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IMPROVING PROCESS QUALITY IN FRICTION WELDING FOR BIMETAL LUGS

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ABSTRACT

The purpose of this study is to investigate the effect of process parameter settings on quality of bimetal lugs produced by friction welding process. The study was conducted in a local electrical power components manufacturer. The company faced high reject rates of bimetal lugs. To avoid disturbance to the actual production line, the relevant historical process data were extracted and analysed. The data were mapped into full factorial experimental design matrix. The significance of operating parameters, namely, the rotational speed, friction pressure and friction time were investigated. The data analysis reveals the recommended optimum setting should be; rotational speed at high level (1450 Rpm), friction pressure at low level (39.2 Pa) and friction time at low level (4 s). The first order models are also proposed for prediction of the responses; tensile strength, upset and temperature.

Keywords: *Friction Welding, Bimetal Lugs, Design of Experiment, Full Factorial*

1.0 INTRODUCTION

Bimetal refers to an object that is made of two separate metals joined together. Instead of being a mixture of two or more metals like alloys, bimetallic objects consist of layers of different metals. Figure 1 shows a joined copper palm with aluminium barrel as being used in the production of bimetal lugs. Such bimetal component can be used for termination and connection in electricity power supply system. Welding of copper and aluminium is usually difficult by conventional fusion welding processes because the thermal diffusivity is higher compared to many steels alloys [1]. To overcome this problem, friction welding, one of the solid state welding techniques is normally used for joining copper and aluminium material, particularly in fabrication of bimetal lugs.

Friction welding involves complex interrelated processes such as heat generation, abrasion of common surfaces, plastic deformation, inter diffusion of metal and penetration of microscopic metal parts from one piece into another piece [1]. The objective of the study was to investigate the effects of process parameters setting for the friction welding machine on the quality of bimetal lugs. Full factorial experimental design matrix was used in mapping of the historical process data to identify the significant operating parameters and to determine their optimum setting.

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The rest of this paper is organised as follows: Section 2 provides the project background, Section 3 discusses on the project methodology, Section 4 presents the analysis of results, and finally Section 5 concludes the paper.

Figure 1: Bimetal lug

2.0 PROJECT BACKGROUND

The study was conducted in a local electrical power components manufacturer. The company faced high reject rates for bimetal lugs produced by the friction welding machine. There are several process parameters that need to be adjusted before running this machine which are friction time (second), friction pressure (Pascal) and rotational speed (rpm). Currently the operational parameter setting was decided based on ad hoc experience rather than a systematic scientific investigation.

When joining dissimilar metals such as copper and aluminium, problems such as brittle inter-metallic compounds and high thermal conductivity may arise. As such, the friction welding parameters and their settings must be carefully selected to achieve strong welds and minimize rejects. A non-uniform liberation of heat on the friction surfaces can cause temperature variation on the friction surface. The speed of relative motion and the axial unit force determine the intensity of heat liberation.

Operating at non optimum process condition may result in undesirable output such as; (i) partial destruction and removal of oxidized films, (ii) non-uniform heating of the cross section of the welded specimens, (iii) an increase in the overheating of the metal and (iv) grain growth in the joint and in the heat affected zone. Thus, the strength of the welded joint may decrease. The application of pressure cycle has advantages such as increase the welded joint and allows the heating process to be conducted at lower pressure.

In the continuous drive friction welding method, one of the components is held stationary while the other is rotated at a constant speed. The two components are brought together under axial pressure for a certain friction time. Then, the clutch is separated from the drive, and the rotary component is brought to stop within the braking time while the axial pressure on the stationary part is increased to a higher upset pressure for a predetermined upset time.

This study focuses on the application of design of experiment technique to determine the effect of process parameters (factors) on desired response and to find the optimum combination of factors that will yield the optimum desired response. Design of experiment techniques have been used in previous works, which investigated the characterization of operating conditions for ball bearings [4], process optimization of vacuum forming process [5], and optimization on solder paste printing parameters [6].

Based on our limited review, we are unable to locate previous undergraduate projects investigated on process quality in friction welding for bimetal lugs using design of experiment technique.

3.0 PROJECT METHODOLOGY

Among of all the products produced by the company, bimetal lugs was one of the highly demanded products. Unfortunately, the company was facing with high reject rate for this product. This product should be produced according to the specified diameter and often the machine parameters need to be adjusted to reduce variability in diameter.

Conducting experiments in a real production line is very expensive and often will disturb the company operation. Fortunately in this study no new data need to be collected since sufficient historical process data were available. The historical process data from July to September 2011 was referred and analysed. From the full sheet of historical data, only relevant data that matched the experimental matrix of factorial design were selected and mapped.

The quality of the welded junction and particularly the efficiency of the friction welding process depend to a large degree on the relative velocity of the friction surfaces and on the axial force applied during the heating period. The quality of the connection also depends on the amount of plastic deformation at the ends of the welded pieces. This deformation can be measured by the axial deformation. Therefore, the relative speed of the friction surfaces (rpm), the axial friction pressure (Pa) and friction time (s) were regarded as key parameters of the process. Table 1 shows the range of parameter values for low and high level settings for each parameter (factor). Tensile strength, upset and temperature on the bimetal lugs were selected as the responses. The temperature determines the quality of the welded connection.

Table 1: The range of parameter values for friction welding process

No.	Welding Parameters	Low (-1)	High (+1)
1	Speed (rpm)	1250-1350	1450-1550
2	Friction Pressure (Pa)	39.2- 43.0	45.8-52.0
3	Friction time (s)	3-5	6-8

A two-level full factorial design matrix with three replicates was used in data extraction and mapping. A total of one hundred historical data were screened and only twenty-four data that matched to experimental plan matrix were selected and analysed using statistical software, Minitab. Data analysis was conducted to identify the significant parameters that affect the cause of tensile strength, upset and temperature between two sliding metal of bimetal lugs. Analysis of variance (ANOVA) was used to investigate the main effects of the factors together with the two levels interaction effects to the output responses.

First-order model equations were formulated to predict the optimum responses. The error percentage between the actual performance and the predicted value was estimated using the following formula (Equation 1). Finally, confirmation of the optimum setting was made through verification of the result against the historical process record.

$$\text{Error (\%)} = \frac{|\text{Actual} - \text{Predicted Value}| \times 100\%}{\text{Predicted Value}} \quad (1)$$

4.0 RESULTS AND ANALYSIS

This section covers the experimental matrix, results and analysis, analysis of variance, main effects plots, predictive models and the optimum setting.

4.1 The Experimental Matrix and Responses

A full factorial design of 2^3 was adopted in the mapping of the historical process data. With three replicates, the design requires twenty four treatment combinations. The experimental matrix and the responses are summarised in Table 2. The sign -1 means the machine setting was set at low level while the sign +1 means the machine setting was set at high level.

Table 2: The experimental matrix and the responses

Run Order	Speed (rpm)	Friction Pressure (Pa)	Friction Time (s)	Ultimate Tensile Strength (MPa)			Upset (mm)			Temperature (^oC)		
				Replicate			Replicate			Replicate		
				1	2	3	1	2	3	1	2	3
1	-1	-1	-1	194.40	208.74	210.15	6.2	3.0	5.2	188	186	206
2	1	-1	-1	267.32	250.69	250.45	5.6	3.7	6.0	183	214	258
3	-1	1	-1	192.83	220.90	227.95	9.8	8.0	7.5	183	196	205
4	1	1	-1	270.83	239.30	252.84	13.7	7.2	7.4	230	188	181
5	-1	-1	1	211.63	187.71	211.63	6.8	5.3	5.6	251	263	286
6	1	-1	1	260.45	256.60	242.65	6.9	4.5	6.9	251	250	219
7	-1	1	1	218.74	227.95	233.22	13.0	13.0	11.3	286	268	277
8	-1	1	1	218.74	227.95	233.22	13.0	13.0	11.3	286	268	277

4.2 Results Analysis

The results in Table 2 were analysed and interpreted in terms of estimated effects, analysis of variance (ANOVA), normal probability plots, and main effects plots. Based on these analyses, the significant factors were determined and predictive models were formulated.

4.2.1 Estimated Effects

The estimated effects based on the responses are given in the Table 3 (ultimate tensile strength), Table 4 (upset) and Table 5 (temperature). There was only one main factor (speed) that affect significantly the response for the ultimate tensile strength (Table 3). There were two main factors (friction pressure and friction time) that affect significantly the response for the upset (Table 4), and only one main factors (friction time) that affect significantly the response for temperature (Table 5). None of the interactions were significant to the responses.

Table 3: Estimated effects and coefficients for ultimate tensile strength (coded units)

Term	Effect	Coef	SeCoef	T	P
Constant	233.860	2.439	95.89	0.000	
Speed	43.412	21.706	2.439	8.90	0.000
Friction Pressure	8.984	4.492	2.439	1.84	0.084
Friction Time	4.621	2.310	2.439	0.95	0.358
Speed*Friction Pressure	-7.238	-3.619	2.439	-1.48	0.157
Speed*Friction Time	-1.364	-0.682	2.439	-0.28	0.783
Friction Pressure*Friction Time	3.867	1.934	2.439	0.79	0.439
Speed*Friction Pressure* Friction Time	-2.891	-1.445	2.439	-0.59	0.562

Table 4 : Estimated effects and coefficients for upset (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant	8.0417	0.3775	21.30	0.000	
Speed	0.3000	0.1500	0.3775	0.40	0.696
Friction Pressure	5.1333	2.5667	0.3775	6.80	0.000
Friction Time	2.0500	1.0250	0.3775	2.72	0.015
Speed*Friction Pressure	0.0500	0.0250	0.3775	0.07	0.948
Speed*Friction Time	-0.5000	-0.2500	0.3775	-0.66	0.517
Friction Pressure*Friction Time	1.3000	0.6500	0.3775	1.72	0.104
Speed*Friction Pressure* Friction Time	-0.1500	-0.0750	0.3775	-0.20	0.845

Table 5 : Estimated effects and coefficients for temperature (coded units)

Term	Effect	Coef	Se Coef	T	P
Constant	233.250	3.049	76.50	0.000	
Speed	0.667	0.333	3.049	0.11	0.914
Friction Pressure	7.333	3.667	3.049	1.20	0.247
Friction Time	70.000	35.000	3.049	11.48	0.000
Speed*Friction Pressure	1.500	0.750	3.049	0.25	0.809
Speed*Friction Time	-7.833	-3.917	3.049	-1.28	0.217
Friction Pressure*Friction Time	9.500	4.750	3.049	1.56	0.139
Speed*Friction Pressure* Friction Time	5.000	2.500	3.049	0.82	0.424

4.2.2 Analysis of Variance

The analysis of variance (ANOVA) was used to partition the total variation. Table 6 confirms the main effect for rotational speed (Table 3) is significant ($P < 0.05$). Table 7 confirms the significant main effects are the friction time and the friction pressure (Table 4). Table 8 confirms the significant main effect is the friction time (Table 5). All interactions were insignificant.

Table 6 : Analysis of variance for ultimate tensile strength (coded units)

Source	Df	Seq Ss	Adj Ss	Adj Ms	F	P
Main Effects	3	11920.3	11920.3	3973.43	27.83	0.000
2-Way Interactions	3	415.2	415.2	138.40	0.97	0.431
3-Way Interactions	1	50.1	50.1	50.14	0.35	0.562
Residual Error	16	2284.0	2284.0	142.75		
Pure Error	16	2284.0	2284.0	142.75		
Total	23	14669.6				

Table 7 : Analysis of variance for upset (coded units)

Source	Df	Seq Ss	Adj Ss	Adj Ms	F	P
Main Effects	3	183.862	183.862	61.2872	17.92	0.000
2-Way Interactions	3	11.655	11.655	3.8850	1.14	0.364
3-Way Interactions	1	0.135	0.135	0.1350	0.04	0.845
Residual Error	16	54.727	54.727	3.4204		
Pure Error	16	54.727	54.727	3.4204		
Total	23	250.378				

Table 8 : Analysis of variance for temperature (coded units)

Source	Df	Seq Ss	Adj Ss	Adj Ms	F	P
Main Effects	3	29725.3	29725.3	9908.4	44.41	0.000
2-Way Interactions	3	923.2	923.2	307.7	1.38	0.285
3-Way Interactions	1	150.0	150.0	150.0	0.67	0.424
Residual Error	16	3570.0	3570.0	223.1		
Pure Error	16	3570.0	3570.0	223.1		
Total	23	34368.5				

4.2.3 Normal Probability Plots

Figures 2, 3 and 4 show the normal probability plots of standardized effects for ultimate tensile strength, upset and temperature. The plots confirm that speed (A) is the only significant factor for the ultimate tensile strength as shown in Figure 2. The friction pressure (B) and the friction time (C) are confirmed significant for upset as shown in Figure 3. The friction time (C) is confirmed significant for the temperature.

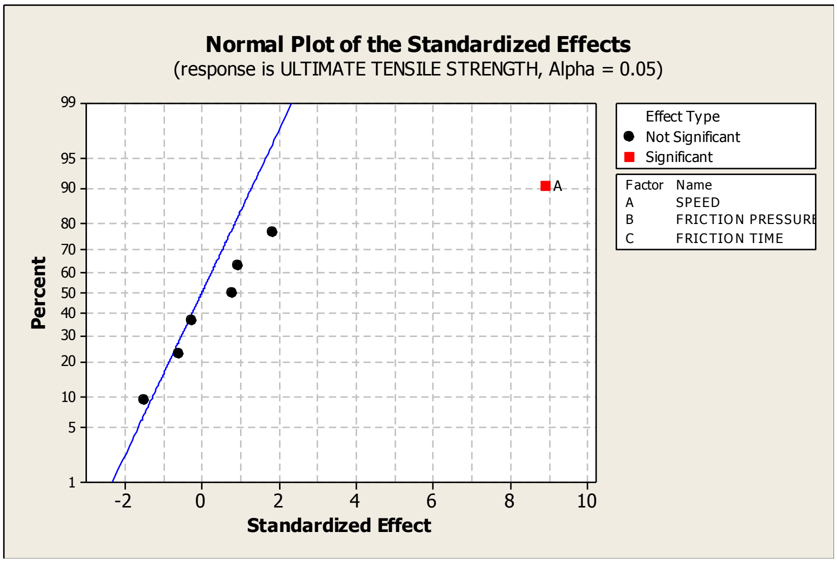


Figure 2 : Normal probability plot for ultimate tensile strength

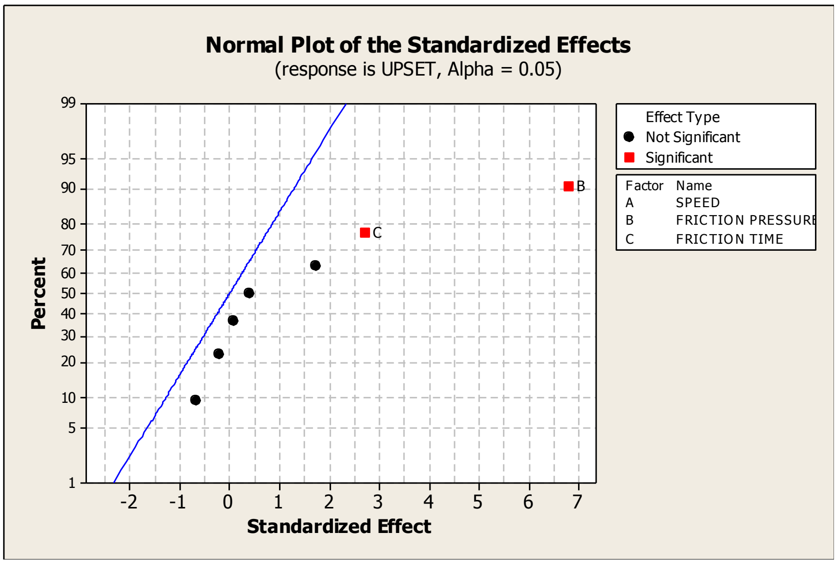


Figure 3 : Normal probability plot for upset

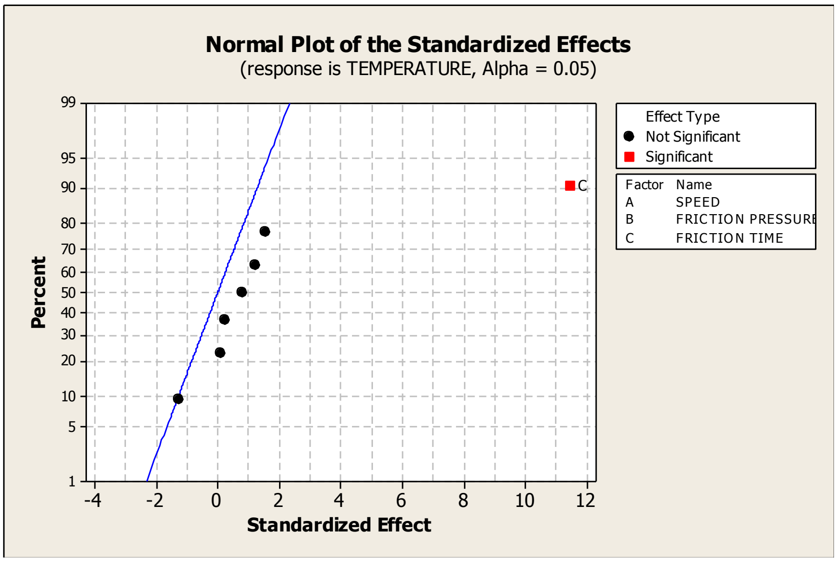


Figure 4 : Normal probability plot for temperature

4.2.4 Main Effects Plots

Figure 5 shows the main effect of rotational speed to the formation of the ultimate tensile strength on the bimetal lugs. The result shows that to obtain maximum effect, the speed should be set at the high level which is at 1450 rpm. Among the factors, rotational speed gives the highest effect to the tensile strength.

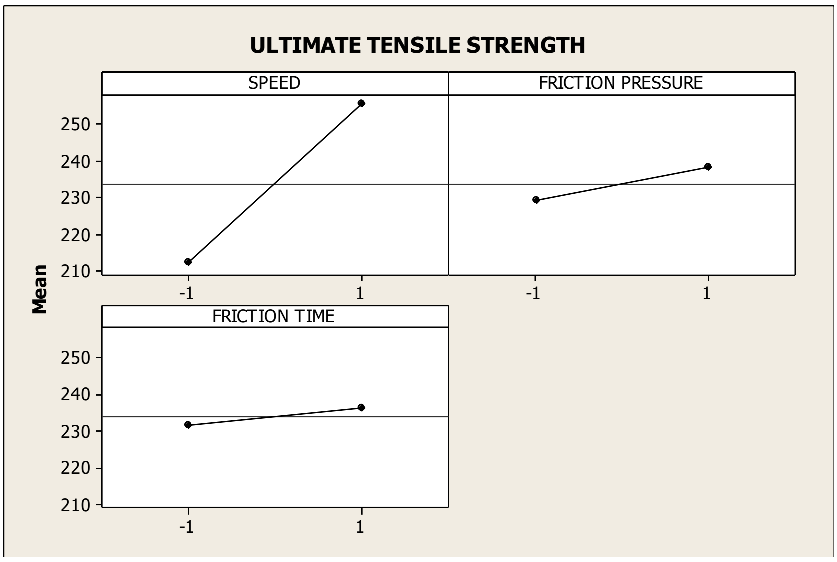


Figure 5: Main effect of rotational speed (A) to the ultimate tensile strength

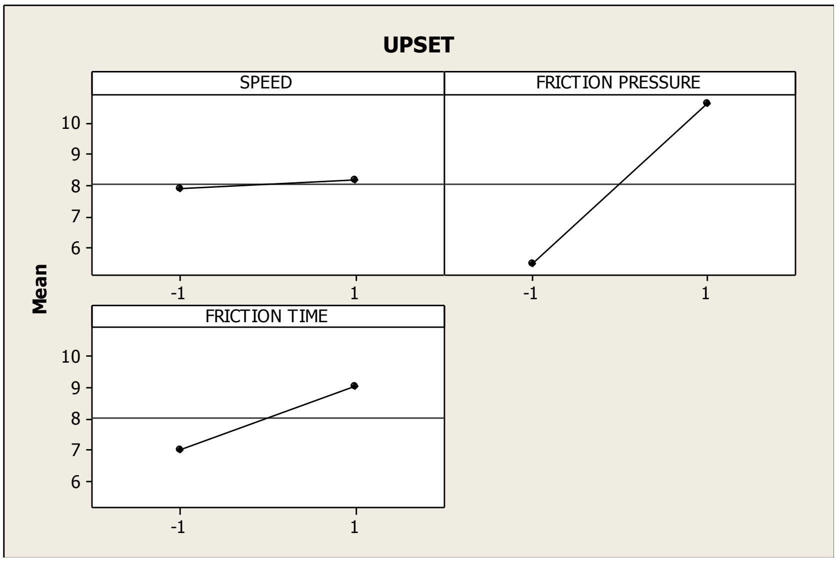


Figure 6: Main effect of friction pressure (B) and friction time (C) to the upset

The significant factors for upset response were friction pressure (B) and friction time (C) as shown in Figure 6. The friction time should be set at low level (3 - 4 sec), and the friction pressure also should be set at the low level (39.2 Pa).

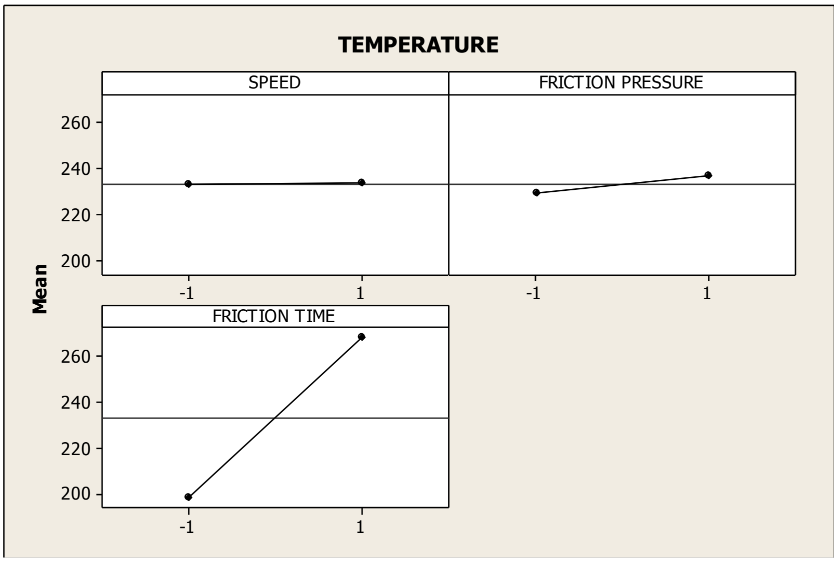


Figure 7: Main effect of friction time (C) to the temperature

The significant effect for temperature response was the friction time as shown in the Figure 7. The friction time should be set at the low level in order to minimize the effect of temperature. No analysis on interaction plots is necessary since only main effects are significant. The analysis is continued by formulating first-order models to predict the responses.

4.2.5 Predictive Models

From the ANOVA results, the predicted first-order models were formulated. The significant main effect for the ultimate tensile strength response was rotational speed (A), while for the upset response was the friction pressure (B) and the friction time (C). For the temperature response, the significant main effect was the friction time (C). The following equations are the coded models for ultimate tensile strength, upset and temperature responses.

The first-order model in term of coded factors for ultimate tensile strength is to maximise Y_1:

$$Y_1 = 233.86+21.706A \tag{2}$$

The first-order model in term of coded factors for upset is to minimise Y_2:

$$Y_2 = 8.0417+2.5667B+1.0250C \tag{3}$$

The first-order model in term of coded factors for temperature is to minimise Y_3:

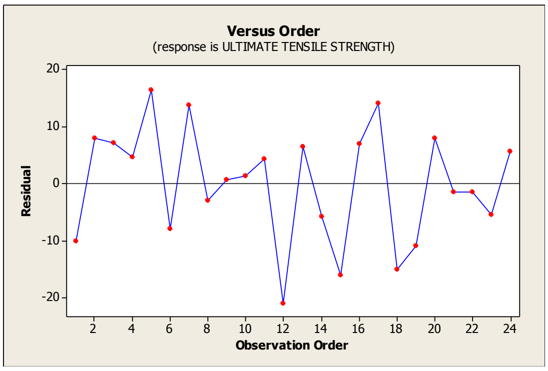
$$Y_3 = 233.25+35C \tag{4}$$

These first-order model equations were formulated based on the values of coefficient for each significant main effect. Based on the results analysis, the overall optimum setting to maximise the ultimate tensile strength response (Y_1) and to minimise the upset response (Y_2) and the temperature response (Y_3) are: (i) Speed (A) at the high level (+1), 1450 Rpm (ii) Friction pressure (B) at the low level (-1), 39.2 Pa, (iii) and Friction time (C) at the low level (-1), 4 s. The predicted value for the ultimate tensile strength is 255.566

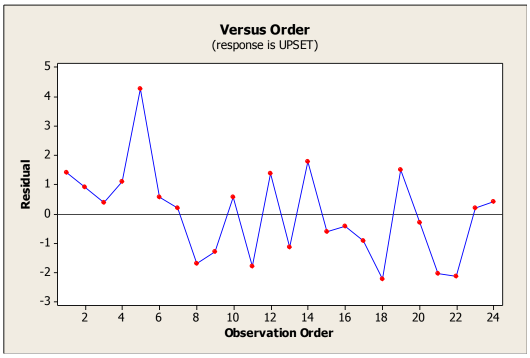
MPA, for the upset is 4.45 mm, and for the temperature is 198.5°C. These values are obtained by substituting the coded factors with appropriate sign (+1 or -1) in the Equations 2, 3 and 4 respectively. The errors of the predicted values obtained based on Equation (1) which are within ±10% suggest that the proposed models are acceptable.

4.2.6 Residual Plots

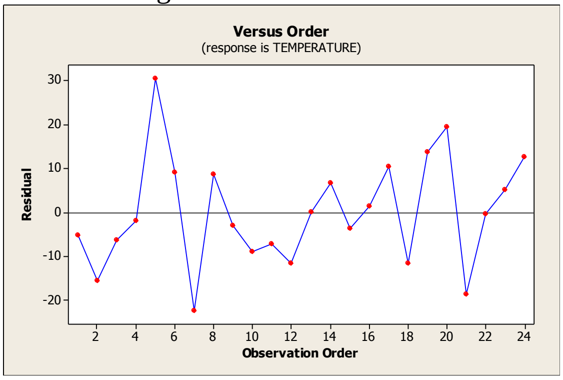
Residual plots are performed for model adequacy checking. The Residual plots shown in the Figures 8 (a) and 8 (c) suggest that the residuals are randomly distributed. Thus, the proposed models to predict the ultimate tensile strength (Y_1) and temperature (Y_3) are adequate. However from Figure 8 (b), it seems that the model for upset (Y_2) requires additional consideration and adjustments.



a) Residual plots for ultimate tensile strength



b) Residual plots for upset



c) Residual plots for temperature

Figure 8**:** Residual plots for the predicted models

4.2.7 Optimum Setting

Confirmation run is necessary in order to confirm the proposed treatment will produce the optimal result as expected. Due to practical constraint in the case study company, the confirmation was done through verification with historical process records. The verified optimum process setting and its respective responses are summarised in Table 9. The suggested settings can be used to overcome the high number of rejects of the bimetal lugs produced.

Table 9: Proposed optimum setting

Run	Speed (rpm)	Friction Pressure (Pa)	Friction Time (s)	Ultimate Tensile Strength (MPa)	Upset (mm)	Temperature (^oC)
18	1450	39.2	4	250.69	3.7	214

5.0 CONCLUSIONS

This project was conducted in a local electrical power components manufacturer. The company faced a high rejection rate in the friction welding process. The study investigated three main friction welding parameters namely, rotational speed, friction pressure and friction time that affect the ability of the bimetal lugs in terms of their tensile strength, upset and temperature. The weld joint with optimum friction pressure and friction time absorbed valuable amount of energy to produce complete bonding and good weld strength at the interface.

The full factorial design of experiment was used to investigate the optimum parameter. The study reveals that the optimum parameters should be set for speed (1450 rpm), friction pressure (39.2 Pa) and friction time (4s). The First-order models in term of coded factors for ultimate tensile strength, Y_1 is 233.86+21.706A, for upset, Y_2 is 8.0417+2.5667B+1.0250C, and for temperature, Y_3 is 233.25+35C. The method used in this study which used historical process data suggests that this alternative approach can be useful when practical constraints do not allow direct data collection.

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