연구논문

Parameter Design and Analysis for Aluminum Resistance Spot Welding

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Abstract

Resistance spot welding of aluminum alloys is based upon Joule heating of the components by passing a large current in a short duration. Since aluminum alloys have the potential to replace steels for automobile body assemblies, it is important to study the process robustness of aluminum spot welding process. In order to evaluate the effects of process parameters on the weld quality, major process variables and abnormal process conditions were selected and analyzed. A newly developed two-stage, sliding-level experiment was adopted for effective parameter design and analysis. Suitable ranges of welding current and button diameters were obtained through the experiment. The effects of the factors and their levels on the variation of acceptable welding current were considered in terms of main effects. From the results, it is concluded that any abnormal process condition decreases the suitable current range in the weld lobe curve. Pareto analysis of variance was also introduced to estimate the significant factors on the signal-to-noise (S/N) ratio. Among the six factors studied, fit-up condition is found to be the most significant factor influencing the S/N ratio. Using a Pareto diagram, the optimal condition is determined and the S/N ratio is significantly improved using the optimal condition.

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Key Words : Aluminum, Resistance Spot Welding, Design of Experiment, Parameter Design, Analysis of Variance

1. Introduction

Resistance spot welding (RSW) have grown remarkably since 1933, when the first all steel welded automobiles were introduced. Now it is one of the primary joining processes employed in the automotive industry. The popularity of resistance spot welding is due to the fact that this process is economical, rapid and flexible. As the demand for highly fuel-efficient and lightweight automobiles increases, aluminum alloys are considered to be the alternative material candidate competing with steels. Aluminum has been used in the manufacture of automotive assemblies for many years, however its use has been limited to low-volume vehicles and closure panels such as doors, hood and deck lids. Nevertheless aluminum has a number of advantages for auto body application compared to steel. Since the density of aluminum is just one-third that of steel, reductions in the weight of body-in-whites can be achieved up to 50%. With reduced overall vehicle weight, fuel consumption can also be significantly reduced1). Unlike steel, which has to be coated, aluminum has good inherent corrosion resistance due to the protective oxide layer. Particularly with regard to recycling, the energy to re-melt aluminum is approximately 5% of that required to produce new aluminum2).

Aluminum has two remarkable features that cause it to perform differently than steel during RSW. One feature is that aluminum has an electrical resistivity that is 1/2 to 1/4 and a thermal conductivity that is 2 to 4 times that of steel. The other feature is that the oxide film has high electrical resistance (or in some cases, acts as an insulator) on the surface of the aluminum3). Therefore, high, short duration current is needed at the early phase of the RSW cycle. Although a lot of researches have been focused on aluminum spot welding, there is still much to be done for mass production environment because aluminum has a narrow temperature range between the solid and liquid phases (not more than about 30°C) and a low melting temperature (around 670°C)[4]. Consequently, a detailed consideration of the effect of process parameters on the weld quality is highly desired in production.

Early work on spot-welded aluminum alloy was mostly focused on high-strength alloy in the aerospace industry, showing that riveting had a better performance in terms of fatigue resistance[5]. Such aluminum alloy is now becoming available to be spot welded in the automotive industry[6]. Research in aluminum resistance welding has mostly concentrated on the effect of various welding process parameters, such as electrode force, welding current, welding time, electrode life and type, and surface condition, on the weld quality such as shear strength and nugget diameter[7-12]. Little has been conducted to understand the effects of abnormal process conditions, which may cause large weld quality variation in a production environment. Some work has been done for steel welding. Nagel considered abnormal conditions in order to develop and apply a new automatic process control[13]. Karagoulis studied the electrode misalignment as a possible abnormality in the plant environment, reporting that a slight shift of the lobe curve was observed[14]. Li, et al., characterized process abnormal conditions and considered the effects of both normal and abnormal welding conditions on the weld quality[15]. However, a systematic study on the effects of various process conditions for aluminum remains not available.

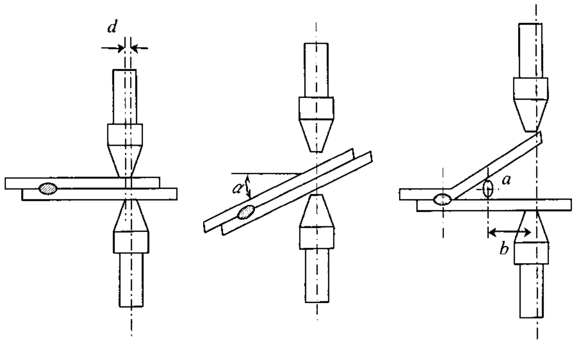
In this study, the effects of welding parameters on the quality of aluminum spot welding are discussed. Six process variables including abnormalities are studied. Due to the fact that it is difficult for the welding current to be a fixed-level factor, two-stage, sliding-level experiment was applied in the parameter design. The quality characteristic is expressed in a signal-to-noise (S/N) ratio for estimating the significant factors. The effects of the factors and their levels on the welding current and weld quality are also discussed via Pareto analysis of variance.

2. Quality of Aluminum Resistance Welding

2.1 Process parameters

There are three major process parameters affecting the nugget formation: welding current, electrode force and welding time. Since Joule heat is produced via I^2R, where I is current and R is resistance, significant increase in welding current is required to join aluminum, compared to steel[1]. During a design of experiment, however, setting of welding current is simple due to the combined effect of other process variables. For example, a change in electrode force leads to changes in the current range required to form a good weld. In addition, many abnormal process conditions lead to the change of contact resistance, hence, heat generation. Therefore, systematical considera- tion of these abnormalities is needed.

The abnormal conditions investigated in this study are focused on the mechanical alignment and electrodes wear, which are known as the most dominant abnormalities in production[16]. In the initial stage of this research, six abnormal conditions were examined and they were: axial misalignment, angular misalign- ment, poor fit-up, edge weld, poor electrode cooling, and electrode wear. After a screening experiment, however, only two of them are kept for further consideration. Poor electrode cooling hardly affects the weld quality, and therefore is taken as a held-constant factor. Edge weld is so influential that it overshadows other abnormal conditions. Therefore it is taken as a nuisance factor for the purpose of the present experiment[17]. Also, electrode wear is replaced by electrode size of tip radius r because electrode wear affects the process mainly through the change of the electrode contact area. Schematic diagrams of the definition of these abnormal conditions, except electrode size, are shown in Fig. 1. Axial misalignment in Fig. 1-(a) indicates that the axes of the upper and lower electrodes deviate from each other



(a) Axial misalignment (b) Angular misalignment (c) Poor fit-up

Fig. 1 Abnormal process conditions in aluminum resistance spot welding by a distance *d*. Fig. 1-(b) shows the angular misalignment condition in which the parts are tilted relative to the axis of the electrode by an angle of α. When the two sheet metal parts separate, poor fit-up condition exists. Shown in Fig. 1-(c), this condition is created by inserting a piece of wire with a diameter of *a* at a distance *b* (15 mm) from the centerline of the electrodes.

2.2 Quality characteristics and objective function

Robust engineering design is achieved by maximizing an objective function while minimizing the effects of noise factors. In spot welding, one of the responses observed for weld quality is the size of welded nugget, which is closely related to weld strength. The quality characteristic to be measured in this study is the button diameter after peel test, which is a continuous, nonnegative, and larger-the-better factor. By adopting a quadratic loss function, the objective function to be maximized is denoted by equation (1) in terms of the signal-to-noise (S/N) ratio η.

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

Where, n is the number of data and y_i is the observed button diameter in mm.

3. Design of Experiments

3.1 Two-stage, Sliding-level Experiment Design

In order to study the effect of the process parameters and abnormal process conditions on the weld quality, a newly developed two-stage, sliding-level experiment[15] was adopted. When the experiment matrix[18] is developed, it is difficult for the welding current to be a fixed-level factor because of interdepend- ency among the process variables. On a lobe diagram for resistance spot welding[19-22], there is an acceptable range of current under certain conditions of other process variables in an experiment matrix. In this case, welding current is chosen to be a sliding factor since it has natural boundaries of undersized weld and expulsion.

The first stage of the two-stage experiment was to find a suitable range of welding current for the designed conditions. Low current boundary was found by decreasing welding current of 0.84kA intervals starting from initial preset current level. High current boundary was also obtained by increasing the current of same amount until expulsion occurs. In order to make it easy to analyze the effect of process variables on these ranges, they were characterized by using two response variables: the center of the current range and the length of the current range. At the second stage, the experiment was carried out based upon the results of the first stage to make weld samples and evaluated the weld quality, which was used for analysis of variance.

The matrix experiment is given in Table 1, which was constructed using parameter design matrix given in Taguchi[18]. In the table, six factors including process parameters, electrode force *F*, weld time *T*, and electrode size *S*, as well as abnormalities, poor fit-up *Fit*, axial misalignment *Ax*, and angular misalignment *Ang* are listed with their levels. The value of *Fit*, *Ax*, and *Ang* are denoted respectively by *a*, *d*, and α, as shown in Fig. 1. The preset levels are identified by a subscript '0' for process parameters and 'none' for abnormalities. The alternate levels for the factors are also shown in the table; for example, the two alternate levels of three-leveled electrode force are F_0-1.2kN and F_0+1.2kN, whereas the other alternate level of two-leveled poor fit-up condition is 5mm. Each of the values of preset level is listed in Table 2 except three abnormal process conditions. The matrix experiment in Table 1 consists of 18 individual experimental runs corresponding to the 18 rows.

3.2 Experimental procedure

The experiments were conducted on a medium frequency DC welding machine with spherical radiused electrodes. Weld samples were produced using commercial aluminum alloy AA5754 of 2 mm thickness. The weld quality was evaluated by measuring the diameter of weld button in a peel test[23]. A specially designed fixture was used to reproduce the abnormal process conditions shown in Fig. 1.

Table 1 Design matrix and factor assignment

Exp. number	Electrode force F (kN)	Weld Time T (cycle)	Electrode size S (r, mm)	Poor fit-up Fit (a, mm)	Axial misalignment Ax (d, mm)	Angular misalignment Ang (α,°)
1	F_0-1.2	t_0-4	S_0-25	*none*	none	none
2	F_0-1.2	t_0-4	S_0	*none*	1.5	none
3	F_0-1.2	t_0-4	S_0+25	*none*	none	10
4	F_0-1.2	t_0	S_0+25	5	none	10
5	F_0-1.2	t_0+4	S_0-25	5	1.5	10
6	F_0-1.2	t_0+4	S_0+25	5	1.5	none
7	F_0	t_0-4	S_0-25	5	1.5	none
8	F_0	t_0-4	S_0	5	1.5	10
9	F_0	t_0	S_0-25	*none*	none	10
10	F_0	t_0	S_0	*none*	none	none
11	F_0	t_0	S_0+25	*none*	1.5	none
12	F_0	t_0+4	S_0-25	5	none	10
13	F_0+1.2	t_0-4	S_0	5	none	10
14	F_0+1.2	t_0	S_0	5	1.5	none
15	F_0+1.2	t_0	S_0+25	5	1.5	10
16	F_0+1.2	t_0+4	S_0-25	*none*	1.5	none
17	F_0+1.2	t_0+4	S_0	*none*	none	10
18	F_0+1.2	t_0-4	S_0+25	*none*	*none*	none

Table 2 Design factors and their preset levels

	Electrode force	Welding time	Electrode size	Welding current
Preset level	F_0 = 6.3kN	T_0 = 12cycle	S_0 = 50mm	sliding level

4. Results and Discussion

4.1 Process parameter effect on welding current

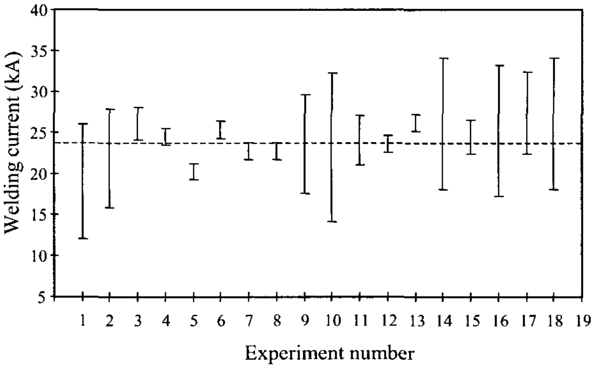


Fig. 2 Suitable welding current ranges on weld lobe diagram for each experiment combination

The first stage in data analysis is focused on the effects of the process parameters on suitable welding current settings. In the first stage of this experiment, the welding current needs to be determined to ensure acceptable welds under all the designed conditions of the other process variables. Suitable current ranges for all experimental run in Table 1 are in Fig. 2. As a whole, acceptable welds could be made from 11.99kA through 34.16kA. The average of the current ranges, which was 24.05kA, is shown as a dashed line in the figure. More detailed considerations are presented with Fig. 3 and Fig. 4, showing the main effects of the factors and levels on the welding current. In case of the center of the current range, the first three welding parameters, such as welding force, time and electrode size, seem to be more significant than the other three abnormal conditions, such as poor fit-up, axial misalignment and angular misalignment. When electrode force or electrode size has a higher value, acceptable welds could be obtained through a higher welding current. As suggested by other researchers earlier[6,19], this is due to the electro-thermal heating mechanism of the welds, i.e., the heating of the faying surface could be delayed or reduced in case of low current

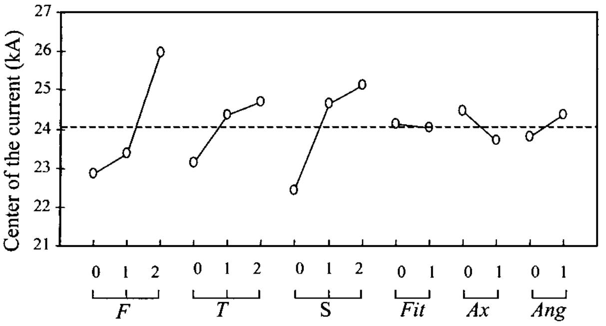


Fig. 3 Factor effects on the center of acceptable welding current

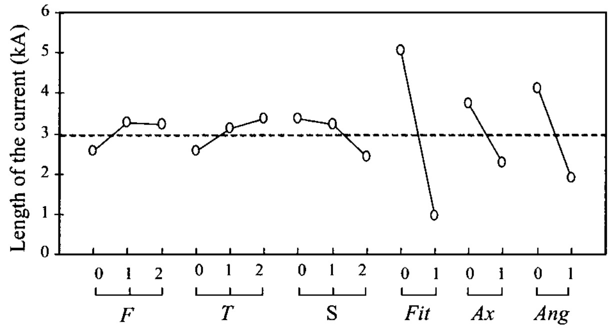


Fig. 4 Factor effects on the length of acceptable welding current

density resulted from a higher electrode force or a larger electrode size. The variations of the center of the current of these two factors were 3.09kA and 2.67kA, respectively. They were both higher than that of weld time (1.55 kA). As for the effects of the abnormalities, axial misalignment showed the largest value of 0.75. Yet, it is unlikely to be significant. On the other hand, the effect of the abnormalities on the length of the current range seemed to be quite significant in Fig. 4. It is easy to see that the length of current range is not much affected by electrode force, welding time and electrode size, whereas fit-up, axial alignment and angular alignment have significant current differences as far as more than 4kA in the case of fit-up. In general, if there is any abnormal condition during spot welding process, the length of the suitable current range decreases and will result in poor weld quality.

4.2 Pareto Analysis of Variation

After the analysis of the welding current, the data was analyzed with the objective function defined in Eq. (1) in order to understand the effect of each factor on the weld quality. As the first step of the data analysis, the data for each experiment was summarized by average button diameter and the S/N ratio η. The mean diameters for the 18 experimental runs ranged from 4.32mm to 9.35mm and the variance from 0.05mm to 1.44mm. For computational simplicity and easy understanding, 16 was subtracted from S/N ratio η, which showed the larger-the-better characteristic of button diameter.

In order to estimate the effect of each factor and find significant factors affecting the S/N ratio, an analysis of variance (ANOVA) was conducted. A simpliflied ANOVA method called the Pareto ANOVA[24)] was used to analyze the results of parameter design. It does not require an ANOVA table and, therefore, dose not use F-tests. Table 3 shows the analysis results of the Pareto ANOVA during aluminum spot welding. Because the experimental matrix has mixed levels depending upon the factors, the sum of squares of the factors of two and three levels should be considered with a degree of freedom φ. In Table 3, in which the first three factors are three-level factors and the last three are two-level factors, the sum of squares of the two-level factors S are calculated by $(A_0-A_1)^2$

Table 3 Pareto ANOVA table for the welding parameters with each level

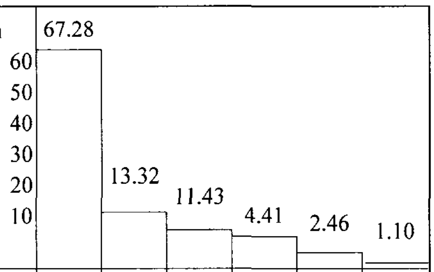
Factors		*F*	*T*	*S*	*Fit*	*Ax*	*Ang*	Total
Sum at factor level (dB)	0	-5.36	-1.55	-0.78	14.40	6.93	4.39	1.91
	1	-0.11	2.33	4.05	-12.48	-5.02	-2.48	
	2	7.37	1.12	-1.36				
Sum of squares of differences S		245.61	23.61	52.82	722.53	142.98	47.31	1234.86
Degree of freedom φ		2	2	2	1	1	1	
S/φ		122.80	11.81	26.41	722.53	142.98	47.31	1073.84
Contribution ratio (%)		11.43	1.10	2.46	67.28	13.32	4.41	100

whereas those of the three-level factors by $(B_0-B_1)^2+(B_1-B_2)^2+(B_2-B_0)^2$. A and B are used to denote two- and three-level factors, respectively. The subscript 0, 1 and 2 are used to denote the levels of each factor. The adjusted sum of squares S/φ by using the degree of freedom φ and their contribution to the total variance are also presented. In the Pareto diagrams shown in Table 4, it is easily seen that the fit-up condition is the most significant factor in terms of the S/N ratio. It contributed 67.28% of total variance. It reduces not only the suitable current range but also the button diameter. Therefore, among others, it is the most significant abnormality during aluminum resistance spot welding. Axial misalignment also played an important role in weld quality. It contributed 13.32% to the total variance. Angular misalignment also influenced the weld quality. However, together with electrode size and welding time, it contributed less than 10% of the total variance, as shown on the Pareto diagram, and therefore, considered as a non-significant factor.

As for the welding control factors, electrode force was shown as the most significant factor among them. Moreover, even though a higher welding current was needed, it was recommended to use the largest value among the three levels to obtain large button size and small variation. Welding time and electrode size contributed less than 10% of the total variance, were non-significant factors.

Among the significant factors, the optimum level of the electrode force is Level 2, denoted by F_2, with no abnormal conditions such as Fit_0 and Ax_0. When the other factors are chosen as non-significant factors, the final optimal condition is $F_2Fit_0Ax_0$. At this condition, the estimated S/N ratio is 19.39dB, which shows the 3.28dB increase in S/N ratio from the average value to optimum condition.

Table 4 Pareto diagram for the welding parameters

Pareto diagram						
Factors	*Fit*	*Ax*	*F*	*Ang*	*S*	*T*
Cumulative contribution ratio (%)	67.28	80.60	92.04	96.44	98.90	100

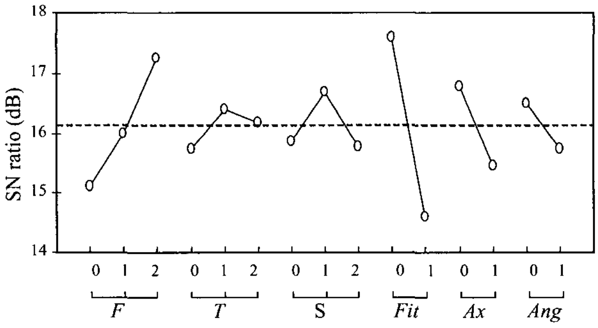


Fig. 5 Effects of factors and levels on the S/N ratio of button diameter

5. Conclusions

The effects of welding process parameters and abnormal process conditions on the welding current and button diameter were studied using the two stage, sliding level experiment for resistance spot welding of aluminum alloys. The following conclusions can be drawn from the study:

1) The effects of the factors and their levels on acceptable welding current were discussed in terms of the average main effect. In case of the center of the current range, welding force, time, and electrode size were more significant than the abnormal conditions. However, the effects of the abnormalities, such as poor fit-up, axial misalignment, and angular misalign- ment, on the length of the current range were more significant, showing that if there was any abnormal condition in the spot welding process, the length of the suitable current range decreased and would result in poor weld quality.

2) The Pareto analysis of variance was introduced to find significant factors based on the S/N ratio. Mixed level factors were analyzed with the degrees of freedom of the sum of squares. Among the six factors, fit-up condition was the most significant factor contributing 67.28% of the total variance. It was followed by axial misalignment and electrode force, which contributed 13.32% and 11.43% of the total variance, respectively.

3) Excluding the three non-significant factors, which cumulatively contributed less than 10% of the total variance, the optimal S/N ratio could be obtained at the condition of $F_2Fit_0Ax_0$. From the observations, the S/N ratio could be improved by more than 3dB from its grand average.

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