



Optimization of ultrasonic welding parameters to maximize the tensile shear fracture load bearing capability of lap welded ABS plastic sheets

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Abstract

ABS is a popular material for structural applications in automotive sector because of its low cost, high apparent shine and finishing, ease of property improvement, simplicity in forming complicated shapes while preserving strength, and durability. It is preferred to be joined using ultrasonic welding (USW) process. So, in this study, the ultrasonic welding (USW) parameters specifically welding time, amplitude, axial pressure and holding time were optimized for enhancing the tensile shear fracture load (TSFL) bearing capability of acrylonitrile butadiene styrene (ABS) plastic lap joints for automotive applications. The computational and stastical approach of response surface methodology (RSM) was used for formulating the parametric empirical relationship (PER) and optimize the USW parameters. The PER was validated using analysis of variance. The response surfaces were created using RSM and analyzed. From the results, it was observed that the ABS joints created using the welding amplitude of 80%, welding time of 2.0 s, axial pressure of 2 bar, and holding time of 5.0 s exhibited greater tensile shear fracture load (TSFL) bearing capability of 1.30 kN. The PER accurately predicted the TSFL of ABS joints within 1% error on 95% confidence.

Keywords Ultrasonic welding · ABS plastic · Optimization · Tensile shear fracture load

1 Introduction

The growing popularity of lighter and cost-effective thermoplastics is rising in automotive sector to reduce the weight and cost of vehicle. This is crucial to reduce the usage of fuel, exhaust emissions, cost of metal sheets and enhance the mileage [1]. The plastic sheets are often required to be

welded using suitable joining techniques to make an automotive part. Thermoplastics are welded using plastic welding processes, which involves heating plastic components until they are flexible and joining them into a single structure after that. To produce the best weld quality, surfaces must be clean, just like with other welding techniques [2]. Plastics are fused together at the moment of melting. They entirely fuse after they have cooled. Due to its great efficiency and ability to work with a variety of materials, plastic welding is growing in popularity among manufacturers across a number of sectors [3]. Contrary to certain other connecting techniques, such fasteners and adhesive bonding, it often doesn't necessitate the acquisition of extra parts and supplies. Plastic welds produce superior results while being lightweight and affordable. Plastic welding also offers adaptability and compatibility with various joint forms. Since there are less fumes produced throughout the procedure than during some other conventional welding techniques, the welds remain permanent [4]. Plastic welding is done by hot gas welding, laser beam welding [5–7], spin welding [8], vibration welding [9], hot plate welding [10], high frequency welding [11] and solvent welding [12]. A typical thermoplastic used to create light, stiff, moulded items including piping, car bodywork,

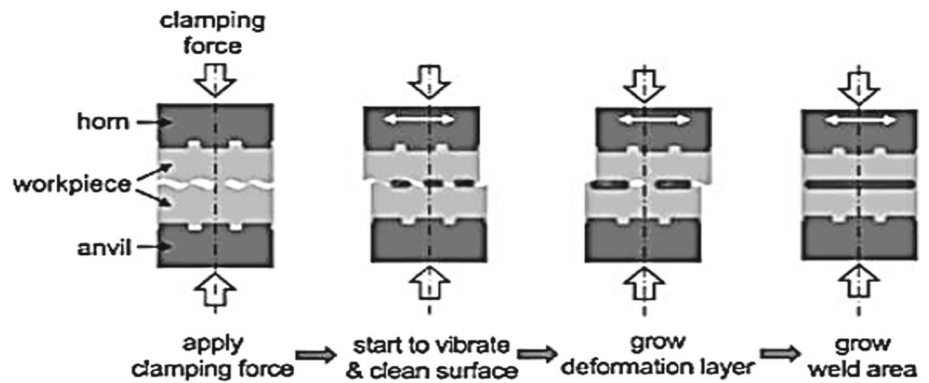
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Fig. 1 Mechanism of USW process



wheel covers, enclosures, and protective headgear is called Acrylonitrile Butadiene Styrene, or ABS. It is developed by the copolymerization of acrylonitrile (A, 23–41%), butadiene (B, 10–30%), and styrene (S, 29–60%). ABS exhibits good impact toughness, mechanical strength, creep resistance, dimensional stability, and stiffness [13]. ABS is a popular material for structural applications because of its low cost, high apparent shine and finishing, ease of property improvement, simplicity in forming complicated shapes while preserving strength, and durability. ABS is useful as a cheap electronic substrate material due to its strong electrical resistivity and low thermal coefficient value. ABS offers chemical resistance to the majority of chemicals, including highly concentrated hydrochloric acid (HCl), aqueous acids, mineral oil, and alcohols. This is another benefit of using ABS in pipes and fittings in the chemical sector [14].

ABS is preferred to be joined using ultrasonic welding (USW) process [15]. High-frequency, low-amplitude mechanical vibrations are used in ultrasonic welding to produce heat. In order for the plastic to melt and form a weld between two plastic surfaces, friction caused by the vibrations must be present. UW is quick and doesn't apply direct heat. As a result, it is a great option for welding ABS that are likely to produce fumes when employed with other methods [16]. In this investigation ultrasonic welding (USW) is performed on ABS plastic sheets. In USW, the components to be welded are clamped together under pressure and then exposed to ultrasonic vibrations, which are typically 20 kHz, while the industry sometimes uses frequencies between 15 and 60 kHz according to the application [17]. If the parts are suitably engineered, the heat produced by the alternating strains can be concentrated at the joint, where it is generated via intermolecular friction. The working mechanism and schematic of USW machine is illustrated in Figs. 1 and 2. The power source (generator), transducer, booster, horn, control system, and a fixture to hold the parts make up the USW equipment [18]. Electrical power is transformed into mechanical vibrations by a transducer made of piezoelectric material and then sent via the booster. The booster changes the transducer's vibration amplitude into the quantity that

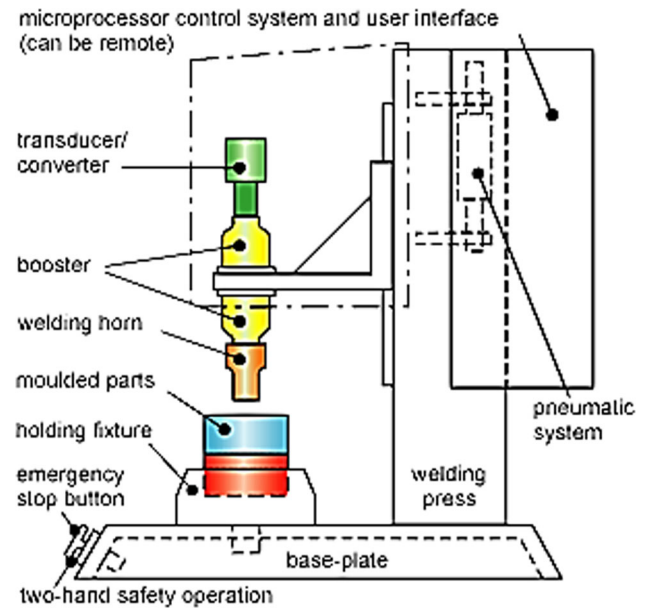


Fig. 2 Schematic of an USW machine [18]

the horn needs. In order to obtain amplitude changes which, the horn cannot produce on its own, the booster is attached between the transducer and horn. The vibrations generated by booster are amplified and sent to welding components by a horn or sonotrode. These horns serve as impedance transformers; it must be matched to the booster's amplitude at one end of it and to the parts at the other end [19]. The ultrasonic metal welding is quite distinct from an allied ultrasonic plastic welding. The ultrasonic vibrations in metal welding are parallel to the part surfaces, whereas they are perpendicular to the surfaces in plastic welding. The ultrasonic metal welding is achieved in solid state i.e., without melting and fusion of adjacent metal surfaces. In ultrasonic plastic welding, the joining is done by melting and coalescence of adjacent plastic material. The schematic of ultrasonic plastic and metal welding is shown in Fig. 3 [20].

The research work on welding of ABS is mainly reported on laser welding [21–23], friction stir welding [24–27], vibration welding [28] and rotary friction welding [29]. There

Table 1 Defects observed in USW of ABS plastic sheets







Parameters	Range	Bond appearance	Observation	Reason
Welding time	> 2.5 s		Joined but deformed	Due to the more welding, time the material gets plastically deformed since the strength of the material usually decreases with increase in time
Welding pressure	> 1 Bar		Joined but deformed	At high pressures combined with heating reduces the strength of the material and thus leads to the deformation
Amplitude	> 80%		Joined but deformed	Due to the more amplitude is given for welding to occur accompanied by higher temperature leads to the deformation on surface area of the material
Welding time	< 2.5 s		Joined without deformation	Due to the sufficient welding time provide to joined the material by time-dependent phenomenon
Welding pressure	< 1 bar		Joined without deformation	Due to the sufficient pressure that is lead to break the surface integrations for the joined to occur
Amplitude	< 80%		Joined without deformation	Due to the sufficient amplitude provided to welding to occur

Table 2 Working limits of USW parameters for joining ABS plastic sheets

S. No	Parameter	Notation	Unit	- 1	0	1
1	Amplitude	AMP	%	70	80	90
2	Welding time	WT	s	1.5	2	2.5
3	Holding time	HT	s	4	5	6
4	Axial pressure	AP	Bar	1.5	2	2.5

Table 3 Design matrix and TSFL test results

Expt. no	AMP (%)	WT (Sec)	HT (Sec)	AP (Bar)	TSFL (kN)
1	70	1.5	5	2	0.62
2	90	1.5	5	2	0.77
3	70	2.5	5	2	0.72
4	90	2.5	5	2	0.84
5	80	2	3	1.5	0.42
6	80	2	7	1.5	0.34
7	80	2	3	2.5	0.38
8	80	2	7	2.5	0.32
9	70	2	5	1.5	0.72
10	90	2	5	1.5	0.77
11	70	2	5	2.5	0.45
12	90	2	5	2.5	0.66
13	80	1.5	3	2	0.41
14	80	2.5	3	2	0.76
15	80	1.5	7	2	0.56
16	80	2.5	7	2	0.45
17	70	2	3	2	0.21
18	90	2	3	2	0.56
19	70	2	7	2	0.37
20	90	2	7	2	0.3
21	80	1.5	5	1.5	0.72
22	80	2.5	5	1.5	0.86
23	80	1.5	5	2.5	0.71
24	80	2.5	5	2.5	0.83
25	80	2	5	2	1.2
26	80	2	5	2	1.3
27	80	2	5	2	1.2
28	80	2	5	2	1.3
29	80	2	5	2	1.2
30	80	2	5	2	1.3

is lack of study on USW of ABS plastic. The welding parameters significantly influence the integrity and strength performance of joints [30]. Hence it is necessary to optimize the USW parameters for joining ABS plastic material. The researchers have reported the application of response surface methodology (RSM) in optimization of welding parameters for joining engineering materials to enhance the strength performance of joints [31–33]. So, in this study, the ultrasonic welding (USW) parameters specifically welding time, amplitude, pressure and holding time were optimized for enhancing the tensile shear fracture load (TSFL) strength of ABS plastic lap joints for automotive applications. The computational and statistical approach of RSM was deployed for creating the strength prediction models (SPM) and optimize the USW parameters. The response surfaces were created using RSM and analyzed.

2 Experimental methodology

The 3 mm thick sheets of ABS plastic sheets were utilized for optimizing USW parameters. The size of the ABS sheets was kept as $75 \times 25 \times 3$ mm. The USW machine was employed for joining ABS plastic sheets. The welding amplitude (%), welding time (s), holding time (s) and axial pressure (AP) were observed to be important parameters affecting the TSFL of USW joints. The defects observed during the setting of USW parameters are shown in Table 1. The joint quality was accessed on the basis of defects, weld appearance and TSFL strength of joints.

The working limits for joining ABS plastic sheets were fixed after several tests using several combinations of USW parameters. The working limits of USW parameters for joining ABS plastic sheets are tabulated in Table 2. The

Table 4 ANOVA test results for ABS plastic material

Source	Sum of squares	DF	Mean square	F- value	P-value prob > F	Validation	
Model	2.72	14	0.19	67.23	< 0.0001	Significant	
AMP	0.055	1	0.055	18.90	0.0007		
WT	0.037	1	0.037	12.93	0.0029		
HT	0.013	1	0.013	4.61	0.0498		
AP	0.019	1	0.019	6.64	0.0220		
AMP × WT	2.25E-004	1	2.25E-004	0.078	0.7844		
AMP × HT	0.044	1	0.044	15.25	0.0016		
AMP × AT	6.4E-003	1	6.4E-003	2.21	0.1590		
WT × HT	0.053	1	0.053	18.29	0.0008		
WT × AP	1.0E-004	1	1.0E-004	0.035	0.8552		
HT × AP	1.0E-004	1	1.0E-004	0.035	0.8552		
AMP ²	0.66	1	0.66	228.46	< 0.0001		
WT ²	0.17	1	0.17	58.62	< 0.0001		
HT ²	2.02	1	2.02	698.09	< 0.0001		
AP ²	0.57	1	0.57	195.72	< 0.0001		
Residual	0.040	14	2.892E-003				Not significant
Lack of fit	0.028	10	2.849E-003	0.95	0.5719		
Pure error	0.012	4	3.000E-003				
Cor total	2.76	28					
Fit statistics	Std. Dev	0.054	R ²	0.9853			
	Mean	0.69	Adjusted R ²	0.9707			
	C.V. %	7.82	Predicted R ²	0.9338			
			Adeq	26.275			
			Precision				

Box-Behnken Design (BBD) matrix was created with Design Expert software. It has 30 experimental runs, 04 factors, and 03 levels, as shown in Table 3. The - 1 and + 1 criteria act as upper and lower values of USW parameters.

The specimens of TSFL were made. The TSFL tests were carried out using a semi-automatic, UTM machine (50 kN capacity). The total of 03 TSFL joints were tested, and the mean of recorded values was given as the final value. Table 3 displays the TSFL results of ABS joints.

3 Results and discussion

3.1 Developing parametric empirical relationship (PER)

The PER for ABS joints made using USW were formulated for predicting the TSFL. The AMP, WT, HT, and AP notations represented Welding Amplitude, welding time, holding time, and axial pressure. The response surfaces for USW of ABS plastic sheets are given in Eq. 1 as a function of process

variables.

$$Y = f(\text{AMP}, \text{WT}, \text{HT}, \text{AP}) \tag{1}$$

In order to fit the PER of ABS joints using multiple regression, a response function of 2nd order was utilized. The polynomial USW regression equations of 2nd order were used for generating the response surface "Y."

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j + e_r \tag{2}$$

The polynomial equation of 2nd order for the 04-input independent USW parameters could be represented as:

$$\begin{aligned} \text{TSFL} = & b_0 + b_1 (\text{AMP}) + b_2 (\text{WT}) + b_3 (\text{HT}) + b_4 (\text{AP}) \\ & - b_{11} (\text{AMP}^2) - b_{22} (\text{WT}^2) - b_{33} (\text{HT}^2) \\ & - b_{44} (\text{AP}^2) + b_{12} (\text{AMP} \times \text{WT}) + b_{13} (\text{AMP} \times \text{HT}) \\ & + b_{14} (\text{AMP} \times \text{AP}) + b_{23} (\text{WT} \times \text{HT}) \\ & + b_{24} (\text{WT} \times \text{AP}) + b_{34} (\text{HT} \times \text{AP}) \end{aligned} \tag{3}$$

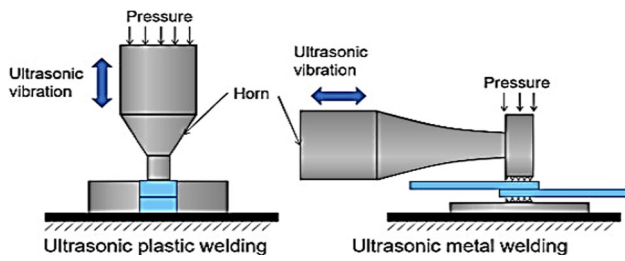


Fig. 3 Comparison between ultrasonic plastic and metal welding [20]

Table 5 Comparing actual TSFL value with PER predicted TSFL value

Run order	SL-TSFL		
	Actual value	Predicted value	% error
9	0.72	0.64	0.17
24	0.83	0.79	0.16
26	1.30	1.34	0.18

where Y = response, X_i and X_j = encoded independent variables, b_0 = mean response and b_i , b_{ii} and b_{ij} = coefficients depending on linear, interaction and quadratic effects of parameters.

For establishing the PER of USW parameters, the regression coefficients may be calculated using the following formulae.

$$b_0 = 0.142857(\sum aY) - 0.035714 \sum a \sum a (X_{ii}Y) \tag{4}$$

$$b_i = 0.041667(\sum aX_iY) \tag{5}$$

$$b_{ii} = 0.03125 \sum a (X_{ii}Y) + 0.00372 \sum a \sum a (X_{ii}Y) - 0.035714(\sum aY) \tag{6}$$

$$b_{ij} = 0.0625 \sum a(X_{ij}Y) \tag{7}$$

Using Design-Expert software, the regression coefficients of 2nd order model for ABS joints were assessed with a 95% level of confidence. The equations with coefficient values were used for establishing PER. The significance of USW regression coefficients was assessed. The non-important regression coefficients of USW were avoided. The PER were formulated utilizing substantial USW coefficients. The equation below is the final PER of TSFL of ABS joints.

$$\begin{aligned} \text{TSFL} = & + 1.24 + 0.068 (\text{AMP}) + 0.056 (\text{WT}) - 0.033 (\text{HT}) \\ & - 0.040 (\text{AP}) - 7.500\text{E} - 003 (\text{AMP} \times \text{WT}) \\ & - 0.11 (\text{AMP} \times \text{HT}) + 0.040 (\text{AMP} \times \text{AP}) \\ & - 0.11 (\text{WT} \times \text{HT}) - 5.000\text{E} - 003 (\text{WT} \times \text{AP}) \end{aligned}$$

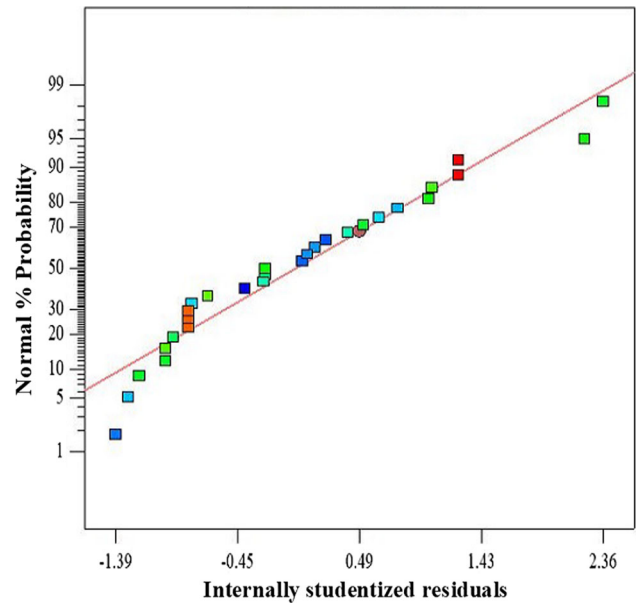


Fig. 4 Residual plot of normal probability of TSFL

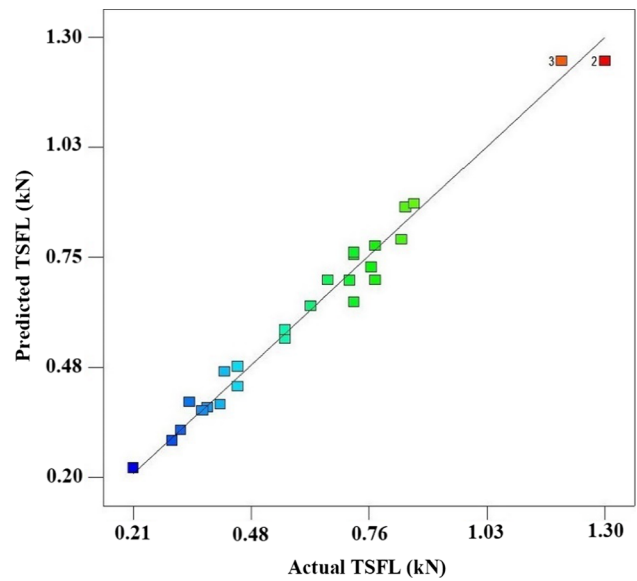


Fig. 5 Plot of actual TSFL (kN) versus predicted TSFL (TSFL) of joints

$$\begin{aligned} & + 5.000\text{E} - 003 (\text{HT} \times \text{AP}) - 0.32 (\text{AMP})^2 \\ & - 0.16(\text{WT})^2 - 0.56(\text{HT})^2 - 0.30 (\text{AP})^2 \text{kN} \tag{8} \end{aligned}$$

where AMP = Amplitude (%), WT = Welding Time (s), HT = Holding Time (s), AP = Axial Pressure (Bar); TSFL = Tensile shear fracture load (kN).

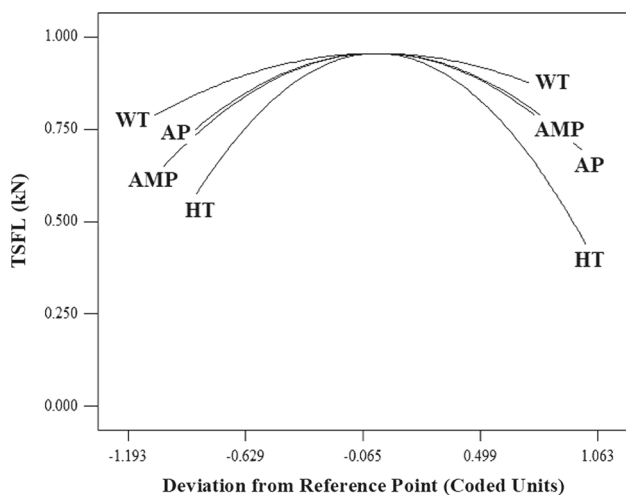


Fig. 6 Perturbation graph for TSFL of ABS joints

3.2 Analysing the validity of formulated PER

The ANOVA (Analysis of Variance) was made to use for validating the formulated PER. Tables 4 reported the findings of ANOVA for TSFL of ABS joints. If standard F ratio is greater than experimental F ratio, then PER is validated for feasibility [34, 35]. The findings proved the feasibility of PER at 95% confidence. The importance of formulated PER was revealed by the estimated F-values of 67.23 for TSFL. This high “model F-value” probability being caused noise is 0.010%. This shows that the TSFL of ABS joints are significantly influenced by USW parameters. Because the values of "prob > F" are lesser than 0.050, the USW parameters clearly

have a major effect. Values over 0.10 demonstrate the minimal parametric influence. For the SL-TSFL and CL-TSFL of LBSW-joints, the lack of fit is not substantial when compared to pure error. For TSFL of ABS joints, the "lack of fit" values is 0.95. Noise may increase the higher "lack of fit" probably by 57.19%. A minor absence of fit values is beneficial. The signal-to-noise ratio is defined by the value of "Adeq. Precision," which must be more than 4.0 to be desirable [36, 37]. The "Adeq. Precision" scores for TSFL is 26.275. This indicates that the model’s signal is sufficient. You may use the PER of TSFL to move about the design space.

Figure 4 shows the plot of normal probability of residuals for the TSFL of ABS joints. The residual points drawn on a straight line show the normal distribution of errors. The justifications made it clear that the PER for the TSFL of ABS joints were validated, and they also made them suitable for use in actual USW. By changing the values of the USW parameter in coded terms, the existing PER for TSFL prediction of ABS joints may be effectively used. The test of conformance was carried out to evaluate the precision of PER. The % error was calculated using the comparison of actual and anticipated TSFL values, as shown in Tables 5. It was determined from the results that the mean % error in TSFL prediction is not more than 1.0%. Figure 5 displays the plot for the actual and predicted values of TSFL of ABS joints. Figure 6 illustrates the perturbation plot for TSFL of ABS joints which contrasts the impact of USW parameters at a specific region in the design space. The sensitivity of ABS joints for TSFL at their respective levels of USW parameters is displayed in the perturbation plot by steep curvature associated with USW parameters.

Table 6 Numerical optimization criteria

Name	Objective	Lower limit	Upper limit	Importance
Amplitude, AMP (%)	In range	70	90	–
Welding time, WT (s)	In range	1.5	2.5	–
Axial pressure, AP (bar)	In range	1.5	2.5	–
Holding time, HT (s)	In range	4	6	–
TSFL (kN)	Maximize	0.21	1.30	5

Table 7 Optimized solution for TSFL of USWed ABS joints

Sr. No	AMP (%)	WT (s)	HT (s)	AP (Bar)	TSFL (kN)	Desirability	Decision
1	81.10	2.10	4.94	1.97	1.25	0.995	Selected

Table 8 Optimized USW parameters for welding ABS plastic sheets

Condition	AMP (%)	WT (s)	HT (s)	AP (Bar)	TSFL (kN)
Experimental optimization	80	2.0	5.0	2.0	1.30
Predicted by RSM	81.10	2.10	4.94	1.97	1.25

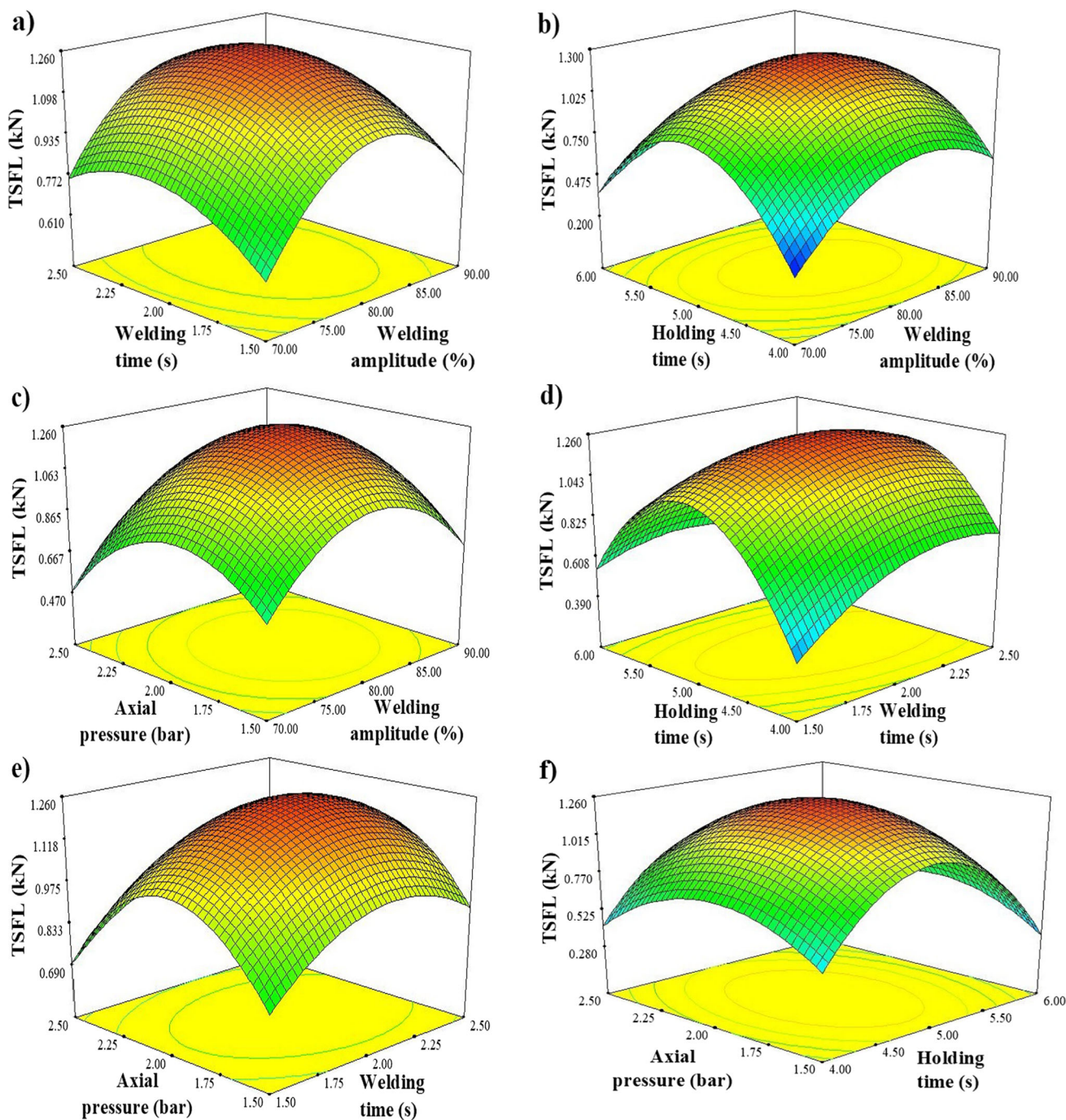


Fig. 7 Response surface graphs of ABS joints: a WT versus AMP, b HT versus AMP, c AP versus AMP, d HT versus WT, e AP versus WT, f AP versus HT

3.3 Optimization of USW parameters

The parametric combination of USW that satisfies the demands set on factors and responses concurrently is identified by the optimization module. A multi-objective problem is designed to increase the TSFL strength of ABS joints. To increase the TSFL of ABS joints, the existing PER was utilized to optimize the USW parameters. Table 6 displays

the USW parameter’s higher and lower values, its relevance level, and the goal of the optimization research. Based on the maximizing criteria selected for the optimization research, Table 7 provides the combinations of USW parameters. For joining ABS plastic sheets, the USW parameter was selected based on desirability function. For joining ABS plastic sheets, the USW parameters with the greatest desirability

function of 0.995 was selected as the ideal process parameters.

Figure 7a–f show the 3D response surfaces showing greater TSFL of ABS joints by red coloured top region. The results showed that the ABS joints created using the welding amplitude of 80%, welding time of 2.0 s, axial pressure of 2.0 bar, and holding time of 5.0 s exhibited greater TSFL of 1.30 kN. Table 8 shows the optimum actual and expected USW values for joining ABS plastic sheets. The findings indicated good agreement between the experimental and predicted USW parameter and TSFL of ABS joints. The predictions revealed that the ABS joints created using the welding amplitude of 81.10%, welding time of 2.10 s, axial pressure of 1.97 bar, and holding time of 4.97 s exhibited greater TSFL of 1.25 kN.

4 Conclusions

1. The 3.0 mm thick ABS plastic sheets were lap welded successfully using solid state ultrasonic welding (USW) without defects.
2. The ultrasonic welding (USW) parameters specifically welding amplitude, welding time, holding time and axial pressure were optimized to maximize the tensile shear fracture load (TSFL) of ABS joints.
3. The ABS joints welded using welding amplitude of 80%, welding time of 2.0 s, holding time of 5.0 s and axial pressure of 2.0 bar disclosed greater TSFL of 1.30 kN.
4. The parametric empirical relationship (PER) was formulated using the equations of regressions. It correctly predicted the TSFL of ABS joints with less than 1% error.
5. The prediction showed that the ABS joints lap welded using amplitude of 81.10%, welding time of 2.10 s, holding time of 4.94 s and axial pressure of 1.97 bar disclosed greater TSFL of 1.25 kN.
6. Holding time is the most predominant parameter in USW of ABS plastic sheets. It significantly influences the TSFL of ABS joints followed by axial pressure, welding time and amplitude.
7. The optimal USW parameters set are locally optimal rather than globally optimal. The PER used to predict the optimal process parameter set is applicable locally.

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