Predicting the load-bearing capability of resistance spot welded advanced high strength DP-1000 steel spot joints for automotive structural and body frame applications

P. Rajalingam[1], S. Rajakumar[2*], V. Balasubramanian[3], Tushar Sonar[4], S. Kavitha[5]

[1,2,4]*Centre for Materials Joining and Research (CEMAJOR), Annamalai University, Annamalai Nagar, Tamil Nadu, India.*
[4]*Centre for Welding and Additive Manufacturing (C-WAM), G. S. Mandal's Maharashtra Institute of Technology, Aurangabad, Maharashtra, India.*
[5]*Department of Electronics and Instrumentation Engineering, Annamalai University, Annamalai Nagar, Tamil Nadu, India.*

KEYWORDS

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Resistance Spot Welding,
Optimization,
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ABSTRACT

Resistance spot welding (RSW) is used to overcome the issues in fusion welding of DP-1000 steel such as softening in heat affected zone (HAZ), solidification cracking, high thermal residual stresses and distortion. The main objective of this investigation is to develop the empirical relationships to predict the tensile shear fracture load bearing capability of spot joints for automotive applications. The three factor – three level box-behnken design (3X3-BBD) consisting ofless experiments was chosen for developing the experimental matrix. The lap tensile shear fracture load (LAP-TSFL) and cross tensile shear fracture load (CROSS-TSFL) tests were performed to determine the load bearing capability of spot joints. The empirical relationships of LAP-TSFL and CROSS-TSFL of spot joints were developed using polynomial regression equations incorporating the process parameters in coded form. Analysis of Variance (ANOVA) was executed to check the viability of developed empirical relationships for LAP-TSFL and CROSS-TSFL. The empirical relationship accurately predicted the LAP-TSFL and CROSS-TSFL capability of spot joints with less than 1% error at 95% confidence level.

1. Introduction

The joining of AHSS steel by fusion welding is difficult due to its complex dual phase microstructure and higher strength. It leads to the problems in welding such as softening in heat affected zone (HAZ), solidification cracking, high thermal residual stresses and distortion due to the high heat input and slower cooling rate. This significantly deteriorates the mechanical performance of joints. Hence the fusion welding processes finds less suitability for joining AHSS steel in automotive applications (Rajarajan et al., 2022). Dual phase 1000 (DP-1000) steel is an advanced high-strength steel (AHSS), typically developed by controlling the rate of cooling from austenitephase (γ) in hot rolled sheets or from the ferrite plus austenitephase (α + γ) in cold-rolled sheets to convert some austenite (γ) to ferrite (α) before rapid cooling to modify the residual austenite to martensite (Chabok et al., 2019). The microstructure of DP steel shows a soft matrix of ferrite containing a second phase of hard martensite which leads to many beneficial effects including a high rate of initial work hardening, ductility and strength (Xue et al., 2017). This makes it an important high strength lightweight material for automotive applications.

*Corresponding author,
E-mail: srkcemajor@yahoo.com

In this investigation resistance spot welding (RSW) used to join DP-1000 steel to develop spot welds of superior quality and high strength. RSW is a type of solid-state welding (SSW) process which involves resistive heating of joining surfaces under pressure at a temperature less than melting point of metal. This significantly reduces the welding related problems in joining DP-1000 steel such as softening in HAZ, solidification cracking, residual stresses and distortion. Li et al. (2014) investigated the evolution of weld pool and temperature field modelling of LB welded DP-1000 steel joints and observed that the width of soft HAZ and its distance from the centre of weld increases with increase in the power of laser. Aydin (2015) studied the dissimilar RSW of DP-600 and DP-1000 steel using different levels of welding current and found that increase in welding current up to 10 Ka results in increase in the tensile shear loads (TSL) of the joints.

The spot joints developed using lower levels of welding current (8 to 9.5 kA) failed on the side of DP-1000 steel, while the spot joints developed using the higher levels of welding current (10 to 11 kA) fractured on the side of DP-600 steel. Rocha et al. (2015) investigated the tensile properties and microstructure of butt joints of DP-1000 steel developed using gas metal arc welding (GMAW) process and observed significant softening in HAZ owing to the tempering of martensite. Alves et al. (2017) performed investigation on LBW of DP-1000 steel and concluded that the spot joints made using 2.0 kW laser power and 150 mm/s laser welding speed reduces the softening of HAZ. Khraisat et al. (2018) investigated the influence of direction of rolling on tensile strength and microstructure of DP-1000 steel joined by GMAW and found that the HAZ softening does not influence the tensile strength of joints for the specimens joined parallel to the direction of rolling. Chabok et al. (2018) studied the influence of single and double pulsing modes on cross tension strength and microstructure of DP1000-GI sheets joined by RSW and observed that double pulsing at lower level of welding current decreases the energy absorption capacity and cross-tension strength of spot joints. Pizzorni et al. (2019) investigated the static and fatigue behavior of DP-1000 steel joints developed by ductile adhesive - RSW and observed that the combination of RSW with epoxy-polyurethane greatly increases fatigue life of joints.

From the literature it is well understood that lots of research work have been carried on LBW of DP-1000 steel. Some research papers are reported on RSW of DP-1000 steel. However, they are mainly associated with the microstructural characterization and strength of joints. There is a lack of stastical investigation on optimization of RSW parameters for joining thin sheets of D-P1000 steel carries significant importance in automotive sector. Research is still going on for enhancing joint performance of DP-1000 steel joints. So, the main objective of this research work is to study the optimization of RSW parameters for joining thin sheets of DP-1000 steel using response surface methodology (RSM) to maximize the tensile shear fracture load (TSFL) capability of spot joints.

2. Experimental Methodology

1.2 mm thick cold-rolled steel sheets of DP-1000 steel were employed for the optimization of process parameters. The elemental composition of DP-1000 steel is shown in Table 1 and mechanical properties are presented in Table 2. The sheets were obtained in the size of

Table 1
Chemical composition (wt.%) of DP1000 steel sheets.

C	Si	Mn	P	Cr	Ni	Al	Cu	Nb	Fe
0.012	0.48	1.44	0.021	0.012	0.02	0.04	0.01	0.01	Balance

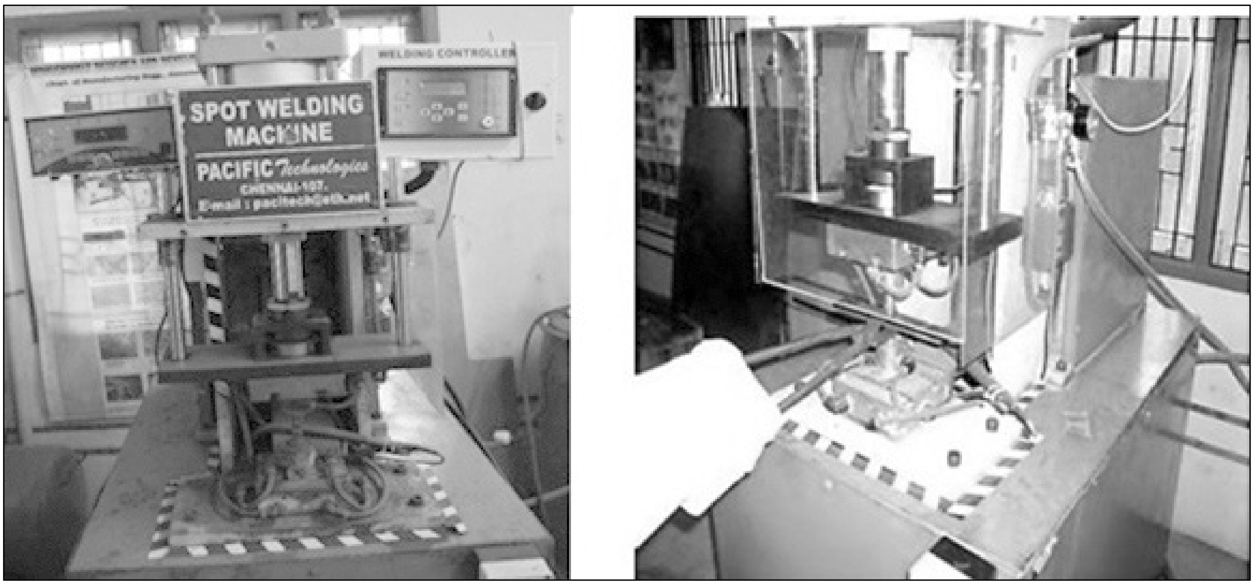

Fig. 1. Photographic view of the RSW machine.

300 x 300 x 1.2 mm. The sheets were sheared to make the specimens of tensile shear fracture load (TSFL). Figure 1 shows the dimensions of Lap-TSFL and Cross-TSFL specimens. The rocker-arm foot operated type RSW machine (semi-automatic) was employed for joining DP-1000 steel sheets of 1.2 mm thickness as shown in Figure 2. The welding current (A), welding time (T), and electrode pressure (P) were found to be the most significant input parameters influencing the shear strength of RSW spot joints. A Conical type water-cooled electrode made of copper (Cu) was employed for the present investigation with dimensions of 16 mm shank and 5 mm lid diameter. The diameter of Cu electrode tip was determined as 6 mm from the equation d=4√t, where t is the thickness of the sheet in mm. Extensive trials with a combination of various RSW parameters were performed to determine the possible working limits for joining DP-1000 steel. Figure 3 displays the cause-and-effect diagram showing the working limits of RSW for developing the lap joints of DP-1000 steel. The feasible limits were determined by analysing the influence of copper electrode impression formed on the both sides of steel sheets, hot expulsion at weld spots, and other defects in RSW. Response surface methodology (RSM) is commonly employed for optimizing process parameters. The main idea of RSM is to develop an experimental design to attain an optimal condition of process parameters. Table 3 shows the three factors and five levels of RSW parameters that were utilised to develop the matrix of box-behnken design (BBD). Design Expert 7.0 software was used to generate the BBD matrix. As given in Table 4, it includes 17 experimental runs, 3 factors, and 3 levels. Upper and lower values of RSW factors are represented by the encoded conditions -1 and +1. For the evaluating the lap tensile shear fracture load and cross tensile shear fracture load, the cut specimens were joined using RSW machine inlap joint configuration. The spot joints were developed without the defects of solidification cracking and porosity. Figure 4 shows the macrographs of spot joints showing no defects of fusion welding. The TSFL specimens were developed using the ASTM (E8-13) standard.

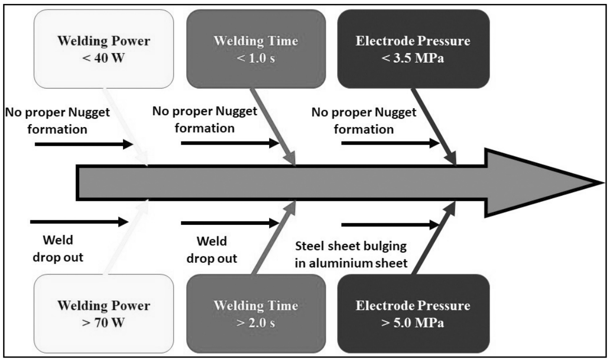

Fig. 2. Working limits of process paraemters for RSW of DP-1000 steel sheets.

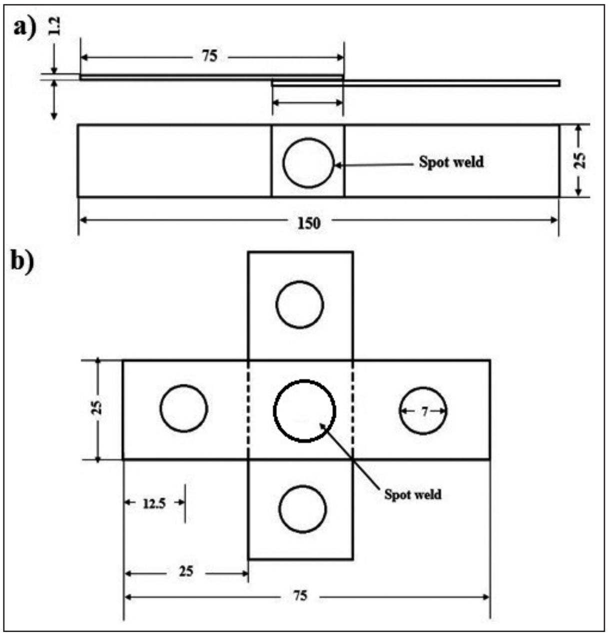

Fig. 3. Dimensions of tensile shear fracture load test specimen: a) LAP-TSFL; b) CROSS-TSFL.

Table 2
Mechanical properties of DP1000 steel sheets.

Tensile Strength (MPa)	0.2% Yield Strength (MPa)	Elongation in 50 mm gauge length (%)	Micro-hardness ($HV_{0.5}$)
1048	806	27	340

Table 3
Working limits of the process parameters.

Sr. No.	Parameter	Notation	Units	Level		
				-1	0	+1
1.	Welding power	W	Watt	40	55	70
2.	Welding time	T	Second	1.0	1.5	2.0
3.	Electrode pressure	P	MPa	3.5	4.25	5

Table 4
Design matrix of actual, coded values and their corresponding outputs.

Exp. No	Coded value			Original value			LAP-TSFL (kN)	CROSS-TSFL (kN)
	W	T	P	W (W)	T (s)	P (MPa)		
1	-1	-1	0	40	1	4.25	15.1	7.14
2	1	-1	0	70	1	4.25	22	9.1
3	-1	1	0	40	2	4.25	19.43	8.31
4	1	1	0	70	2	4.25	21.23	7.62
5	-1	0	-1	40	1.5	3.5	15	6.2
6	1	0	-1	70	1.5	3.5	19.2	7.38
7	-1	0	1	40	1.5	5	16.2	6.3
8	1	0	1	70	1.5	5	20.63	6.34
9	0	-1	-1	55	1	3.5	17	6.9
10	0	1	-1	55	2	3.5	20.7	7.45
11	0	-1	1	55	1	5	20.16	7.1
12	0	1	1	55	2	5	20	6.34
13	0	0	0	55	1.5	4.25	16.5	6.86
14	0	0	0	55	1.5	4.25	16.55	6.88
15	0	0	0	55	1.5	4.25	16.5	6.88
16	0	0	0	55	1.5	4.25	16.6	6.9
17	0	0	0	55	1.5	4.25	16.6	6.9
(Where, Welding Power =W; Welding time =T; Electrode pressure =P; Lap tensile shar fracture load =LAP-TSFL; Cross tensile shar fracture load =CROSS-TSFL								

A semi-automatic servo-controlled universal testing machine with a maximum capacity of 50 kN was used to perform the tensile shear strength (TSS) tests. The TSFL specimens were loaded at 1.5 kN/min until the joint surfaces were sheared. Three TSFL specimens were tested and the average was reported as final reading. The TSFL results are reported in Table 5.

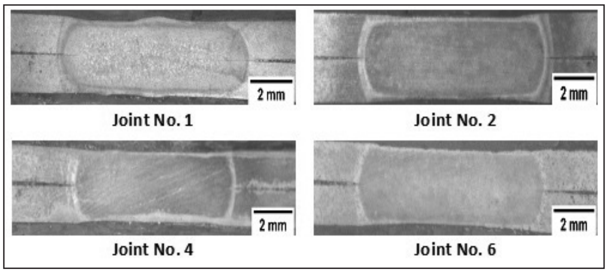

Fig. 4. Typical macrograph of spot joints showing no defects.

3. Results and Discussion

3.1 Development of empirical relationships

The empirical relationships for spot joints of DP-1000 steel was established for predicting the lap tensile shear fracture load (LAP-TSFL) and cross tensile shear fracture load (CROSS-TSFL).

The welding power, welding time and electrode pressure were represented as W, T and P respectively. In equation 1, the response surface for RSW of DP-1000 steel is provided as a function of process parameters.

$$Y = f(W, T, P) \qquad ....(1)$$

For the present prediction, RSW's 2^{nd} order regression model was chosen above the 1^{st} order model, which only approximates the genuine response surface in a smaller region. Multiple regression of a 2^{nd} order response function was used to the mathematical model of RSW parameters. For the development of the response surface 'Y,' the polynomial RSW regression equation of 2^{nd} order was used.

Table 5
ANOVA test results for LAP-TSFL.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	84.27	9	9.36	4591.4	< 0.0001	**significant**
W	37.54	1	37.54	18408.95	< 0.0001	
T	6.3	1	6.3	3089.93	< 0.0001	
P	3.24	1	3.24	1588.06	< 0.0001	
W X T	6.5	1	6.5	3188.62	< 0.0001	
W X P	0.0132	1	0.0132	6.49	0.0383	
T X P	3.72	1	3.72	1826.57	< 0.0001	
W^2	1.47	1	1.47	721.77	< 0.0001	
T^2	22.25	1	22.25	10910.43	< 0.0001	
P^2	1.6	1	1.6	784.1	< 0.0001	
Residual	0.0143	7	0.002			
Lack of Fit	0.0043	3	0.0014	0.57	0.6639	**not significant**
Pure Error	0.01	4	0.0025			
Cor Total	84.28	16				
	Std. Dev.	0.0452	**R^2**	0.9998		
Fit Statistics	**Mean**	18.2	**Adjusted R^2**	0.9996		
	C.V. %	0.2481	**Predicted R^2**	0.999		
			Adeq Precision	201.5666		

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

The polynomial equation of second order for the three-input independent RSW parameters could be represented as:

$Y=\{\beta_0 + \beta_1 (W) + \beta_2 (T) + \beta_3(P)+\beta_{12}(W X T)+\beta_{13}(W X P)+ \beta_{23} (T X P) + \beta_{11} (W)^2 + \beta_{12} (T)^2 + \beta_{23} (P)^2\}$ ....(3)

where Y = response, Xi and Xj = encoded independent variables, b_0 = mean response and bi, bii and bij = co efficients depending on linear, interaction and quadratic effects of parameters.

The equations below can be used to calculate the regression coefficients for mathematical modelling of RSW.

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

$b_i = 0.041667 (\sum aX_iY)$ ....(5)

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

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

The regression coefficients of the 2nd order model for spot joints of DP-1000 steel were evaluated with 95 percent confidence using the Design-Expert 13.0 software. The parametric empirical relationships were formulated using the afore mentioned equations with coefficient values. A T-test and backward elimination were used to determine the significance of RSW regression coefficients. The RSW regression coefficients and answers that were insignificant were eliminated without affecting the prediction accuracy. The empirical relationships were developed using significant RSW coefficients. The following are the final empirical relationships of LAP-TSFL and CROSS-TSFL of spot joints.

LAP-TSFL (kN) = + 16.55 + 2.16625 (W) + 0.8875 (T) + 0.63625 (P) - 1.275 (W x T) + 0.0575 (W x P) - 0.965 (T x P) + 0.59125 (W^2) + 2.29875 (T^2) + 0.61625 (P^2) ....(8)

CROSS-TSFL (kN) = + 6.884 + 0.3025 (W) - 0.05625(T) - 0.23125 (P) - 0.645(W x T) - 0.285 (W x P) - 0.3275 (T x P) + 0.37425 $(W)^2$ + 0.76675 $(T)^2$ - 0.70325 $(P)^2$ ....(9)

Table 6
ANOVA test results for CROSS-TSFL.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	8.54	9	0.9487	4760.56	< 0.0001	**significant**
W	0.732	1	0.732	3673.37	< 0.0001	
T	0.0253	1	0.0253	127.02	< 0.0001	
P	0.4278	1	0.4278	2146.73	< 0.0001	
W X T	1.66	1	1.66	8350.32	< 0.0001	
W X P	0.3249	1	0.3249	1630.32	< 0.0001	
T X P	0.429	1	0.429	2152.81	< 0.0001	
W^2	0.5897	1	0.5897	2959.26	< 0.0001	
T^2	2.48	1	2.48	12421.32	< 0.0001	
P^2	2.08	1	2.08	10449.12	< 0.0001	
Residual	0.0014	7	0.0002			
Lack of Fit	0.0003	3	0.0001	0.3274	0.8071	**not significant**
Pure Error	0.0011	4	0.0003			
Cor Total	8.54	16				
	Std. Dev.	0.0141	**R^2**	0.9998		
Fit Statistics	**Mean**	7.09	**Adjusted R^2**	0.9996		
	C.V. %	0.1991	**Predicted R^2**	0.9993		
			Adeq Precision	261.3803		

Table 7
Comparison of actual experimental value with RSM predicted value for LAP-TSFL.

Run Order	LAP-TSFL		
	Actual Value	Predicted Value	% Error
7	17	16.98	0.12
9	16.6	16.55	0.30
13	16.5	16.55	-0.31

Table 8
Comparison of actual experimental value with RSM predicted value for CROSS-TSFL.

Run Order	CROSS-TSFL		
	Actual Value	Predicted Value	% Error
4	6.34	6.33	0.16
9	6.9	6.88	0.29
12	7.38	7.37	0.14

Where W = Welding power, T = Welding time, P= Electrode pressure

3.2 Checking viability of the developed empirical relationships

Analysis of Variance (ANOVA) and analysis of regression was employed to check the viability of the developed EMPIRICAL RELATIONSHIPs. The results of ANOVA for LAP-TSFL and CROSS-TSFL are presented in Table 5 and 6. The EMPIRICAL RELATIONSHIPs were proved to be viable if the standard F ratio (from table) is higher than the calculated F ratio at a given level of confidence. The results showed that the developed empirical relationships are viable at 95% confidence level. The estimated F-value of 4591.4 and 4760.56 for LAP-TSFL and CROSS-TSFL reported the significance of the developed empirical relationships. The probability of this high "model F-value" due to noise is 0.01%. This indicates that RSW parameters extends significant effects on LAP-TSFL and CROSS-TSFL of spot joints. The values of "prob > F" are less than 0.05 which shows significant effect of RSW parameters. Values greater than 0.1 shows the insignificant parametric effect. Compared to pure error, the lack of fit is not significant for LAP-TSFL and CROSS-TSFL of spot

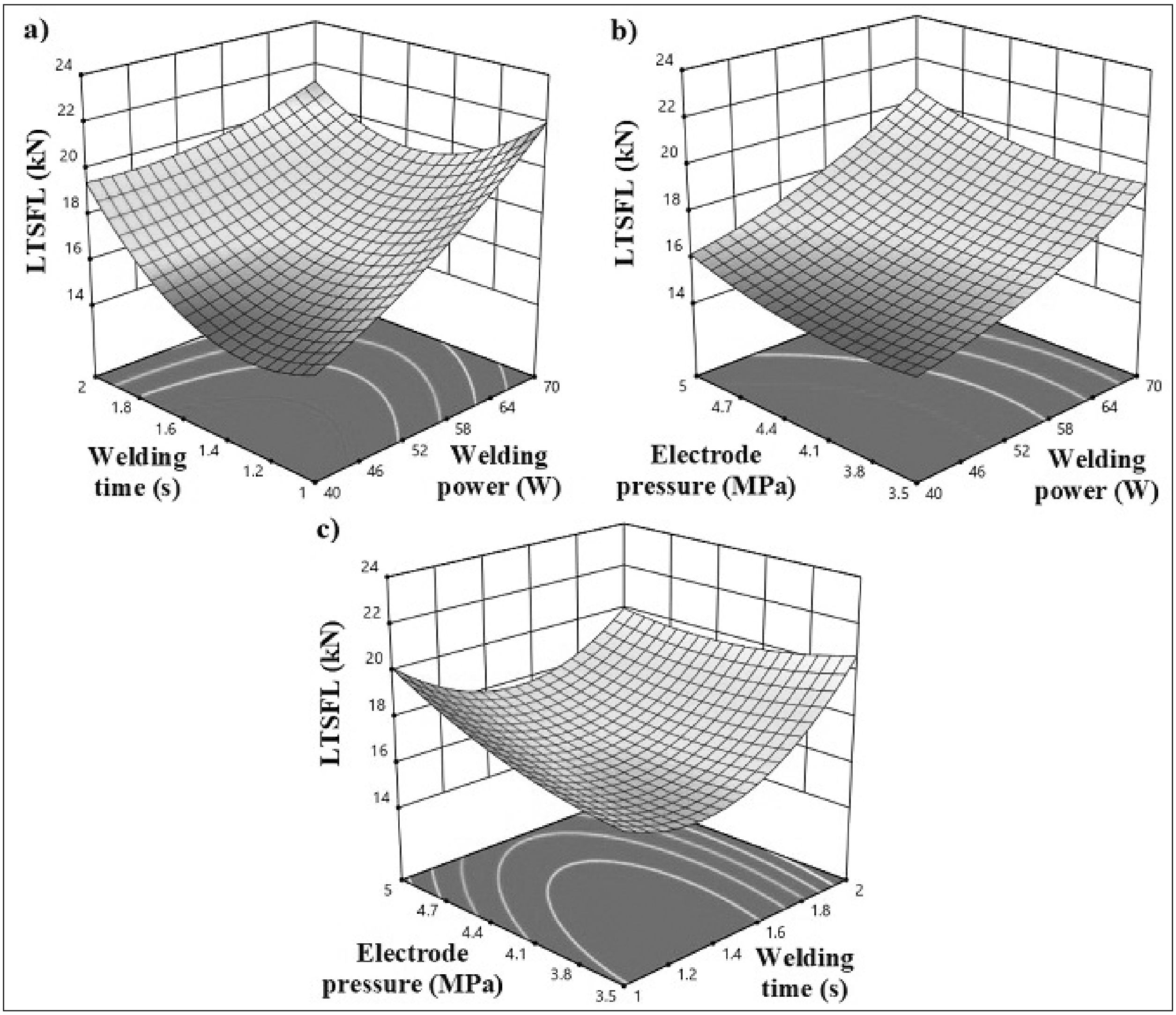

Fig. 5. 3D response surface graphs for LAP-TSFL of spot joints: a) welding power vs welding time, b) welding power vs electrode pressure, c) welding time vs electrode pressure.

joints. The "lack of fit" values for LAP-TSFL and CROSS-TSFL of spot joints are of 0.57 and 0.33. The probability of larger "lack of fit" for LAP-TSFL and CROSS-TSFL is 66.39% and 80.71% respectively. The value of "Adeq. Precision" defines the ratio of signal to noise and for desirability it must be larger than 4.0. The values of "Adeq. Precision" for LAP-TSFL and CROSS-TSFL are 201.570 and 261.380 which shows the adequate signal of the model. The empirical relationships of LAP-TSFL and CROSS-TSFL can be employed to navigate the space of design. The developed parametric LAP-TSFL and CROSS-TSFL mathematical models can be employed efficiently for predicting the LAP-TSFL and CROSS-TSFL of DP-1000 steel spot joints by substituting the values of RSW parameter in coded terms. To check the accuracy of LAP-TSFL and CROSS-TSFL mathematical models, the test of conformity was done. The actual and predicted LAP-TSFL and CROSS-TSFL values were compared and the percentage error was determined as shown in Table 7 and 8. Results showed that the percentage error for LAP-TSFL and CROSS-TSFL is not greater than 1.0%.

3.3 Optimization

- Development of 3D response surfaces (Experimental optimization)

The developed empirical relationships were used to create 3D response surfaces that illustrate the process window and optimal region of RSW parameters. The 3D response surface graphs for LAP-TSFL and CROSS-TSFL of DP-1000 steel spot joints are presented in Figure 5 and 6. The higher values of LAP-TSFL and CROSS-TSFL are shown by the orange-colored zone. Experimental

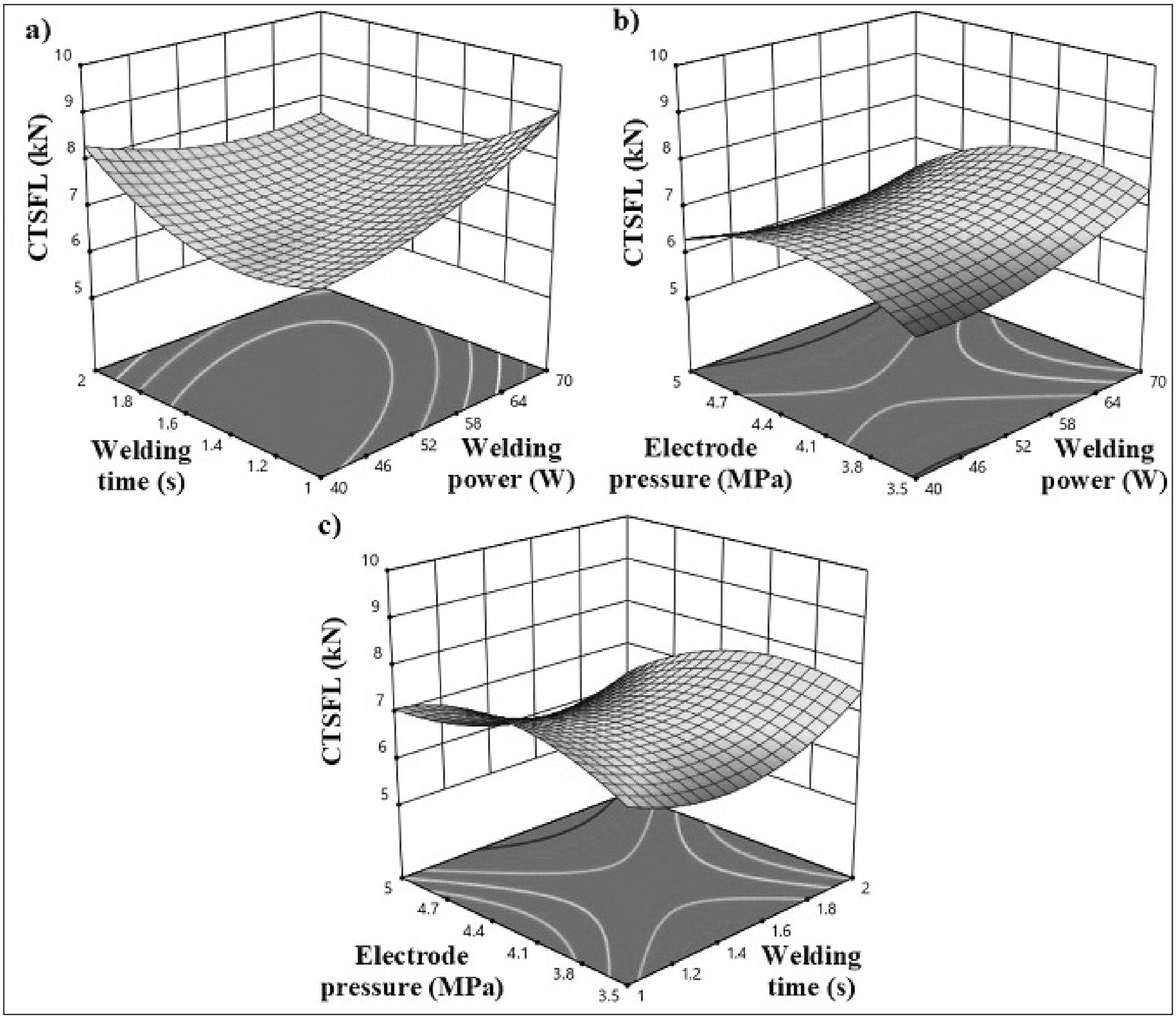

Fig. 6. 3D response surface graphs for CROSS-TSFL of spot joints: a) welding power vs welding time, b) welding power vs electrode pressure, c) welding time vs electrode pressure.

Table 9
Optimized RSW parameters and TSFL properties.

Condition	W (W)	T (s)	P (MPa)	LAP-TSFL (kN)	CROSS-TSFL (kN)
Experimental	70	1.0	4.25	22	9.1
Predicted	69.979	1.0	4.259	22.008	9.024

results showed that the joints made using the welding power of 70 W, welding time of 1.0 s and electrode pressure of 4.25 MPa exhibited higher LAP-TSFL of 22 kN and CROSS-TSFL of 9.1 kN. Table 9 shows the optimal values of process parameter for joining DP-1000 steel, as determined by tests and predicted by RSM. The maximum LAP-TSFL of 22.008 kN and CROSS-TSFL of 0.024 kN were predicted for the welding power of 69.979 W, welding time of 1.0 s and electrode pressure of 4.259 MPa. Thus, the optimized process parameters under the conditions of experimental and prediction are in similar. Also, the LTSFL, CTSFL, and NZH of spot joints of DP-1000 steel under the conditions of experimental and prediction are also quite similar.

4. Conclusions

1. The RSW parameters were optimized using response surface methodology (RSM) for joining DP-1000 steel to maximize lap tensile shear fracture load (LAP-TSFL) and cross tensile shear fracture load (CROSS-TSFL) capability of spot joints.

2. The empirical relationships developed using regression equations accurately predicted the LAP-TSFL and CROSS-TSFL of spot joints with less than 1% error and at 95% confidence level.
3. The experimental results showed that the spot joints made using welding power of 70 W, welding time of 1.0 s and electrode pressure of 4.25 MPa exhibited maximum LAP-TSFL of 22kN and CROSS-TSFL of 9.1 kN respectively.
4. The prediction by RSM showed that the spot joints made using welding power of 69.979 W, welding time of 1.0 s and electrode pressure of 4.259 MPa exhibited maximum LAP-TSFL of 22.008 kN and CROSS-TSFL of 9.024 kN respectively.
5. Welding power is the most significant parameter in RSW of DP-1000 steel which influences the LAP-TSFL and CROSS-TSFL capability of spot joints followed by welding time and electrode pressure. It is mainly due to the resistive heating of nugget offered by the welding power which significantly influences the nugget formation and TSFL of spot joints.

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P. Rajalingam is working as a Senior Technical Trainer in Dubai. He is completing his Ph.D Manufacturing Engineering (Welding) from Annamalai University. He completed his M.E (Manufacturing Engineering) from Anna University and B.E (Mechanical Engineering) from JRNRV University. He has a total of 3 years of work experience in research and one year of teaching. His research interests include Different Welding, Advanced Materials for Automobile use.
(E-mail: hairaju1976@gmail.com)

Dr. S. Rajakumar is working currently as Associate Professor from Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, India. He completed his graduation (Mechanical and Production Engineering), post-graduation (Production Engineering) and Ph.D (Production Engineering) from Annamalai University, Chidambaram. He has 18 years of teaching experience and 15 years of research experience. He has published more than 60 papers in SCOPUS indexed Journals and his 'h' index is 20. He has supervised 3 Ph.D Scholars and guiding 6 more scholars. He has completed 8 R & D projects worth of Rs. 1.5 crores from various funding agencies. His areas of interest are Materials Joining, Surface Engineering and Optimization.

Dr. V. Balasubramanian is currently working as Director for Directorate of Research and Development (DRD) in Annamalai University. He is Professor & Director of Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University. He has h-index of 52 and is included in top 2% scientist list in materials by Stanford University, USA. He graduated from Government College of Engineering, Salem, University of Madras in 1989 and obtained his post-graduation from College of Engineering Guindy, Anna University, Chennai in 1992. He obtained his Ph.D from Indian Institute of Technology Madras (IITM), Chennai in 2000. He has 28 years of teaching and 25 years of research experience. He has published 420 research papers in international journals and supervised 22 Ph.D scholars. His areas of interest are Materials Joining, Surface Engineering and Nanomaterials. (E-mail: visvabalu@yahoo.com)

Dr. Tushar Sonar is working as a Research Assistant Professor in G. S. Mandal's Maharashtra Institute of Technology, Aurangabad. He completed Ph.D Manufacturing Engineering (Welding) from Annamalai University in the year 2021. He is a recipient of ISRO RESPOND research fellowship. He has published 30 research papers in international peer reviewed journals and presented 14 research papers in international conferences. He has total of 6 years of work experience including teaching, industry and research. His research interests include Welding and Joining, Additive Manufacturing and Heat Treatment of Metals.
(E-mail: tushar.sonar77@gmail.com / tushar.sonar@mit.asia)

Dr. S. Kavitha is working as Assistant Professor, Department of Electronics and Instrumentation Engineering, NPMaSS National MEMS Design Centre, Annamalai University, Annamalai Nagar. She completed her graduation (Electronics and Instrumentation Engineering) and post-graduation (Process Control and Instrumentation Engineering) from Annamalai University in 1997 and 2002 respectively. She obtained her Ph.D (Microelectronics and MEMS) from Annamalai University in 2015. She has a total of 18 years of teaching experience, 1 year of industrial experience and 10 years of research experience. She has completed 4 R&D projects worth of Rs. 68 lakhs from various funding agencies like DST, AICTE and UGC. Her areas of research interests are Microelectronics and MEMS, Structural Health Monitoring and IoT. She received 'Best Researcher Grant Award' from Annamalai University in the year of 2017.
(E-mail: kaviraj_2003@rediffmail.com)