Effect of copper electrode pressure on nugget diameter and mechanical performance of resistance spot welded thin DP800 steel sheets

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ABSTRACT

DP800 is an advanced high strength steel containing duplex microstructure of ferrite and martensite phases. It is broadly used in automotive structural frame applications owing to its high strength to weight ratio. DP steel is mainly joined by resistance spot welding (RSW) to avoid the problems of solidification cracking and severe HAZ softening. In this study, the effect of copper electrode pressure on nugget diameter and mechanical performance of resistance spot welded 1.2 mm thick DP800 steel sheets are investigated. The tensile shear strength (TSS) properties were evaluated in straight lap (SL-TSS) and cross lap (CL-TSS) joint configuration. Results showed that the DP-800 steel spot joints developed using the electrode pressure of 4.0 MPa exhibited superior SL-TSS of 830 MPa and CL-TSS of 684 MPa. It is attributed to the evolution of finer martensitic needles in nugget zone.

KEYWORDS

Dual-Phase Steel,
Resistance Spot Welding,
Tensile Shear Strength,
Microstructure,
Electrode Pressure.

1. Introduction

The advanced high strength steels (AHSS) of dual phase 800 (DP-800) grade is widely preferred in fabrication of thin walled automotive structural frames in battey electric vehicle (BEV's) applications (Fonstein, 2017). DP-800 steel is more popular among AHSS steel in BEV's due to the superior mechanical and metallurgical properties. The researchers concern DP-800 steel as being more attractive to automakers due to its high strength-to-weight ratio (Mazaheri et al. 2014). In conventional fusion welding processes, high heat input causes wider heat affected zones (HAZ) and premature failure in the weld joint (Rajarajan et al. 2022). The failure occurred due to the decomposition of martensite islands into softer islands of tempered martensite in HAZ, which reduces the joint efficiency (Li, 2011). Resistance spot welding is a relatively low heat input process, with a minimum width of the heat affected zone and less degree of premature failure for welding of thin sheet (Ambroziak and Korzeniowski, 2010).

Wan et al. (2014) studied the influence of welding current on spot welded DP600 steel and temperature distribution along the weld zone by a numerical model. The nugget size and shape are highly dependent on welding current. Kishore et al. (2019) studied the weldability and failure behavior of galvanized and bare DP600 steel joints. They revealed critical nugget diameter to be 4.4 mm and transition of mode of failure from interfacial to pull out failure in the welded joint. The interfacial fracture occurred because of the small nugget diameter. Aslanlar et al. (2008) studied the impact welding time on resistance spot welded micro-alloyed steel. The higher welding time causes high heat input in the outer region of the electrode surface so failure initiated from HAZ through the base metal. Baltazar Hernandez et al. (2010) investigated the softening behavior of heat affected region in resistance spot welded Dual-phase steel through nanoindentation. They analyzed individual ferrite and tempered martensite grains in the subcritical cooling region. Also, they reported tempered martensite in the form of a broken appearance of about 100 µm. Santos et al. (2019) studied the defect identification of RSW DP600 and DP800 steel. They found globular aluminum oxide inclusion initiates the voids defects in the weldment.

Resistance spot welding (RSW) being a solid-state welding (SSW) process is used to overcome the problems in fusion welding of AHSS DP800 steel such as HAZ softening, solidification cracking,

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Table 1
Chemical composition (wt-%) of parent metal.

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	bal

Table 2
Mechanical properties of parent metal.

Material	0.2% offset Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation in 50 mm gauge length (%)	Microhardness (HV)
DP-800	604	832	26	295

HAZ cracking and distortion which significantly deteriorates the mechanical properties of AHS DP800 steel joints. In previous investigations, RSW parameters were optimized to attain superior load bearing capability of DP-800 steel using response surface methodology (Rajarajan et al. 2022). Increase in welding current results in increase in nugget diameter and tensile shear strength (TSS) properties up to 5.5 kA. Further increase results in significant reduction in TSS properties of joints (Rajarajan et al. 2020). The literature on resistance spot welding of AHS steel principally pertains to DP600 steels (Nesterova et al. 2015; Liao et al. 2010; Akulwar et al. 2021; Ramazani et al. 2015). However limited limited research work is being reported on DP-800 steel. This expains the necessity of further experimental work in investigating the direct effect of RSW parameters for joining DP-800 steel. The direct effect of RSW parameters on nugget formation and TSS properties of AHS DP-600 steel is studied by researchers. Neverthless, a definite relationship between RSW parameters, nugget formation, microstructure and TSS properties of joints will evolve through only extensive experimental work. The main objective of this investigation is to study the effect of electrode pressure on nugget formation, microstructural features and tensile shear fracture properties of RSW AHSS lap joints of DP-800 grade for fabrication of thin walleed structural frames in electric vehicle applications. The one factor at time approach of design of experiments was followed to study the direct effect of electrode pressure.

2. Experimental Methodology

2.1. Material selection and spot welding

The AHS DP-800 steel of 1.6mm thickness was employed in present investigation to develop spot joints. The chemical compositions of DP-800 steel is presented in Table 1. Table 2 presents the mechanical properties of DP-800 steel. Figure 1 displays the optical microstructure of DP-800 steel. It consists of 20% martensite and 80% ferrite phase. The average grain size of ferrite is 7-9 µm and martensite is 5-7 µm.

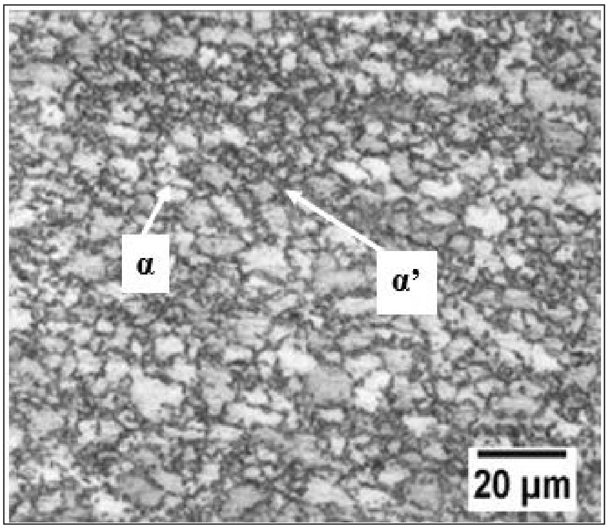

Fig. 1. Optical microstructure of DP-800 steel.

The three major RSW process parameters are electrode pressure, welding current and time. To study the direct effect of electrode pressue, one variable at a time approach was used in which electrode pressure was varied from level to higher level at 5 distinct levels while other parameters (welding current and time) were kept at const level. The Electrode Pressure (EP) was varied from 3.75 MPa to 4.75 MPa while other parameters i.e. welding current and Welding time were kept constant at 5.0 kA and 1.50 s. Table 3 show the process parameters used to spot weld the joints. The welding experiment were done by pedaling type semi-automatic RSW machine as shown in Figure 2. The RSW machine consisted of a conical type water-cooled electrode.

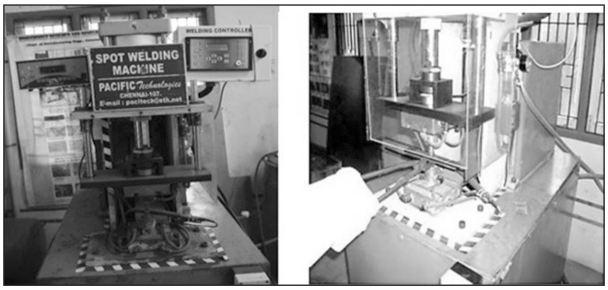

Fig. 2. Photograph of RSW machine.

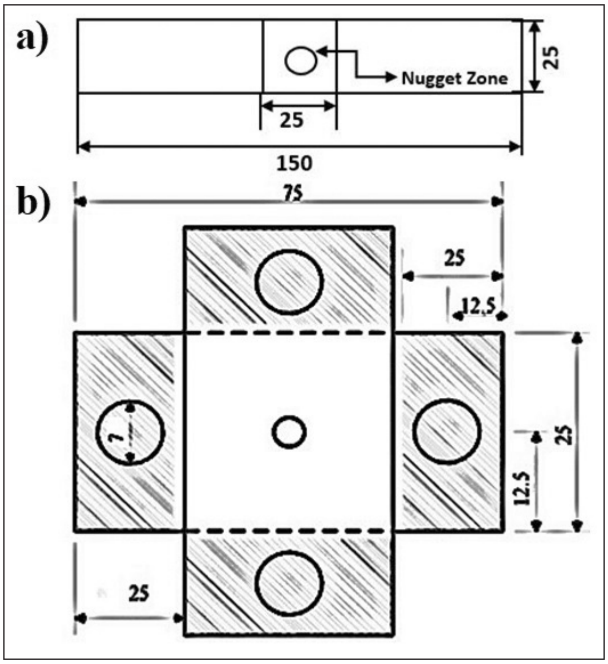

Fig. 3 Schematic arrangement of TSS specimens: a) SL-TSS; b) CL-TSS.

Table 3
RSW parameters used to develop lap joints of DP-800 steel.

Joint no.	Electrode pressure (MPa)	Welding time (s)	Welding current (kA)
1	3.5	2.0	5.5
2	3.75	2.0	5.5
3	4.0	2.0	5.5
4	4.25	2.0	5.5
5	4.5	2.0	5.5

2.2 Tensile shear fracture test

Figure 3 represents the dimensions of SL-TSS and CL-TSS joints. The tensile shear strength (TSS) test was conducted in both SL-TSS and CL-TSS samples according to ANSI/AWS/SAE/D8.9-9 standard. The shear fracture test was conducted using a servo-controlled universal testing machine. The hardness survey was carried out using Vickers microhardness tester with a load of 0.5 kg and dwell time of 15 sec.

2.3 Microstructrue

The cross-section of spot joint was polished and etched using Villas reagent. The Villas reagent was prepared using 1g Picric acid, 5ml hydrochloric acid and 100 ml ethanol. Stereozoom macroscope was used to analyze the nugget quality and size for the various electrode pressure levels. The microstructural features of weld nugget were analyzed using optical microscope (OM). The fractured section of TSS specimens was analyzed using SEM.

3. Results and Discussion

3.1 Macrostructure

The effect of electrode pressure on nugget formation of RSW DP 800 steel joints is shown in Figure 4. Increase in electrode pressure from 3.5 MPa to 4.5 MPa causes increase in width of nugget and considerable reduction in sheet thickness at higher level of electrode pressure. The DP 800 RSW joint developed using lower level of electrode pressure showed improper nugget formation and penetration. This leads to poor load bearing capability of RSW joints. The RSW joints developed using the electrode pressure of 4.5 MPa revealed defect-free weld and optimum nugget formation. This ensures better load bearing capability of RSW joints. The joints developed using higher level of electrode pressure i.e., 4.75 MPa revealed wider weld nugget area and more plastic deformation. Such type of weld nugget is not desirable. Also, the thickness of weld nugget was reduced by 15% and confirms the inferior strength of DP 800 steel RSW joints.

Table 4 shows the effect of electode pressure on weld nugget characteristics. The spot joints of DP-800 steel developed using electrode pressure of 4.0 MPa exhibited better quality weld nugget with a NZ diameter of 5.55 mm and optimum area of 25.95 mm^2. However the joints developed using electrode pressure of 4.5 MPa showed higher poor quality weld nugget with NZ diameter of 7.10 mm and area of 33.78 mm^2. Thus it showed 27.92% and 30.17% increment in NZ diameter and area of spot joints at higher level

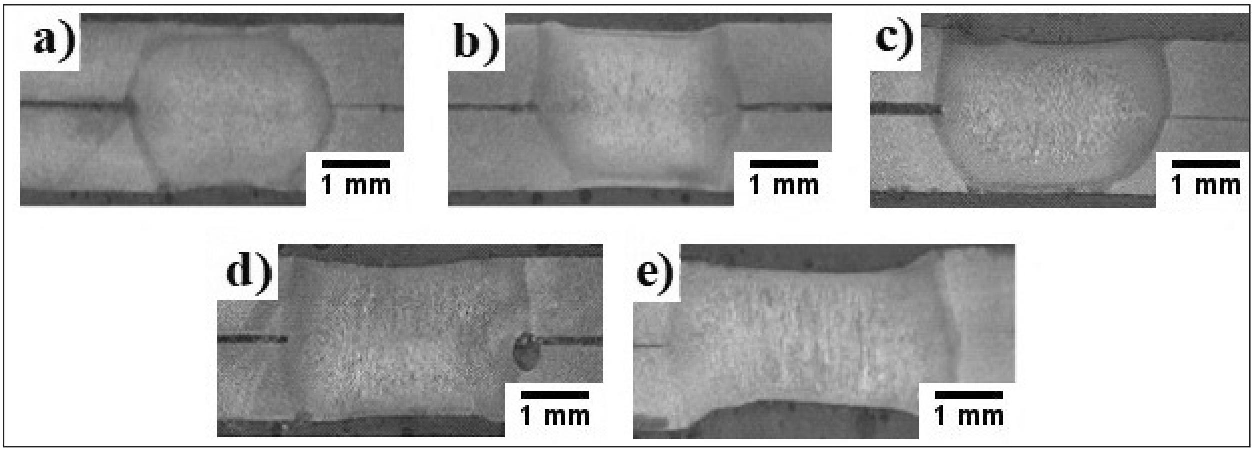

Fig. 4. Effect of electrode pressure on weld nugget formation of DP 800 RSW joints:
a) 3.5 MPa; b) 3.725 MPa; c) 4.0 MPa; d) 4.25 MPa; e) 4.5 MPa.

Table 4
Effect of copper electrode pressure on weld nugget characteristics.

Electrode pressure (MPa)	Nugget diameter (mm)	NZ area $(mm)^2$
3.5	4.80	19.31
3.75	5.15	22.38
4	5.55	25.95
4.25	6.00	29.11
4.5	7.10	33.78

Table 5
Tensile shear strength properties of welded joints.

Electrode Pressure (MPa)	SL-TSS (MPa)	CL-TSS (MP)	Weld failure location
3.5	431	278	Interface
3.75	525	379	Interface
4	830	684	CGHAZ
4.25	571	496	CGHAZ
4.5	367	302	CGHAZ

of electrode pressure. It is mainly due to the severe plastic deformation of nugget resulting in localized heating of nugget at higher level of electrode pressure.

3.2 Tensile shear strength

Figure 5 shows the photgraph of tested SL-TSS and CL-TSS specimens. Most of the spot joints failed in HAZ. Table 5 shows the tensile shear strength properties of RSW DP-800 steel joints. Increase in electrode pressure from 3.0 MPa to 4.0 MPa causes increase in SL-TSS and CL-TSS of

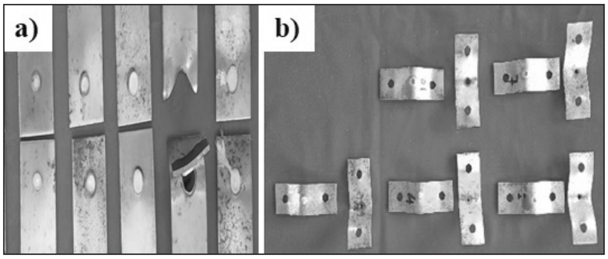

Fig. 5. Photograph of tested specimens:
a) SL-TSS; b) CL-TSS

DP-800 steel spot joints. Further increase results in significant reduction in SL-TSS and CL-TSS of joints. The spot joints of DP-800 steel developed using electrode pressure of 4.0 MPa exhibited superior SL-TSS of 830 MPa and CL-TSS of 684 MPa respectively. Thus it showed only 0.29% and 17.83% reduction in SL-TSS and CL-TSS compared to parent metal. However the joints developed using electrode pressure of 4.5 MPa revealed SL-TSS of 367 MPa and CL-TSS of 302 MPa respectively. Thus it showed 55.87% and 63.67% reduction in SL-TSS and CL-TSS compared to parent metal. It is mainly attributed to significant deformation of nugget resulting in localized thinning of nugget area of higher level of electrode pressure. The localized deformation and thinning of nugget act as stress concentration sites and drastically lowers TSS of joints.

3.2 Microhardness

Figure 6 shows the effect of electrode pressure on microhardness of spot joints. Increase in electrode pressure results in increase in hardness of NZ and HAZ of spot joints. The joints made using higher electrode pressure of 4.5 MPa disclosed higher hardness of NZ up to 590 HV. The joints made using electrode pressure of 4.0 MPa showed optimum hardness of 550 HV. The hardness of NZ

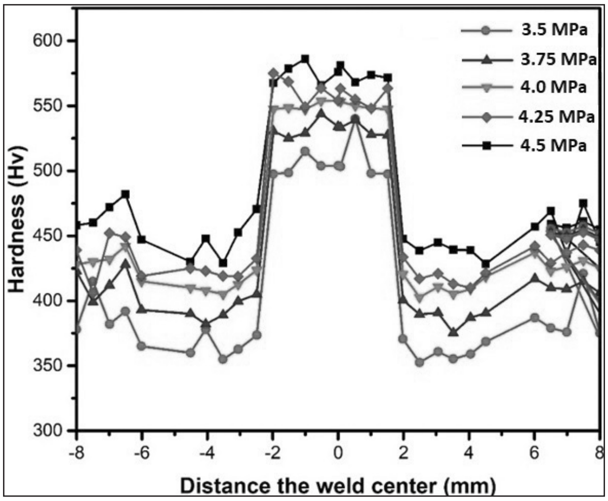

Fig. 6. Effect of copper electrode pressure microhardness distribution of spot joints.

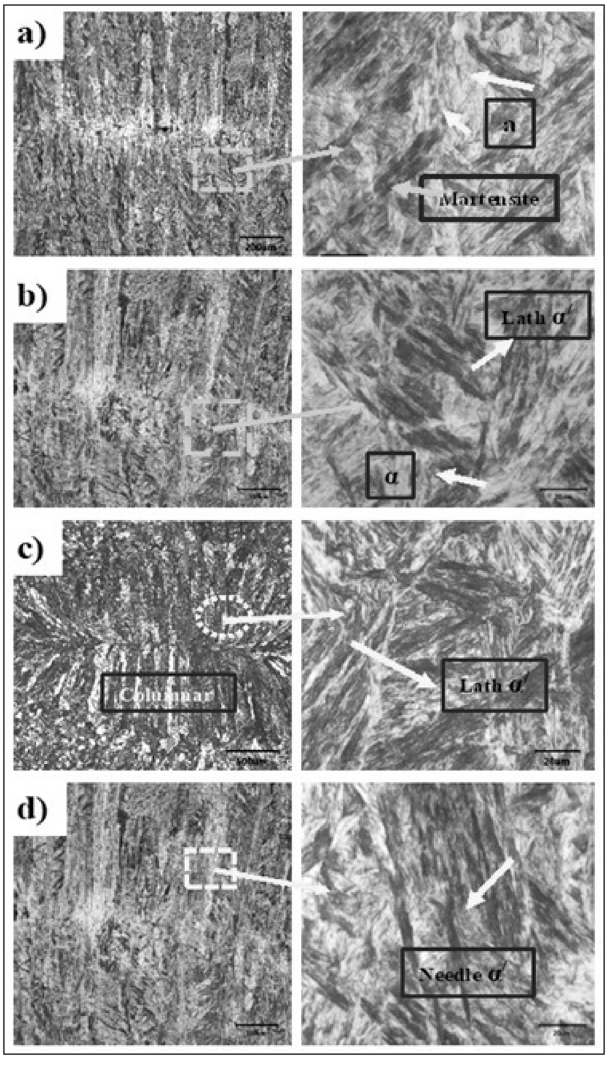

Fig. 7. Effect of copper electrode pressure on NZ of spot joints: a) 3.5 MPa; b) 3.75 MPa; c) 4.0 MPa; d) 4.25 MPa; e) 4.5 MPa.

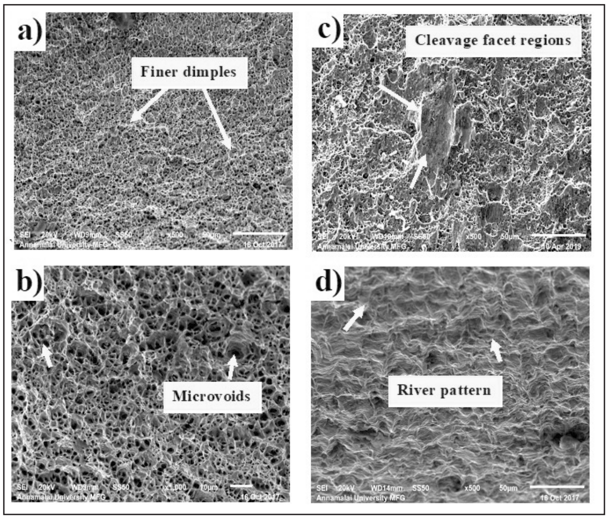

Fig. 8. SEM fractograph of TSS specimens of joint made using an electrode pressure of 4.0 MPa at lower and higher magnification: a) & b) SL-TSS; c) & d) CL-TSS specimen.

is higher than parent metal due to the evolution of large volume fraction of martensite phase in ferrite matrix. The weld region of spot joints was differentiated by nugget zone (NZ), coarse grain heat affected zone (CG-HAZ), fine grain heat affected zone (FG-HAZ), and Parent Metal (PM). The average hardness value of martensite and retained austenite structures were recorded in the range of 420-600 HV and 300 HV. The HAZ showed softening in spot joint due to the severe grain growth in CG-HAZ.

3.3 Microstructure

Figure 7 shows the effect of electrode pressure on microstructure of DP-800 steel spot joints. The SEM microstructure of NZ at higher and lower magnification, CG-HAZ and FG-HAZ are shown in Figure 8. The NZ consists of martensite (α/) and retained austenite (RA) phases in the ferrite (α) matrix. The nugget shows the needle like martensitic strcutres in ferrite matrix. Increase in electrode pressure results in increase in volume fraction of finer needle like martensites in NZ. The joints made using lower level of electrode pressure showed the evolution of coarser plates of martensite in ferrite matrix. The joitns made using electrode pressure of 4.0 MPa disclosed finer martensitic needles. However further increase in electrode pressure to 4.5 MPa causes the evolution of large volume fraction of finer needle like martensite in ferrite matrix. It is mainly attributed to the increased plastic deformation of nugget zone resulting in transformation of coarser matertnsite plates into finer martensite needles in NZ. The NZ microstructure shows dynamic recrystallization of grains exhibiting a columnar structure. It suggests the formation of martensite phases in the ferrite matrix during solidification. The superior TSS and NZH of spot joints made using optimum electrode pressure of 4.0 MPa is attributed to the evolution of needle/lath-like martensitic structure in nugget zone.

3.5 Fracture surface analysis

The fractured surface of SL-TSS and CL-TSS specimens was analyzed by SEM as shown in Figure 8. The failure occurred in the periphery of the weld nugget due to severe plastic deformation. The fractured surface showed finer dimpled features in SL-TSS and CL-TSS specimens. The size of dimples has a significant effect on the mechanical and metallurgical properties of the welded joints. The dimple and microvoid size observed in fractured surfaces of SL-TSS specimens is much finer whereas it was observed to be slightly coarser in CL-TSS specimens. The CL-TSS specimens revealed the presence of cleavage facet regions. It is mainly attributed to the presence of carbides. The breakage of carbides during the tensile shear loading provides the crack imitation and propagation path resulting in the formation of cleavage facet region and river pattern.

4. Conclusions

1. Electrode pressure plays a significant role in controlling the weld nugget formation, micrstructure and TSS properties of RSW DP-800 steel lap joints.
2. The TSS of joints increases with increase in electrode pressure up to 4 MPa. Further increase results in drastic reduction in TSS properties of RSW DP-800 steel spot joints.
3. The DP-800 steel spot joints developed using the electrode pressure of 4.0 MPa exhibited superior SL-TSS of 830 MPa and CL-TSS of 684 MPa respectively.
4. The superior TSS properties of DP-800 steel joints is mainly attributed to the evolution of finer needle like martensitic structure in nugget zone.
5. The inferior TSS properties of DP-800 steel spot joins at higher level of electrode pressure is mainly attributed to significant deformation of nugget resulting in localized thinning of nugget area.

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