Investigation on Joining Divergent Geometric Profiles using 20KHz Ultrasonic Sound Waves

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Abstract. In the modern scenario of solid-state welding, Ultrasonic metal welding (USMW) has emerged as one of the successful and efficient method of joining metal specimens with dissimilar profiles (cylindrical – flat). As the methods and procedures involved in repairing flaws are not cost effective, many industries require a systematic approach to forecast weld strength before manufacturing the weld joints. This study is carried out to develop a mathematical model for predicting the weld strength using response surface method. Experiments are conducted based on response surface design matrix comprising of five factors such as the weld time, amplitude, weld pressure, sheet thickness and wire diameter and the weld strength of each experimental trials evaluated in terms of T-peel load are measured. Also, a feed forward back propagation artificial neural network with supervised training has been developed to predict the T-peel load and it tends to be consistent throughout the entire range values.

Keywords: Ultrasonic metal welding, Response surface methodology, Artificial neural network.

1 Introduction

Ultrasonic Metal Welding (USMW) is a solid-state welding procedure in which identical or dissimilar metallic work parts are bonded together using high-frequency vibrations in plane with the interface while under moderate pressure. When compared to the melting point of the metal, the temperature created between the pieces in USMW is quite low. The procedure can be done in a matter of seconds without affecting the material's qualities.

The quality of weld mainly depends upon the strength and the load it can withstand when applied in practical conditions. Weld failure occurs suddenly, resulting in lost production, part rejection, and customer dissatisfaction. T-peel load generally influences the quality of weld, whereas the T-peel load is influenced by factors such as pressure, amplitude, weld time, sheet thickness and wire diameter. Weld time helps in determining bonding between sheet and wire, better bonding leads to increased T-peel load, and pressure also helps in maintaining a constant contact pressure between sheet and wire, and amplitude which determines the frequency of vibration of horn which helps in penetrating wire into the sheet.

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Chen Y C et al. (2012) discovered that ultrasonic metal welding utilizes significantly less energy than traditional resistance spot welding. Bonding is commonly achieved in ultrasonic metal welding at a low temperature. In ultrasonic metal welding bonding of metal molecules is attained at low temperature (< 300^o C in short weld cycle typically for 0.5 sec). Annoni M et al (2011) evaluated the effects of high frequency shear vibrations, typically 20 kHz, on the removal of oxide and contaminated layers, as well as the production of heat by shear deformation. Softening occurs as the temperature rises and acoustic energy is absorbed, lowering the material's yield strength. As a result, metals come into touch with one another, causing adhesion and inter diffusion at the interface. Hu S I et al (1996) examined that weld quality or bond strength of ultrasonic metal welding specimen is quantified by the T-peel test as used in resistance spot welding. The joining technique avoided frequent concerns related with fusion welding, such as rapid intermediate production, evolution of brittle phases, and distortion in weld portions, according to Neppira E A et al (1965).

In many of the earlier works only the process parameters are concerned, whereas the geometric profiles of the specimens are not considered effectively. In this work the combination of both the process parameters and the geometric profiles are taken into consideration.

The influence of process parameters on T-peel load is analyzed using analysis of variance technique (ANOVA). The mathematical model is developed for the process and the validity of the mathematical model was further trained by ANN.

2 Response Surface Methodology (RSM)

Simultaneous study of multiple variables can be done using the statistical technique of design of experiments, in which equal number of test conditions is allowed for each individual factor. An efficient plan for conducting the experiments can be obtained using the statistical design of experiments to finally yield objective conclusions.

The Response surface methodology (RSM) is commonly employed for modeling - analysis with a final interest of funneling the factors of interest to an objective maximum by following mathematical and statistical techniques. The change in response in different directions is understood according to the design variables. The goal is to proceed quickly and efficiently along a path in order to get a maximum or minimum response that is optimum.

Identifying important process variables, determining their limits, developing the design matrix, conducting experiments according to the design matrix, recording the responses, developing a mathematical model, checking the adequacy of the model developed, and finally analyzing the results are all steps involved in response surface methodology for experimental investigation..

3 Identification of process variables

In order to achieve a larger T-peel load, it is critical to identify the optimal process parameters. By carefully selecting the independently controlled process factors, the desired T-peel load can be attained. Pressure (bar), amplitude (m), weld duration (sec), sheet thickness (mm), and wire diameter (mm) are chosen as factors to conduct out experimental work and construct a mathematical model among independently adjustable variables affecting T-peel load. Table 1 lists the factors that were taken into account.

Table 1 Attribution of levels to factors

Variable Name	Weld Parameters	Levels		
		-1	**0**	**1**
X1	Weld Pressure (bar)	3	4	5
X2	Amplitude (μm)	28	42.5	57
X3	Weld Time (sec)	3	4	5
X4	Sheet Thickness (mm) - Aluminum	0.1	0.2	0.3
X5	Wire Diameter (mm)- Aluminum	0.9	1.2	1.6

The working ranges for all the parameters must be fixed and the design matrix has to be constructed as per Response surface methodology. This is accomplished by running tests in which one of the process variables is changed while the others remain constant.

Figure 1 Ultrasonic Metal Welding Machine

Figure 2 Tensile Testing Machine.

3.1 Experiment design matrix

The tests are carried out for all possible combinations of parameter levels, which are listed in Table 2, where rows correspond to different process variables and columns correspond to variable levels, forming the design matrix. A five factor three level central composite design with 32 experiments was chosen as the design matrix for the experiment.

4 Experimental Details

The experiments are conducted as per the design matrix and they are performed in the order of run order. The experiments are carried out in USMW setup shown in the Figure 1. Figure 2 depicts the experimental setup for determining the T-peel load. For performing the tensile testing operations the aluminum specimens are prepared according to standard shown in Figure 3. The results of the experiments are shown in the Table 2.

The welded specimens are as shown in Figure 4 and the position of holding of the welded specimens is shown in the Figure 5.

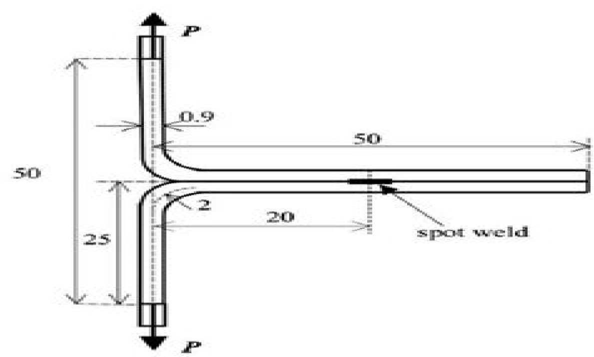

Figure 3 T Peel Specimen

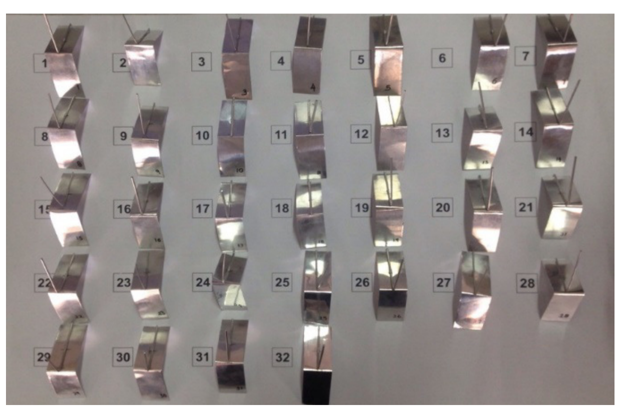

Figure 4 Welded aluminum specimens

Table 2 Comparison of T Peel load values of experimental values, mathematical model and ANN predicted values

Run order	X1	X2	X3	X4	X5	T-peel Load in kgf				
						Experimental Results	Mathematical model Results	Error	ANN Results	Error
1	5	57	3	0.1	1.6	0.023	0.0231	-0.0001	0.028	-0.005
2	3	57	3	0.1	0.9	0.01	0.0104	-0.0004	0.01	0.00
3	3	28	5	0.1	0.9	0.0105	0.0103	0.0002	0.01008	0.00042
4	5	28	3	0.1	0.9	0.0185	0.0187	-0.0002	0.01011	0.00839
5	4	42.5	4	0.2	1.25	0.0535	0.0494	0.0041	0.05105	0.00245
6	4	42.5	4	0.2	1.25	0.047	0.0494	-0.0024	0.05105	-0.00405
7	3	28	3	0.1	1.6	0.014	0.0118	0.0022	0.01288	0.00112
8	4	42.5	4	0.2	0.9	0.023	0.0197	0.0033	0.02476	-0.00176
9	4	28	4	0.2	1.25	0.0475	0.0544	-0.0069	0.04657	0.00093
10	4	42.5	4	0.2	1.6	0.055	0.062	-0.007	0.06719	-0.01219
11	3	57	5	0.1	1.6	0.015	0.0148	0.0002	0.0205	-0.0055
12	5	57	5	0.3	1.6	0.057	0.0574	-0.0004	0.0586	-0.0016
13	3	42.5	4	0.2	1.25	0.042	0.0479	-0.0059	0.04314	-0.00114
14	3	28	3	0.3	0.9	0.0145	0.0132	0.0013	0.0299	-0.0154
15	4	42.5	4	0.2	1.25	0.0535	0.0494	0.0041	0.05105	0.00245
16	4	42.5	5	0.2	1.25	0.0505	0.0496	0.0009	0.05656	-0.00606
17	3	57	5	0.3	0.9	0.0145	0.0152	-0.0007	0.0314	-0.0169
18	3	28	5	0.3	1.6	0.0985	0.0966	0.0019	0.1026	-0.0041
19	3	57	3	0.3	1.6	0.1015	0.1002	0.0013	0.1021	-0.0006
20	4	42.5	4	0.2	1.25	0.0535	0.0494	0.0041	0.05105	0.00245
21	5	28	5	0.1	1.6	0.024	0.0235	0.0005	0.02488	-0.00088
22	4	42.5	4	0.2	1.25	0.05	0.0494	0.0006	0.05105	-0.00105
23	5	57	5	0.1	0.9	0.0145	0.0166	-0.0021	0.01147	0.00303
24	5	28	3	0.3	1.6	0.12	0.1184	0.0016	0.1032	0.0168
25	4	42.5	4	0.1	1.25	0.019	0.0192	-0.0002	0.0113	0.0077
26	4	42.5	3	0.2	1.25	0.0535	0.0581	-0.0046	0.04538	0.00812
27	4	57	4	0.2	1.25	0.0515	0.0483	0.0032	0.05488	-0.00338
28	5	57	3	0.3	0.9	0.0135	0.0145	-0.001	0.0174	-0.0039
29	5	28	5	0.3	0.9	0.0075	0.0079	-0.0004	0.00699	0.00051
30	4	42.5	4	0.3	1.25	0.0525	0.056	-0.0035	0.04492	0.00758
31	5	42.5	4	0.2	1.25	0.051	0.0488	0.0022	0.05792	-0.00692
32	4	42.5	4	0.2	1.25	0.0535	0.0494	0.0041	0.05105	0.00245

Figure 5 T-peel specimen held in Tensile testing machine

5 Development of Mathematical model

Based on the design matrix, experiments are conducted and the results were observed. Using these values an empirical relationship (Equation 1) was found using MINITAB 16.0 Software. The experimental T-peel load for weld joint specimen is presented in Table 2. The second order regression equation for the T-peel load is developed as a function of factors such as weld pressure (bar), amplitude (µm), weld time (sec), sheet thickness (mm) and wire diameter (mm).

6 Predicted T-peel load

The mathematical model for predicting the T-peel load is given below. This equation helps in predicting the T-peel load values.

T-peel load =

$$0.0480078X_1 + 0.0018441X2 + 0.0022117X_3 + 0.395398X_4 + 0.203443X_5 - 0.00101X_1^2 + 0.00001X_2^2 + 0.00449X_3^2 - 1.17629X_4^2 - 0.06949X_5^2 - 0.00028X_1X_2 - 0.00441X_1X_3 - 0.03844X_1X_4 - 0.00170*X_1X_5 - 0.00009X_2X_3 - 0.00213*X_2X_4 - 0.00076X_2X_5 - 0.04406X_3X_4 - 0.00973X_3X_5 + 0.54375X_4X_5 - 0.30120 \quad (1)$$

The inputs are fed in the mathematical equation for predicting the T-peel load. The values that are predicted using Equation 1 is shown in the Table 2.

7 Artificial Neural Network (ANN)

The fundamental purpose of an artificial neural network is to imitate the operation of the human brain or neural system. These are enormous parallel-connecting networks made up of basic computing pieces known as neurons connected by unidirectional interconnected channels known as the connection, which mimics the human brain.

The feed forward back propagation method is the most often utilised approach in this study. This kind has three layers: an input layer, a concealed layer, and an output layer. The input layer is where the problems' inputs are received. The relationship between the input layers is determined and represented in weights in the hidden layer. The problem's output is emitted in the output layer. In the prediction of results, the training of an ANN is critical. The accuracy of the model is primarily determined by the ANN's training. Table 3 shows the network properties of the ANN employed in this study. The network model for T-peel load prediction is often trained in MATLAB..

Table 3 ANN network properties

Type of network	Feed Forward back propagation
Data input	Training input
Data target	Training output
Function for training	TRAINLM
Function for adaptive learning	LEARNGDM
Function for performance	MSE
No. of layers	2
No. of neurons	2
No. of Epochs	100

The predicted values of T-peel load using the ANN algorithm are shown in the Table 2.

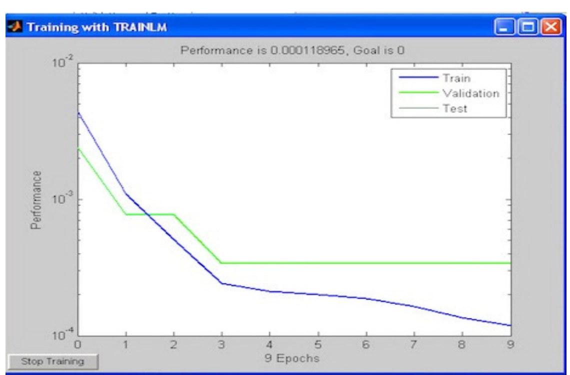

Figure 6 ANN Performance chart

The error in the performance of the ANN process is found to be 0.000118965 as shown in Figure 6.

8 ANOVA plot

ANOVA plot is employed to identify the percentage contribution of each factor. The percentage effect of the various control factors on the T-peel load is shown in Figure 7. The Figure 7 shows that the T-peel load depends on the wire diameter by 50%, sheet by 40%, weld pressure by 6%, weld time by 2% and amplitude by 1.49%.

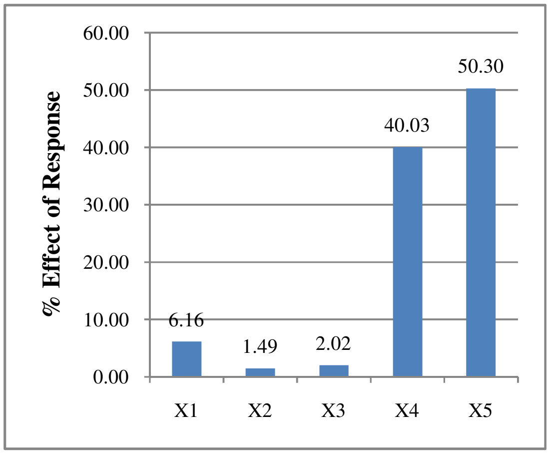

Figure 7 ANOVA Plot

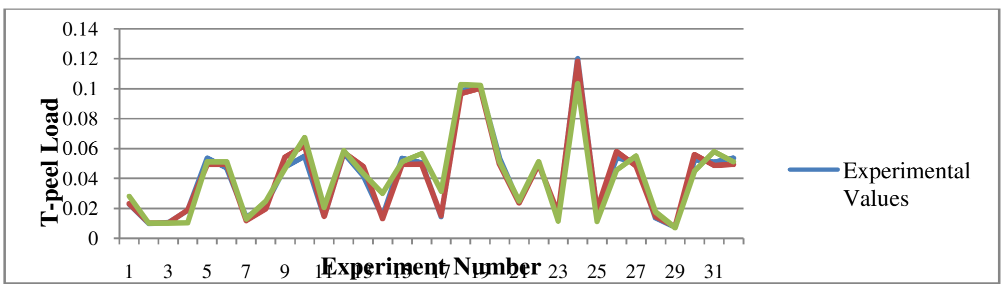

Figure 8 Comparison of experimental values, predicted values (Mathematical model and ANN).

From the graph shown in Figure 8 the mathematical model results said to be more promising than the ANN results and the maximum error percentage is found to be 0.5% for the mathematical model whereas in ANN it is found to be 1.5%. The correlation between the experimental and predicted results was found to be 98.8% and this clearly explains there is a better correlation between them.

9 Conclusions

Prediction of the weld strength plays a dominant role in many of the industrial process applications. A mathematical model and artificial neural network are being developed to forecast weld strength in terms of T-peel load. Experiments are conducted based on the central composite response surface design matrix. The parameters considered are the weld pressure, amplitude, weld time, sheet thickness and wire diameter. Based on the ANOVA plot it is conclusive that the geometric profiles of the welded specimens play a crucial role in establishing the weld strength apart from process parameters. This study brings out the influence of geometric profiles on the weld strength effectively. The mathematical model is found to predict the weld strength more effectively with 0.3% error than the artificial neural network with 1.56% error.

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