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Selection of Optimal Process Variables for Improving the Al/Cu Joint Length in Magnetic Pulse Welding

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Abstract— ***Magnetic pulse welding process (MPW) is one of the useful welding processes of the dissimilar sheet and tubular materials joining, because this process only use the electromagnetic force through electromagnetic interaction between welding coil and materials. MPW process variables which are related to joint length are the gap between coil and outer material, overlap length between coil and outer material and impact angle. Especially, the Al/Cu joint length for applying the refrigerant tube is important in terms of function, but MPW joint length is under 10% of the overlap length for welding. Therefore, the objective of this study is to investigate the effect of process variables on Al/Cu joint length and to selection the optimal process variables for improving the joint length Al/Cu using DOE (Design of Experiment). In order to carry out this, RSM (Response Surface Method) was employed to design of experiment and then results of designed experiment were analyzed the effect of process variables and optimal process variables using MINITAB. As analysis results, regression model was developed for prediction of joint length and the optimal process variables were selected. Developed regression model and selected optimal process variables will be useful method for ensuing the required joint length for integrity.***

Index Terms—**Magnetic pulse welding, Joint length, Optimal process variables, DOE, Regression model.**

I. INTRODUCTION

Since aluminum is very low and lighter in comparison with copper, to use the aluminum leads to reduction of manufacturing cost and product weight. With these reasons, aluminum has been focused as a replace material of copper in refrigeration tube, and its application is being expanded not only to home appliances, but also to automobiles. However, dissimilar materials which have difference material properties welding using fusion welding such as brazing or resistance welding generally causes a defect such as solidification, cracking of joint and transformation of base materials. Such a defect deteriorates the quality of the joint as well as generates environmental pollutants due to leakage of refrigerant gas caused by corrosion. Therefore, it is required to develop solid state welding process for dissimilar materials that can achieve the high quality joint, saving the manufacturing cost, improving the working environment and reduce the total emission of environmental pollutants. MPW process has been developing as a welding process for light weight materials and dissimilar materials in industry since 1948. This welding process only uses the high electromagnetic force for welding. When charged high electrical energy at capacitor bank, passes through a welding coil instantaneously, eddy current is induced on materials and then flowing current on welding coil and opposite direction current on tubes is repulsive Fig. 1. This repulsive force which is called electromagnetic force applies to outer material and consequently outer material flying to inner material with high speed. Consequentially, outer material has to impact inner material in the range of roughly about 250m/s and above. The impact between outer material and inner material has to occur under a certain impact angle. This leads to a collision point travelling across the surface. Due to the high strains and strain rates in this area, superficial oxides and impurities are removed and driven out of closing gap. The metallically pure surfaces are then pressed together by the immense pressure of the impact, which finally evokes the metallurgical joint. As no heat is applied to the material, no defect occurs due to the difference in the material properties, and high quality joint can be obtained. Moreover, to use the high speed electromagnetic force for welding without shielding gases and filler, achieves the environmentally friendly welding process and increases the productivity. For such a reason, MPW process can be diversely applied across the whole industry including electric/electronic, automobile and aerospace industries.

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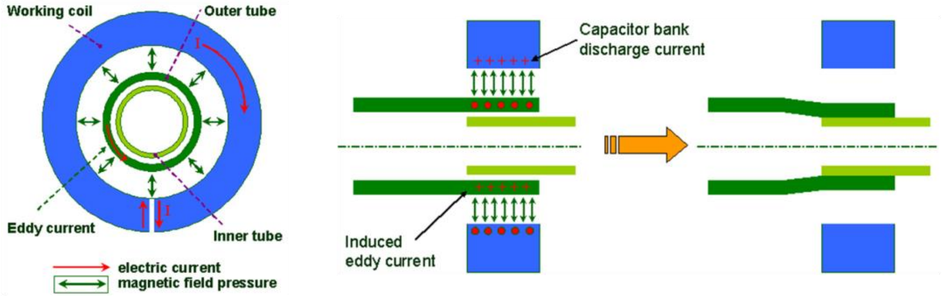

Fig. 1 Principle of Magnetic Pulse Welding

Many MPW researches which include analysis the process and manufacturing the prototype have been carrying out for a long time. Especially, experiments based on tubular welding have been tried by Kojima et al firstly. The purpose of this work is to examine the availability of MPW so, tried to similar and dissimilar materials welding such as aluminum/carbon steel, aluminum/copper and aluminum/stainless steel. The theory of main process variables in MPW process was studied by P. Zhang [4], and D. Dudkoet. et. al[7] reported the dynamic behavior of materials when high speed electromagnetic force is applied. Also, Hokari et al. investigated the effect of gap between outer material and inner material on quality of joint by leakage test and selected the optimal ranges of process variables. This work also was employed various dissimilar materials. V. Shribman [8] analyzed the effect of process variables on the joint in metallurgical aspect by observing the interface after welding aluminum/carbon steel in different welding conditions. Faes et al. reported that the overlap of welding coil edge and the outer material had a significant effect on tube welding condition for copper/brass joints. Furthermore, Shim [9] studied the effect of process variables on the joint quality when welding aluminum and steel using the experiment design method and developed a regression equation, there was a limit that it could only be utilized for dissimilar welding of a aluminum/stainless steel joint. Kim [10] studied the effect of the gap between materials on welding strength. Recently, These studies on MPW process is carried out around IUL(Institute of forming technology and lightweight construction), IWS(Fraunhofer Institute for Material and Beam Technology) and OSU(Ohio state university) through establishment of systematic theory, welding experiment of dissimilar materials and numerical analysis. [1-4] According to these researches, the process variables of MPW are charged voltage as electromagnetic force, the gap between materials and dimension of the materials under using the same apparatus and materials. The quality of MPW joint was decide by these process variables and was verified leakage test which uses the water and gas, peel test. The analysis the interface of joint often has been trying for investigating the joint characteristic. As results of these researches, optimal process variables for joint length along the circumferential direction had been selected under specific materials. Otherwise the investigation of joint length along the longitudinal direction did not carried out although life and durability of product were decided by joint length along the longitudinal direction in terms of refrigerators function. In other words, analysis of joint length along the longitudinal direction is very important in commercializing this process and expanding its application field. Therefore this study focused on the analysis the effect of process variables on joint length along the longitudinal direction and selection of optimal process variables for improving the on joint length. In order to carry out, the gap between working coil and outer tube, positions of outer tube and impact angle were selected as the main process variables on the bases of related researches [1-8]. And the experiment design for Al/Cu tubular MPW was established in accordance with CCD (Center Composite Design) using MINITAB R14, a statistical software. After MPW, experiments results were analyzed effect of process variables and developed regression model for prediction of joint length. For verify the developed regression model verification experiments in random welding condition were performed in and found the optimal process variables finally.

II. EXPERIMENTAL WORKS

A. Design of experiment

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 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

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Composite Design(CCD) is the most commonly used.[14] For three factors (n=3) and two levels(low and high), the total number of experiments was 20 determined by the expression:2n(2^3=8: factor points)+2n(2×3=6: axial points)+6(center points: six replications), as shown in table 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 gap between working coil and Al tube (X_1), the overlap length between coil and Al tube (X_2) and impact angle (X_3). The mathematical relationship of the response 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 is joint length(%), is the average of the results of the replicated center point, , and are the main half-effects of the coded variables X_1, X_2 and X_3 respectively. b , b and b are two factor interaction half-effects.

Table 1 Process variables and levels

Factors	Symbol	Coded levels				
		-	-1	0	1	+
Gap between working coil and outer tube	G (mm)	0.7	1.0	1.5	2.0	2.3
Positions of outer tube	O (mm)	-1.7	-1.0	0	1.0	1.7
Impact angle	A (°)	-2.0	0	3.0	6.0	8.0

The number of is 2.37

Table 2 Experimental design and results of the central composite design

Run Order	Variables in coded levels						Y
	X_1	X_2	X_3	G	O	A	(Joint length)
1	1	-1	-1	2.0	-1.0	0	2
2	1	0	1	2.0	1.0	6.0	0
3	1	-1	1	2.0	-1.0	6.0	0.3
4	0	0	0	1.5	0	3.0	4
5	0	0	-	1.5	0	-2.0	1.5
6	0	0	0	1.5	0	3.0	4
7	1	0	-1	2.0	1.0	0	2
8	0	0	0	1.5	0	3.0	4
9	0	-	0	1.5	-1.7	3.0	5
10	-1	1	-1	1.0	1.0	0	5
11	-	0	0	0.7	0	3.0	7
12	-1	0	1	1.0	1.0	6.0	2.5
13	+	0	0	2.3	0	3.0	0.5
14	0	+	0	1.5	1.7	3.0	3
15	0	0	0	1.5	0	3.0	4
16	-1	-1	-1	1.0	-1.0	0	5
17	0	0	0	1.5	0	3.0	3.8
18	-1	-1	1	1.0	-1.0	6.0	4.5
19	0	0	0	1.5	0	3.0	4
20	0	0	+	1.5	0	8.0	0

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B. Experimental setup and procedure

MPW equipment, called W-MPW, which is manufactured by WELMATE Co., Ltd. was employed in this study as shown Fig. 2. This MPW system could be charged up to 53kJ.

Fig. 2 Magnetic pulse welding system for this study

Charged voltage which was selected by Al/Cu MPW preliminary and kept the 10kV (27.2kJ) during experiment. Additionally, in order to observe a discharge waveform, Rogowski coil was installed in working coil. The specimens were employed AA1070 for outer tube, and C12200 for inner rod respectively. Outer tube of 0.7mm in thickness, 110mm in length, and 8mm in diameter was machined. Inner rod of 5mm diameter was employed. For tube joint, the gap between outer tube and inner tube was 0.8mm and overlap distance between tubes kept 10mm. Before experimenting, the specimens were ground using emery paper (#400~#1500) prior to welding in order to remove machine marks sustained during machining. In addition, ultrasonic cleansing was carried out for approximately 10 minutes within acetone in order to remove grease. Experimental procedure is as following, firstly, the power source and specimens have to set up under the designed welding conditions as shown Table 2. After the welding, cross section of joint was observed by microscope for measuring the wavy pattern which is characteristic of successful solid state welding joint and the joint length was measured.

III. RESULTS AND DISCUSSION

A. Development of the regression model

“Y" values from Tables 2 show the joint length after MPW under designed experimental condition. To analysis the effect of the process variables on the joint and to develop the regression model were performed by Analysis of Variance (ANOVA). Since an exploratory tool to explain observations, ANOVA model has been widely used in the study of effects of multiple factors for designed experiments, ANOVA models with fixed effects has received a lot of attention in the past decades. The p value was employed to estimate whether Fisher F-test is large enough to indicate statistical significance. If p value is lower than 0.05, it indicates that the model is statistically significant.[12] Table 3 shows the results of analysis of variance. As shown in Table 3, the p values of linear terms and squared terms were 0.000. It means effect of linear terms and squared terms were statistically significant, but two factor interactions term were insignificant. These results show that there is no interaction between process variables. Therefore, each process variables were affected on ratio of joint length. As a results of Fisher F-test, F value was calculated 19.93 with a very low probability value (p>F=0.000). It demonstrates a high significance for the regression model. The efficiency of corrected model was checked by the coefficient of determination (R^2). In this case, the value of the determination coefficient (R^2=94.72%) indicates that only 5.28% of the adjusted determination coefficient (Adj. R^2=89.97%) is also high to advocate a high significance of the model. The regression model is represented by the equation below:

Table 3 Analysis of variance for ratio of joint length

Source	Degree of freedom	Sum of square	Adj sum of square	Adj mean of square	F-value	*p*
Regression	9	7410.63	7410.63	823.40	19.93	0.000
Linear	3	5183.06	5183.06	1727.69	41.82	0.000
Square	3	2068.19	2068.19	689.40	16.69	0.000

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Interaction	3	159.37	159.37	53.12	1.29	0.332
Residual error	10	413.12	413.12	41.31		
Lack-of-fit	5	329.79	329.79	65.96	3.96	0.079
Pure error	5	83.33	83.33	16.67		
Total	19	7823.75				

$$\text{Joint length} = 38.441 - 17.7732G - 4.2935O + 6.7232A - 1.2490G^2 + 0.5188O^2 - 11.8556A^2 + 3.1250GO - 0.6250GA - 3.125(\quad (2)$$

Fig. 3 shows the comparison between measured and calculated results from the developed regression model. As you can be seen, the calculated joint length was good agreement with measured joint length.

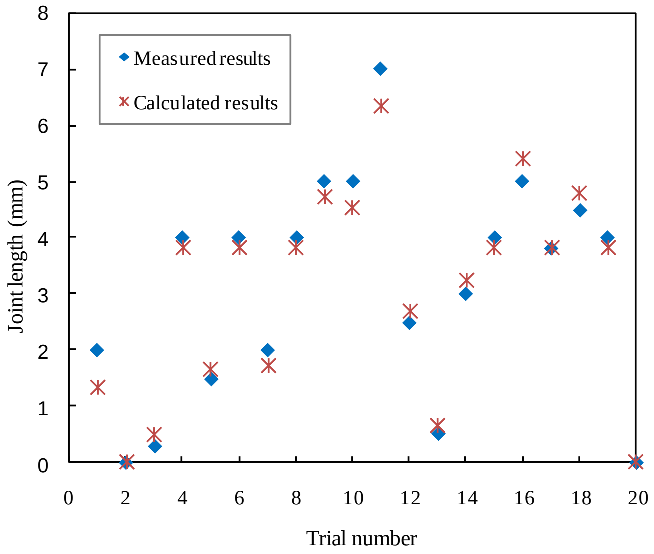

Fig. 3 Comparisons between measured and calculated results

After developing the regression model in order to predict the joint length according to the variation of process variables, the effect of process variables was analysis by the plot of main effect as shown Fig 4. As the gap between working coil and outer tube (G) has been increased, joint length has been decreased sharply. Actually, the reason of this result for electromagnetic force depends on the gap between working coil and outer tube, namely the gap between working coil and outer tube is wider, electromagnetic force is decreased by low electromagnetic interaction under same charged electrical energy of power source. Also as the positions of outer tube moved on working coil outside, joint length is decreased because distribution length of electromagnetic force on outer tube is wider, value of electromagnetic force is lower than other results. Moreover, because amount of outer tube for flying to inner tube is increase, joint length was decreased resultantly. And joint of length was changed by varied the impact angel. The impact angel between tubes in MPW process means the acceleration of impact velocity on outer tube, namely the impact angel between working coil is wider; impact velocity between tubes is faster under same charged electrical energy of power source. But if the impact angel is too wide, impact velocity will be decrease the by resistance of outer tube kinetic energy. But the effects of positions of outer tube and impact angel were slight in terms of variation range, therefore it is found that the gap between working coil and outer tube is the most effective process variable on the joint length.

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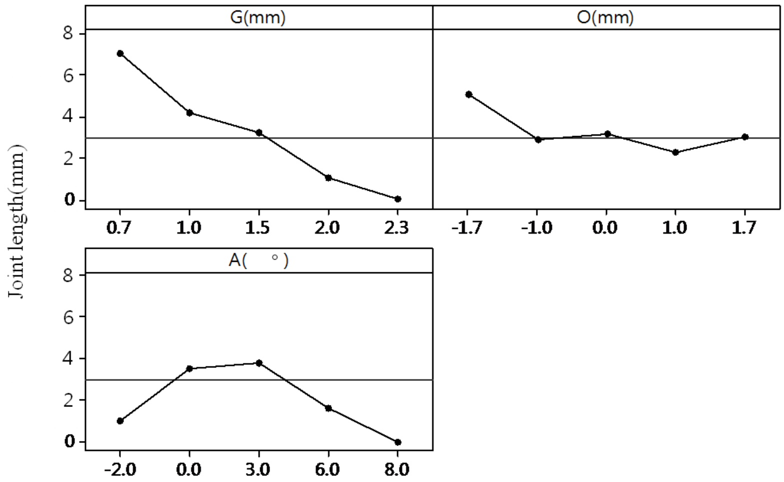

Fig. 4 Main effects plot ratio of weld interface

B. Verification experiments

Verification experiments were performed as to check the accuracy of the developed regression model.

Table 4 Welding condition for verification experiments

Trial No.	G(mm)	O(mm)	A(°)
1	1.5	1.0	5
2	1.0	1.5	2
3	1.5	0	0
4	1.0	-1.0	2
5	1.0	0	4

The experiment was carried out on 5 welding conditions which were designed by random process variables as shown Table 4. After experiment, the measured joint length as shown Fig 5 and calculated joint length using developed regression model were compared as shown Table5.

Table 5 Results of verification experiments

Trial No.	G(mm)	O(mm)	A(°)	Joint length (mm)		Error (%)
				Experiment	Prediction	
1	1.5	1.0	5	2.1	2.2	8.3
2	1.0	1.5	2	4.5	4.7	4.9
3	1.5	0	0	3.1	3.3	7.1
4	1.0	-1.0	2	6	6.2	4.1
5	1.0	0	4	5	5.1	3.0

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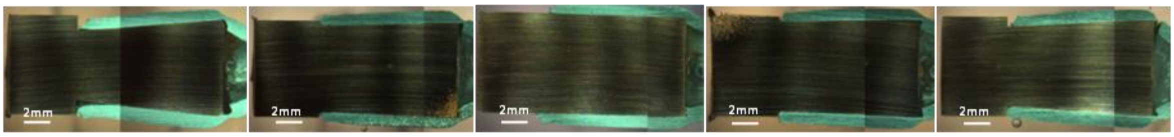

(a) Trial No. 1 **(b) Trial No. 2** **(c) Trial No. 3** **(d) Trial No. 4** **(e) Trial No. 5**

Fig. 5 Cross section of joint

The errors between the measured and calculated results are showed in Table 5. The errors between the calculated and measured results were less than 10% under the experimental numbers, so the developed regression model could expect leakage pressure exactly. Fig. 6 shows a graph that is the comparison between measured and the calculated results.

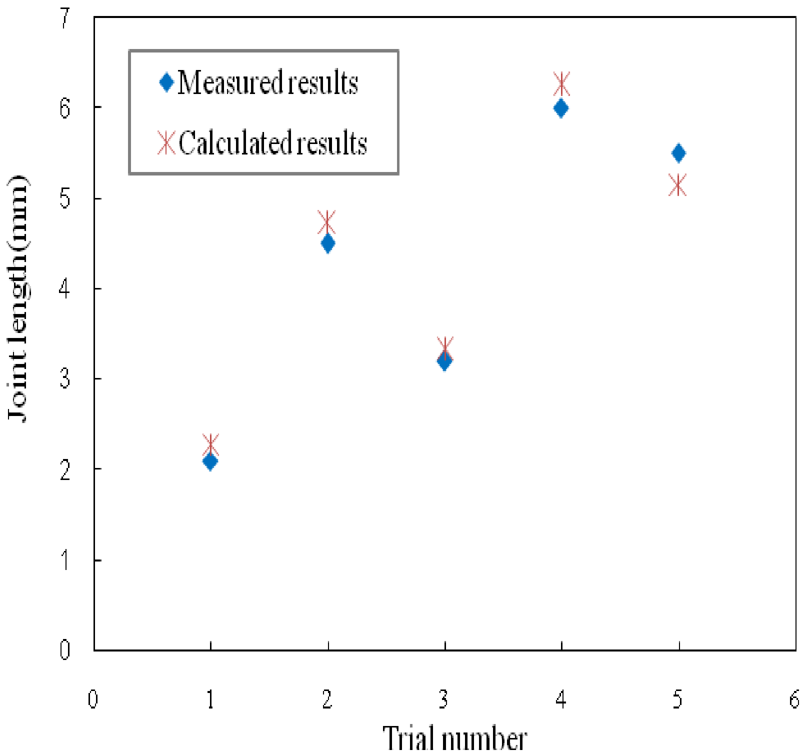

Fig. 6 Comparisons between measured and calculated results on verification experiments

C. Optimization of process variable

After developing the regression model for predict the joint length and investigating the effect of process variables in MPW process, to find the optimal process variables were carried using MINITAB. The goal was inputted the maximum joint length. Fig. 7 shows the selected optimal process variables. The gap between working coil, outer tube positions and tube impact angle were chosen 0.7mm, 1.6mm and 2.9° respectively. When MPW experimented under these optimal process variables, length of joint was measured 8mm in interface of joint as shown Fig. 8. Especially, wavy patterns which are feature of joint using sold state welding process were observed along the joint part. Fig. 6 shows the wavy pattern of joint.

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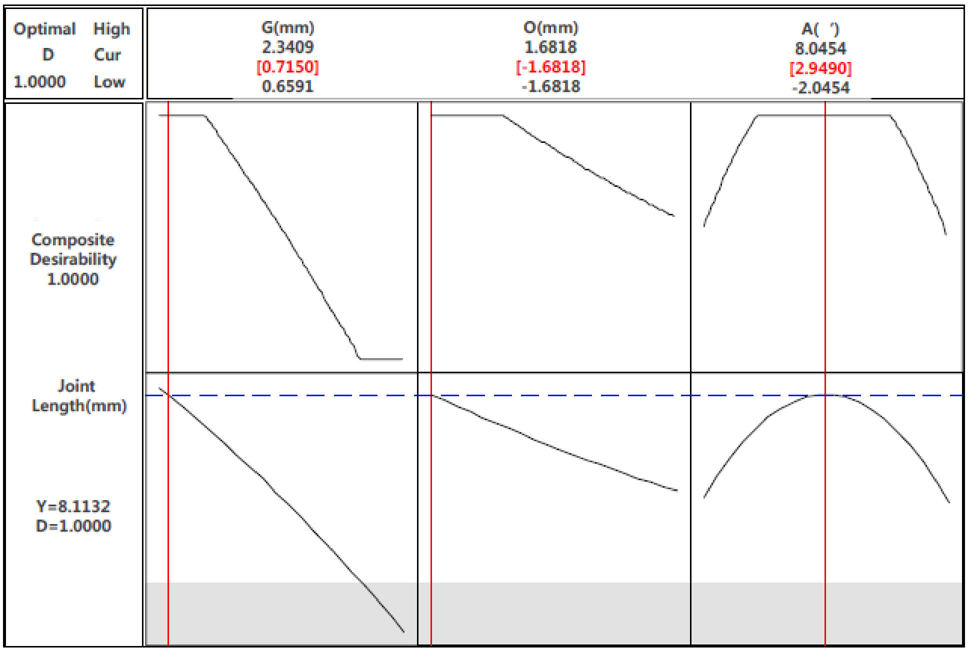

Fig. 7 Optimal process variables

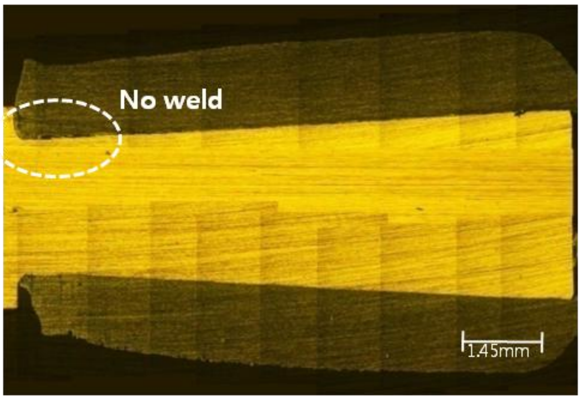

Fig. 8 Interface of joint

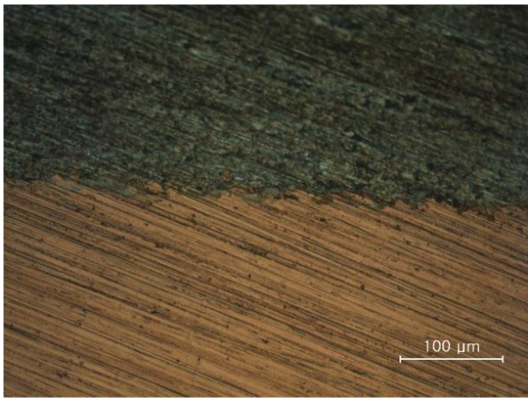

Fig. 9 Wavy pattern on joint

IV. CONCLUSIONS

This research has been concentrated to improve the Al/Cu joint length of MPW by analysis the effect of process variables and selection the optimal process variables.

(1) Based on the related research, process variables were chosen such as gap between working coil and outer tube, positions of outer tube and impact angle. After selecting the process variables, the CCD was employed for design of experiment. The mathematical model was developed by experiment results using analysis of variance which is analysis code in MINITAB.

(2) The experiment results indicated joint length was increased as decreasing the gap between working coil and the positions of outer tube. Also the gap between working coil and outer tube is strongly affected process variable on the Al/Cu joint length and the effect of the positions of outer tube, and impact angle was slight.

(3) Regression model which can expect the joint length and optimal process variables were drawn from statistical analysis. The optimal process variables for getting the over 8mm joint length were selected 0.7mm gap between working coil, 1.6mm positions of outer tube and 2.9° impact angle and uniform wavy pattern was observed on

Al/Cu joint.

(4) The developed regression model and optimal process variables can be employed to expect joint length when the MPW process applies on manufacturing the Al/Cu tubular components for electric/electronic, automobile and aerospace industry. The developed regression model and selected optimal process variables could be used to the Al/Cu tubular welding of 10mm and less.

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