

Modeling and Optimization of Shear Strength of the Welded Joint Produced by Ultrasonic Welding of Copper Wire to Aluminum Sheet

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Received: 26 August 2023 / Accepted: 16 April 2024 / Published online: 9 May 2024
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Abstract Ultrasonic welding is a subset of frictional solid-state joining processes. This process, with its ability to join thin and dissimilar metallic materials, has been noticed by researchers. On the other hand, the dissimilar joining of aluminum and copper wires and electrodes in the battery of electric cars and hybrid electric cars to reduce the cost and weight of the car structure has been raised as one of the important industrial challenges. Therefore, in this research, ultrasonic welding of dissimilar joining of Al 1050 sheet with a thickness of 0.2 mm and copper wire with a cross-sectional area of 2.5 mm² was studied. For this purpose, the experiment was designed based on the response surface methodology (RSM) and Box-Behnken design (BBD). Static pressure, welding time, and vibration amplitude were selected as input variables in three levels. Then, the tensile test was performed on the specimens to evaluate the shear strength of the welded joint. The results of ANOVA showed that the linear and second-order effects of static pressure and vibration amplitude have the greatest effect on the shear force. Also, the regression model of shear force was extracted as a function of linear, interactive, and quadratic terms from the input variables. Finally, the optimal combination of input variables to achieve the maximum shear force was determined with a desirability of 0.935, and by performing the verification test, the competence of the regression model to predict the shear force was confirmed.

Keywords Ultrasonic welding · Shear strength · RSM · Desirability method

1 Introduction

Ultrasonic welding is a solid-state joining method that is performed by applying vibrations and creating a frictional movement between the surfaces that are under the pressure of the vibrating tool (horn) and the anvil [1]. This process with the ability to join thin and dissimilar materials and joining metals with high conductivity has been considered by researchers [2]. In this regard, Watanabe et al. [3] investigated the ultrasonic welding of low-carbon steel sheets to aluminum-magnesium alloy sheets. The results showed that the weld strength decreases with increasing time and pressure. Zhao et al. [4] conducted an experimental study to see how ultrasonic welding energy affects the joint between aluminum and copper. They found that applying the lower energy decreases joint strength and increases the probability of joint failure.

Lee et al. [5] investigated the quality of ultrasonic welding between nickel-coated copper sheets by controlling the weld power and displacement of the vibrating tool. They provided an online and reliable system to monitor the quality of ultrasonic welding of metals. Chen and Zhang [6] simulated ultrasonic spot welding between aluminum and copper sheets to study the acoustic softening phenomenon. They found that acoustic softening has a significant effect on the mechanical behavior of welded joints and it leads to a complete and strong joint. Haddadi [7] studied experimentally the state of the rapid growth of intermetallic compounds undergoing high strain rate deformation during the ultrasonic spot welding between aluminum and steel. He found that the vacant spaces caused by deformation during

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thermodynamic welding accelerate the creation of intermetallic compounds and reduce the mechanical performance at the joint. In another study, Chen and Zhang [8] investigated the effect of vibrating tool geometry in the ultrasonic welding of aluminum to copper. The FEM results showed that the geometry of the vibrating tool is significantly effective on the values of the stress, strain, and displacement of the tool on the joint interface. Because the specific geometry of the vibrating tool causes the local concentration of stress, plastic strain, and pressure distribution in the joint. Komiyama et al. [9] studied the effect of tool edge geometry in two trapezoidal and serrated states in the ultrasonic welding of 1050 aluminum sheets. They found that the vibration amplitude of the serrated pattern is more than that of the trapezoidal pattern. Also, in the serrated edge, due to increasing the temperature, more plastic deformation occurs, which leads to an increase in joint strength. Ni and Ye [10] studied the ultrasonic spot welding of aluminum and copper sheets with the help of Al 2219 intermediate particles. The results showed that the presence of intermediate particles increases the friction coefficient and removes the oxide layers between the two surfaces. Therefore, by creating contact between two polished metal surfaces and generating heat due to more friction, a favorable plastic deformation occurs and as a result, it increases the quality of the joint. Matos et al. [11] studied the mechanical properties of joints resulting from the ultrasonic welding of copper wires, half of which were insulated with PVC and the other half with ETFE insulation, under different temperature conditions. It was found that the tensile strength of the welded joint of PVC-coated copper wires is higher than that of ETFE-coated copper wires.

Gester et al. [12] experimentally studied the mechanical and microstructural properties of ultrasonic welding between aluminum wire and copper terminal. The results of the tensile test showed that the tensile strength of the joints is 31% lower than the base material. Abdi et al. [13] simulated the ultrasonic welding of copper and aluminum using a three-dimensional thermomechanical model. The results showed that increasing the static pressure and welding frequency increases the amount of plastic deformation. Also, it was observed that increasing the static pressure increases the mechanical strength of the joint. Ma et al. [14] investigated the joint quality in ultrasonic welding between aluminum and copper by using molecular dynamics simulation, mechanical tests, and microstructural study. Study of the weld zone showed that the microstructural evolution of the weld, including material flow, grain morphology, and orientation, is focused on the side of softer materials. Singh et al. [15] investigated the weldability of dissimilar metal sheets (copper and low-carbon steel) using ultrasonic welding. The findings indicated that by increasing the values of the welding process parameters (pressure, time, and vibration amplitude), the joint

strength during the lap-shear and T-peel tests decreases and increases, respectively. Silva et al. [16] investigated the effect of parameters of ultrasonic spot welding on the joint quality between copper and aluminum sheets. They evaluated the welding quality based on the tensile strength and metallographic examination. The experiments were conducted based on a full factorial design. The results showed that welding time has the greatest effect on welding energy and tensile strength. Also, increasing the welding time will increase the heat input to the joint zone. This will cause the joint to become weaker. Pöthig et al. [17] studied the effect of different surface conditions of the copper terminal on the mechanical properties of the joint resulting from the ultrasonic welding of aluminum wire to the copper terminal. The results showed that the maximum fracture loads could be attained with the structured terminals (structuring process by laser and milling). On the other hand, contaminated terminals and terminals with notches revealed reasonably poor fracture loads.

A review of previous research shows that ultrasonic welding of metals has been given special attention by researchers. On the other hand, the desirable physical, mechanical, and electrical properties of aluminum and copper have made this group of metals and alloys widely used in various industries. Also, today, due to the increase in environmental pollution caused by the consumption of fossil fuels and the limitation of natural resources to supply them, the use of electric cars and hybrid-electric cars is rapidly growing and developing. In these cars, lithium-ion batteries are usually used to provide propulsion power, which provides greater efficiency and energy density. Aluminum and copper are known as part of the metals used in the cathode and anode electrodes of this group of batteries. In addition, due to the reduction of natural and mineral reserves of copper metal and the significant increase in its price, the replacement of this metal with the use of aluminum metal has attracted the attention of important industries. Therefore, studying and investigating their welding process using ultrasonic technology is necessary and unavoidable.

By reviewing the previous research, it can be seen that the joining of copper wire to aluminum sheets using ultrasonic welding has not been considered so far. Also, the shear strength of such a joint has not been studied based on a statistical method and in terms of input variables. Hence, considering the aforementioned research gaps, in this research, the modeling and optimization of variables affecting the shear strength of ultrasonic welding of copper wire to aluminum sheet was done. The innovative aspects of the present research include: ultrasonic welding of aluminum sheet to the copper wire, extraction of mathematical function to predict the response parameter (shear force) based on the analysis of variance (ANOVA), and achieving the favorable composition of input variables using the desirability method.

2 Materials and Methods

In this research, the shear strength of the welded joint between the aluminum sheet and copper wire is evaluated. Therefore, the shear force that can be tolerated by the joint was selected as the response parameter. By reviewing the background of the research, it can be found that parameters such as ultrasonic frequency, compressive static force, vibration amplitude, welding time, type of materials to be joined, the geometry of workpieces, and geometrical and dimensional characteristics of the horn (vibrating tool) are known as effective variables in this process. Meanwhile, the parameters of pressure (vertical static force), vibration amplitude (depending on the generator power), and welding time can be adjusted on the ultrasonic welding machine. On the other hand, any change in the ultrasonic frequency requires a change in the experimental setup (including the generator, transducer, booster, and horn), which will be very expensive. Therefore, in this research, three variables of static pressure, welding time, and vibration amplitude were chosen as the experiment factors, and each of them was investigated at three levels: low, central, and high (Table 1). Due to the importance of correctly choosing the range of input parameters to achieve a good weld, preliminary tests were performed on aluminum sheets and copper wires.

Experimental tests were designed based on the response surface methodology (RSM) [18]. For this purpose, the Box-Behnken design (BBD) was used (Fig. 1).

In this method, by using the regression model and the second-order polynomial function, the effect of each of the input variables (x) on the response parameter (y) is expressed as follows:

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \epsilon \quad (1)$$

In the above function, β_0 is a constant value, β_i is a linear coefficient, β_{ii} is a quadratic coefficient, β_{ij} is an interactive coefficient, x is the independent variable, k is the number of independent variables, and ϵ is the error value observed in the response. The design of the experiment was carried out using the Minitab software [20] with 15 runs and repeatability at the central level (Table 2).

Table 1 Introduction of input variables

No	Input variable	Symbol	Level		
			-1	0	+1
1	Static pressure (bar)	P	3	4.5	6
2	Welding time (s)	T	0.5	1	1.5
3	Vibration amplitude (%)	A	40	75	110

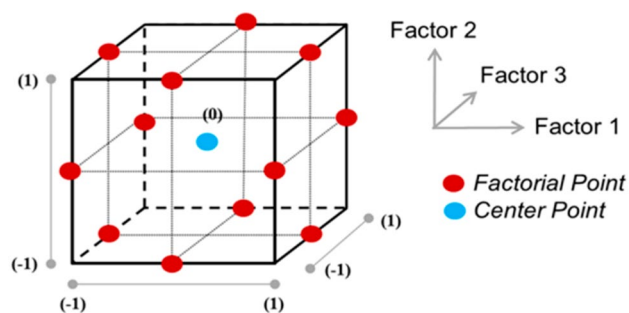


Fig. 1 Box–Behnken design [19]

The welding process was performed using an ultrasonic welding machine with a maximum power of 2000 watts and a resonance frequency of 20 kHz (Fig. 2).

The main components of this machine include an ultrasonic generator, transducer, booster, and vibrating tool (horn). The transducer, booster, and vibrating tool are designed and manufactured in such a way that each of them separately has a longitudinal resonance frequency of 20 kHz, and after assembling them, the resonance frequency of this assembly will also be equal to 20 kHz [21]. A specific and prominent pattern is machined on the vibrating tool. This pattern includes several vertical and horizontal rows that are created in the form of a pyramid (Fig. 3).

In this research, copper wire with a cross-section of 2.5 mm² and aluminum sheet 1050 with a thickness of 0.2 mm was used for the ultrasonic welding process. High-quality copper wire was used under the national standard of Iran under the number ISIRI 607-3 [22] and under the international standard under the number IEC 60227-3 [23]. The

Table 2 Design of experimental tests

No	Input variables			Shear force (N)
	Amplitude (%)	Time (s)	Pressure (bar)	
1	40	0.5	6	162.4
2	75	1.5	4.5	121.6
3	110	1	4.5	179.5
4	75	1	4.5	216.3
5	75	1	4.5	216.3
6	40	1.5	6	247.7
7	75	0.5	4.5	186.4
8	40	1.5	3	157.5
9	75	1	3	147.2
10	75	1	4.5	216.3
11	110	1.5	3	149.6
12	110	0.5	6	216.8
13	110	0.5	3	144.7
14	75	1	6	165.3
15	40	0.5	3	119.2

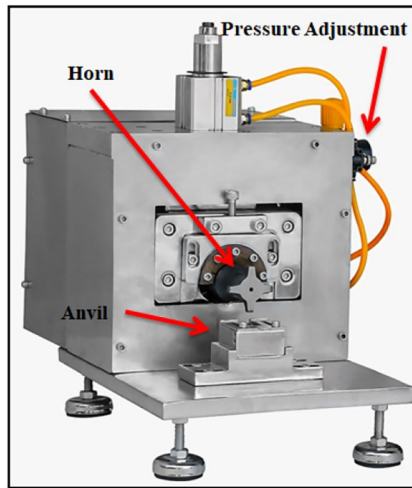


Fig. 2 Ultrasonic welding machine [21]

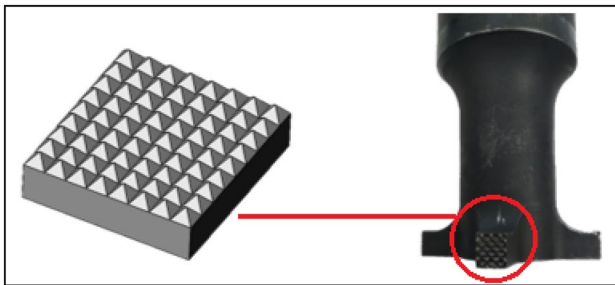


Fig. 3 The created pattern on the vibrating tool

Table 3 Physical and mechanical properties of Al 1050 sheet [24]

Property	Value
Density	2.705 gr/cm ³
Hardness	21 Brinell
Tensile strength	76 MPa
Shear strength	51 MPa
Yield strength	28 MPa
Young modulus	69 GPa
Poisson coefficient	0.33

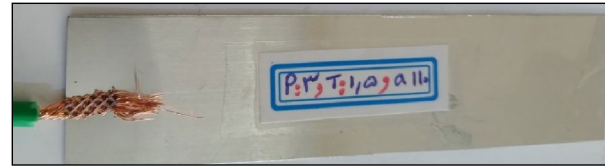
wire cover is made of PVC and its thickness is 0.8 mm. The external diameter of the wire is 3.4–4.1 mm. The physical and mechanical properties of 1050 aluminum sheets are presented in Table 3.

Figure 4 shows several welded specimens under the settings listed in Table 2.

The shear force that can be tolerated by the welded joint was determined as the response parameter. This parameter was measured by a tensile test machine (Fig. 5).



(a) No.10 (P = 4.5 bar, T = 1 s, A = 75 %)



(b) No.11 (P = 3 bar, T = 1.5 s, A = 110 %)

Fig. 4 Some of the welded specimens

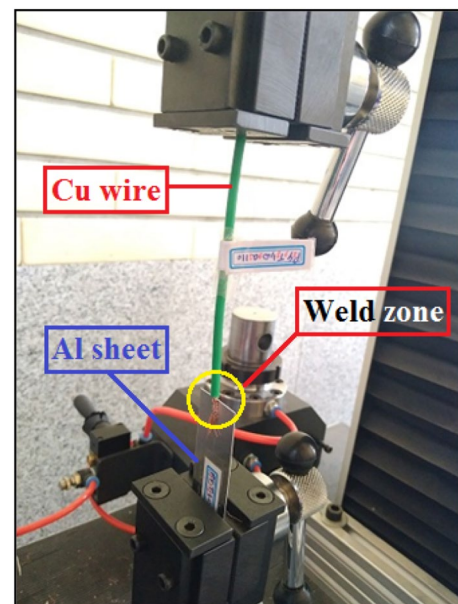


Fig. 5 Running the tensile test to measure the shear force

It should be noted that during the test, uniaxial tensile force is applied to the specimen. In this situation, the amount of adhesion of the copper wire to the aluminum sheet is measured, which will report the maximum shear force required to break the welded joint.

3 Results and Discussion

3.1 Statistical Analysis

The results of shear force measurement are presented in the last column of Table 2. The analysis of the results is done by use of analysis of variance (ANOVA). The ANOVA is a useful tool to investigate the importance of a factor and

detect the significance of its effect. Also, regression analysis is used to create a mathematical function between the response parameter and the effective variables [25]. The level of confidence was considered equal to 0.05. In other words, the final model will be able to estimate the response parameter with an inaccuracy of less than 5%. According to

the AVOVA results and *P* values less than or equal to 0.05 (Table 4), it can be seen that the linear effects of pressure (P) and vibration amplitude (A) and the second-order effects of pressure (P²) and vibration amplitude (A²) are known as the effective terms on the response parameter (shear force). Therefore, the compressive static force (perpendicular to the surface of the specimens) and the shearing force resulting from the application of vibrations (parallel to the contact surface of the specimens) can be named as the effective forces in ultrasonic welding.

Table 4 The ANOVA results

Source	DF	Adj SS	Adj MS	F Value	P Value
Regression model	9	18,834	2092.7	4.56	0.055
Linear effect	3	6461.8	2153.9	4.69	0.065
P	1	3794.4	3794.4	8.27	0.035
T	1	239.8	239.8	0.52	0.502
A	1	4026	4026	8.77	0.031
Second-order effect	3	13,732.5	4577.5	9.97	0.015
P ²	1	3989.5	3989.5	8.69	0.032
T ²	1	221.5	221.5	0.48	0.518
A ²	1	10,655.7	10,655.7	23.22	0.005
Interactive effect	3	883.7	294.6	0.64	0.620
PT	1	552.3	552.3	1.20	0.323
PA	1	270.6	270.6	0.59	0.477
TA	1	60.8	60.8	0.13	0.731
Residual error	5	2294.5	458.9	–	–
Lack of fit	3	1637.2	545.7	1.66	0.397
Pure error	2	657.3	328.7	–	–
Total	14	21,128.5	–	–	–
R ² = 89.14%					

significance of bold values show the *F* values related to the significant terms

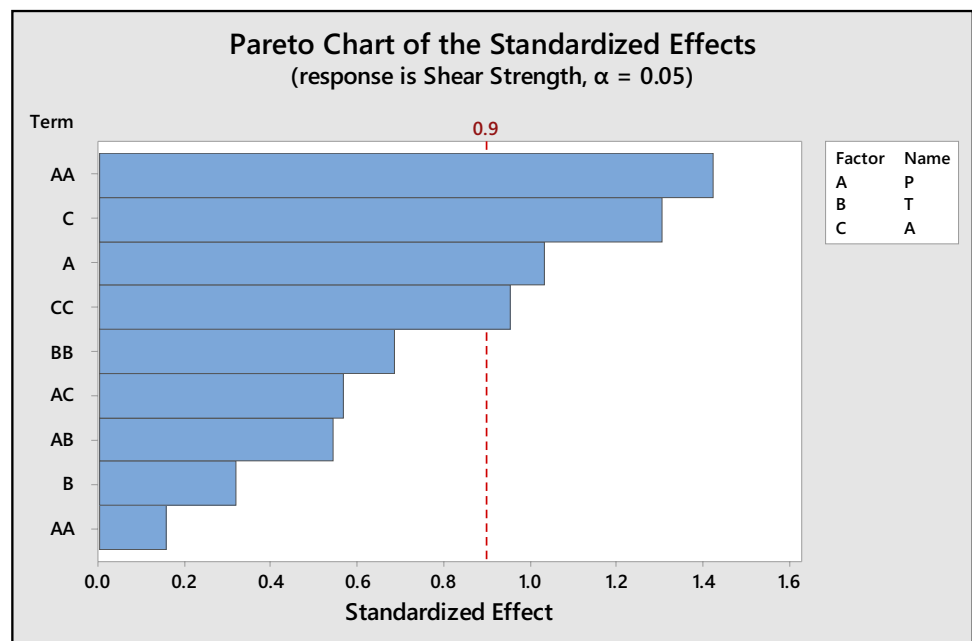
Also, the regression model of the shear force was extracted as a function of linear, interactive, and second-order terms:

$$Shearforce = -319.271 + 142.392P + 86.802T + 5.238A - 14.609P^2 - 30.983T^2 - 0.044A^2 - 15.667PT + 0.157PA + 0.223TA \tag{2}$$

As can be seen in Table 4, the R² parameter shows a high value of 89.14%. Therefore, there is a strong relationship between the data observed in the experimental tests and the predicted answers obtained from the regression equation. Also, according to the *P*-value of the lack of fit (LOF), it is clear that the model fits well with the experimental data. Figure 6 shows the effect of input variables on the shear force in the form of a Pareto chart.

The residual is defined as the difference between the response measured in the experiment and the response predicted by the regression model. To assess the correctness of the normal distribution of residuals, the normal probability diagram is used. According to Fig. 7, it can be seen that the residuals generally follow a straight line and there is no evidence of non-normality.

Fig. 6 Pareto chart including independent, interactive, and quadratic effects of process variables



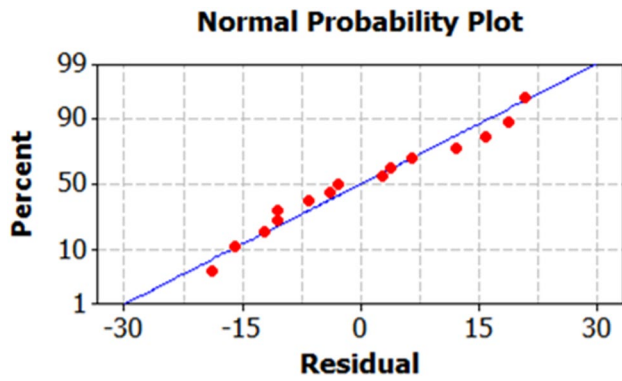


Fig. 7 Normal probability plot

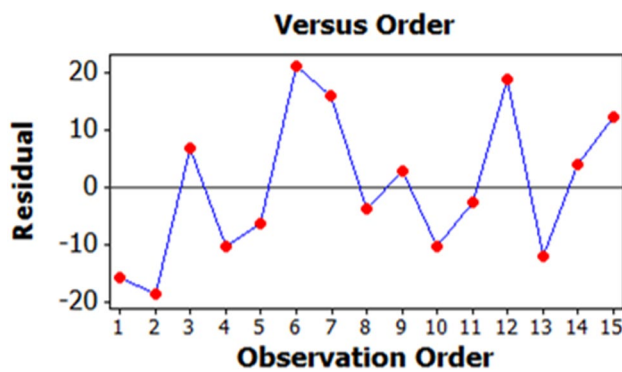


Fig. 8 Chart of residuals

If the regression model is appropriate, the residuals should be unstructured. As shown in Fig. 8, the residuals are randomly distributed around the zero axis, and the graphs do not contain any specific patterns and are completely unstructured.

On the other hand, it is possible to show the behavior of shear force based on the change of input factors in the shape of a 3D plot and 2D plot (Fig. 9). Therefore, it can be concluded that by fixing the welding time at 1 s and by choosing a value of 40% for the vibration amplitude, and considering the static pressure values in the range of 4.5–6 bar, a higher shear force can be achieved (Fig. 9a). Also, by fixing the value of the static pressure at 4.5 bar and choosing a value of 40% for the vibration amplitude, and considering the welding time between 1 and 1.3 s, the maximum shear strength of the welded joint will be achieved (Fig. 9b). In addition, by fixing the value of the vibration amplitude at 75% and by choosing the welding time and static pressure at values of 1 s and 5 bar, respectively, the maximum shear force can be attained (Fig. 9c).

Figure 10 shows the separate effects of input factors on the shear force. According to this plot, the vibration amplitude at the central level (75%) has the most independent effect to achieve the maximum shear force.

3.2 Optimization and Verification

In this study, the desirability method was used to optimize the input variables [26]. The objective of the desirability function is to maximize the shear force. Therefore, the desirability function is defined by the following equation:

$$d = \begin{cases} 0 & y < L \\ \left(\frac{y-L}{U-L}\right)^r & L \leq y \leq U \\ 1 & y > U \end{cases} \quad (3)$$

L and U are the lower limit and upper limit of the response value of y , respectively. Also, r is the weight field of the data, which varies from 0.1 to 1. The optimization results are shown in the form of a sectional diagram in Fig. 11. This diagram shows the behavior of the shear force and the desirability function at the optimal point. The desirability value obtained from the optimization process was 0.935. The optimal setting of the input factors was obtained as follows: Static pressure = 5.3 bar, welding time = 1.18 s, and vibration amplitude = 40% (Fig. 11).

To verify the optimal combination of input factors, the experimental test was performed based on the optimal values. The shear force resulting from the tensile test (240.269 N) was measured with a small difference (0.36%) compared to the predicted shear force resulting from the regression model (239.408 N). Therefore, the correctness and accuracy of the optimization process to determine the optimal combination of input factors was confirmed.

Experimental observations showed that if the values of pressure, vibration amplitude, and welding time are set at the lowest levels, they will lead to the creation of welded joints with weak mechanical strength. On the other hand, if the highest levels of the aforementioned variables are used, they will lead to weld breakage. Therefore, the optimal combination of input variables will be achieved based on the ability to create favorable frictional conditions and maintain the appropriate temperature in the weld interface. Figure 12 displays the SEM image of the welded zone between the copper wire (bright color) with the aluminum sheet (dark color). This image was prepared using a FESEM device.

As can be seen, due to the optimal adjustment of input variables, a good joint has been established. The ultrasonic vibration, by creating frictional conditions and also plastic deformation due to static pressure, causes the breaking and dispersing of oxide films, which results in the spreading of micro welds in the joint. On the other hand, an increase in

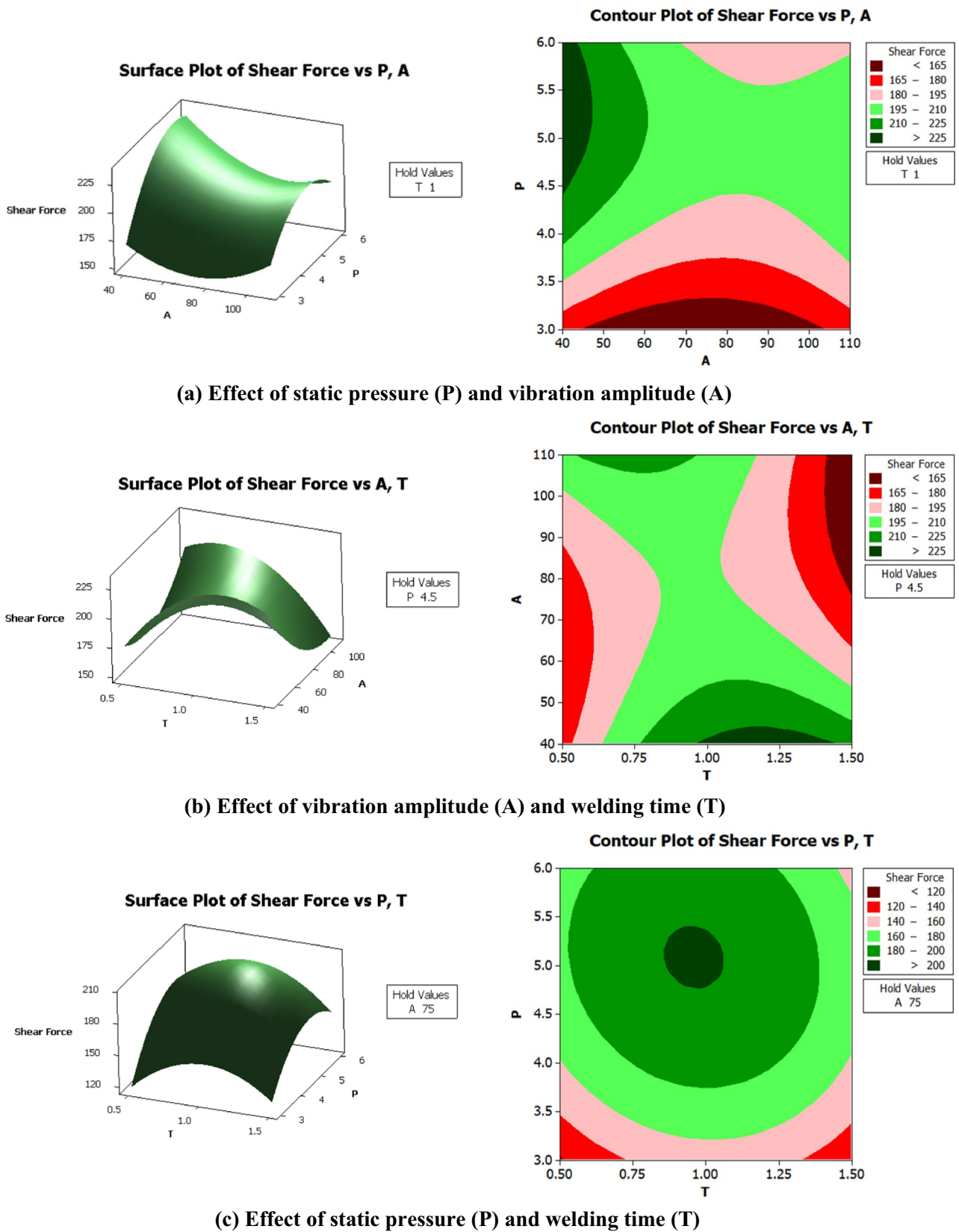


Fig. 9 Interactive effects of input factors on the shear force

Fig. 10 The separate effect of input variables on the shear force

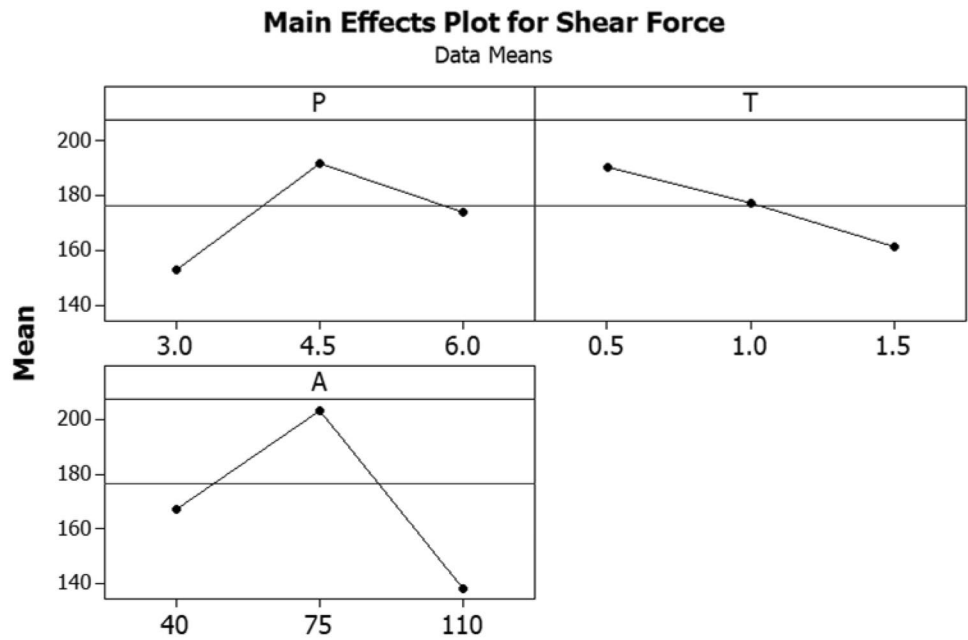
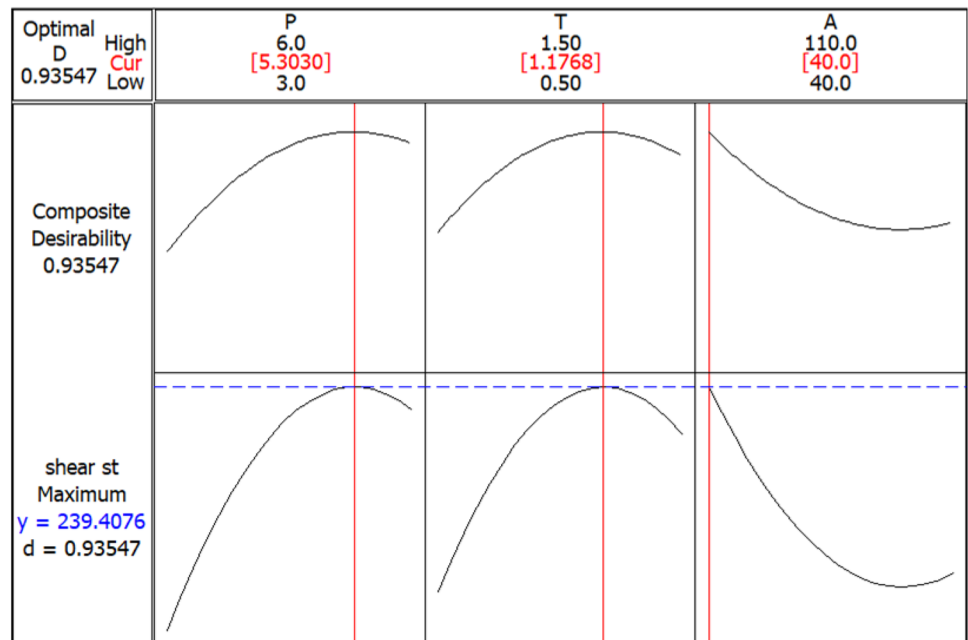


Fig. 11 A sectional diagram resulting from the optimization process



temperature in the joint zone causes a decrease in the local yield strength of the aluminum sheet and copper wire, which increases the plastic deformation of the material.

In addition, Fig. 13 shows the EDS image of the welded zone. Energy dispersive X-ray spectroscopy (EDXS) is an analytical technique used for the elemental analysis or chemical characterization of a sample. As can be seen in Fig. 13, in addition to identifying the chemical elements in

the welded zone (manganese, carbon, oxygen, etc.), their distribution in copper wire and aluminum sheet is also shown.

4 Conclusion

In this paper, the modeling and optimization of variables affecting the shear strength of the welded joint were studied.

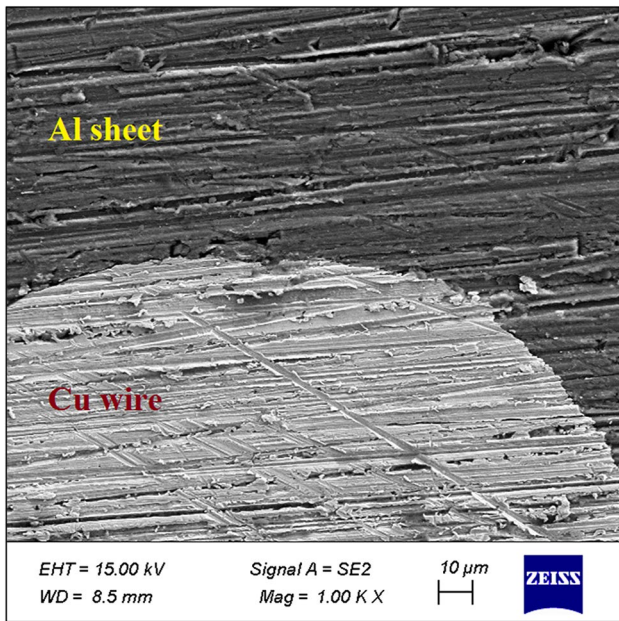


Fig. 12 SEM image of the welded zone (1000×)

Ultrasonic welding was used for joining the copper wire to the aluminum sheet. For this purpose, the response surface methodology and Box-Behnken design were chosen as the experimental design method. Static pressure (P), welding time (T), and vibration amplitude (A) were considered as the input factors. The important results of this research are summarized as follows:

- The regression model to predict the maximum shear force was extracted in terms of linear, interactive, and second-order expressions from the input variables.
- The competence and adequacy of the regression model were investigated and confirmed based on the coefficient of variation (R^2), the lack of fit test, the normal probability diagram, and the residual behavior.
- According to the ANOVA results, the effective parameters on the maximum shear force include linear effects of pressure (P) and vibration amplitude (A) and second-order effects of P^2 and A^2 .
- The optimal setting of the input factors to achieve the maximum shear force was extracted as follows: static pressure = 5.3 bar, welding time = 1.18 s, and vibration amplitude = 40%.
- The comparison between the results of the verification test and the optimization process showed that the error of the regression model for predicting the maximum shear force is less than one percent (0.36%). Therefore,

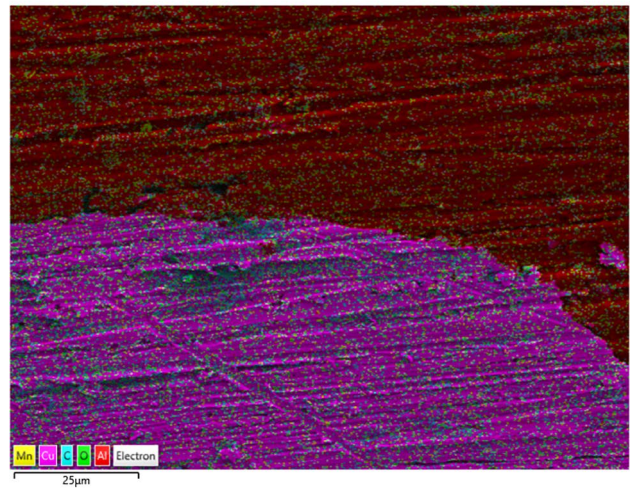
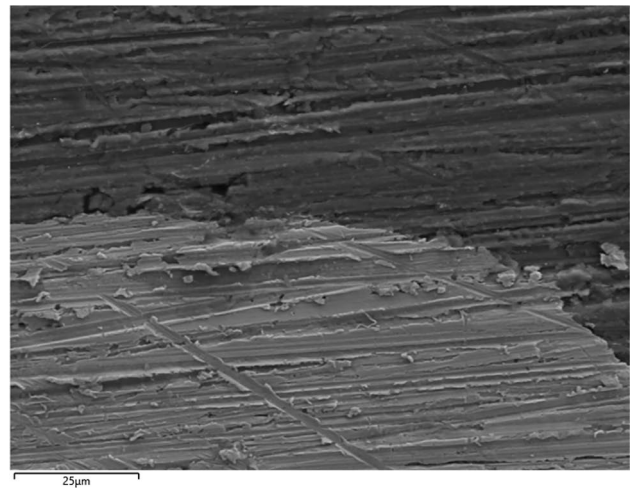


Fig. 13 EDS image of the welded zone

the correctness and accuracy of the regression equation to predict the response parameter was confirmed.

Acknowledgements The authors express their gratitude and appreciation for the support of the management and personnel of Iranultrasonic Company. This work was supported by the Iran National Science Foundation (INSF) [Grant Number 99022838].

Data Availability The authors state that the data supporting the results of this research are available in the paper. Also, data sets created during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they do not have any conflicts of interest to report about the current study. The authors state that they do not have any financial conflicts of interest or personal relationships that may have affected their work.

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