brazing of an actual exhaust muffler using the optimized conditions, various reliability tests were conducted to validate the arc brazed prototype for an exhaust muffler.

Acknowledgement

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References


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Jin-Chul Ryu received the in mechanical engineering from University of Ulsan, Korea, in 2003. He is currently working for the company as a director since 2003. His company produces muffler exhaust system components and he is particularly interested in the arc welding process about stainless steel.