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Process Robustness and Effect of Process Parameters on Rapid Joining of Electrical Contacts by Ultrasonic Vibrations

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Abstract

Recent technological developments in producing electrical contacts are evolving at a rapid rate, resulting in reliable functioning of a wide variety of customer durable products. Tensile strength is of a predominant requirement for an electrical contact joint to perform the satisfactory function. In this work, an effort has been taken to propose realistic joining conditions for process improvement in ultrasonic metal welding of joining an electrical contact comprising of metallic wire and a flat metallic sheet made of copper material. Taguchi's method is incorporated for the design of experiments. An experimental investigation is carried out to study the effect of process parameters such as clamping pressure, the amplitude of vibration of the sonotrode and weld time on tensile strength of the electrical contacts. Analysis of variance is performed to establish the significant effect of joining conditions on the response variable. The regression model has been developed using the results obtained from experiments to predict the strength of the joint for varying combinations of process parameters. The results of this study indicate that the clamping pressure is the significant parameter influencing the strength of the joint followed by the amplitude of vibration of the sonotrode and the weld time. The parameters identified for achieving maximum tensile strength of the joint are the clamping pressure of 2 bar, the amplitude of vibration of the sonotrode of 57 μm and the weld time of 2.5 seconds. Confirmation experiments are carried out to validate the optimum combination of process parameters for achieving the maximum strength of the joint.

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Keywords: Ultrasonic metal welding, Taguchi's method, Design of experiments, Sonotrode, Clamping pressure, Amplitude of vibration of the sonotrode, Weld time, Tensile strength, Regression model;

1. Introduction

The need for rapid joining an electrical contact comprising of copper wire and a copper sheet (terminal plate, lead tab, etc.) is continually increasing in the modern world, especially in large scale manufacturing , such as home appliances, automotive components, switch gears, bus bars, fuses, circuit breakers, ignition modules, contacts, starter motors, microelectronic wires, and battery connectors. In the current industrial world, conductive materials such as aluminum and copper are extensively used for making electrical contacts and there exists a great demand for superior quality joints in various electrical contact applications at minimum cost. One of the significant alternative green manufacturing processes evolved over a period for making such electrical contacts is ultrasonic metal welding (USMW). D. Ensminger [1] stated that the ultrasonic metal welding process is one of the most advanced solid-state welding processes in which similar or dissimilar metallic components are joined rapidly in 1 to 3 seconds by the application of high - frequency vibrations (> 20 kHz) and clamping pressure (1 to 6 bar). Satpathy et al [2] reported that the process of USMW is one in which high - frequency ultrasonic vibrations create relative motion between two abrading surfaces that are held together under moderate clamping pressure. The relative motion deforms the local surface asperities, disperse oxides and contaminants at the interface and improve metal-to-metal contact resulting in effective joining between the parts to be welded. The predominant problems confronted by the industries using the ultrasonic metal welding process are the inferior quality of the weld and strength of the joints. The success of the process while joining aluminum and brass sheet specimens essentially depends on process parameters such as vibration amplitude of the sonotrode, clamping pressure and weld time. Long et al [3] estimated that the number of wires bonded per year is more than 15 trillion which corresponds to 1 million bonds per second which indicated the successful industrial adaptability of this process. Panteli et al [4] studied the effect of process parameters, such as weld energy, weld time, clamping pressure and surface preparation on lap shear strength of the joint while joining aluminum and magnesium alloys. The study revealed the following: Increase in clamping pressure result in the formation of more number of micro bonds accelerating the formation of the weld joint, Increase in the

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amplitude of vibration result in the development of intermetallic layer from isolated areas. As the welding action progressed, those islands of weld increase in size and spread across the interface until they coalesced into a continuous layer resulting in the formation of an effective joint. T sujino et al [5] conducted experiments for joining flat copper braid wires on a terminal plate. The results from experiments disclosed that the contribution of clamping pressure was more on influencing the strength of the joint when compared with other process parameters. Tian et al [6] investigated the joining of copper wire with Au/Ni plated copper sheet and reported that the process parameters such as ultrasonic power, clamping force and weld time had a significant effect on tensile strength of the joint. Sarangapani et al [7] presented an investigation on interface morphology and metallurgical behavior of the joint formed between wire and bond pad for varying process conditions such as wire diameter and thermal aging and reported that the copper joints were found to be more reliable at elevated temperatures. T Sujino et al [8] observed rapid formation of void at the interface based on variation in clamping force resulting in poor quality of the joint while joining polyurethane - coated copper wires of 0.36 mm and copper plates of 0.3 mm thickness at optimal setting of process parameters using 40 kHz, 60 kHz and 100 kHz complex ultrasonic welding systems. This study exhibited that the strength of the welded joint was almost the strength of the copper wire. Kodama [9] made a study on the effects of vibration frequency, specimen dimensions, surface roughness and contamination of the specimens along with other process parameters while welding a metallic wire with a flat metallic sheet and proved that the joint strength obtained by USMW process was far superior to the joint strength obtained by conventional soldering and brazing process. Hisashi Imai and Shinichi Matsuoka [10] investigated the joint interface of aluminum alloy joints welded using optimal ultrasonic welding process parameters and indicated that the junction was complete after the removal of the oxide film and organic coating due to the combined action of clamping pressure and amplitude of vibration of the sonotrode. Saadat Ali Rizvi and S P Tewari [22] optimized the welding parameters using Taguchi method and employed statistical methods, such as signal to noise ratio and analysis of variance to determine the effects of various process parameters on the mechanical properties and failure modes of GMA welded joints. Shashi Dwivedi and Satpal Sharma [23] optimized and studied the effects of resistance welding process parameters based on response surface plots for welding SAW 1010 steel sheets.

Many industries and researchers primarily focus on evaluating the strength of the joints before making the joint as the procedures and processes involved in rectifying the defects are not cost - effective. Based on the literature survey, research about study on the effect of process parameters during ultrasonic welding of electrical contacts seems to be not reported. This study is carried out to fill this gap and this study also presents a systematic approach addressing the significant issues pertaining to process parametric design using Taguchi's design of experiments.

2. Details of experiments

2.1. Methodology

Taguchi's method of experimental design provides a simple, efficient and systematic approach for conducting experimental trials [14, 15, 24]. The methodology adopted in this research work is shown in Figure 1.

2.2. Selection of factors and levels

Based on initial experimental trials and literature survey predominant process parameters such as clamping pressure, the amplitude of vibration of the sonotrode and weld time are considered as control factors and these factors are varied at three levels as shown in Table 1 [18-20]. The tensile strength of the welded electrical contact joint is considered as the output quality characteristic response variable.

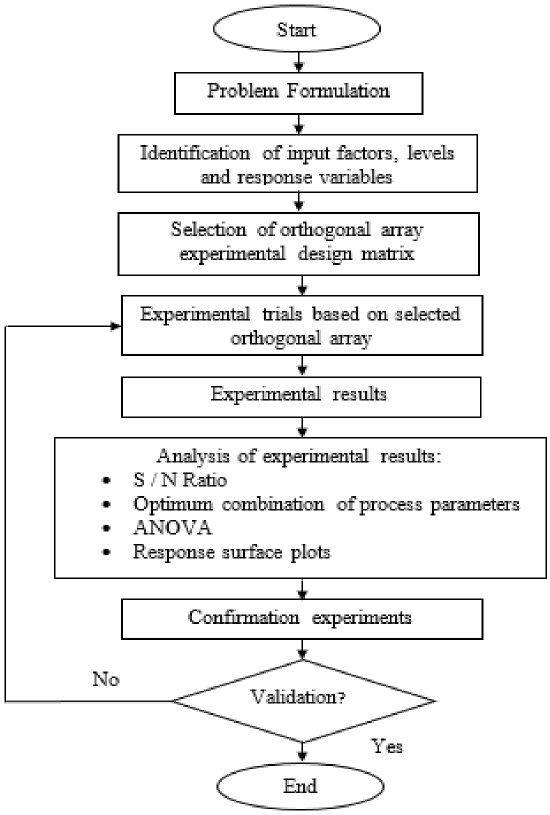

Figure 1: Taguchi Methodology

Table 1: Factors and Levels

Factors	Unit	Level 1	Level 2	Level 3
Clamping pressure (A)	bar	2	3	4
Amplitude of vibration of sonotrode (B)	μm	30	42.5	57
Weld time (C)	sec	2	2.5	3

2.3. Materials and Methods

The experiments are conducted using a conventional ultrasonic metal welding machine (National Indosonic, Bangalore, India) (2500 W, 20 kHz) for different ranges of process parameters. The specimens used in this work are the copper sheet (as received) of 100 mm length, 25 mm width, 0.3 mm thickness and the copper wire (as received) of 1.6 mm diameter and 100 mm length with an overlap length of 6 mm in lap joint configuration [11-13]. The schematic representation of the joint is shown in Figure 2. The specimens are prepared according to ASTM international codes for testing the strength of the joint under tensile loading [16,18]. The specimens are cleaned thoroughly with acetone to get rid of dirt and other impurities before welding.

The experimental trials are carried out based on Taguchi's L27 orthogonal array as shown in Table 2. The order of running the experiments is made random to reduce errors in the experimental results. Each experimental trial is repeated thrice to increase the accuracy of the experimental results. A few welded electrical contact joints thus obtained after experiments are shown in Figure 3. The welded specimens are subjected to tensile testing in a 10 kN tensile testing machine (Hitech, Coimbatore, India). During tensile testing, the wire is gripped in the upper jaw and the sheet is gripped in the lower jaw of the tensile testing machine as shown in Figure 4 to avoid errors in the measurement of the tensile strength of the joint. Minitab 16 statistical software is used for analyzing the experimental results in terms of S/N ratio calculation, ANOVA and development of response surface plots.

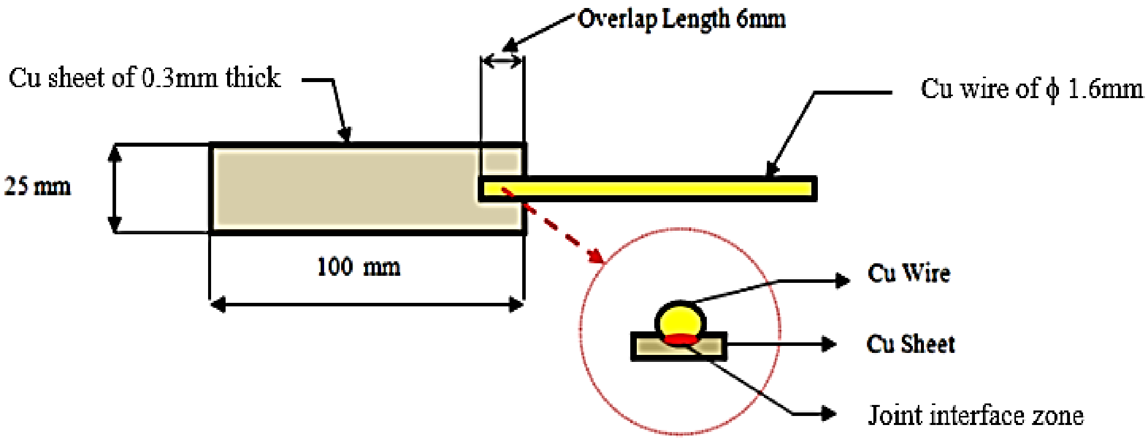

Figure 2: Schematic representation of the joint

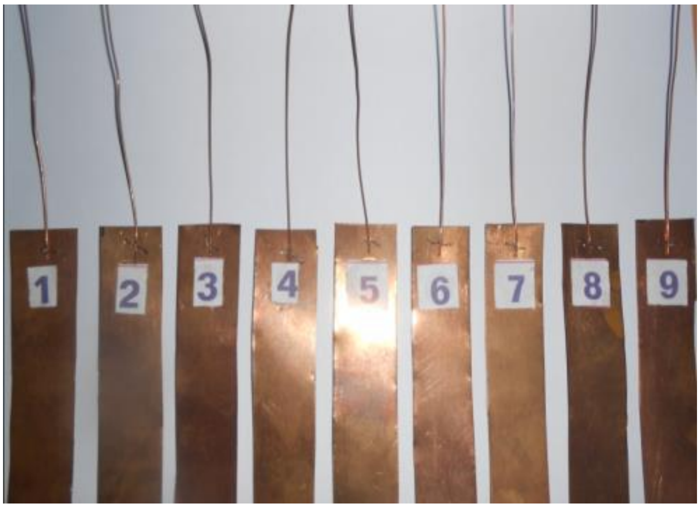

Figure 3: Welded joints

Figure 4: Tensile loading

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Trial No.	Clamping pressure (A) (bar)	Amplitude of vibration of sonotrode (B) (μm)	Weld time (C) (sec)	Tensile strength of the electrical contact joint (N)				S/N ratio
				Trial I	Trial II	Trial III	Average (μ)	
1	2	30	2	224.124	224.301	224.568	224.331	47.0178
2	3	30	2	223.871	223.322	224.759	223.984	47.0043
3	4	30	2	218.545	219.241	222.109	219.965	46.8471
4	2	42.5	2.5	236.282	236.081	236.057	236.140	47.4634
5	3	42.5	2.5	228.534	228.772	228.716	228.674	47.1843
6	4	42.5	2.5	225.231	225.542	226.249	225.674	47.0696
7	2	57	3	229.992	231.016	230.693	230.567	47.2559
8	3	57	3	229.671	229.761	230.241	229.891	47.2304
9	4	57	3	227.061	225.985	227.591	226.879	47.1159
10	2	30	2.5	232.579	232.89	232.421	232.630	47.3333
11	3	30	2.5	224.899	225.864	226.298	225.687	47.0701
12	4	30	2.5	221.842	222.135	223.784	222.587	46.9500
13	2	42.5	3	225.143	225.972	224.929	225.348	47.0571
14	3	42.5	3	223.768	223.109	223.386	223.421	46.9825
15	4	42.5	3	223.190	222.765	224.332	223.429	46.9828
16	2	57	2	229.986	231.433	233.141	231.520	47.2918
17	3	57	2	229.118	228.994	227.817	228.643	47.1832
18	4	57	2	224.189	225.099	223.144	224.144	47.0105
19	2	30	3	222.899	223.282	223.782	223.321	46.9786
20	3	30	3	224.010	223.865	226.195	224.690	47.0317
21	4	30	3	217.231	216.664	216.793	216.896	46.7250
22	2	42.5	2	228.112	226.995	228.023	227.710	47.1476
23	3	42.5	2	226.124	226.953	227.593	226.890	47.1163
24	4	42.5	2	223.548	224.109	223.287	223.648	46.9913
25	2	57	2.5	236.190	236.290	236.09	236.190	47.4652
26	3	57	2.5	231.789	230.980	232.133	231.634	47.2960
27	4	57	2.5	226.892	227.546	228.656	227.698	47.1472

3. Results and Discussions

3.1. Evaluation of signal to noise ratio

In Taguchi's method, the term signal represents the desired value for the output attributes and the noise represents the undesirable value for the output attributes. There are three types of quality characteristics, such as lower–the-better (LB), the nominal –the better (NB) and the higher-the-better (HB). Since the strength

of the joint should be maximum, higher – the – better type of S/N ratio is used in this

study. The S/N ratio for the higher-the-better type is calculated as shown in Equation 1.

$$S/N_{HB} = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \quad (1)$$

where, n= number of repetition in a trial y_i = tensile strength of the joint for ith trial. The S/N ratio is calculated for each of the experimental trials and the results are shown in Table 2. The average values of signal to noise ratio at different levels of selected parameters are shown in Table 3. From Table 3, it is observed that the optimum combination of process parameters resulting in minimum variation of tensile strength of the joint are clamping pressure (A), amplitude of vibration of sonotrode (B) and weld time (C) at 1st, 3rd and 2nd levels respectively i.e. clamping pressure of 2 bar, the amplitude of vibration of sonotrode 57 μm and weld time of 2.5 seconds. From Table 2, it is inferred that the highest signal to noise ratio value (47.4652) corresponds to the above combination of parameters (Trial 25) which ultimately results in maximum tensile strength of the joint of 236.19 N.

3.2. Analysis of Varaince

The Analysis of variance (ANOVA) is used to interpret results from the actual experiments. The objective of ANOVA is to extract the amount of variation caused by each factor relative to the total variation observed in the actual results from experiments. ANOVA also establishes the relative significance of factors in terms of their percentage contribution to the response variable. ANOVA is performed for a confidence level of 95% and the results are shown in Table 4. The F_{Cal} value for each process parameter is calculated and compared with F_{Tab} values obtained from the F-test table [14]. A factor to be statistically significant, the calculated F_{Cal} value for each process parameter must be greater than F_{Tab} value as shown in Table 4. It reveals that the factors clamping pressure, the amplitude of vibration of sonotrode, weld time and interaction between clamping pressure and weld time are statistically significant on the tensile strength of the joint. The contributions are in the following order: Clamping pressure (34.45%), the amplitude of vibration of sonotrode (30.12%), weld time (22.03%) and interaction between clamping pressure and weld time (6.87%). The signal to noise ratio graph for interactions of process parameters is shown in Figure 5. It is seen from this figure that a significant interaction exists between clamping pressure and weld time. The average and standard deviation of experimental results are shown in Figure 6.

Table 3. Average S/N ratio for various levels of factors (Tensile strength of the joint)

Level	Clamping pressure (bar)	Amplitude of vibration of the sonotrode (μm)	Weld time (sec)
1	**47.22**	47.00	47.07
2	47.12	47.11	**47.22**
3	46.98	**47.22**	47.04
Delta	0.24	0.23	0.18
Rank	1	2	3

Table 4: ANOVA for tensile strength of the joint

Factor	DF	SS	MS	F_{Cal}	F_{Tab}^{*}	Inference	% Contribution
A	2	0.264160	0.132080	45.54	4.46	Significant	34.45
B	2	0.230830	0.115415	39.80	4.46	Significant	30.12
C	2	0.168885	0.084442	29.12	4.46	Significant	22.03
A X B	4	0.009996	0.002499	0.86	3.84	Insignificant	----
A X C	4	0.052663	0.013166	4.54	3.84	Significant	6.87
B X C	4	0.016856	0.004214	1.45	3.84	Insignificant	----
Error	8	0.023198	0.002900				6.53
Total	26	0.766587					100

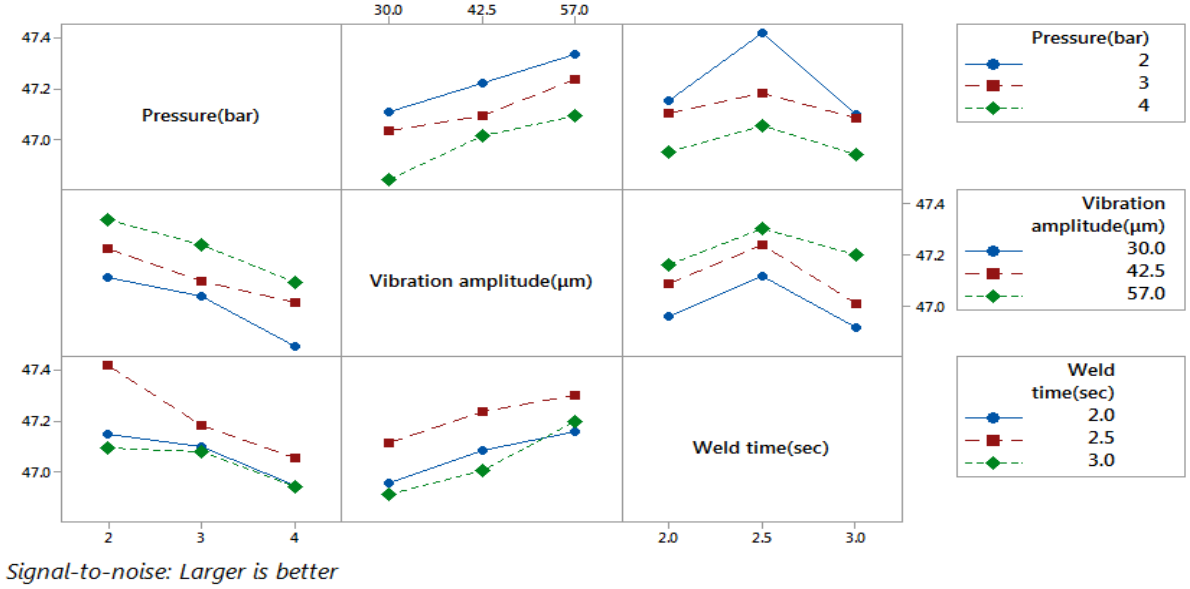

Figure 5: S/N ratio for interactions at various levels of factors

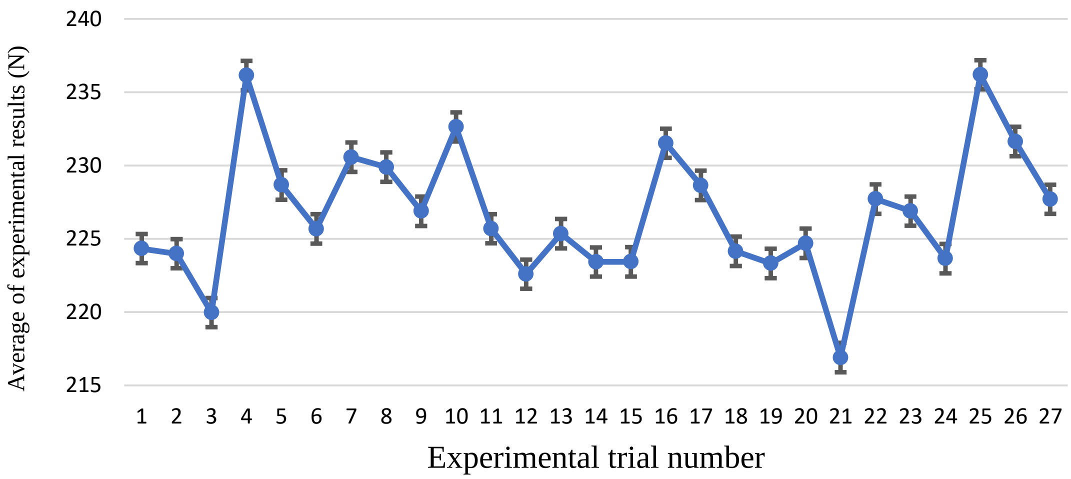

Figure 6: Average and standard deviaition of experimental results

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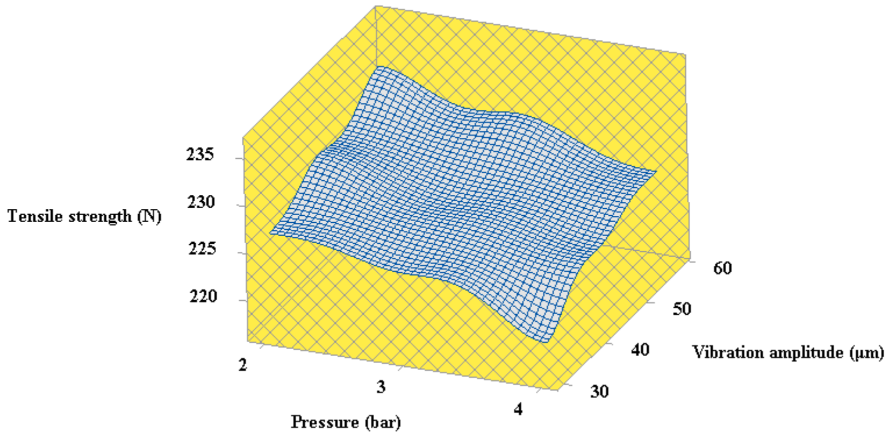
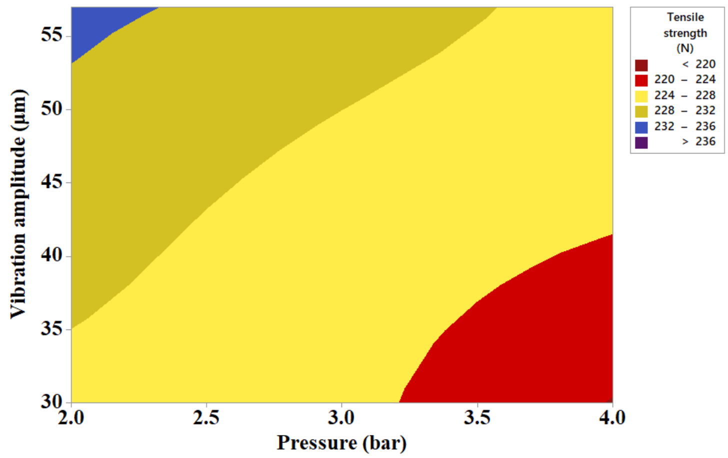
3.3. Effect of process paramters

Response surface and contour plots are developed to understand the effect of the process parameters on the tensile strength of the joint [20]. The influence of clamping pressure and the amplitude of vibration of the sonotrode on strength of the joint is shown in Figure 7. It can be noted from this figure that, the strength of the joint decreases with the increase of clamping pressure since the increase in clamping pressure restricts the rubbing action between wire and sheet and tend to severely deform the wire resulting in the reduction of the strength of the joint. The excessive amount of pressure applied on the wire by the sonotrode makes the wire deform and penetrate considerably into the sheet resulting in the formation of cracks and tear at the interface as shown in Figure 8. An increase in clamping pressure also restricts the sliding motion between the specimens leading to reduced welding action and hence reduced strength. Hence, a low level of clamping pressure (2 bar) is found to be effective. The maximum strength of the joint of about 235 N is achieved using a lower level of clamping pressure (2 bar) and a higher level of amplitude of vibration of the sonotrode (57µm). The contour plot shows that the strength of the joint is more sensitive to changes in clamping pressure than the amplitude of vibration of the sonotrode

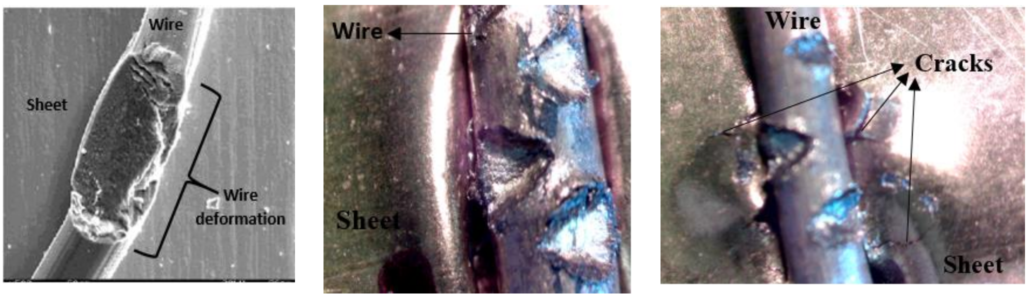


a) Response surface plot



b) Contour plot

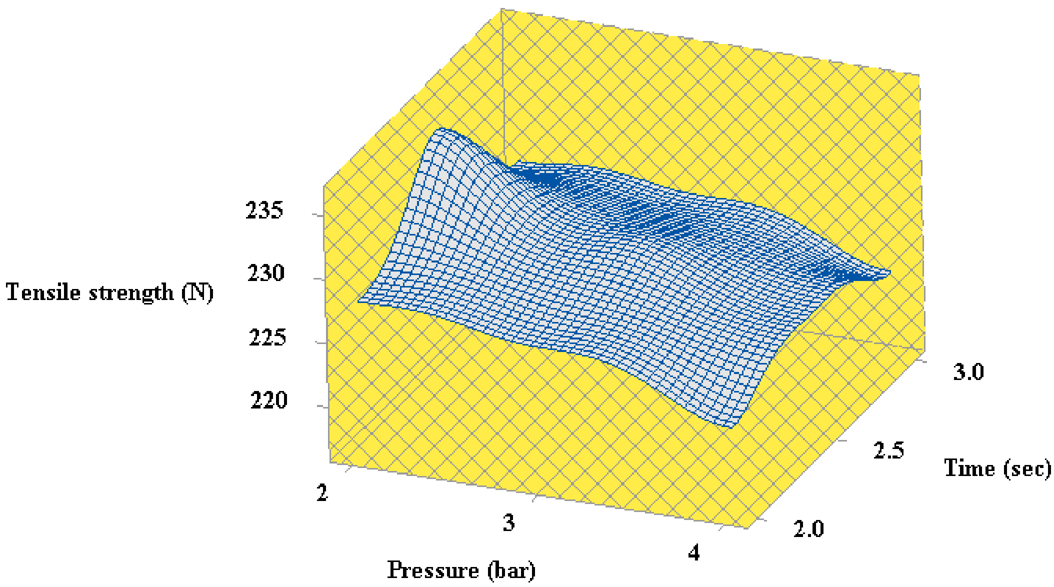
Figure 7: Effect of clamping pressure and amplitude of vibration of the sonotrode on strength of the joint (a) Response surface plot (b) Contour plot



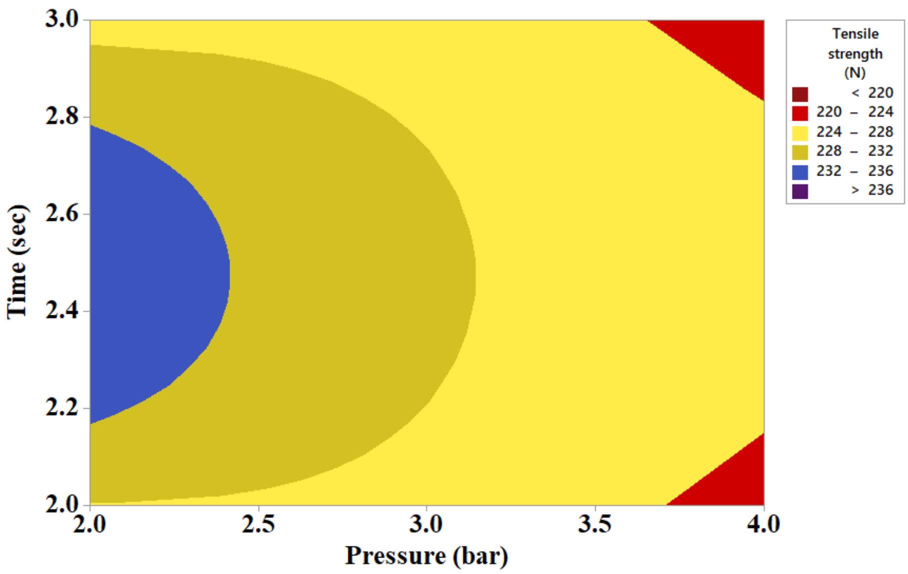
(a) Wire deformation (b) Wire penetration into the sheet (c) Cracks at the joint interface

Figure 8: Electrical contact joint defects

The effect of clamping pressure and weld time on strength of the joint shown in Figure 9. It can be seen from this figure that the lower level of clamping pressure (2 bar) and a medium level of weld time (2.5 seconds) result in maximum strength of the joint (235 N). The strength of the joint increases up to 2.5 seconds, a further increase in weld time results in the reduction of the strength of the joint. Initially, the asperities between wire and sheet join to make pure metal-to-metal contact. Due to prolonged rubbing action, the previously formed bond between wire and sheet is disturbed resulting in minimization of the strength of the joint. This can be further investigated by extending the scope of this work in the future through microstructural studies [21]. The contour plot shows that the strength of the joint is more sensitive to the changes in weld time than clamping pressure.



a) Response surface plot



b) Contour plot

Figure 9: Effect of clamping pressure and weld time on strength of the joint

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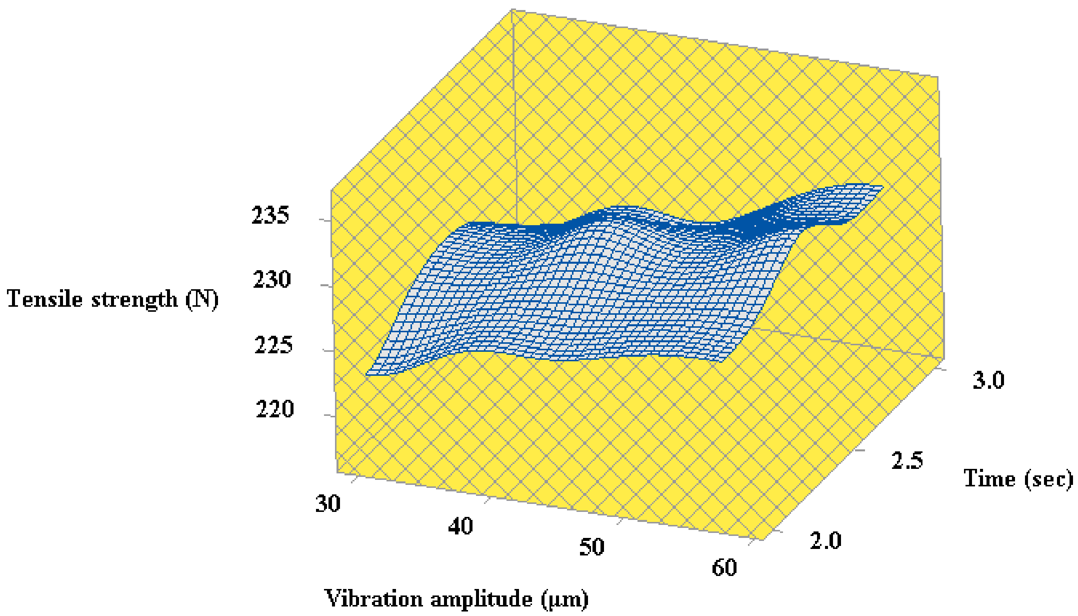
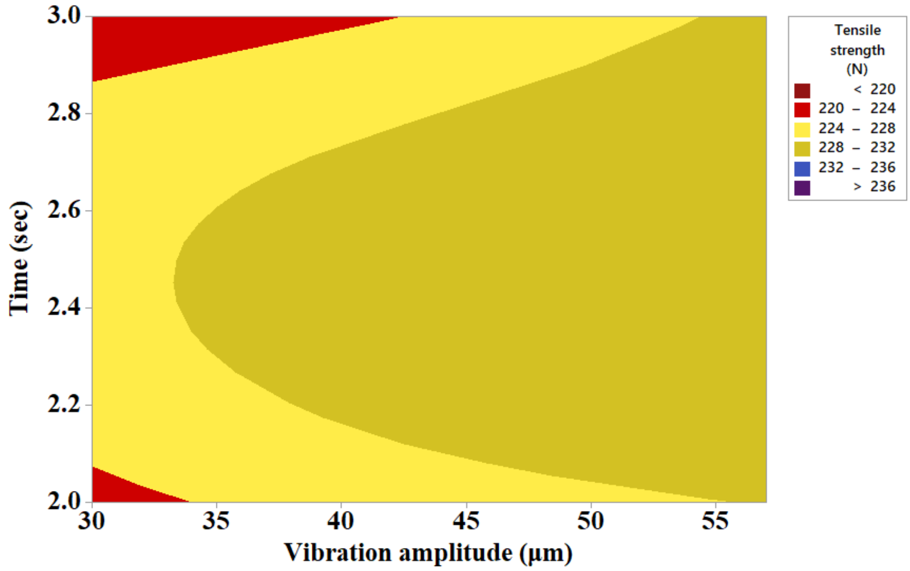
The effect of the amplitude of vibration of the sonotrode and weld time on tensile strength of the joint is shown in Figure 10. It can be observed from this figure that, the strength of the joint increases with an increase in the amplitude of vibration of the sonotrode [19, 20]. since the increase in amplitude of vibration of the sonotrode facilitates effective abrading action between wire and sheet leading to better bonding and a substantial increase in strength of the joint. The maximum strength of the joint is obtained at a higher level of amplitude of vibration of the sonotrode (57µm) and a medium level of weld time (2.5 seconds). The contour plot shows that the strength of the joint in more sensitive to changes in weld time than the amplitude of vibration of the sonotrode.



a) Response surface plot



b) Contour plot

Figure 10: Effect of amplitude of vibration of the sonotrode and weld time on tensile strength of the joint.

3.4. Confirmation experiments

Confirmation experiments are to be carried out to validate the optimum combination of process parameters for achieving the maximum strength of the joint. After identification of the optimum combination of process parameters, the mean of response(μ) is estimated using Equation 2.

$$\mu = T + (A_1 - T) + (B_3 - T) + (C_2 - T) \quad (2)$$

where, T is the overall mean of response and has a value of 226.748N. The estimated mean for the optimum parameters treatment condition (A_1, B_3, and C_2) is calculated as 235.704 N. The estimated mean is calculated based on the average results of the experiments. Hence, a confidence interval for the predicted mean on a confirmation treatment condition is calculated using Equation 3 [14,15].

$$CI = \left(F_{\alpha,1,v_e} V_e \left[\frac{1}{\eta_{eff}} + \frac{1}{R}\right]\right)^{1/2} \quad (3)$$

where, $F_{\alpha,1,v_e}$ is the value of 'F' from F-Tables, α is the risk level= 0.05, V_e is the error variance = 0.0029, v_e is the degrees of freedom(DOF) for the error, R is the number of repetitions for confirmation experiments = 5, η_{eff} is the effective number of replications and calculated using Equation 4.

$$\eta_{eff} = \frac{N}{(1+U)} \quad (4)$$

where, N is the total number of experiments = 54, U is the degree of freedom associated with the estimate of mean response =10, Substituting these values in Equation 4.3, η_{eff} is calculated as 4.91, $F_{0.05,1,8}$. = 5.32. Thus, the confidence interval (CI) calculated using Equation 5 is ±0.079. The 95% confidence level of the predicted optimum strength of the joint is given by

$$[\mu - CI] < \mu < [\mu + CI] \quad (5)$$

=> 233.625< 235.704 < 235.783

A successful confirmation experiment is one that is carried out with the optimum combination of process parameters (clamping pressure 2 bar, the amplitude of vibration of the sonotrode 57 µm, weld time 2.5 seconds) and the strength of the joint fall within the calculated confidence interval. The number of experimental trials carried out for validating the combination of process parameters is 5. The strength of the joints thus obtained for five confirmation experiments along with average and standard deviation are shown in Table 5. The average of all the responses of the confirmation experiments is 235.694 which is found to be well within 95% of the confidence interval of the true mean. Therefore, the optimal settings of process parameters and their levels are found to be significant.

Table 5: Results from Confirmation experiments

Trial No	Tensile strength of the joint(N)
1	235.712
2	235.689
3	235.654
4	235.709
5	235.723
Mean	235.694
Std. dev.	0.028

t-statistic test is carried out to validate the results from confirmation experiments. The mean and standard deviation are claculated as shown in Table 5. The standard error of the mean is calculated using Equation 6.

$$\text{Std. Error} = \text{Std. deviation} \,/\, \sqrt{n} \quad (6)$$

where n is the number of observations.

Std. Error = 0.028 / √5 = 0.0125

The standard error of the mean has n-1 degrees of freedom. So 5-1 = 4 degrees of freedom. For 95% confidence interval

t(4; 0.05) = 2.132

The confidence interval is calculated as

235.694 ± (2.132 x 0.0125) N

=> 235.667 < 235.694 < 235.721

The mean of confirmation experimental results lies within the confidence intervals. Hence the validation.

3.5. Regression model

In this work, a regression model has been developed based on results from experiments to characterize the relationship between independent and dependent variables. The response variable tensile strength of the joint is dependent on independent variables such as clamping pressure (A), the amplitude of vibration of the sonotrode (B) and weld tine (C). The regression model developed for prediction of tensile strength of the joint is shown in Equation 7. The goodness of fit of the regression model is characterized by the coefficient of determination (R^2). The R^2 value of the model is found to be 0.91. The variation between the experimental and predicted responses (strength of the joint) is illustrated in Table 6. Figure 11 indicates that the developed regression model can represent the system under the given experimental domain.

$$\text{Strength of the joint (N)} = -3.5 + 22.9\,A + 2.46\,B + 157.8\,C + 0.064\,AB - 0.925\,BC - 10.4\,AC - 2.61\,A^2 - 0.0151\,B^2 - 25.60\,C^2 - 0.000110\,A^2B^2 + 0.00231\,B^2C^2 + 0.369\,A^2C^2 \quad (7)$$

where A = clamping pressure, B= amplitude of vibration of the sonotrode, C= weld time.

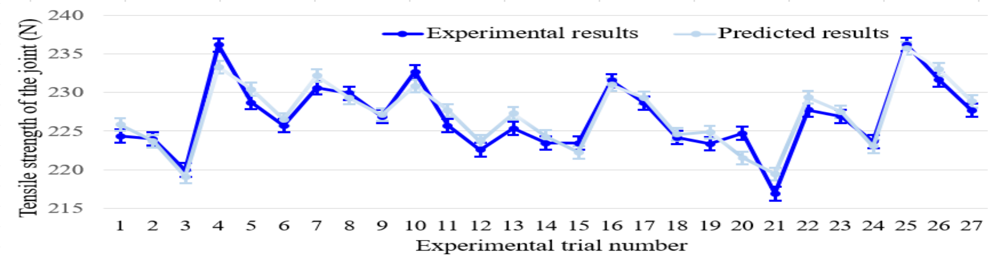


Figure11: Comparison of expermental results and predicted results

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Table 6: Results predicted by regression model

Trial No	Experimental values	Predicted values
1	224.331	225.83
2	223.984	223.69
3	219.965	219.08
4	236.140	233.30
5	228.674	230.41
6	225.674	226.51
7	230.567	232.14
8	229.891	229.26
9	226.879	227.08
10	232.630	230.86
11	225.687	227.66
12	222.587	223.66
13	225.348	227.28
14	223.421	224.26
15	223.429	222.27
16	231.520	230.96
17	228.643	229.25
18	224.144	224.56
19	223.321	224.86
20	224.690	221.54
21	216.896	219.44
22	227.710	229.35
23	226.890	227.51
24	223.648	223.00
25	236.190	235.71
26	231.634	232.95
27	227.698	228.87

4. Conclusions

Based on the results obtained from this research work, it can be concluded that:

- The strength of the joint was found to be significantly sensitive to the variations in the levels of process parameters.
- The optimum level of process parameters to achieve maximum strength in the range of 236 N is found to be clamping pressure (2 bar), the amplitude of vibration of the sonotrode (57 µm) and weld time (2.5 seconds).
- The highly effective parameter for achieving maximum strength of the joint was found to be the clamping pressure.
- The results predicted by the developed empirical model were found to be in good agreement with results from experiments.
- The confirmation test validated the process robustness based on the Taguchi method for enhancing the welding performance and optimizing the welding parameters in the ultrasonic metal welding process.
- The electrical contact joints thus made can be further studied for electrical, electronic, magnetic and thermal characterization as future work.

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