Microstructural analysis of weld nugget properties on resistance spot-welded advance high strength dual phase (α+α′) steel joints

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Abstract
This research work focuses on production of sound weld by Resistance Spot Welding (RSW) process and correlate the mechanical properties of Dual Phase (DP) steel joints with its microstructural features. The main application of resistance spot welding was used to build white body assembly in automotive industry. The welded joint recorded maximum value of 21.3 kN in TSFL and 18.3 kN in CTSFL. The Scanning Electron Microscope (SEM) and Optical Microscope (OM) of the Nugget Zone (NZ) revealed lath/needle like microstructures with effect of severe cooling rate. The TEM microstructure exposed the formation of martensite (α′) in the Nugget Zone (NZ) and tempered martensite (Tα′) in Heat Affected Zone (HAZ), which accounts for superior joint strength of DP lap shear joints. Furthermore, crystallography studies reported the phase composition and crystallinity in weldments as cementite and magnesium carbide in [101] and [200] indices that accounts for high hardness of 584 Hv in the weldments.

1. Introduction

The Advanced high strength steels are of main interest due to the impressive mechanical properties offered in comparison with commercial alloy steels. These steels provide an excellent combination of high strength and ductility with good formable and machinable characteristics [1, 2]. Weldability of DP steels is one of the significant factors governing their application in the automotive industry. Lot of welding technique was used to weld the dual phase steels, and the resistance spot welding technique has the major advantages like simplest, fastest and most controllable compared to other processes. In fusion process such as arc and laser welding, the formation of acicular ferrite phase influences the softening of the heat-affected zone which plays a major role in the mechanical properties of dual-phase steel weldments [3]. Resistance Spot Welding (RSW) is employed in automotive industry because of its green and cost-effective joining technology. Moreover, this process offers high productivity and high structural integrity of the vehicle. The RSWed DP steels showed extensive crack toughness compared with other welding process [4]. Ramazani et al investigated metallurgical characteristics and mechanical behavior of gas metal arc welded dual phase steel (DP600) and reported variation of HAZ microstructure from bainite to dispersed coarse grain ferrite and tempered martensite with enhanced mechanical characteristics [5]. Xinjian Yuan et al reported the effect of welding parameters on DP600 and DC54D dissimilar joints. The reports provided a characteristic relation between nugget features and mechanical properties of the welded joints [6]. Baltazar Hernandez et al investigated the nanoindentation and microstructure behavior RSWed DP980 steel and reported the softening effects of tempered martensite in subcritical HAZ [7]. P Banerjee et al analyzed the notch geometry and effect of nugget size on high cycle fatigue performance of spot-welded DP590 steel. The results revealed the fatigue performance was satisfactory under low load conditions than high load which attributed to presence of smaller nugget zone in the former and kink crack initiation in the latter [8]. Aslanlar et al reported the impact of welding time on RSWed micro alloy steel with different weld cycles. The joints resulted in tensile peel during tensile shear fracture test in optimized
Onar et al. reported the effect of welding process parameters on nugget size formation in the resistance spot welding of TWIP 950 and DP 800 steel joints. The weld nugget area with less than 30% sheet thickness was characterized by superior mechanical properties. Darabi et al. studied the experimental and numerical investigation on micromechanical properties of DP 800 and DP 980 steels and reported the deformation behaviour of DP joint through the 3D micromechanical modelling.

The above literatures detailed lots of resistance spots welded automotive steels in white body application. But very scanty investigation on DP 800 steel joints. Most of the authors studied on 3D modelling and mechanical properties of DP 800 steel joints. Hence, this research work focused on critical load carrying capacity of resistance spot welded DP800 steel joint with optimized welding parameters, thereby correlating the mechanical properties with its microstructural features to estimate the weld quality and integrity.

2. Experimental work

For this research work, a cold-rolled DP800 steel with 1.6 mm thickness was used. The chemical composition and mechanical properties of DP800 steel were depicted in Table 1 and Table 2.

From figure 1 illustrates the parent metal microstructure of 85% ferrite and 15% martensite. The faces to be welded were cleansed to remove the corrosion and scaling to avoid shrinkage and distortion effects. The experimental work was completed in Semi-Automatic Electric Resistance Spot Welding (ERSW) machine to evaluate the optimized welding parameters (electrode pressure, welding current, and welding time) and to analyze the effect of microstructure on mechanical properties of the weld joints. The schematic of the specimens to be welded and welded specimens according to ANSI/AWS/SAE/D8.9–9 standards were shown in figures 2(a), (b) and 3(a), (b).

The shear fracture test was conducted in 500 kN semi-automatic, servo-controlled Universal Testing Machine. The microhardness survey was conducted by Vickers method with 0.5 kg load and 15 s dwelling time.
as experimental conditions. The specimens were polished and etched by Villella’s regent (Picric Acid 1 gram, Hydrochloric acid 5 ml, and Ethanol 100 ml) with a dwell time of 30–60 s to carry out the microstructural studies. The macrostructure of the weld quality was observed from stereo zoom Zeiss macroscopy. The microstructure of the weld joints was studied using Nikon Climax optical microscopy. The elemental composition and fractography studies were performed with JEOL scanning electron microscopy SAED detector. Further deep morphological studies were observed from JEOL TEM.

3. Results

3.1. Macrostructural characteristics of weld joints
Optical macrograph was used to characterize the weld joint in different welding conditions as illustrated in table 3. From the macrograph studies, the optimized working limits for DP 800 joints were presented in table 4.

3.2. Shear strength properties
The tensile shear testing and cross tensile shear testing of the optimized joints was conducted as per the standard. The weld joints, recorded a maximum tensile shear strength and cross tensile shear strength as 21.3 kN and 18.3 kN with nugget hardness 584 Hv as mentioned in the table 5.
| Sl. no | Parameter      | Operating range | Macrostructure                  | Result                              |
|-------|----------------|-----------------|---------------------------------|------------------------------------|
| 1     | Welding Current| $< 4.0 \text{kA}$ | ![Image](image1.png)            | Joint was separated                |
|       | Electrode Pressure | = 4.5 bar       |                                 |                                    |
|       | Welding Time    | = 2 s           |                                 |                                    |
| 2     | Welding Current | $> 6.0 \text{kA}$ | ![Image](image2.png)            | Metal deformation take place       |
|       | Electrode Pressure | = 4.5 bar       |                                 |                                    |
|       | Welding Time    | = 2 s           |                                 |                                    |
| 3     | Welding Current | = 5.5 kA        | ![Image](image3.png)            | Less indentation                   |
|       | Electrode Pressure | < 3.5 bar       |                                 |                                    |
|       | Welding Time    | = 2 s           |                                 |                                    |
| 4     | Welding Current | = 5.5 kA        | ![Image](image4.png)            | More indentation                   |
|       | Electrode Pressure | > 4.5 bar       |                                 |                                    |
|       | Welding Time    | = 2 s           |                                 |                                    |
| 5     | Welding Current | = 5.5 kA        | ![Image](image5.png)            | Tiny defect in center              |
|       | Electrode Pressure | = 4.5 bar       |                                 |                                    |
While shear testing, all the weld failure occurred in the ridge or interface zone of lap joints. The predicted interface failure mostly occurred in coarser grain HAZ region due to sub-critical cooling rate [10, 11]. Tear type failure and pulled out failure were observed from both TSFL and CTSFL joints in figure 4(a), (b).

3.3. Hardness evaluation
The hardness behaviour in different regions of optimized welded condition was studied from figure 5. The weld zone of the DP 800 joints recorded 584 Hv in the nugget zone, which was higher when compared with the base metal hardness of 295 Hv. The higher hardness in the nugget zone was observed due to formation of columnar/lath/leaf like martensite phase in the NZ as high cooling rate was observed in the process [12].

3.4. Structural characteristics of weld joints
3.4.1. Optical microscopy studies
The optical microscopy revealed the features around the weld area which were designated as nugget zone, coarse grain HAZ, fine grain HAZ, and unaffected base metal as in figure 6(a). During the welding process, the material flow pattern was depicted in figure 6(d). The nugget zone of the weld region and its false colour image from figures 6(b), (c) designates the columnar grains in the joints, which attributed to the high heat input at the welding interface and severe cooling rate (>400 °C s⁻¹) associated with the process [13]. Moreover, the lath/needle like martensite structure was observed in the nugget zone due to the cooling rate of the process as shown in figures 6(e), (f). In coarse grain HAZ and fine grain HAZ regions, the regions around the nugget zone, the formation of tempered martensite and ferrite was observed as in figures 6(g)-(l).

3.4.2. SEM microstructural studies
The nugget morphology was studied by the secondary electron detector of scanning electron microscopy. Figures 7(a), (b) reveals twinned martensitic structures in the ferrite matrix (α) of the weld zones. The CGHAZ

Table 3. (Continued.)

| Sl. no | Parameter            | Operating range | Macrostructure | Result              |
|-------|----------------------|-----------------|----------------|---------------------|
| 6     | Welding Time        | <0.5 s          |                | Wider nugget formation |
| 6     | Welding Current     | =5.5 kA         |                |                     |
|       | Electrode Pressure  | =4.5 bar        |                |                     |
|       | Welding Time        | >2.5 s          |                |                     |

Table 4. Optimized welding parameter for DP 800 steel joints.

| Welding Current (kA) | Electrode pressure (bar) | Time (sec) |
|----------------------|--------------------------|------------|
| 5.5                  | 4.5                      | 1.53       |

Table 5. Mechanical properties of dual phase welded joints.

| Joint          | Tensile shear fracture load (kN) | Cross tensile shear fracture load (kN) | Nugget hardness (Hv) |
|----------------|----------------------------------|----------------------------------------|----------------------|
| DP800 RSW joint| 21.3692                          | 18.3311                                | 584.706              |

While shear testing, all the weld failure occurred in the ridge or interface zone of lap joints. The predicted interface failure mostly occurred in coarser grain HAZ region due to sub-critical cooling rate [10, 11]. Tear type failure and pulled out failure were observed from both TSFL and CTSFL joints in figure 4(a), (b).
and FGHAZ regions of the weldments exhibited tempered martensite and retained austenite structures which is shown in figure 7(c), (d). The tempered martensite formation was characterized by the grain distortion in the regions of joints due to softening effect which accounts for high heat dissipation during the process [14].

3.5. Elemental studies
The energy dispersive spectroscopy, a prominent tool of SEM was employed to study the probable elements in the weldment. The EDS spectrum of SEM analysis revealed the elemental composition by atomic mass and diffracted angles of the crystal in the nugget zone as Fe, Mn, Cr, C with traces of Si, P and S in figure 8.

Further, the XRD peaks characterized the presence of Iron Carbide (Fe₃C) and Manganese Carbide (Mn₃C) phases which was correlated with elemental analysis results as in figure 9. The miller indices [101], [200] from XRD and deep morphological characterization, from figure 10 confirmed the above-mentioned phases [15].
3.6. Fractography studies

The topographical results predicted the crack initiation at the softened zone and crack propagation through the periphery of the nugget to the base metal. These results were also accorded with the tear type failure and pull out failure in TSFL and CTSFL joints of the weld [16]. The fine-dimples characterized from figures 11(a), (d) indicates the presence of hard precipitates in the DP steel weldments. Further, the fracture surface was characterized by presence of carbides, voids which initiates the crack and the crack propagated region was characterized by beach marks and striations as in figure 11(b), (c).

Figure 6. (a) Interface; (b)—(f) Nugget zone; (g)—(i) Coarser grain heat affected zone; (j)—(l) Finer grain heat affected zone.
4. Discussion

The optimized welding parameter for sound weld was found for welding current 5.51 kA, electrode Pressure 4.5 bar and welding time 1.53 s. Macrograph studies for welding parameters with welding current < 4.0 kA, electrode pressure < 3.5 Bar and welding time < 0.5 s resulted in poor joining and diffusion at the interface. Further with welding current > 6.0 kA, electrode pressure > 4.5 bar and welding time > 2.5 s yielded high deformation at the interface with macro voids and wider HAZ regions in the interface. The TSFL, CTSFL and hardness value of the joints recorded 21.3 kN, 18.3 kN and 584 Hv for the optimized welding conditions. The high hardness observation was with severe cooling rate associated with the process accounting for the formation
martensite in the nugget zone than in nearer zones which again in turn attributed for the pull out and tear type failure of around the joints [17]. Due to severe cooling rate of the process lath/plate martensite was characterized in the nugget zone by optical micrograph which was also found in agreement with SEM indicating twinned martensite phases. The HAZ regions have tempered martensite as their characteristic feature which enabled the tensile failure to propagate through them without affecting the weld [18]. In FGHAZ, the impact of elastic distortion is minimal which led to the higher hardness value than base material. The average grain size in the FGHAZ region is 7–10 μm [19]. TEM microstructure elaborated the morphology of the nugget and heat affected region. It revealed the presence of tempered martensite (T α') in the interface of CGHAZ regions, which assisted the weld failure. The elemental composition at the nugget zone revealed Fe, Mn, Cr, C with traces of Si, P and S, which was accredited from TEM microstructures as iron carbide and manganese carbide phases confirmed from SAED patterns. Further the bright field and dark field image of the TEM micrographs along with XRD results confirmed the phases [101], 2.00520 Å and [200], 1.42582 Å as iron carbide and manganese carbide in the nugget zone. They assumed as cementite and ferrite phases formed in the partially deformed regions. The fracture
studies revealed the failure area with tempered martensite as soft phase alongwith carbide phases as beach marks/striations pattern which also attributed for tear or pullout failures of the joints.

5. Conclusion

The following conclusion derived for Dual phase (DP800) spot welded joint:

- The microstructure of nugget zone consisted of lath and needle-like martensite structure with retained austenite in the ferrite matrix. The formation of martensite phase was due to critical cooling rate which associates for nucleation of twinning grains in the weldment.
- Cementite (Fe₃C) and manganese carbide (Mn₃C) are confirmed phases in the DP800 weld, which was evident from SAED, XRD, and EDS.
- Most of the weld failure occurs at coarser grain heat-affected region, which was due to elastic strain and distortion in the HAZ region. The TSFL recorded was 21.3 kN and observed pullout failure also CTSFL recorded was 18.3kN observed with tear type failure.
- The weld joint was characterized with high hardness value 584 Hv because of formation of martensite in the nugget zone with formation of martensite as conferred by other zones.

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