The Use of $L_9$ Orthogonal Array with Grey Relational in Optimizing of Friction Welding Parameters of AlCuBiPb Alloy

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Abstract: The characteristic of friction welding process is its ability to weld alloys and combinations of alloys. Aluminum alloys are welded to similar or to dissimilar aluminum alloys. It would be beneficial for industrial applications to improve the quality of joints of the aluminum alloys. In this study, an investigation of friction welding parameters is carried out by applying Taguchi method and grey relational analysis method. The $L_9$ orthogonal array (OA) is selected for this study with three parameters (rotational speed, friction pressure, and forge pressure), and three levels for each parameter for optimizing multiple quality characteristics (metal loss and hardness) for joining similar aluminum alloys (AlCuBiPb type). The optimization for single quality (Taguchi method) shows that the forge pressure affects the metal loss, while the friction and forge pressures influence the hardness. However, the improvement of the quality of the welded joints, using the grey relational grade for multiple quality optimizations show that the optimal parameters are determined more precisely by this method. The optimal parameters obtained for this set of experiments are rotational speed 164.9 m/min, friction pressure 42 bars, and forge pressure 100 bars with 81.9% contribution. The produced welding joints have hardness in the range of 75% to 95% of the base metal hardness for the selected set of experiments and the forge pressure is the most influencing parameter.

Key words: Friction welding, aluminum alloys, metal loss, hardness, Taguchi and grey relational methods.

1. Introduction

The driving force for product improvement and development has led engineers and researchers to find solutions with cost effective to solve materials and manufacturing problems. The friction welding process has a wide range of applications in the automotive industry due to its simple, rapid and automatic control. Friction welding is a solid-state welding where no melting of metal takes place, and that the two metal surfaces are brought together under pressure and an intermetallic bond is formed. The controllable welding variables are the rotational speed, applied heating pressure (friction pressure), forge pressure, and heating duration. The amount of heat generated, thermal conductivity, initial microstructure and mechanical properties at elevated temperatures are affecting the quality of the welded joint. The disadvantage of this process, one component must rotate in which restricted the shape and size of the components to be welded, and the components to be welded cannot be brought at an angle.

The Taguchi [1] philosophy provides that the reduction in variation (improved quality) of a product or process represents a lower loss to society, and the proper development strategy can significantly reduce variation. The Taguchi design of experiment (DOE) makes use of orthogonal arrays to minimize the number of parameters

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or factors combinations that are required to test the parameter or factor affected the process and can be performed at a lowered cost and time with results comparable to a full factorial experiment.

The application of Taguchi method reported in the literatures used for determining optimal process parameters for single quality characteristics. Hatab and Zaid [2] investigated the effects of interactions and factors of cutting parameters on surface roughness in turning for the commercial aluminum alloy (1100-H18 type). It was shown that there are no strong interactions between factors and the significant factors affecting the surface roughness were the insert radius and feed rate. The optimal cutting parameters for surface roughness in turning of AISI 1030 carbon steel bars was reported by Nalbant et al. [3]. Ma et al. [4] optimized the electrolytic plasma oxidation process parameters for the corrosion protection of magnesium alloy AM50. Vijian and Arunachalam [5] reported the optimization of squeeze cast parameters of LM6 aluminum alloy for surface roughness. Sahin [6] investigated the wear behavior of various types of steels based on the Taguchi method.

Materials and manufacturing processes performance depend on many quality characteristics, so it is important to optimize process parameters that can produce a better performance level for multiple quality characteristics at the same time. Deng [7, 8] had suggested grey relational analysis; the grey theory can handle both incomplete information and unclear problems very precisely. The grey relational coefficient can give the relationship between the desired and actual experimental results. The grey relational analysis as reported by Chang et al. [9] and Tarng et al. [10] can convert the optimization of multiple quality characteristics into a single quality optimization called grey relational grade, which can provide an optimum process parameters.

The literature survey for optimizing friction-welding parameters with Taguchi method or grey relational analysis method is rather lacking to the best of our knowledge. Therefore, the aim of this study is to apply Taguchi method and grey relational analysis in optimizing the process parameters for multiple quality characteristic, namely metal loss (flash) and the hardness of the joint of similar friction welded aluminum alloy (AlCuBiPb).

2. Experimental Procedure

2.1 Materials

The as-received material for this study is in the form of rod AlCuBiPb alloy with diameter of 25 mm. The welding is conducted such that the starting lengths in the rotating side and the stationary side of the joint are equal in lengths (150 mm each). The welding is performed using direct drive friction welding machine, with maximum pressure and speed of 140 bars and 2,500 rev/min, respectively. After welding, the lengths are measured using a digital vernier. The metal loss length is calculated by the difference between initial and final lengths. For microhardness test, the welded samples are machined to remove the flash and to obtain two parallel flat surfaces with thickness of ~23 mm. The flat surfaces are ground using SiC emery papers 240 to 1,000, followed by polishing with 1 and 0.05 micron of alumina. The microhardness measurements were carried out on LEICA VMHT-GA-E with read out system, using a diamond pyramid indenter, 200-gram load and a total load time of 10 seconds.

2.2 Design of Experiment

In this investigation, the friction welding parameters namely, rotational speed, friction pressure, and forge pressure each at three levels are considered. The interactions between the welding parameters are neglected. The total degrees of freedom (DF) for the three parameters in each of three levels are six (the degree of freedom for each factor is the number of levels minus one). The total degrees of freedom for orthogonal arrays (OA) must be greater than or equal to those in process parameters. Thus, standard Taguchi experimental of L9 orthogonal array with three levels is selected to investigate the combinations of friction
welding parameters. The selection of friction welding parameters and their levels are shown in Table 1 and Table 2, respectively.

3. Determination of Optimal Friction Welding Parameters

3.1 Signal-to-Noise Ratio Using Taguchi Method

Taguchi method [1] proposes the use of the loss function to measure the performance characteristic deviating from the desired value. The value of loss function is transformed into a signal-to-noise (S/N) ratio. The S/N ratio is treated as a response of the experiment, which reflects the amount of variation present. There are usually three categories of performance characteristic in the analysis of the S/N ratio: lower-is-better (LB), nominal-is-best (NB), and higher-is-better (HB). The higher S/N ratio value no matter the category of the performance is corresponding to the better performance characteristic. Thus, the optimal level of the process parameters is the level of the highest S/N ratio. The following equations give the calculations of S/N ratios for LB, HB, or NB:

\[
(S/N)_{LB} = -10 \log \left( \frac{1}{r} \sum_{i=1}^{r} y_i^2 \right) \quad (1)
\]

\[
(S/N)_{HB} = -10 \log \left( \frac{1}{r} \sum_{i=1}^{r} y_i ^2 \right) \quad (2)
\]

\[
(S/N)_{NB} = -10 \log \left( \frac{1}{r} \sum_{i=1}^{r} 1/y_i^2 \right) \quad (3)
\]

where \( r \) is the number of measurements in the trial, and \( y_i \) is the \( i \)th measured value in a row, and \( V_e \) is the variance.

3.2 Signal-to-Noise Ratio Using Grey Relational Method

The grey relational analysis [8-10] is an effective method of analyzing and establishing the relationships between sequences (multiple responses). The grey relational analysis requires less data and can analyze many factors that can overcome the disadvantages of statistics method. In the grey relational analysis, the data preprocessing must be performed first (generation of grey relation) in order to normalize the experimental results in the range of zero to one. The normalization can be performed for the lower-is-better (LB), nominal-is-best (NB), and higher-is-better (HB). The normalized S/N ratios [9, 10] are calculated using the following equations:

\[
(x_{y_i})_{LB} = \frac{X_{max} - X_{y_i}}{X_{max} - X_{min}} \quad (4)
\]

\[
(x_{y_i})_{NB} = 1 - \left[ \frac{X_{y_i} - X^o}{X_{max} - X^o} \right] \quad (5)
\]

\[
(x_{y_i})_{HB} = \frac{X_{y_i} - X_{min}}{X_{max} - X_{min}} \quad (6)
\]

Table 1  Friction welding parameters and their levels for AlCuBiPb alloy.

<table>
<thead>
<tr>
<th>Friction welding parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  Rotational speed (m/min)</td>
<td>164.93</td>
<td>180.94</td>
<td>196.35</td>
</tr>
<tr>
<td>B  Friction pressure (bar)</td>
<td>36</td>
<td>39</td>
<td>42</td>
</tr>
<tr>
<td>C  Forge pressure (bar)</td>
<td>90</td>
<td>95</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2  Taguchi orthogonal array L_9 [1].

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Rotational speed (A)</th>
<th>Friction pressure (B)</th>
<th>Forge pressure (C)</th>
<th>error (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
where \( x_{ij} \) is the normalized S/N ratio for the \( j^{th} \) performance characteristic in the \( i^{th} \) experimental run. \( X_i \) is the S/N ratio for the \( j^{th} \) performance characteristic in the \( i^{th} \) experimental run. \( X_{\text{min}} \) and \( X_{\text{max}} \) are the minimum and the maximum of the S/N ratios for the \( j^{th} \) performance characteristics in all the experimental runs, and \( X^o \) is the desired S/N ratio.

The next step for the grey relational analysis is to calculate the grey relational coefficient, which represents the relationship between the ideal (best) and the actual normalized S/N ratio of the experimental results. Eq. (7) gives the grey relational coefficient \( \xi_{ij} \) for the \( j^{th} \) performance characteristic in the \( i^{th} \) experimental run:

\[
\xi_{ij} = \frac{\min \left\{ x^o_j - x_{ij} + \beta \cdot \max \left\{ X_{\text{max}} - x_{ij} \right\} \right\}}{\max \left\{ X_{\text{max}} - x_{ij} \right\}}
\]

where \( x^o_j \) is the ideal normalized S/N ratio for the \( j^{th} \) performance characteristic in the \( i^{th} \) experimental run, \( x_{ij} \) the normalized S/N ratio for the \( j^{th} \) performance characteristic in the \( i^{th} \) experimental run, \( \beta \) is the distinguish coefficient which is defined in the range \( 0 \leq \beta \leq 1 \). The general used value for \( \beta \) is 0.5. After obtaining the grey relational coefficient, the weighting method can be used to determine the grey relational grade \( \gamma \), thus the overall evaluation of multiple responses is based on value of grey relational grade and is given by Eq. (8):

\[
\gamma = \frac{1}{R} \sum_{i=1}^{N} w_i \cdot \xi_{ij}
\]

where \( w_i \) is the weighting factor for the \( j^{th} \) performance characteristic, and \( n \) is the number of performance characteristics. In the present study, the weighting factor for metal loss and hardness are taken as 0.5.

4. Results and Discussion

4.1 Analysis for Signal-to-Noise Ratio Using Taguchi Method

The calculated metal loss length is treated as the lower-is-better (LB) quality characteristic. The experimental results of metal loss and the corresponding S/N ratios are shown in Table 3.

The S/N response data and the plotted means of S/N and metal loss length as function of the main parameters are shown in Table 4 and Fig. 1, respectively. The results in Table 4 indicate that the most influence parameter on metal loss length is the forge pressure followed by friction pressure and the least influence parameter is rotational speed. The
The results indicate that the amount of the metal loss (flash) increases with increasing the forged pressure, which may be attributed to the generation of heat at the interface that cause the metal become softer and the alloy loss its strength and more metal loss is resulted. In addition, the other measured response is the joint hardness, and treated as the higher-is-better (HB) quality characteristic. Table 5 shows the experimental results for hardness and the calculated S/N ratios. Table 6 and Fig. 2 show the response data and the plotted graphs indicate the effects of friction welding parameters on the means.

The results show that the hardness is influenced by friction pressure, followed by forge pressure and the least influence factor is rotational speed, which may be related to microstructural changes in the welded zone.

### 4.2 Analysis for Signal-to-Noise Ratio Using Grey Relational

Table 7 shows the normalized experimental results (data preprocessing). The higher value of the normalized S/N ratio represents the better performance when compared with the ideal value of one. The grey relational grade is

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Rotational speed A (m/min)</th>
<th>Friction pressure B (bar)</th>
<th>Forge pressure C (bar)</th>
<th>Hardness, HV</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>164.93</td>
<td>36</td>
<td>90</td>
<td>83.6</td>
<td>38.593</td>
</tr>
<tr>
<td>2</td>
<td>164.93</td>
<td>39</td>
<td>95</td>
<td>97.6</td>
<td>39.527</td>
</tr>
<tr>
<td>3</td>
<td>164.93</td>
<td>42</td>
<td>100</td>
<td>102.2</td>
<td>40.422</td>
</tr>
<tr>
<td>4</td>
<td>180.94</td>
<td>36</td>
<td>95</td>
<td>96.9</td>
<td>39.988</td>
</tr>
<tr>
<td>5</td>
<td>180.94</td>
<td>39</td>
<td>100</td>
<td>92.0</td>
<td>39.469</td>
</tr>
<tr>
<td>6</td>
<td>180.94</td>
<td>42</td>
<td>90</td>
<td>98.0</td>
<td>39.498</td>
</tr>
<tr>
<td>7</td>
<td>196.35</td>
<td>36</td>
<td>100</td>
<td>96.0</td>
<td>39.383</td>
</tr>
<tr>
<td>8</td>
<td>196.35</td>
<td>39</td>
<td>90</td>
<td>95.3</td>
<td>39.727</td>
</tr>
<tr>
<td>9</td>
<td>196.35</td>
<td>42</td>
<td>95</td>
<td>97.0</td>
<td>39.022</td>
</tr>
</tbody>
</table>

### Table 6  S/N response data for hardness for AlCuBiPb alloy.

<table>
<thead>
<tr>
<th>Friction welding parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Max.-Min.</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>A- Rotational speed</td>
<td>39.514</td>
<td>39.318</td>
<td>39.377</td>
<td>0.196</td>
<td>3</td>
</tr>
<tr>
<td>B- Friction pressure</td>
<td>38.988</td>
<td>39.574</td>
<td>39.647</td>
<td>0.659</td>
<td>1</td>
</tr>
<tr>
<td>C- Forge pressure</td>
<td>39.273</td>
<td>39.179</td>
<td>39.758</td>
<td>0.579</td>
<td>2</td>
</tr>
</tbody>
</table>

Total mean S/N ratio = 39.403
The Use of L9 Orthogonal Array with Grey Relational in Optimizing of Friction Welding Parameters of AlCuBiPb Alloy

![Fig. 2](image.png)  
**Fig. 2**  Effects of friction welding parameters on: (a) mean S/N ratios and (b) mean hardness, for AlCuBiPb alloy.

Table 7  Normalized S/N ratios for AlCuBiPb alloy.

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Metal loss length</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>1</td>
<td>0.2041</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.6167</td>
<td>0.5107</td>
</tr>
<tr>
<td>3</td>
<td>0.7215</td>
<td>1.0000</td>
</tr>
<tr>
<td>4</td>
<td>0.7796</td>
<td>0.2160</td>
</tr>
<tr>
<td>5</td>
<td>0.8082</td>
<td>0.4790</td>
</tr>
<tr>
<td>6</td>
<td>0.3263</td>
<td>0.4948</td>
</tr>
<tr>
<td>7</td>
<td>1.0000</td>
<td>0.4320</td>
</tr>
<tr>
<td>8</td>
<td>0.0000</td>
<td>0.6200</td>
</tr>
<tr>
<td>9</td>
<td>0.7939</td>
<td>0.2346</td>
</tr>
</tbody>
</table>

![Fig. 3](image.png)  
**Fig. 3**  Plot of grey relational grade vs. experimental number for AlCuBiPb alloy.

Table 8  Calculated grey relational grade and its orders for AlCuBiPb alloy.

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Grey relational grade (γ)</th>
<th>Orders</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3596</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>0.5357</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>0.8212</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0.5418</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0.6063</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>0.4617</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>0.7341</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>0.4508</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>0.5341</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 9  Grey relational grade response data for for AlCuBiPb alloy.

<table>
<thead>
<tr>
<th>Friction welding parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Max-min.</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Rotating speed</td>
<td>0.5722</td>
<td>0.5366</td>
<td>0.5730</td>
<td>0.0364</td>
<td>3</td>
</tr>
<tr>
<td>B-Friction pressure</td>
<td>0.5452</td>
<td>0.5309</td>
<td>0.6057</td>
<td>0.0748</td>
<td>2</td>
</tr>
<tr>
<td>C-Forge pressure</td>
<td>0.4240</td>
<td>0.5372</td>
<td>0.7205</td>
<td>0.2965</td>
<td>1</td>
</tr>
</tbody>
</table>

Total mean value of the grey relational grade = 0.5606
4.3 Analysis of Variance (ANOVA) for Multiple Performance Characteristics

The Anova [1] can be accomplished based on the total sum of the squares (\(SS_T\)) deviations from the total mean of the grey relational grade (\(\gamma\)), and given by Eq. (9):

\[
SS_T = \sum_{i=1}^{m} (\gamma_i)^2 - \frac{1}{m} \left[ \sum_{i=1}^{m} (\gamma_i) \right]^2
\]  

(9)

where \(m\) is the total number of experiments, and \(\gamma\) is the \(i^{th}\) calculated value in a row. The \(SS_T\) is decomposed into the sum of squares due to each tested factor (\(SS_P\)) and the sum of squares due to the error (\(SS_e\)), which are given by Eqs. (10 & 11), respectively:

\[
SS_P = \sum_{j=1}^{q} \frac{((\gamma_{ij})^2)}{q} - \frac{1}{m} \left[ \sum_{i=1}^{m} (\gamma_i) \right]^2
\]  

\[
SS_e = SS_T - \sum SS_P
\]  

(11)

where subscript (\(P\)) represents one of the experiment parameters, \(j\) the level number of the specific parameter, \((q)\) is the repetition of each level of the parameter. The F-test named after Fisher is used to determine which friction welding parameters have a statistically significant effect on performance characteristics. The larger the F-value, the greater the effect on the metal loss length and the joint hardness resulted from the change of the friction welding parameters.

The percentage (\(P\)) of the contribution to the total variation is determined for each parameter using Eq. (12):

\[
P = \frac{SS_P}{SS_T} \times 100
\]  

(12)

The ANOVA results given in Table 10 show that the highest contribution parameter is forge pressure with 81.94%. Thus, the optimum friction welding process is 164.93 m/min rotational speed, 42 bar friction pressure, and 100-bar forge pressure or A1B3C3, which is consistent with experiment 3 shown in Table 2.

4.4 Confirmation Test

The confirmation experiment is the final step to verify the multiple quality characteristics using the optimal level of the friction welding process. If the results of the confirmation test do not agree with the results of the experiment runs, then new experiments are required. The predicted grey relational grade (\(\gamma\)) for the friction welding process can be obtained using Eq. (13):

\[
(\gamma)_{conf} = (\gamma)_{mean} + \sum_{i=1}^{n} ((\gamma_{opt} - (\gamma)_{mean})
\]  

(13)

The estimated grey relational grade using Eq. (13) is shown in Table 11. The initial friction welding parameters or experiment number 1 (A1B1C1) is chosen for comparison purpose. It is shown in Table 11 that the hardness of the welding joint has been greatly improved by 23.5% (from ~85 to ~105 HV) with minimized metal loss length of 18 mm. In addition, the welding joint produced by optimal welding parameters

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
Friction welding parameters & Degrees of freedom & Sum of squares & Variance percentage & F-value & Contribution (P) \\
& (DF) & (SS) & & & \\
\hline
A-Rotating speed & 2 & 0.0026 & 0.0013 & 0.1477 & 1.59 \\
B-Friction pressure & 2 & 0.0094 & 0.0047 & 0.5341 & 5.74 \\
C-Forge pressure & 2 & 0.1343 & 0.0672 & 7.636 & 81.94 \\
Error & 2 & 0.0176 & 0.0088 & - & 10.73 \\
\hline
Total & 8 & 0.1639 & & & 100 \\
\hline
\end{tabular}
\caption{Results of the ANOVA for grey relational.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|}
\hline
Initial & Optimal friction welding parameters & \\
prediction & experiment & \\
\hline
Level & A1B1C1 & A1B3C3 & A1B3C3 \\
Hardness, HV & 85 & 105 & \\
Metal loss length (mm) & 14.8 & 18 & \\
Grey relational grade & 0.3596 & 0.7772 & 0.8212 \\
\hline
\end{tabular}
\caption{Results of confirmation test for friction welding parameters.}
\end{table}
possesses hardness of ~95% of the base metal hardness.

5. Conclusions

The present study revealed the suitability of grey relational method for determining optimum friction welding parameters for multiple performances more effectively than using single performance characteristics. The application of Taguchi method, employing metal loss length or the joint hardness measurements as a single quality characteristic to efficiently establishing optimal friction welding parameters for joining similar aluminum alloy. The results show that the optimal friction welding parameters for this set of experiments are A3B2C1 for metal loss length and A1B3C3 for hardness. However, the optimization of multiple quality characteristics using grey relational grade for determining the optimum parameters of the friction welding process are rotational speed 164.93 m/min, friction pressure 42 bar, and forge pressure 100 bar with 81.94% contribution. The produced welding joint has hardness in the range of 75 to 95% of the base metal hardness. A comparison of grey relational grade between the predicted friction welding performance and actual (experimental) friction welding are consistent in this set of the friction welding experiments.

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References