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ORIGINAL ARTICLE

Optimization of ultrasonic welding parameters for copper to copper joints using design of experiments

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Abstract Ultrasonic welding is a solid-state joining process that produces joints by the application of high-frequency vibratory energy in the work pieces held together under pressure without melting. In electronic and automotive applications, copper wires are connected to the equipment (alternator/rectifier) by a solid state joining process. For such an application ultrasonic metal welding is useful. The dominant problem faced by industry dealing with ultrasonic metal welding process is the poor weld quality and strength of the weld due to improper selection of weld parameters. In this work welding parameters like welding pressure, weld time and amplitude of the vibration are considered while producing ultrasonically welded joints of copper whose thickness is 0.2 mm. If other modes of joining are used, this size being very small, it may damage the weld. A suitable experimental design based on Taguchi's robust design methodology was designed and executed for conducting trials. The analysis of variance (ANOVA) and signal to noise ratio analyses are employed to investigate the influence of different welding parameters on the weld strength and to obtain the optimum parameters.

Keywords Ultrasonic welding · Taguchi's robust design · ANOVA · Signal to noise ratio · Weld strength

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1 Introduction

Ultrasonic metal welding (USMW) is a solid-state welding process in which similar or dissimilar metallic work pieces are joined by the application of high frequency vibrations which are in plane with the interface under moderate pressure as shown in Fig. 1.The high frequency relative motion between the parts leads to solid progressive shearing and localized joining of the parts. In USMW the temperature developed between the parts are very less compared to the melting point of the metal. The process can be completed in a few seconds without causing changes in the properties of work pieces. Ultrasonic metal welding is quite different from the ultrasonic plastic welding. The ultrasonic vibrations in metal welding are parallel to the surfaces to be joined whereas in plastic welding vibrations are perpendicular to the surfaces.

This work is taken up as there are many variables and there is enough scope to study ultrasonic metal welding. Using Taguchi's method a set of experiments is designed at different levels of weld parameters to obtain weld strength. Analysis of variance and signal-to-noise ratio of robust design were employed to investigate the influence of different welding conditions on weld strength.

The field of ultrasonic metal welding is one of the discussed topics in the manufacturing of accessories used in automotive and electrical applications and several researchers have reported their findings on the mechanism of joint formation, temperature distribution at the interface and bonding strength, etc,. Some of the important observations are presented below.

Junhui LI et al [1] explains the section of the transducer, vibration transmission and power of the equipment. Ultrasonic vibration transmission is a very critical and

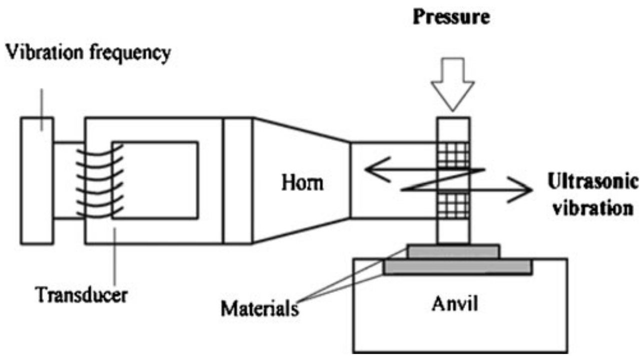


Fig. 1 Basic principle of USMW

complex problem in bonding equipment. Ultrasonic vibration displacement, velocity and energy density increase with decreasing section of the transducer. Locus in ultrasonic longitudinal-complex transverse vibration system can be obtained by controlling ultrasonic frequencies, vibration displacement, and phase. Coupling characteristics will improve microstructure characteristics, and enhance mechanical and electronic performance.

Tarng et al [2] presented an application of fuzzy logic using Taguchi method for the optimization of submerged arc welding process with multiple performance characteristics. The performance characteristics such as deposition rate and dilution were simultaneously considered and improved through this approach instead of using engineering judgment. A novel and efficient approach for quality optimization of manufacturing systems with a consideration of multiple performance characteristics has been proposed in this study.

Acarer et al [3] explains the effect of mechanical properties on the bonding quality. Tensile, shear and bending tests showed that heat treated specimens have more strength than that of unheated-treated ones. According to tensile shear test results, straight and wavy interfaces had similar strength. Also, bending zone has shown some cracks after the bending test of unheated specimens.

The work carried out by Saurav et al [4] on optimization of bead geometry in submerged arc bead-on-plate welding uses Taguchi method. Taguchi's L25 orthogonal array (OA) design and the concept of signal-to-noise ratio to derive objective functions to be optimized within experimental domain. The objective functions have been selected in relation to parameters of bead geometry viz. bead width, bead reinforcement, depth of penetration and depth of HAZ. The Taguchi approach followed by Grey relational analysis has been applied to solve this multi-response optimization problem. The significance of the factors on overall output feature of the weldment has also been evaluated quantitatively by analysis of variance method (ANOVA).

Flood [5] discussed methods to weld copper to aluminum using USW and describes the process and parameters that influence the weld strength. This work also listed the number of copper to aluminum welding applications in electrical, electronics and automobile industry.

Jeng and Horng [6] has investigated the effects of applied load, surface roughness, welding power and welding time on bonding strength of ultrasonically welded joints. The experiments revealed that, a decrease in load or ultrasonic power produces a wide weldable range. It was found that the contact temperature plays an important role in bonding strength in the initial phase of welding and surface roughness is the dominant factor in the final stages. The maximum bonding strength occurs in the initial period for different loads and surface roughness values.

Wen and Iwamura [7] have proposed α–cost minimization model under Hurwicz criterion. This model is dealing with customer demands in real world. To solve the model effectively, a hybrid intelligent algorithm is used in this paper. Numerical examples are presented to illustrate the effectiveness of proposed algorithm.

Hsiao et al [8] developed a robustness design of Fuzzy control via neural network (NN) based approach to overcome the influence of modeling error. In this approach, first neural network model is employed to approximate the sub system and then the dynamics of each NN model is converted into Linear Differential Inclusion (LDI).Based on delay-dependent stability criterion a set of model based fuzzy controllers are synthesized to stabilize the non-linear multiple time delay large scale system.

Tarng and Yang [9] described an application of the Taguchi method for the optimization of the weld bead geometry in the gas tungsten arc welding process. It has been shown that the Taguchi method provides a systematic and efficient methodology for searching the welding process parameters with optimal weld bead geometry.

Fig. 2 Ultrasonic metal welding setup

Table 1 Chemical compositions of copper specimen

Sample reference	Cu	Pb	Sn	Zn	Fe
Copper Specimen	99.44%	0.032%	0.029%	0.39%	0.10%

Through ANOVA, it is seen that welding speed, welding current and polarity ratio are the important welding process parameters for the determination of weld bead geometry. Also, the confirmation experiments were conducted to verify the optimal welding process parameters.

Numerous researchers have measured the temperature developed at the weld interface during USMW. In many cases, the measured temperatures were 30 to 80 percent of the melting point of the metals. Also, from the literature review it was clearly observed that weld pressure, weld time and amplitude are critical parameters in deciding the weld strength and quality of the weld. But, Taguchi's method for optimization of weld parameters in ultrasonic metal welding seems to be not reported. Therefore a systematic study on ultrasonic welding of copper to copper and optimization of the process parameters using Taguchi techniques is taken up in this work. Fuzzy logic and neural networks approach can be applied in the optimization studies of ultrasonic welding and its parameters. However, that is not attempted in the present study.

The predominant problems faced by industries with respect to ultrasonic metal welding process are the poor weld quality and strength of the weld. Selection of parameters which have significant influence on the strength of the weld is very important as they very much affect the quality and the strength of the bond formation. The objective of this study is to conduct experiments using Taguchi's design of experiments methodology to find out the optimum levels of parameters and their interactions that will yield maximum weld strength in the case of Cu –Cu welding.

2 Taguchi based experiments

Though Taguchi's technique of experimental design is well known, a few important steps are presented here while designing experiments. Taguchi designed certain standard orthogonal arrays using which simultaneous and independent evaluation of two or more parameters for their ability to affect the variability of a particular process characteristic can be done using minimum number of tests.

There are three categories of Process characteristics.

1. Lower The Better
2. Nominal The Better
3. Higher The Better

In this experiment, the objective is to maximize the weld strength and hence it is Higher the Better type characteristic. Regardless of the performance characteristics, greater signal to noise ratio corresponds to better performance with minimum variation. Therefore, the optimal level of the process parameters is the combination of individual parameters with levels having the highest signal to noise ratio.

2.1 Experimental setup

Welding was carried out using a conventional ultrasonic metal welding machine (2500 W, 20 kHz) for different ranges of weld parameters which are shown in Fig. 2 with the data acquisition system. Horn made of titanium alloy was used for this study and anvil is made of steel with serrations at the top surface. The horn area which comes in contact has got serrations similar to the top surface of the anvil for preventing the work piece from sliding during welding. The specimen (0.2 mm copper sheet) was prepared according to ASTM international codes [10] for testing of strength of the joint by tensile loading. The chemical composition of the work material (copper sheet) is shown in Table 1. Before the process is carried out samples were cleaned with acetone to remove the surface impurity as it may affect the bond strength. Figure 3 shows the standard size of specimen from ASTM standard (D 1002 – 01) and Fig. 4 shows the actual welded samples used for joining copper to copper. A universal testing machine was used to determine the weld strengths. During the tensile testing, ductile fracture is observed at weld interface for most of the welded samples and some of the fractured samples are shown in Fig. 5.

2.2 Identification of control and noise factors

Taguchi's technique uses two factors – control and noise factors to identify the optimal process settings that

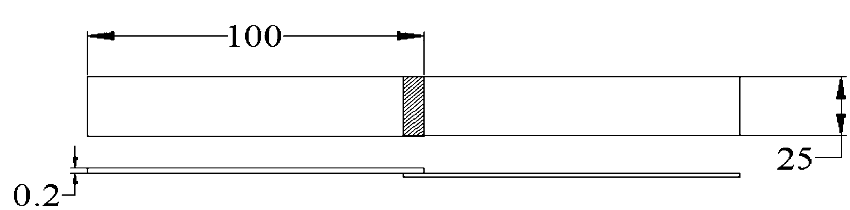


Fig. 3 Standard specimen

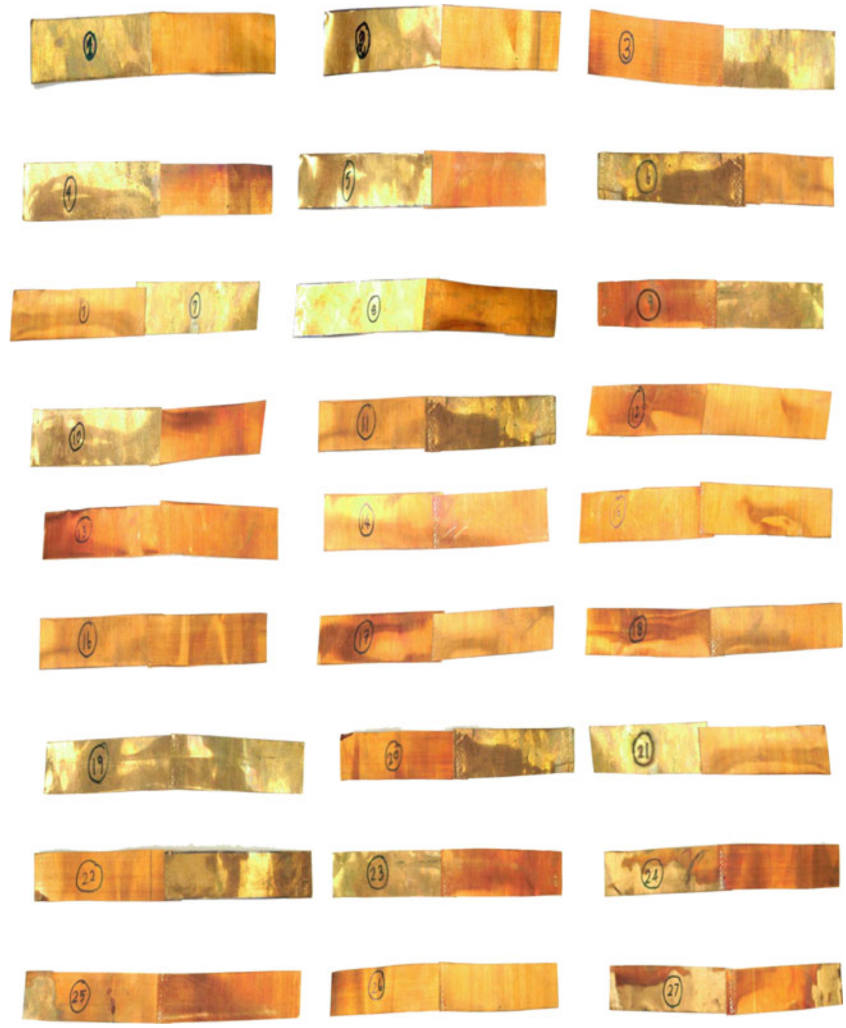


Fig. 4 Welded specimen (Copper)

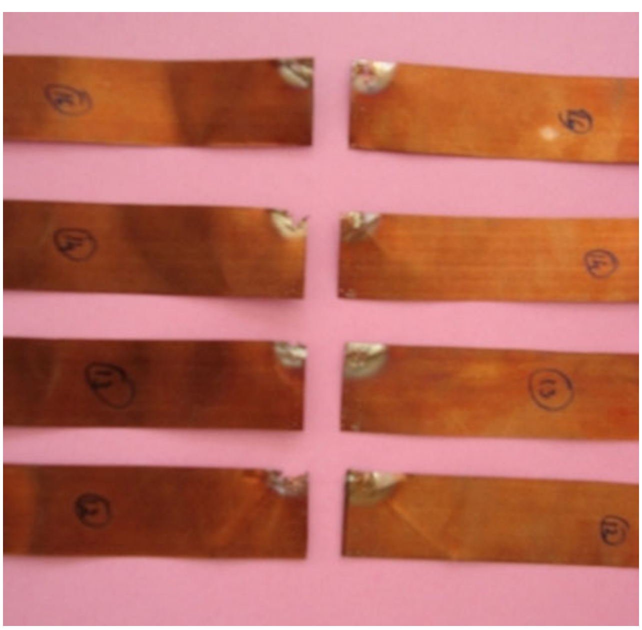


Fig. 5 Tested specimen (Copper)

are minimally sensitive to noise. Control factors are those that can be controlled during the manufacturing process. Noise factors are often uncontrolled variables in a process.

In the present work, welding pressure, welding time and amplitude of the horn were considered as control factors and varied at three levels as shown in Table 2. The three interactions involving the control factors, i.e. interaction between welding pressure and welding time, interaction between welding time and frequency of the horn and interaction between welding pressure and amplitude of the horn are considered. Considering these control factors and their interactions, L27 orthogonal array was found to be appropriate. Also, in the present work no noise factors are considered. L27 orthogonal array shown in Table 3 contains results of 27 trials of various combinations of factors with two repetitions per trial. Signal-to-noise ratio for every combination of weld parameters was calculated and shown in Table 3.

Table 2 The factors and levels

S. No	Factor	Designation	Level 1	Level 2	Level 3
1	Weld pressure(bar)	A	2.0	2.5	3.0
2	Weld time(sec)	B	2.0	2.25	2.5
3	Amplitude(μm)	C	40	45	50

3 Analysis of variance (ANOVA)

This method was developed by Sir Ronald Fisher as a way to interpret the results from actual experiments. ANOVA is a mathematical technique which breaks total variation down into accountable sources [11]. Some of the components in ANOVA are discussed below.

3.1 Sum of squares

The magnitude of each error value can be squared to provide a measurement of total variation present. This is known as “Sum of Squares”.

The basic ANOVA is that the total sum of squares is equal to the sum of sum of the squares due to known components as shown in Eq. 1.

$$SS_T = SS_m + SS_e \tag{1}$$

where,

SS_T Total sum of squares.
SS_m sum of squares due to mean.
SS_e sum of squares due to error.

Table 3 Experimental results

S.No	Pressure (bar)	Time (sec)	Amplitude (μm)	Trial 1	Trial 2	Avg. Strength (10^6N/m^2)	Signal-to-noise ratio
1	2	2	40	0.6	0.84	0.72	2.734
2	2	2	45	0.85	0.77	0.81	1.820
3	2	2	50	0.97	1.4	1.185	-1.615
4	2	2.25	40	0.92	1.26	1.09	-0.853
5	2	2.25	45	1.34	1.21	1.275	-2.121
6	2	2.25	50	1.41	1.42	1.415	-3.015
7	2	2.5	40	1.25	1.3	1.275	-2.112
8	2	2.5	45	1.14	1.35	1.245	-1.934
9	2	2.5	50	1.57	1.63	1.6	-4.084
10	2.5	2	40	0.62	0.88	0.75	2.370
11	2.5	2	45	0.75	0.8	0.775	2.209
12	2.5	2	50	0.9	0.89	0.895	0.963
13	2.5	2.25	40	0.92	1.3	1.11	-1.032
14	2.5	2.25	45	1.2	1.3	1.25	-1.945
15	2.5	2.25	50	1.51	1.41	1.46	-3.292
16	2.5	2.5	40	0.63	0.61	0.62	4.151
17	2.5	2.5	45	1.02	0.9	0.96	0.338
18	2.5	2.5	50	0.85	0.95	0.9	0.902
19	3	2	40	1.25	0.72	0.985	-0.172
20	3	2	45	0.9	1.06	0.98	0.147
21	3	2	50	1.03	0.7	0.865	1.104
22	3	2.25	40	1.23	1.04	1.135	-1.130
23	3	2.25	45	1.13	0.97	1.05	-0.449
24	3	2.25	50	0.98	0.98	0.98	0.175
25	3	2.5	40	1.25	1.15	1.2	-1.591
26	3	2.5	45	1.3	1.1	1.2	-1.614
27	3	2.5	50	0.87	0.93	0.9	0.910

Table 4 Average values of strength at various levels of factors

Factors	Level 1	Level 2	Level 3
Pressure(bar)	1.179	0.969	1.033
Time(sec)	0.885	1.196	1.102
Amplitude(μm)	0.987	1.060	1.133

3.2 Variance due to error

Error variance, usually termed just variance, is equal to the sum of squares of error divided by the degree of freedom of error. Error variance is a measure of the variation due to all the uncontrolled parameters, including measurement error involved in a particular experiment.

3.3 F -test for comparison

The F-test is simply a ratio of sample variances as shown in Eq. 2.

$$F = \frac{{S_{y1}}^2}{{S_{y2}}^2} \tag{2}$$

When this ratio becomes large enough, the two sample variances are accepted as being unequal at some confidence level. To determine whether an F ratio of two sample variances is statistically large enough, three pieces of information are considered. These are the confidence level, degree of freedom associated with the sample variance in the numerator and degree of freedom associated with the sample variance in the denominator. F-test values are found from F-test table [11].

3.4 Percent contribution

The portion of the total variation observed in an experiment attributed to each significant factor and/or interaction is reflected in the percent contribution. The percent contribution is a function of sum of square of significant factor. The percent contribution indicates the relative power of a factor and/or interactions to reduce variation.

3.5 Signal-to-noise ratio

In Taguchi method, the term "signal" represents the desirable value for the output characteristics and the "noise" represents the undesirable value for the output characteristics. The objective of the signal-to-noise ratio is to develop processes that are insensitive to noise. Process parameter setting with highest signal-to-noise ratio always yields the optimum quality with minimum variance. In general, signal-to-noise ratio signifies the ratio of mean to the standard deviation.

The signal-to-noise ratio is defined as given by Eq. 3.

$$S/N = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{3}$$

where,

n number of repetitions in a trial

y_i weld strength for ith trial.

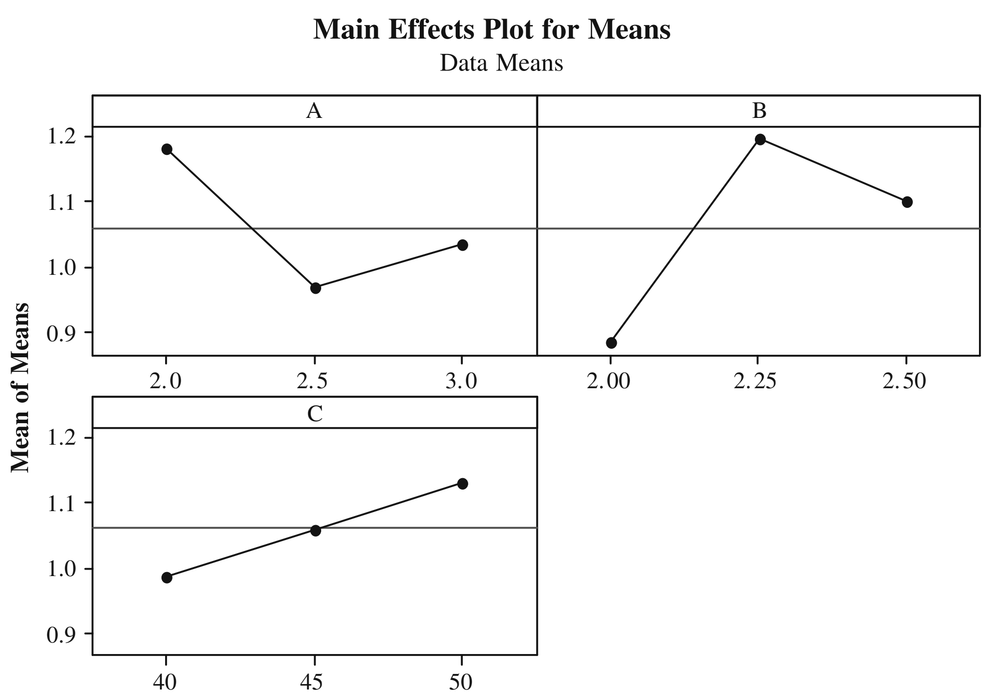


Fig. 6 Plot of main effects for means at various levels of factors

Table 5 ANOVA response

Factor SOURCE	DF	SS	MS	F cal $_{CALU}$	F tab $_{TABLE}$	Inference	% contribution
A	2	0.55356	0.27678	36.7	4.46	Significant	20
B	2	0.78883	0.39441	52.2	4.46	Significant	30
C	2	0.26036	0.13018	17.2	4.46	Significant	9
A×B	4	0.62808	0.15702	20.8	3.84	Significant	23
A×C	4	0.28548	0.07137	9.46	3.84	significant	10
B×C	4	0.02808	0.00702	0.93	3.84	Insignificant	-----
Error	8	0.06034	0.007540				8
Total	26	2.60474					100

Table 6 gives the values of S/N ratio for various factor levels.

3.6 Estimating the mean

Once an experiment is conducted and the optimum treatment condition within the experiment is determined, the most direct way to estimate the mean for that treatment condition is to average all the results for the trials which are set at those particular levels.

The estimated mean is obtained using the Eq. 4

$$\mu = \mathrm{T} + (\mathrm{A}_2 - \mathrm{T}) + (\mathrm{B}_1 - \mathrm{T}) + (\mathrm{C}_2 - \mathrm{T}) \quad (4)$$

where, T is the overall grand mean of the experimental results and has the value of 1.060 (10^6N/m^2). The mean for a selected trial condition for parameters at (A_2, B_1, and C2) is 0.796.

3.6.1 Confidence interval around the estimated mean

The estimate of the mean obtained is only a point estimate based on the average results of the experiment. This means there is a 50% chance of actual mean being greater than estimated mean and another 50% chance that the actual mean is less than the estimated mean. Thus, a confidence interval is to be established within which the actual mean lies at some stated level of confidence. There are three different types of confidence intervals proposed by Taguchi depending on the purpose of the estimate. For the present work, the formula for calculating the confidence interval around the estimated mean in the confirmation experiment is given in Eq. 5:

$$\mathrm{CI} = [\mathrm{F}(\alpha, 1, \mathrm{v_e})\mathrm{V_e}[1/\eta_{\mathrm{eff}} + 1/\mathrm{r}]]^{1/2} \quad (5)$$

where, $F(\alpha, 1, v_e)$ is the value of 'F' from F-tables for confidence level of (1-α), α is the level of risk, V_e is the error variance, v_e is the degrees of freedom for the error, η_{eff} is the effective number of replications and r is the number of trials.

The CI is calculated as follows:

$$\eta_{\mathrm{eff}} = \frac{\mathrm{N}}{1 + \mathrm{U}_{\text{items in the estimate}}}$$

$$\mathrm{N} = \text{Total number of experiments conducted} = 54$$

$$\mathrm{U}_{\text{items in the estimate}} = 14$$

Substituting in the above formula, we get, η_{eff}=3.6

$$\alpha = 1 - \text{confidence limits}\,(95\%) = 0.05.$$

$$\mathrm{F_{ratio}}(0.05, 1, 8) = 5.32(\text{from F tables})$$

$$\mathrm{CI} = +/-[5.32 \times 0.0075[1/3.6 + 1/5]]^{1/2}$$

$$\mathrm{CI} = +/-0.14$$

The 95% confidence level of the predicted optimum of the weld strength is given by:

$$[\mu - \mathrm{CI}] < \mu < [\mu + \mathrm{CI}],\ 0.656 < 0.796 < 0.936$$

3.7 Confirmation experiments

A successful confirmation experiment is defined as one where the average of the samples falls within the predicted confidence interval for the true mean. When the average of the results from the confirmation experiment falls within the confidence interval, it providence evidence that the significant factors as well as their levels are properly chosen.

Table 6 S/N ratio for various levels of factors

Factors	Level 1	Level 2	Level 3
A	-1.242	0.518	-0.291
B	1.062	-1.518	-0.559
C	0.263	0.394	-0.884

Table 7 Results of the confirmation test

Run	Weld Strength (10^6N/m^2)
1	0.66
2	0.82
3	0.75
4	0.90
5	0.87

If the average of the results of the confirmation experiment does not fall within the confidence interval, then there has been some form of misinterpretation of the significant factors and interactions. Also, the repeatability and reproducibility of the measurement system should be verified.

Five confirmation experiments have been conducted at the optimum settings of the process parameters obtained from the experiment. The results of the confirmation run are given in Table 7. The average of the response was found to be 0.80×10^6N/m^2 which lies within the confidence interval around the true mean. Therefore, the selected factors and their levels as well as their interactions are properly chosen and are significant.

4 Results and discussion

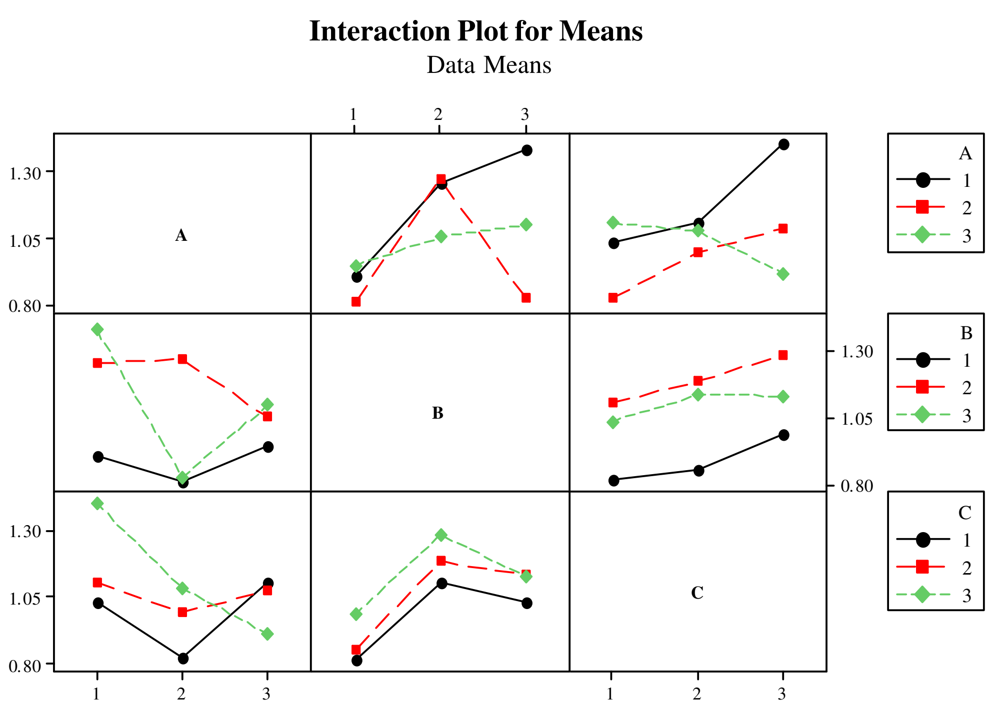
Thus, Taguchi's design of experiments was systematically adopted to optimize the process parameters for joining copper specimens of 0.2 mm thickness. The average strength values for different levels of selected parameters are shown in Tables 4. From the Table 4, it is inferred that when pressure is at level 1(2 bar), the average joint strength values are higher than the strength obtained at pressure level 2 (2.5 bar) and level 3 (3 bar). So among these three levels of pressure, level 1 is the best. This is to be expected since as the pressure increases, horn holds the work pieces without significant amount of rubbing. On similar lines, level 2 (2.25 secs) for weld time and level 3 (50 microns) for amplitude are selected. Figure 6 shows the main effects plot for means obtained from software, which substantiates the conclusions drawn from Table 4.

The results of ANOVA for response are shown in Table 5. From the Table 5, it is found that parameters A, B, C, interactions A×B and A×C are found to have significant effect on the response (weld strength). The percentage contribution of parameters that affect the response is also shown in Table 5.

The average signal-to-noise ratios for weld parameters at various levels are calculated and shown in Table 6. From Table 6, it is concluded that the optimum values of parameters that gives minimum variation in weld strength are A, B and C at 2nd,1st and 2nd levels respectively, i.e. pressure of 2.5 bars, weld time of 2 seconds and amplitude of 45 µm.

It should be kept in mind that the optimal combination of factors and their levels chosen from the analysis of the response (weld strength) represents the set of factors that determine the central tendency of the process (process

Fig. 7 Signal-to-Noise ratio for interactions



average). Similarly, the optimal factor combination obtained from an analysis of the signal to noise ratio values represents the set of factors that help to reduce the variation in the weld strength.

In the present study, the combination of factors that maximizes the weld strength turns out to be Pressure (A) – 2Bar, Weld Time (B) – 2.25 Secs and Amplitude (C) - 50 μm and the combination of factors that minimizes the variation in the weld strength turns to be Pressure (A) – 2.5 Bar, Weld Time (B) – 2.00 Secs and Amplitude (C) - 45 μm (Table 7).

The S/N ratio interaction graph of weld parameters is shown in Fig. 7. It can be found that significant interaction exists between factors A and B and between A and C as the line joining various levels of A and B as well as A and C cross each other. But in the case of B and C, the lines joining the various levels of B and C are almost parallel to each other. Hence, it may be inferred that there is no interaction between factors B and C. In situations where the levels of factors which improve the average and improve uniformity create a conflict, a compromise may have to be reached [11]. Hence in this study, factors that minimize variation and improve uniformity are considered and the combination of optimum process parameter is taken as Pressure (A) – 2.5 Bar, Weld Time (B) – 2.00 Secs and Amplitude (C) - 45 μm.

5 Conclusions

1) The parameters affecting ultrasonic metal welding while joining Cu – Cu were studied. The optimum parameter combinations for maximizing the weld strength, and minimizing weld strength variation were identified.
2) It is observed that weld pressure, weld time and amplitude has significant effect on the response (weld strength). The interactions between weld pressure and weld time and that between weld pressure and weld amplitude have significant effect on weld strength. The interaction between weld time and weld amplitude does not have significant effect on weld strength.
3) The factors weld pressure, weld time and amplitude contribute 20, 30 and 9 percent respectively to the variations observed in the weld strength. The interactions between weld pressure and weld time, weld pressure and weld amplitude have 23 and 10 percent of contribution to the observed variation in weld strength respectively.
4) The parameter settings for achieving the maximum weld strength are pressure of 2 bar, weld time of 2.25 sec and amplitude of the horn at 50 μm. The parameter settings for minimizing the weld strength variation are 2.5 bar pressure, 2.00 Seconds weld time and 45 μm amplitude.

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