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Joining of Aluminum to Steel Pipe by Magnetic Pulse Welding*1

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Magnetic Pulse Welding (MPW) is not only one of the most useful welding processes for the dissimilar metal joining which uses cylindrical materials such as a pipe, but also a new technology for metal welding by means of repulsive force on account of the interaction between magnetic part of working coil and current induced in an outer pipe. Since the factors effected on quality of MPW are the charged voltage, the gap between inner pipe and outer pipes and a thickness of an outer pipe, the this study was focused on the investigation of the effect of process parameters and development of the mathematical model for the prediction on a quality of joint using Response Surface Method (RSM). To achieve the objective, the MPW equipment manufactured by WELDMATE CO., LTD. has been employed and applied for the materials such as the Al 1070, SM45C for Al and steel pipe respectively. After the sequent experiment, leakage test has been done to verify efficiency of the welding. The experimental values have been shown the good agreement with the predicted ones, indicating suitability of mathematical model employed. It is concluded that the gap between outer pipe and inner rod is one of major process parameters for influence on quality of joint while Al/steel pipe welding using the MPW. [doi:10.2320/matertrans.L-MZ201131]

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1. Introduction

Driveshaft is an important component which performs both steering and transferring of rotator power into wheels directly for high efficiency of driveline. Since it receives torque of engine which vibrates constantly, rotating rapidly, many researchers for torsion vibration has been done. Furthermore, bending vibration could be happened at an eccentric state. These torsion and bending vibration improves the NVH (Noise, Vibration and Harshness) and fatigue life by increasing the effect of reducing weight and natural frequency, when existing steel driveshaft is replaced by aluminum driveshaft. In addition, since only aluminum that producing driveshaft is so wasteful and impossible, dissimilar metal joining between aluminum pipe and steel yoke is needed.[1–3]

MPW is also a new technology for metal welding employed by repulsive force on account of the interaction between magnetic part of working coil and current induced in an outer pipe as this technology is one of the most useful welding processes of the dissimilar metal joining which uses cylindrical materials such as pipe, tube. The quality of joint is decided by several process parameters in magnetic pulse welding, so it is really difficult to control quality of the products.[4,5]

As optimal process parameters depend on the property of inner/outer pipes and dimension, it is very important to predict and control the optimal process parameter related to the quality. Zhang[6] organized the process parameters for magnetic pulse welding systematically. Also Kojima[7] reported acceptable limits of process parameters for successful joint of Al/Cu, Al/Steel and Hokari[8–11] researched how a section between inner and outer pipe influences on burst pressure. Recently Shribman[12] observed and reported how the process parameters influence on the joint the section according to process parameters of Al/Steel joint. However, there is no results related to not only correlation between process parameters and outputs as joint quality, but also mathematical models to control of process parameters.

Therefore, the objective of this paper has been studied to investigate the effect of process parameters on outputs and to develop a mathematical model for prediction of joint quality which related to a base to make Al/Steel driveshaft. To achieve the goals, charge voltage, the gap between inner rod and outer pipes and thickness of outer pipe were chosen as process parameters. For reliability test after welding, a change of burst pressure gotten through leakage test is used as welding quality. Reliability test to product driveshaft usually uses vibration, torsion test, but in this paper leakage test is taken for close quality evaluation of joint and convenience. The investigation of effect of process parameters and development of mathematical model has been employed RSM (Response Surface Method) using MINITAB that is a commercial software and then results has been analyzed by using variance and regression analysis. After that, verification experiment in random welding condition was performed in order to verify the developed mathematical model.

2. Experiment Works

2.1 Design of experiments

RMS is one of mathematical and statistical techniques for studying the relationship between the input and the output variable since the technology saves cost and time of experiments by reducing the overall number of required test. In addition, it helps describe and identify, with a great accuracy the effect of the interactions of different independent parameters on the response when they are varied

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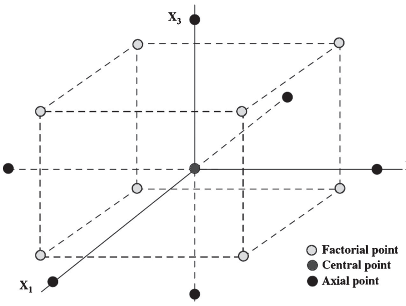

Fig. 1 Schematic diagram of CCD as a function of X_1 (charge voltage), X_2 (gap between inner rod and outer pipe), X_3 (thickness of outer pipe) according to the 2^3 factorial design with six axial points and six central points (replication).

Table 1 Welding parameters and coded levels of input variables.

Process parameters						
Factors	Symbol	Coded levels				
		−2	−1	0	1	+2
Charge voltage	V (kV)	7.7	8.0	8.5	9.0	9.3
Gap between inner rod and outer pipe	G (mm)	0.7	0.8	1.0	1.2	1.3
Thickness of outer pipe	T (mm)	0.5	0.6	0.8	1.0	1.1

simultaneously.[13] An easy way to estimate response surface, a factorial design is the most useful scheme for the variables optimization with the limited number of experiments. A variety of factorial designs are available to accomplish this study. The Central Composite Design (CCD) is the most commonly used.[14] As shown in Fig. 1, this rotatable experimental plan was carried out as a CCD consisting of 20 experiments in this study. For three factors ($n = 3$) and two levels (low and high), the total number of experiments was 20 determined by the expression: 2^n($2^3 = 8$: factor points) + $2n$($2 \times 3 = 6$: axial points) + 6(center points: six replications), as shown in Tables 1 and 2. MPW uses electromagnetic collision energy from high current discharged through working coil which develops collision energy in outer pipe to be welded. Simultaneously, the gap between inner rod and outer pipe and the thickness of outer pipe take the role of accelerating the speed of collision.[7] Therefore the factors in this experiment were the charged voltage (X_1), the gap between inner rod and outer pipe (X_2) and thickness of outer pipe (X_3). The mathematical relationship of the response Y on the three significant independent variables X_1, X_2 and X_3 can be approximated by a quadratic polynomial model including 3 squared terms, 3 interaction terms, 3 linear terms and 1 intercept term as shown below:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 \quad (1)$$

where Y is burst pressure, b_0 is the average of the results of the replicated center point, b_1, b_2 and b_3 are the main half-effects of the coded variables X_1, X_2 and X_3 respectively. b_{12}, b_{13} and b_{23} are two factor interaction half-effects.

2.2 Experimental setup and procedure

Figure 2 shows an experimental setup for this study. The equipment employed in this study is a MPW equipment, called W-MPW, which is manufactured by WELMATE Co, Ltd, and specimens were employed Al 1070 for Al pipe and SM45C for steel rod respectively. Outer pipes of 10 mm in diameter and 110 mm in length were machined from jig. Experiment has been carried out 2 steps, first, the process parameters has to be set according to the welding conditions in Table 2. Second, leakage test has been done to verify the joint parts.

Table 2 CCD for experiment.

Run Order	Variables in coded levels			comment
	x_1	x_3	x_3	
1	+1	+1	+1	Full factorial
2	+1	−1	−1	Full factorial
3	−1	+1	−1	Full factorial
4	0	0	0	Center-full factorial
5	0	0	0	Full factorial
6	−1	−1	+1	Center-full factorial
7	0	0	0	Axial
8	−1	+1	+1	Axial
9	−1	−1	−1	Axial
10	+1	−1	+1	Axial
11	+1	+1	−1	Center-full factorial
12	0	0	0	Center-full factorial
13	0	−2	0	Axial
14	0	+2	0	Axial
15	+2	0	0	Full factorial
16	0	0	−2	Full factorial
17	0	0	0	Full factorial
18	0	0	0	Full factorial
19	−2	0	0	Center-full factorial
20	0	0	+2	Center-full factorial

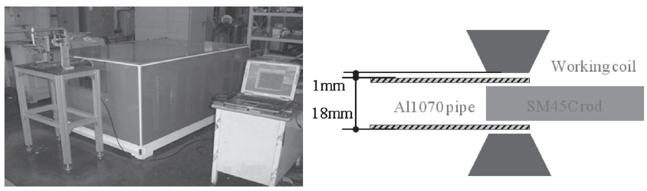

Fig. 2 Experimental setup of MPW process.

3. Results and Discussion

3.1 Development of the empirical model

Tables 3–4 show the results of experiment and analysis of variance for response respectively. The p value is employed to estimate whether F is large enough to indicate statistical significance. If p value is lower than 0.05, it indicates that the model is statistically significant.

As shown in Table 4, effect of linear terms and squared terms were statistically significant, on the other hand two factor interactions term were insignificant. Also quadratic polynomial model was prepared using the regression analysis, which is as follow:

$$\begin{aligned}\text{B.P.} = &-832.774 + 187.387V + 146.877G + 138.537T \\ &- 10.3846V^2 - 182.080G^2 - 41.4665T^2 \\ &+ 12.5VG - 12.5VT - 1.11711e^{-14}GT \end{aligned} \quad (2)$$

where B.P. is burst pressure and V, G, T refer to the charged voltage, the gap between outer pipe and inner pipe and the thickness of outer pipe, respectively.

Table 3 Responses data of experiment.

Run order	B.P.*	Run order	B.P.*
1	3.9	11	5.8
2	9.8	12	7.8
3	3.9	13	9.3
4	7.8	14	2.9
5	7.8	15	8.8
6	7.8	16	8.8
7	7.8	17	7.8
8	3.4	18	7.8
9	9.3	19	5.8
10	8.8	20	6.3

*B.P. = Burst pressure (MPa)

Table 4 Analysis of variance for burst pressure.

Source	Degree of freedom	Sum of square	Adj sum of square	Adj mean of square	F-value	p
Regression	9	8586.40	8586.40	954.04	56.77	0.000
Linear	3	7790.24	7790.24	2596.75	154.53	0.000
Square	3	771.15	771.15	257.05	15.30	0.001
Interaction	3	25.00	25.00	8.33	0.50	0.695
Residual error	8	134.44	134.44	16.80		
Lack-of-fit	5	134.44	134.44	26.89		
Pure error	3	0.00	0.00	0.00		
Total	19	8775.00				

Figure 3 shows the comparison between measured and predicted results from the developed quadratic polynomial model. As can be seen, predicted values good agreement with experimental values with R-Sq of 98% for burst pressure.

Figure 4 represents the residual plots for burst pressure in the mathematical model. The normality of the data was checked by plotting the normal probability of the residuals. A residual value was different from observed and predicted values which are gotten from regression analysis. If the points on the plot fall fairly close to a straight line, then the datum were normally distributed. Figure 4(a) shows a normal plot of residual values so that it could be seen that the experimental points were reasonably aligned, suggesting normal distribution. The residual values versus the fitted values were presented in Fig. 4(b). The residual values were scattered randomly around zero i.e. the errors had constant variances. A histogram of the residual values indicates the distribution of the residuals values. Figure 4(c) represents whether or not residual values lean to certain direction, when there are singular values on data as normal distribution. Also Fig. 4(d) shows the residuals in the order of the corresponding observations. The residuals appear to be randomly

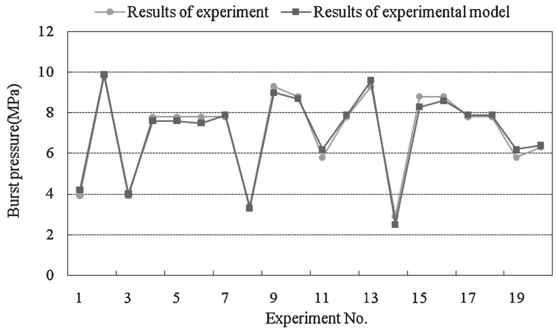

Fig. 3 Comparisons between measured and calculated burst pressures from the developed equation.

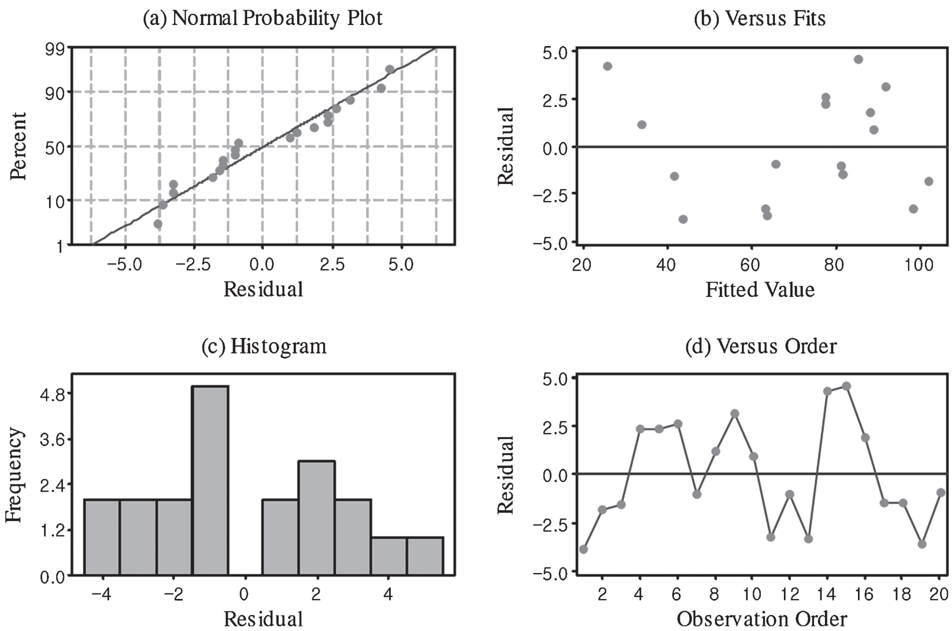

Fig. 4 Residual plots for burst pressure.

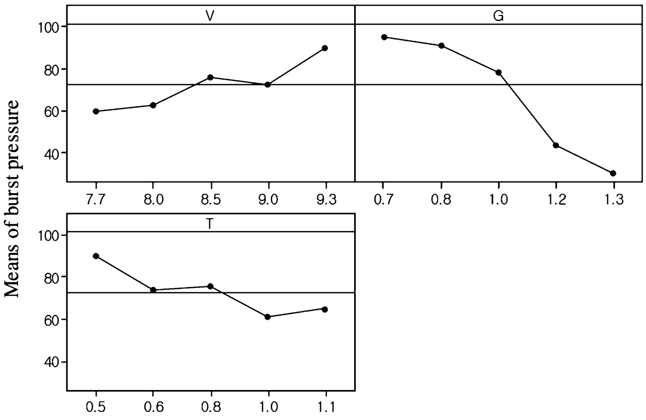

Fig. 5 Main effects plot for burst pressure.

Table 5 Welding condition for verification of the developed model.

Run order	V	G	T
1	7.5	1.2	0.7
2	8.5	1.2	1.0
3	8	1.0	0.7
4	7.5	1.2	1.0
5	8.5	0.7	0.7

scattered about zero and all other points were found to fall in the range of $+5$ to -4.

After developing the mathematical model in order to investigation the effect of process parameters, the plot of main effect was checked and plotted in Fig. 5. As the level of gap between inner and outer pipe has been increased, burst pressure has been decreased sharply. However as charge voltage has been increased, thickness has been also increased, while burst pressure has been varied slightly. As a result it is found that the gap between inner and outer pipe is the most effective factor on the quality of joint.

3.2 Verification experiment

Verification for the developed mathematical model was performed so as to test the accuracy of the developed model according to various process parameters. The experiment was carried out on 5 experiment conditions and the value of expectation and, the result of experiment were compared. Table 5 shows the additional experiment conditions. For getting exact results, experiment has been taken twice.

Figure 6 shows a graph that is the measured and the calculated results employed the developed mathematical model. The errors between the value of expectation and the result of experiment are showed in Table 6.

The errors between the calculated and measured results were less than 10% under the experimental numbers, so the developed mathematical model expected leakage pressure exactly.

4. Conclusions

The effect of process parameters is a significant factor to control quality of dissimilar metal joining using electromagnetic pulse welding. Based on experimental results, process parameters were chosen and empirical model that expects burst pressure has been developed. Using the developed model, the gap between inner and outer pipe has a strong influence on quality of joint among process parameters. Also, through experiment result, the best process parameters to achieve the high quality joint is 9.3 V charged voltage, 0.7 mm gap between inner rod and outer pipe and 0.5 mm thickness of outer pipe. The empirical model developed can also be used to expect burst pressure and tendency that is about effect of process parameters of pipe. It is expected that the model could be used to choose the optimal process parameters in the pipe welding of 10 mm and less.

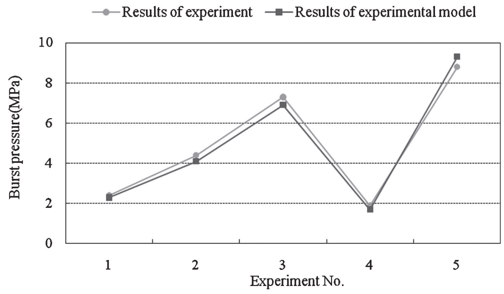

Fig. 6 Comparison plots for verification of the measured and calculated burst pressures.

Table 6 Results of verification of the developed model.

Run order	Burst pressure (MPa)		Error (%)*
	Exp.	Prediction	
1	2.4	2.3	4.1
2	4.4	4.1	6.8
3	7.3	6.9	5.4
4	1.9	1.7	9.4
5	8.8	9.3	5.6

*Error(%) = (Exp. $-$ Prediction)/Exp. $\times$ 100

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