Establishing empirical relationships to predict the tensile shear fracture properties of resistance spot welded advanced high strength steel lap joints

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KEYWORDS

Resistance Spot Welding, Advanced High Strength Steel, Tensile Shear Fracture Load, Microstructure, Nugget Hardness.

ABSTRACT

The joining of advanced high strength steel (AHSS) of type dual phase 800 (DP800) by fusion welding is challenging owing to its high strength and complex microstructural features. It leads to softening of heat affected zone (HAZ) and cracking due to the high heat input associated with fusion welding processes. This significantly deteriorates the tensile shear fracture properties of DP800 steel joints. To overcome this problem, resistance spot welding (RSW) is employed to join DP800 steel thin sheets. It involves resistive heating of joining surfaces under pressure at a temperature less than melting point of parent metal. This significantly reduces the issues in joining DP800 steel such as softening in HAZ, solidification and HAZ cracking and offers precise spot weld. The tensile shear fracture properties of joints are influenced by RSW parameters such as welding current, welding time, and electrode force. Hence, establishing empirical relationships to predict the tensile shear fracture properties of joints is crucial. So, the main objective of this investigation is to establish empirical relationships to predict the tensile shear fracture properties of resistance spot welded dual phase 800 steel lap joints using regression analysis. The optimal process window of RSW is established using response surface methodology (RSM) to attain superior tensile shear fracture properties of DP800 steel joints.

1. Introduction

Advanced high-strength steel (AHSS) is new generation steel that combines high-strength and lower weight properties while maintaining formability, which is critical in the fabrication processes. It is primarily used for fabricating automotive structures in sheet form (Fonstein, 2017). The joining of AHSS by fusion welding is difficult due to its high strength properties and complex microstructure. It leads to the problems in welding such as wider fusion zone (FZ) and heat affected zone (HAZ), softening in HAZ, solidification and HAZ cracking, high residual stresses due to the high heat input (Mazaheri et al., 2014). When the AHSS is heated to the tempering temperature during fusion welding, its softness primarily owing to the transformation of existing hard martensite into soft tempered martensite and carbides precipitation (Nesterova et al., 2015). This significantly deteriorates the mechanical performance of AHS-DP800 steel joints. In this investigation resistance spot welding (RSW) is used to join advanced high strength steel (AHSS) to develop spot welds of superior quality and mechanical performance. RSW is a type of solid-state welding (SSW) process. It involves resistive heating of joining surfaces under pressure at a temperature less than melting point of metal (Zhang et al., 2011). This will significantly reduce the problems in joining AHSS such as softening in HAZ, solidification, and HAZ cracking lower residual stresses, and ensues precise spot weld (Shome & Tumuluru, 2015).

Advanced high strength dual phase 800 (AHS-DP800) steel is a class of AHSS that contains 50% ferrite and 50% martensite phases. It leads to many advantages such as a high work hardening rate, ductility, and superior strength (Rajarajan et al., 2018). These properties prove their viability as high strength lightweight material and are widely

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Table 1
Chemical composition (wt.%) of DP800 steel.

C	Si	Mn	Cr	P	S	Ni	Mo	Ti	Fe
0.146	0.88	1.500	0.025	0.007	0.0036	0.027	0.0018	0.0016	balance

accepted by automobile manufacturers. It helps in achieving lower emission, better mileage, fuel efficiency, weight reduction, and crashworthiness (Li, 2011). It is employed in the fabrication of structural frames and doors in trucks and light passenger vehicles. They are offering a promising approach in manufacturing next-generation lightweight vehicles. Each vehicle contains nearly 10,000 spot welds. It is economical, shop friendly and provides a high production rate. Compared to fusion welding processes, it can be easily automated and maintained. The weld nugget size and associated tensile shear strength are commonly used to check the quality of RSW joints. The microstructure and strength of the nugget are influenced by RSW parameters such as welding current, welding time, and electrode force. Hence process parameter optimization in RSW is crucial to maximizing the performance of joints (Ambroziak & Korzeniowski, 2010).

Response surface methodology (RSM) is commonly employed for optimizing process parameters. It is a set of mathematical equations used to develop a design matrix for predicting the responses. RSM is also utilized to fit the empirical relationships to data obtained from the developed design matrix (Sonar et al., 2021a). Manickam et al. (2020) optimized friction stirs spot welding parameters for joining AA6061 and copper alloy to attain superior shear fracture strength using RSM. Sonar et al. (2020a) optimized process parameters using RSM to attain optimal weld bead geometry of Inconel 718 welds. Sonar et al. (2020b) established empirical relationships and performed process parameter optimization using RSM to enhance the yield strength and elongation of welded joints. Padmanaban and Balasubramanian (2011) optimized FSW parameters using RSM to maximize joint strength of AZ31B magnesium alloy joints. Rajakumar and Balasubramanian (2015) developed RSW empirical equations to predict tensile shear fracture load in interstitial free steel spot welds. Karthikeyan and Balasubramanian (2010) optimized friction stir spot welding (FSSW) parameters using RSM attained superior lap shear strength of AA2024 aluminum alloy welds. Eshraghi et al. (2014) optimized RSW parameters for joining DP600 steel and observed that welding time and sheet thickness significantly influence join properties. Mirzaei et al. (2017) optimized RSW parameters using RSM for joining AHS-DP steels and found that the interaction effect of RSW parameters significantly influences nugget and shear strength of joints. Khodabakhshi et al. (2012) optimized RSW parameters for joining ultra-fine-grained steel using RSM to attain superior join performance. Akulwar et al. (2021) optimized RSW parameters using RSM for joining AHS-DP780 steel and found hardness variation across the nugget cross section. The literature review confirms that the research work on the RSW of AHS-DP800 steel is limited. There is a lack of statistical investigation on process parameter optimization in RSW of AHS-DP800 steel using RSM. This shows the requirement of further research in optimization of process parameters for joining AHSS materials such as AHS-DP800 steel. The tensile shear fracture properties of joints are influenced by RSW parameters such as welding current, welding time, and electrode force. Hence, establishing empirical relationships to predict the tensile shear fracture properties of joints is crucial. So, the main objective of this investigation is to establish empirical relationships to predict the tensile shear fracture properties of resistance spot welded advanced high strength steel lap joints.

Table 2
Mechanical properties of DP800 steel.

0.2% offset Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation in 50mm gauge length (%)	Micro-hardness (HV)
604	832	26	295

2. Experimental Methodology

2.1 Material selection and specimen preparation

Cold-rolled steel sheets of AHS-DP800 steel with a thickness of 1.6 mm are employed for the optimization study of RSW parameters. The chemical composition and mechanical properties of AHS-DP800 steel are presented in Tables 1 and 2. The alloying elements in AHS-DP800 steel assist the evolution of twin phase microstructures of ferrite and martensite. The sheets were received in the size of 300 x 300 x 3 mm. The sheets were cut as per the required dimensions of lap and cross TSFL specimens illustrated in Figure 1. The joining surfaces were washed with isopropyl alcohol to eliminate the dirt and oil residues from the shearing and milling processes.

2.2 Identification of RSW parameters

The semi-automatic medium frequency type RSW machine was employed for joining AHS-DP800 steel sheets of 1.6mm thickness as shown in Figure 2. The one factor at a time approach of DOE was employed by researchers to identify the significant process parameters of welding processes (Sonar et al., 2020c; Sonar, Malarvizhi, Balasubramanian, 2020; Sonar et al., 2021a, 2021b). The welding current (I), electrode pressure (P), and welding time (T) were found to be the most significant input parameters influencing thenugget formation, microstructural features, and strength of AHS-DP800 steel joints in the earlier investigations (Rajarajan et al., 2020a, 2020b; Rajarajan, Sivaraj, Seeman, Balasubramanian, 2020).

2.3 Developing Central Composite Design (CCD) matrix and joints preparation

A Conical type water-cooled electrode was used with dimensions of 16mm shank and 5mm lid diameter. The diameter of the electrode tip was determined as 6mm from the equation $d=4\sqrt{t}$, where t is the thickness of the plate in mm. Extensive trials with a combination of various RSW parameters were performed to determine the possible working limits for joining AHS-DP800 steel. Figure 3 displays the cause-and-effect diagram working limits of RSW for developing the lap joints of AHS-DP800 steel. The feasible limits were determined by analyzing the impact of copper electrodes formed on both the sies of steel, hot expulsion at weld spots, and visually detecting other RSW defects. Table 3 displays 3 factors and 5 levels of RSW parameters used for developing the CCD matrix. CCD was developed by Design Expert 7.0 software. It comprehends 20 experimental runs (2k=8 factorial points, nc=6 centre points, and 2k=6 axial points), 3 factors, and 5 levels (+/-α, +/-1, and 0) as displayed in Table 4. The encoded conditions -1.689 and +1.689 represent upper and lower levels of RSW factors. The cut specimens were joined using an RSW machine in lap joint configuration for lap tensile and cross tensile shear strength determination as per ANSI/AWS/SAE/D8.9–9 standards. The RSW joints of AHS-DP800 steel were developed as per experimental runs.

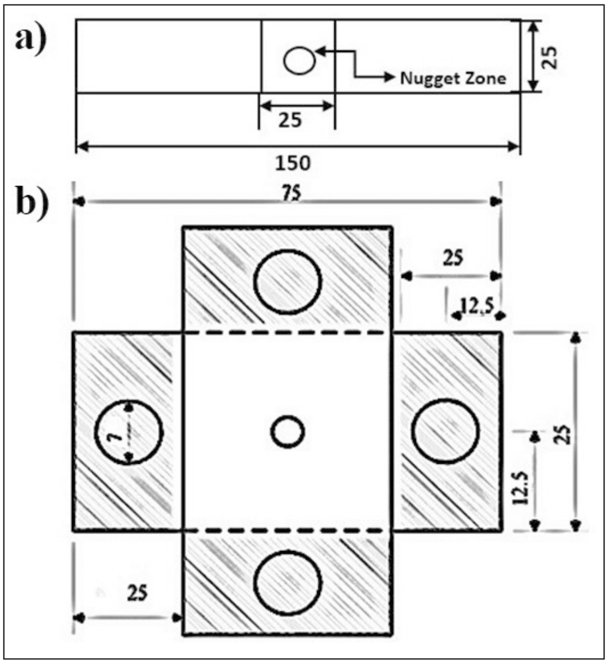

Fig. 1. Dimension of TSFL specimens:
a) LAP-TSFL and b) CROSS-TSFL.

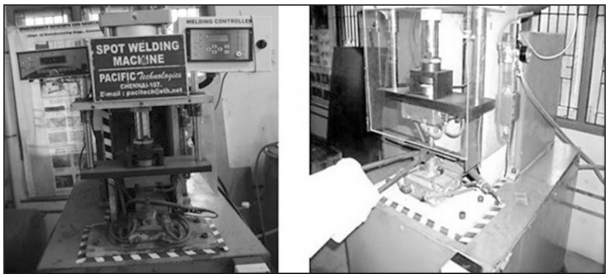

Fig. 2. Photograph of RSW machine.

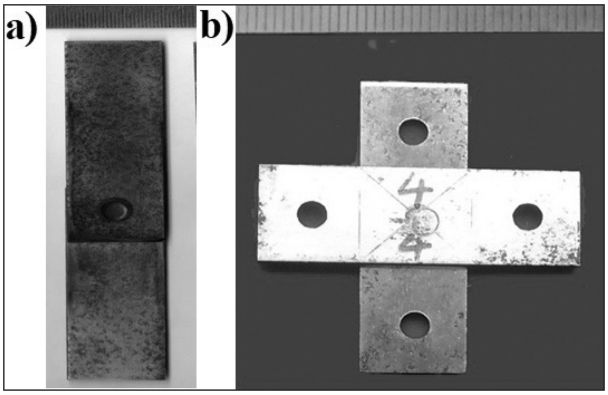

Fig. 3. Photograph of typical TSFL specimens of RSW DP800 steel joints:
a) LAP-TSFL; b) CROSS-TSFL

Table 3
Working limits of the process parameters.

Parameter	Notation	units	Levels				
			-1.68	-1	0	+1	+1.68
Welding current	WC	kA	4.0	4.5	5.0	5.5	6.0
Electrode pressure	EP	MPa	3.5	3.75	4.0	4.25	4.5
Welding time	WT	s	0.5	1.0	1.5	2.0	2.5

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

Exp. No	Coded value			Original value			LAP-TSFL (kN)	CROSS-TSFL (kN)
	WC	EP	WT	WC (kA)	EP (MPa)	WT (s)		
1	-1	-1	-1	4.5	3.75	1.00	13.71	10.93
2	1	-1	-1	5.5	3.75	1.00	11.61	12.63
3	-1	1	-1	4.5	4.25	1.00	12.66	11.37
4	1	1	-1	5.5	4.25	1.00	10.3	9.94
5	-1	-1	1	4.5	3.75	2.00	14.78	12.4
6	1	-1	1	5.5	3.75	2.00	15.87	13.17
7	-1	1	1	4.5	4.25	2.00	10.48	11.33
8	1	1	1	5.5	4.25	2.00	15.97	10.97
9	-2	0	0	4.0	4.00	1.50	9.56	8.59
10	2	0	0	6.0	4.00	1.50	12.77	9.94
11	0	-2	0	5.0	3.50	1.50	10.67	12.33
12	0	2	0	5.0	4.50	1.50	12.5	10.57
13	0	0	-2	5.0	4.00	0.50	8.5	8
14	0	0	2	5.0	4.00	2.50	8.37	9.25
15	0	0	0	5.0	4.00	1.50	21.38	17.3
16	0	0	0	5.0	4.00	1.50	21.7	17.21
17	0	0	0	5.0	4.00	1.50	21.3	17.02
18	0	0	0	5.0	4.00	1.50	21.1	17.37
19	0	0	0	5.0	4.00	1.50	21	17.18
20	0	0	0	5.0	4.00	1.50	21.4	17.65

(Where, Welding current = WC; Electrode pressure = EP; Welding time = WT; Lap tensile shar fracture load = LAP-TSFL; Cross tensile shar fracture load = CROSS-TSFL; Nugget zone hardness = NZH)

2.4 Testing of tensile shear fracture load and hardness of weld nugget

The AHS-DP800 RSW joints were developed following ASTM (E8-13) standard to determine the TSFL of RSW joints. The LAP-TSFL and CROSS-TESFL test was conducted employing a semi-automatic servo-controlled Universal testing machine with a maximum capacity of 1000 kN. The TSFL specimens were loaded at a rate of 1.5 kN/min until the shearing of joint surfaces. The photograph of typical RSW joints of AHS-DP800 steel (Lap-TSFL and Cross-TSFL specimens) before and after testing are shown in Figure 4.

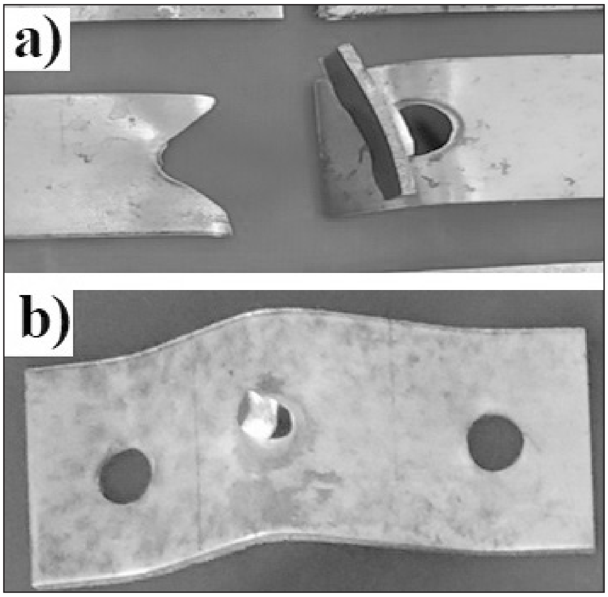

Fig. 4. Failure of optimized joint of RSW DP 800 steel: a) LAP-TSFL and b) CROSS-TSFL specimen.

2.5 Macro and microstructure

The sound RSW lap joints cut along the longitudinal direction of spot weld and polished. The polished RSW metallographic specimens were etched by Villella's reagent for studying the macro and microstructural features. It was developed as a mixed solution of 1 gram picric acid, 5ml HCl, and 100ml ethanol. The macrostructure of RSW joints of DP 800 steel was analyzed at low magnification 100x using stereozoom microscope. The optical microscope was employed to study the microstructural features such as nugget and HAZ of RSW DP 800 steel joints.

3. Results and Discussion

3.1 Establishing empirical relationships

The parametric mathematical relationship for RSW of AHS-DP800 steel joints was established for nugget hardness, lap tensile (Lap-TSFL), and cross tensile shear fracture load (Cross-TSFL). The RSW parameters such as welding current, electrode pressure,and welding time were encoded as I, P, and T respectively. The response for RSW joints of AHS-DP800 steel joints was measured for LAP-TSFL and CROSS-TSFL.

The response surface for joining AHS-DP800 steel joints by RSW is given as a function of process parameters such as I, P, and T in equation 1.

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

The 2nd order model of regression in RSW was chosen for the current forecast rather than the 1st order model, which only approximates the true response surface in a smaller region. The empirical relationships of RSW parameters were subjected to multiple regression of response function of 2nd order. The polynomial RSW regression equation of 2nd order employed for developing response surface 'Y' is

$$Y=b_0+\sum b_i\, x_i+\sum b_{ii}\, x^2_i+\sum b_{ij}x_ix_j+e_r \qquad ....(2)$$

For the 3-input independent RSW parameters the polynomial equation of 2nd order could be written as:

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

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

The regression coefficients for empirical relationships of RSW could be evaluated by employing the equations given below.

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

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

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

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

The Design-Expert 7.0 software was utilized to evaluate the regression coefficients of 2nd order model for RSW joints of AHS-DP800 steel at 95% confidence. From the aforementioned equations with coefficient values, the fundamental RSW mathematical equations were built. The insignificant RSW regression coefficients and responses were removed without influencing the prediction accuracy. Significant RSW coefficients were used to formulate the RSW parametric mathematical equations. The final RSW mathematical equations are given below:

$$\text{LAP-TSFL (kN)} = -913.57 + 9.42\,(I) + 350.27\,(P) - 10.26409\,(T) - 0.086\,(I \times P) + 0.80200\,(I \times T) + 3.16\,(P \times T) - 0.101\,(I^2) - 43.93\,(P^2) - 13.84\,(T^2) \quad \text{..........(8)}$$

$$\text{CROSS-TSFL (kN)} = -691.74 + 10.43\,(I) + 214.64\,(P) + 20.98\,(T) - 0.63\,(I \times P) + 0.11\,(I \times T) + 0.98\,(P \times T) - 0.08\,(I^2) - 23.32\,(I^2) - 10\,(I^2) \quad \text{..........(9)}$$

Where I = Welding current, P = Electrode Pressure, T = Welding Time

3.2 Proficiency verification of established RSW parametric models

Tables 5 to 7 summarize the results of the ANOVA analysis for the responses data values as alongas their FIT statistics such as adjusted R^2 and predicted R^2 values. The F value and p-values of RSW parametric equations were implemented for adequacy verification of models in prediction and developing response surface for RSW of AHS-DP800 steel joint. The RSW model is proficient if F ratio (from table) > F ratio of developed RSW parametric equations. The developed RSW parametric model is proficient with 95% confidence.

The F-value of 2476 and 1145.47 for LAP-TSFL and CROSS-TSFL of joints displays the significance of RSW parametric equations. The chance of this high "model F-value" trending as a result of noise is only 0.01%. It implies that RSW parameters

Table 5
ANOVA test results for LAP-TSFL.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	512.00	9	56.89	2476.00	< 0.0001	**significant**
WC	11.46	1	11.46	498.70	< 0.0001	
EP	0.59	1	0.59	25.47	0.0005	
WT	3.57	1	3.57	155.47	< 0.0001	
WC X EP	0.092	1	0.092	4.02	0.0727	
WC X WT	32.16	1	32.16	1399.72	< 0.0001	
EP X WT	1.25	1	1.25	54.33	< 0.0001	
WC^2	160.73	1	160.73	6995.72	< 0.0001	
EP^2	189.58	1	189.58	8251.06	< 0.0001	
WT^2	301.16	1	301.16	13107.44	< 0.0001	
Residual	0.23	10	0.023			
Lack of Fit	0.046	5	9.152E-003	0.25	0.9235	**not significant**
Pure Error	0.18	5	0.037			
Cor Total	512.23	19				
	Std. Dev.	0.15	**R^2**	0.9996		
Fit Statistics	**Mean**	11.29	**Adjusted R^2**	0.9991		
	C.V. %	1.34	**Predicted R^2**	0.9988		
			Adeq Precision	137.976		

Table 6
ANOVA test results for CROSS-TSFL.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	236.65	9	26.29	1145.47	< 0.0001	**significant**
WC	1.81	1	1.81	78.81	< 0.0001	
EP	3.10	1	3.10	134.94	< 0.0001	
WT	0.25	1	0.25	10.89	0.0080	
WC X EP	4.90	1	4.90	213.39	< 0.0001	
WC X WT	0.57	1	0.57	24.94	0.0005	
EP X WT	0.12	1	0.12	5.23	0.0453	
WC^2	100.96	1	100.96	4398.06	< 0.0001	
EP^2	53.42	1	53.42	2327.07	< 0.0001	
WT^2	157.16	1	157.16	6846.11	< 0.0001	
Residual	0.23	10	0.023			
Lack of Fit	2.073E-003	5	4.147E-004	9.115E-003	0.9856	**not significant**
Pure Error	0.23	5	0.045			
Cor Total	236.88	19				

	Std. Dev.	0.15	**R^2**	0.9990		
Fit Statistics	**Mean**	7.52	**Adjusted R^2**	0.9982		
	C.V. %	2.01	**Predicted R^2**	0.9986		
			Adeq Precision	95.678		

Table 7
Prediction of the joint characteristics of RSW DP800 steel joints and % error.

Condition	LAP - TSFL (kN)	% Error	CROSS - TSFL (kN)	% Error
Experimental	21.70	0.60	17.65	1.78
Predicted	21.57		17.34	

Table 8
Optimized RSW parameters for joining DP800 steel.

Condition	WC (kA)	EP (MPa)	WT (s)	LAP-TSFL (kN)	CROSS-TSFL (kN)
Experimental	5.0	4.0	1.50	21.70	17.65
Predicted	5.05	3.99	1.53	21.57	17.34

have significant effect on TSFL of joints, as well as NZH. The p-values are less than 0.05. It indicates important RSW terms in equations. The p-values > than 0.1000 indicate insignificant RSW parameters. Welding current is most significant parameter influencing the LAP-TSFL of joints followed by welding time and electrode pressure. Electrode pressure extends significant influence on CROSS-TSFL of joints followed by welding current and time. Welding time was found to exhibit a major effect on NZH of joints followed by welding current and electrode pressure. The lack of fit specifically 0.25 and 0.18, are insignificant for LAP-TSFL and CROSS-TSFL. For RSW parametric equations. The Pred. R^2 and Adj. R^2 is in good confirmation for mathematical equations of RSW. The "Adeq. Precision" refers to signal to noise ratio which should be more than

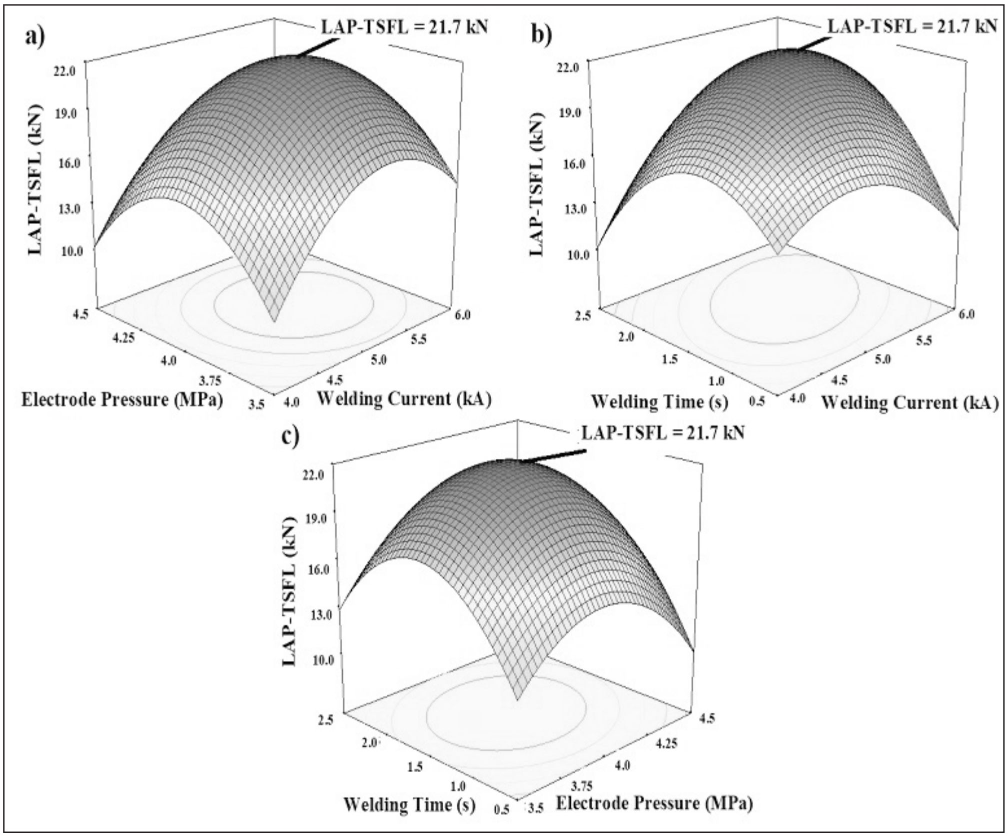

Fig. 5. 3D response surface graphs for LAP-TSFL.

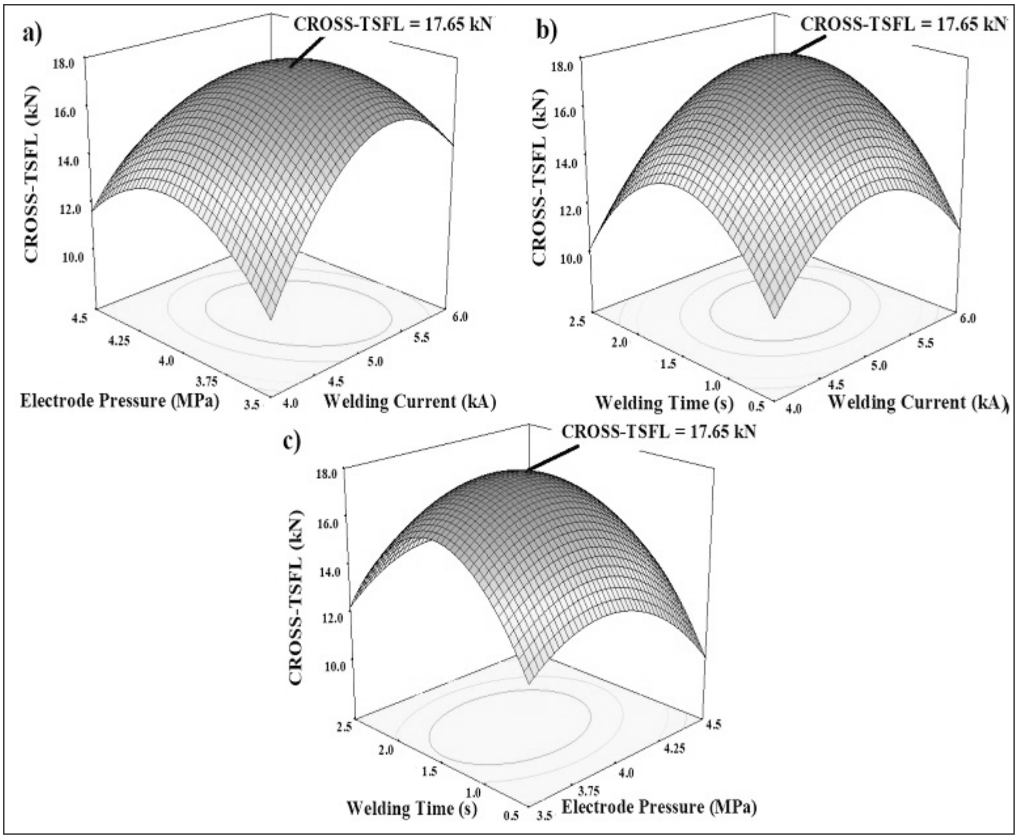

Fig. 6. 3D response surface graphs for CROSS-TSFL.

4 to achieve desirability. The RSW model competency is shown by Adeq. The precision ratio is 137.976 and 95.678 for LAP-TSFL and CROSS-TSFL. The given conditions demonstrate proficiency of RSW parametric mathematical equations and their practical use in joining AHS-DP800 steel.

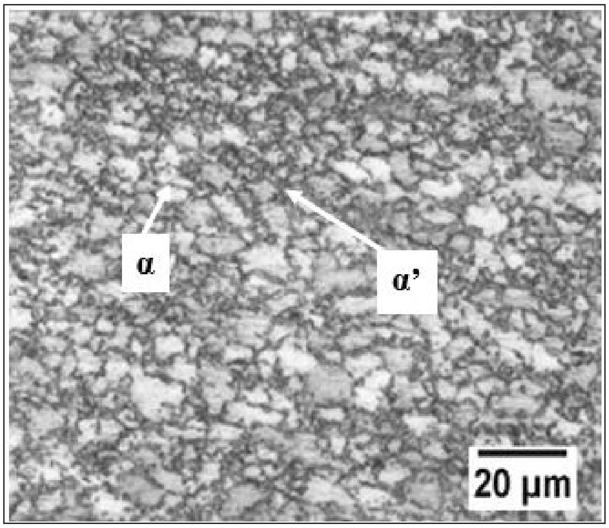

Fig. 7. Optical microstructure of DP800 steel.

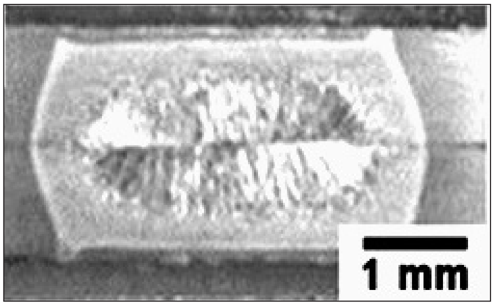

Fig. 8. Macrostructure of AHSS-DP800 RSW joints.

The mathematical equations of RSW parameters can predict LAP-TSFL and CROSS-TSFL of AHS-DP 800 steel joints by putting the values of RSW parameters in coded form. The RSW empirical relationships were passed through a conformity test to ensure that they were consistent. Table 8 compares the experimental and predicted values of LAP-TSFL and CROSS-TSFL and calculated % error. The average inaccuracy for RSW equations of LAP-TSFL and CROSS-TSFL is less than 2%. The experimental values of LAP-TSFL and CROSS-TSFL are near to the values predicted by RSW equations. Thus, the above results indicate that the RSW parametric empirical relationships are significant and suitable for predicting the LAP-TSFL and CROSS-TSFL of AHS-DP800 steel RSW joints.

3.3 Development of 3D response surfaces for optimization of RSW parameters

The RSW welding of AHS-DP800 steel is a multi-objective problem, intending to achieve maximum LAP-TSFL and CROSS-TSFL of spot joints. The 3-dimensional (3D) response surfaces were developed employing the established empirical relationships which show the process window and optimum region of RSW parameters to maximize LAP-TSFL and CROSS-TSFL of joints. Figure 5 and 6 shows 3-dimensional response surface graphs for LAP-TSFL and CROSS-TSFL of RSW DP800 joints. The maximum value of LAP-TSFL and CROSS-TSFL of RSW AHS-DP800 steel joints is displayed by the red-colored ascent portion. It shows that the RSW joints of AHS-DP800 steel made using welding current of 5.0 kA, electrode pressure of 4.0 MPa, and welding time of 1.50 s

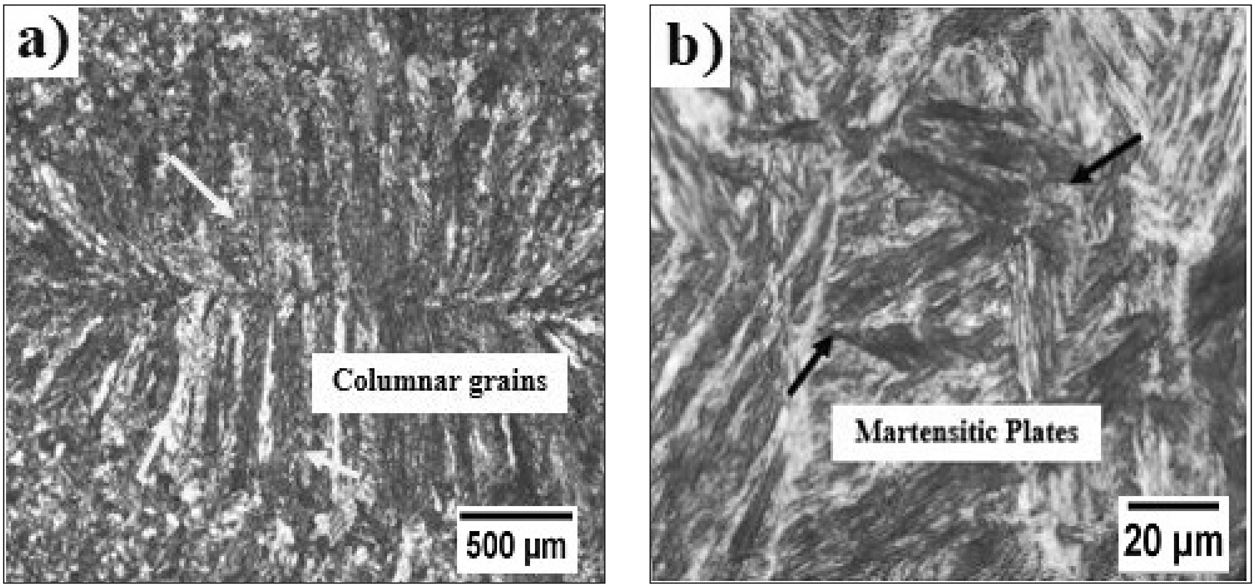

Fig. 9. Optical microstructure of weld NZ: a) lower magnification; b) higher magnification.

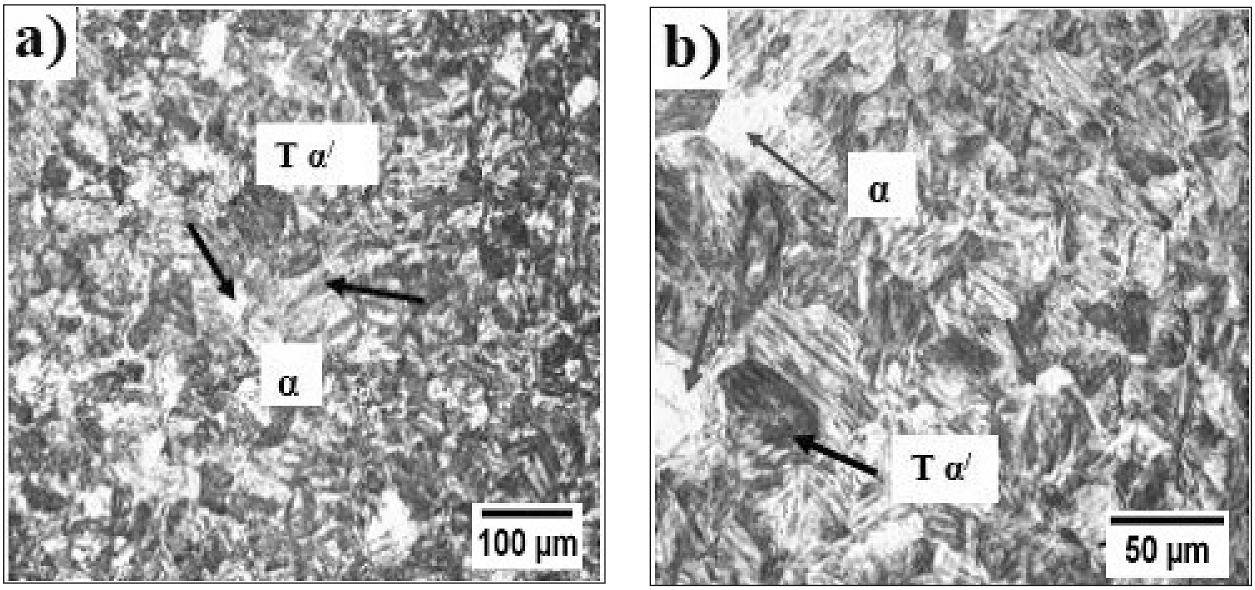

Fig. 10. Optical microstructure of CG-HAZ: a) lower magnification; b) higher magnification.

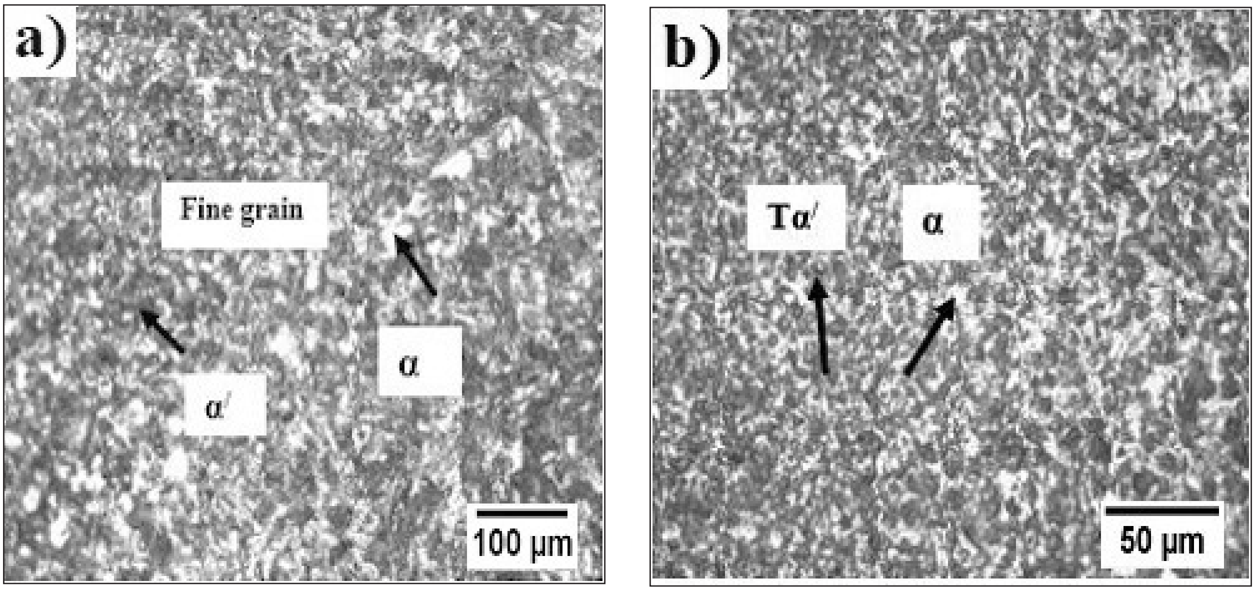

Fig. 11. Optical microstructure of FG-HAZ: a) lower magnification; b) higher magnification.

displayed maximum LAP-TSFL of 21.7 kN and CROSS-TSFL of 17.65 kN.

Table 9 indicates the optimum values of RSW parameters for joining AHS-DP800 steel obtained from experiments and predicted by RSM. The maximum LAP-TSFL of 21.57 kN and CROSS-TSFL of 17.34 kN were predicted for the RSW conditions for joining AHS-DP800 steel as welding current of 5.05 kA, electrode pressure of 3.99 MPa, and welding time of 1.53 s. Thus, the optimized RSW parameters in experimental and prediction conditions are resembling closer. Also, the LAP-TSFL and CROSS-TSFL of joints under the experimental and predicted conditions are closely resembling.

3.4 Microstructure

Figure 7 displays the optical microstructure of DP 800 steel. It reveals the presence of ferrite along with martensite. The average grain size of ferrite phase and martensite phase is 7-9 μm and 3-7 μm respectively. The macrostructure of RSW spot joint of AHSS-DP800 steel is shown Figure 8. The macrostructure showed no weld defects. The weld defects and imperfections were analyzed by the macrostructural characteristics of the weldments. The optical microstructures of NZ, CG-HAZ, FG-HAZ at lower and higher magnification are shown in Figures 9, 10, and 11. The NZ microstructure shows dynamic recrystallization of grains exhibiting a columnar structure.

This formation suggests the formation of martensite and bainite phases in the ferrite matrix during solidification. The superior tensile shear fracture properties of DP800 steel RSW joints are attributed to the evolution of needle/lath-like martensitic structure in nugget zone.

4. Conclusions

1. The resistance spot welding (RSW) parameters (welding current, electrode pressure and welding time) were optimized using response surface methodology (RSM) for joining thin AHS-DP800 steel sheets for fabrication of automotive structural frames.
2. The empirical relationships were established using regression analysis to predict the Lap tensile and cross tensile shear fracture load (LAP-TSFL and CROSS-TSFL) of spot joints at 95% confidence with less than 2% error.
3. The 3-dimensional (3D) response surfaces were developed employing the developed mathematic models which show the process window and optimum region of RSW parameters to maximize the LAP-TSFL and CROSS-TSFL of joints.
4. The maximum LAP-TSFL of 21.57 kN and CROSS-TSFL of 17.34 kN was predicted for the RSW conditions for joining AHS-DP800 steel as the welding current of 5.05 kA, electrode pressure of 3.99 MPa, and welding time of 1.53 s respectively
5. The RSW joints of AHS-DP800 steel made using the welding current of 5.0 kA, electrode pressure of 4.0 MPa, and welding time of 1.50 s displayed maximum LAP-TSFL of 21.7 kN and CROSS-TSFL of 17.65 kN indicating good agreement with the predicted results.
6. The results of ANOVA indicate that welding current, electrode pressure, and welding time significantly influence the LAP-TSFL and CROSS-TSFL joints respectively.
7. The superior tensile shear fracture properties of DP800 steel RSW joints are attributed to the evolution of needle/lath-like martensitic structure in the nugget zone.

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