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Performance Evaluation of Self-Piercing Riveted and Resistance Spot Welded Dissimilar Steel Joints

Akhil Kishore V T[1], Brajesh Asati[2], Nikhil Shajan[2] and Kanwer Singh Arora[2]

[1]*Department of Metallurgical and Materials Engineering, NITK, Surathkal, India*
[2]*Research and Development, TATA Steel, Jamshedpur, India*

ABSTRACT

Self-piercing riveting (SPR) is a mechanical joining process that has the potential to replace resistance spot welding (RSW) and is being adopted in the automotive industry.In this study, a dissimilar stack configuration widely used in the automotive industry was used. Joining was performed using self-piercing riveting and resistance spot welding processes. Welding parameters in spot welding were optimized to produce anugget with a diameter similar to the rivet shank. Tensile and fatigue attributes of these joints were assessed to evaluate the joint performance. Additionally, microstructure-property correlation was performed to evaluate the failuremode and susceptible region in the joint that can lead to crack initiation and failure.

KEYWORDS: Self-piercing riveting; Resistance spot welding; Fatigue; DP590 steel; IF steel; Tempered martensite.

Introduction

Carbon emission norms have nudgedautomotive manufacturers to reduce vehicle weight. Reducing the body weight is aneasy and effective way of reducing the overall vehicle weight. Light-weight materials are being introduced to reduce the cab weight of the vehicle whichin turn necessitates use of novel joining technologies. Self-piercing riveting (SPR) is such a promising technology used for joining multi-material configuration without melting and solidification.

Resistance spot welding is an established joining technology used to join thin sheets in the automotive industry[1],[2]. Complex microstructure and unpredictable nugget formation are few of the challenge associated with spot welding of dissimilar sheets. The difference in chemical composition and thickness alters the thermal and electrical conductivity of the stack combination of low carbon steel and austenitic stainless steel [3], aluminium alloy and stainless steel[4] which results in inconsistent nugget geometries resulting in high mechanical property variation[5]. Spot welded bare steels are prone to corrosion attack, and hence galvanized sheets are used[6]. Zinc coating is commonly used on steel for corrosion protection. The spot welding of galvannealed medium manganese steel and low carbon steel causesliquid metal embrittlement (LME) cracking[7]. Zinc accumulation at the interface of the galvanized TRIP steel affects the failure mode of the joint by forming brittle phases in the zinc rich regions[8]. Similarly difference in surface coating condition is also a factor of influence in regard to expulsion at low current happening in the DP-TRIP combination due to difference in electric resistance[5]. Aluminium alloy joined to GA590 steel using resistance spot welding shows intermetallic formation which results in reduced mechanical properties[9]. As self-piercing riveting is a mechanical joining process, mechanical attributes of riveted joint on aluminium alloys was found to be good resulting in adoption by the automotive industry owing to the difficulty in spot welding[10][11]. Thicker cross-section results in higher flaring of the rivet with resultant better mechanical strength as observed in Aluminium alloy (AA5754) joints[12]. A study on the aluminium and magnesium combination joined using SPR has shown better joint quality when ductile materials were used onthe die side[13]. Difference in flow properties of the dissimilar sheets joined using SPR leads to detrimental mechanical performance of the component [14]. Tensile shear strength is related to the die and rivet properties of joint and has seen to have improved after optimization of the rivet and die geometries[15][16]. The fatigue strength of the joint depends on few factors like base metal thickness, piercing direction and stack configuration. Same grade of aluminium alloy with different thickness and aluminium alloy to HSLA or DP steel with different piercing directionjoined using SPRhasgreat significance in the fatigue properties. stronger sheet at the top withstood more fatigue and tensile load[17]. The surface coating is a key factor that changes the failure modes and load-bearing behaviour in the SPR joints on aluminium- steel joint. Similar to the surface coating, faying surface friction also influence the fatigue failure performance and failure modes in the SPR joints[18]. Vehicles are prone to continuous loading cycles therefore the effect of cyclicloading on the stifness and static strength of the joint is crucial. The stiffness and static strength of the SPR joints on aluminium is found to be increasing after certain fatigue cycles[10]. Fatigue performance of the riveted joint is better compared to spot welding for low carbon steels, high strength steels and aluminium with similar stack combination[19].

Performance of steel to aluminium stack combination joined using SPR has been evaluated and scatterswere observed in the mechanical performance[14], [20]. Crash worthiness has a direct relation to the strength of the material used in the automotives which makes steel a primary material of choice. Comparison study of SPR and RSW joint made on dissimilar steel to steel combination needs detailed analysis to support new standards in the automotive sector.

This research work aims to compare the mechanical performance of self-piercing riveted and resistance welded joints for a dissimilar steel stack configuration (DP 590 1mmto IF steel 1.4mm) and determine joint performance and failure mode through structure-property correlation.

Materials and Methodology

Materials and Properties

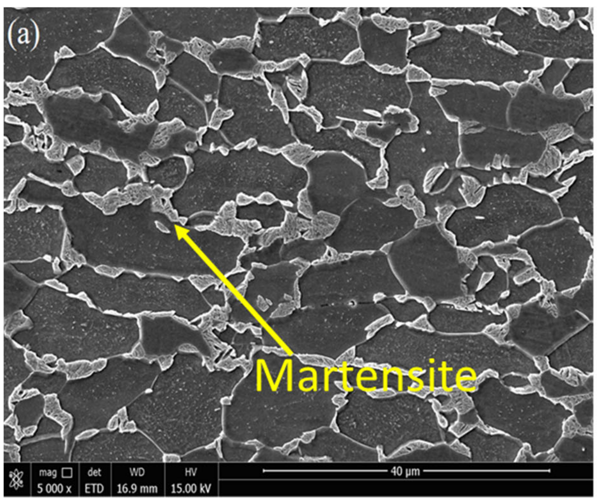
DP 590 and IF Steel processed through the hot rolling mill and subsequentlycold rolled to 1 and 1.4mm thickness respectively were used in this study. DP 590 grade of steel consists of ferrite and martensite phases as shown in Fig. 1a and IF steel consists of a completely ferritic microstructure. The DP590 consists of approximately 22.3% of martensite and rest ferrite. The mechanical properties of the grades are included in Table 1. The chemical composition of the above mentioned grades are given in Table 2.

Self Piercing Riveting Process

A joint configuration with DP steel on rivet (top) side and IF steel on die (bottom) side with sample dimesions of 105mm x 45mm as per BS 1140:1993 was used (Fig. 2). Self piercing riveting was carried out using Tucker made 80kN capacity ERT 80 servo-electric system and boron steel rivets. Die and details are listed in Table 3. Rivet pierced higher strength DP590 first and flared in the softer IF sheet. Rivet penetration corresponded to the applied load.

Resistance Spot Welding Process

Spot welding was performed on a 150kVA pedestal medium frequency direct current (MFDC) spot welding machine with a truncated copper – chromium electrode of 6mm diameter. Welding current was adjusted to obtain a nugget diameter of 5.5mm approximately, comparable to selected rivet shank. Detailed spot welding parameters are listed in Table 4.



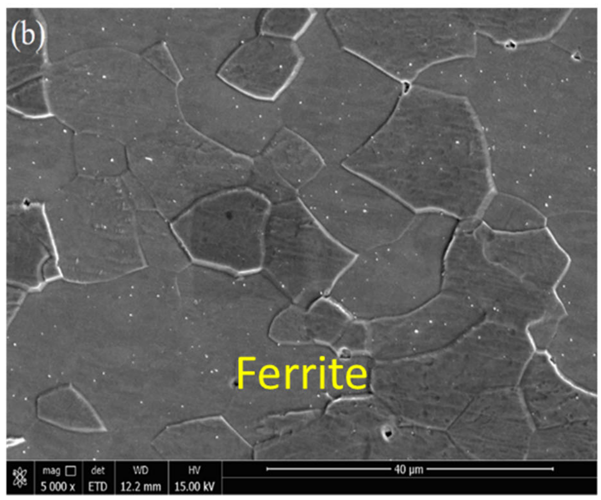


Fig. 1. Base metal microstructure a) DP590 b) IF.

TABLE 1

Mechanical Properties of the Base Materials

Material	Thickness	Yeild Stregth	Tensile Strength	Surface Treatment
DP590	1 mm	345 MPa	615 MPa	Naked
IF	1.4 mm	180 MPa	320 MPa	Galvannealed

TABLE 2

Chemical elemental analysis in Wt%

Materials/ Elements	C	Mn	Si	P	S	Al	Nb	Ti	Cr	N
IF	0.003	0.08	0.007	0.039	0.011	0.035	0.011	0.035	0.014	---
DP 590	0.09	0.86	0.358	0.015	0.008	0.038	----	----	0.021	0.0045

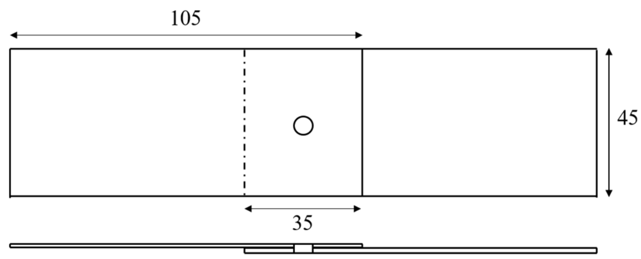


Fig. 2. Lap-shear tensile configuration for SPR and RSW joints

TABLE 3

Rivet and Die parameter

Stack Id	Rivet (mm)	Hardness (HV)	Die Specification	Penetration (mm)
SPR -0.4	5.5 × 5.5	510	D100 200 000	-0.4
SPR -1.2	5.5 × 5.5	510	D100 200 000	-1.2

TABLE 4

Spot welding parametersp

Stack Id	Welding Current (kA)	Electrode Force (kN)	Welding Time (ms)
RSW	7.5	3	250

Evaluation of Mechanical and Metallurgical attributes of Joints

Shear tensile tests were carried out at room temperature using Instron tensile testing machine ata crosshead speed of 5mm/min. Five samples per set of parameters were tested to improve accuracy.For metallurgical analysis, cross-section of the joints were mounted and polished to a mirror finish using emery papers of grit size from 100 to 1200 followed by fine polishing clothes with alumina and diamond slurry. The microstructure was analyzed using LEICA optical microscope. Fractography of fatigue failed samples were done using Zeiss SUPRA-25 scanning electron microscope (SEM) FEG650 equipped with an OXFORD analyzer after ultrasonic cleaning using acetone. Whereas, head height, Interlock and minimum sheet thickness post riveting were measured using a Leica M165C stereomicroscope. Microhardness measurements were carried out using Leco Microhardness machine with 300g force and a dwell time of 10s.

High cycle fatigue life was studied with a frequency of 30Hz and load ratio R=0.1 usingInstron electropulse E10000 system in tension–tension loading. Four load levels between 85 to 40% of tensile load capacity were used to ascertain fatigue performance of joints with a run-out limit of 5 x 10^6 cycles.

Results and Discussions

Macrostructure Analysis of Joined Steels

Figures 3a, 3b and 3c show the stereoscopic images of cross-sections of riveted joints with head heights -0.4mm and -1.2mm and spot weld respectively. To achieve -1.2mm head height, 35% higher load was applied compared to joints with head height of -0.4mm. Consequently, the rivet was observed to be flushed with the top sheet. Minimum bottom thickness is large in figure 3b since the rivet got flared more in the bottom sheet compared to figure 3a. For the spot weld, nugget diameter is similar to the rivet shank diameter i.e. 5.5mm(figure 3c). Nugget thickness was observed to be large in IF steel compared to DP steel. Silicon is the major element which contributes to resistance of the materials. While spot welding diffusion of the elements takes place as shown in figure 3d from DP steel side to IF steel side, so the chemistry difference did not affect the nugget side on both sides. Each points in the EDS point maping was taken such that distance between the points is 0.08mm and between surface and end point is 0.08mm. Base material chemical composition of both materials are showed as reference dotted lines. The effect of silicon rich chemistry of DP steel in nugget formation is negligible. When the thickness of the sheet increases, resistance increases and large nugget was formed. IF steel is thick compared to dual-phase steel, hence the large nugget size was observed more towards IF steel.

Shear Tensile Strength Estimation

Self-piercing riveting was performed with two desired head height of -0.4mm and -1.2mm, abbreviated as SPR -1.2 and SPR -0.4. Spot welded joints were observed to be ~26% stronger than riveted SPR -1.2 joints. Strength of SPR -1.2was 11% higher than SPR -0.4 joints, owing to higher rivet penetration. Higher static strength of SPR -1.2jointsresulted from wider interlocking as observed in figure 3a and 3b. Spot welded joint has metallurgical bond between the sheets whereas in SPR, rivet and sheets are not fused together since it is a mechanical joint. The piercing on the top sheet reduces the area of load-bearing which reduces the tensile strength of the joint and makes top sheet as weakest link in the part. Once the deformation started on the joint, strength reduces suddenly. Sudden drop of strength in spot-welded joint was seen since failure initiates at the notch interface. Tensile failure occurs in the soft tempered martensite region in the heat-affected zone. More ductile tempered martensite in the HAZ delays the separation of the sheets and increase the displacement.

Fatigue Life Estimation

Fatigue test result for spot welded and riveted samples is plotted in the figure 6. From the result, the number of cycles decreases with increase in the maximum load for all three combinations. SPR -1.2 is prominent in the fatigue loading eye brow cracking as the failure mode. The spot-welded joint ran significantly less number of cycles for all the loading levels compared to SPR joints.

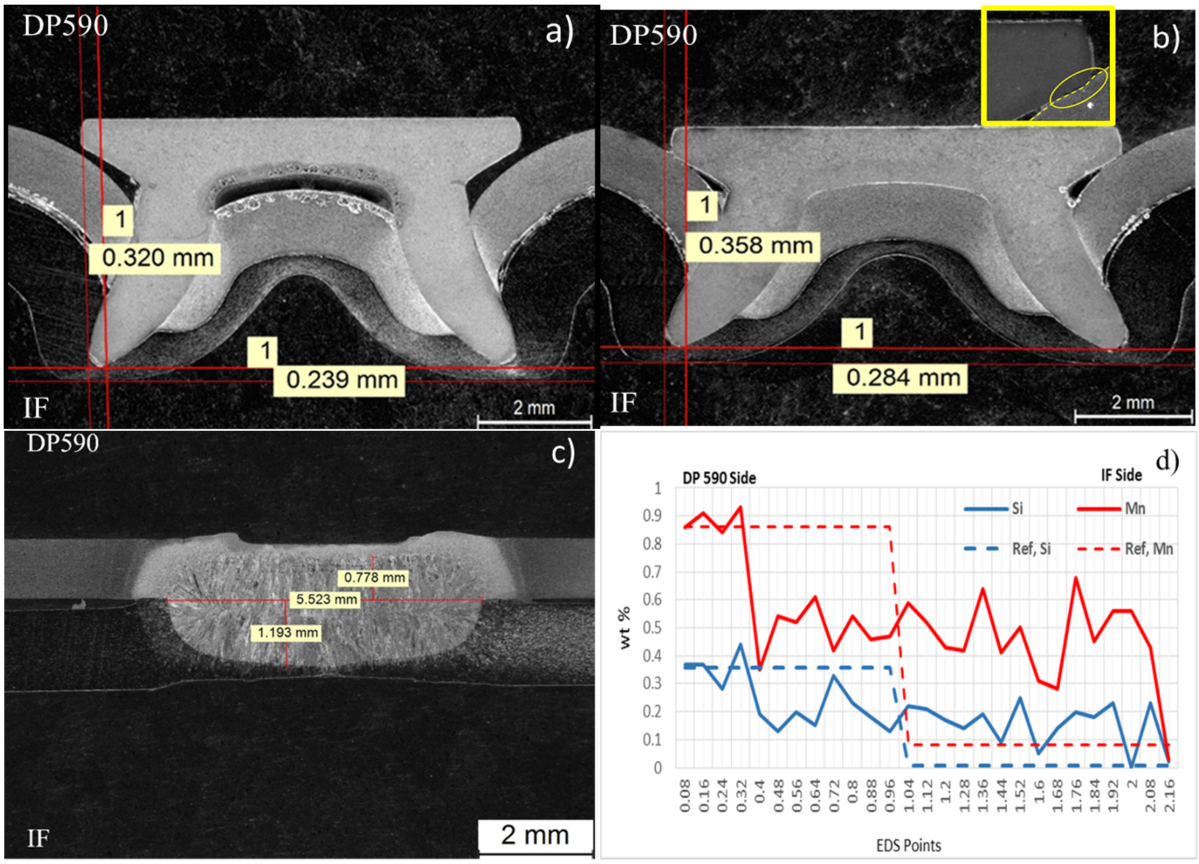


Fig. 3. Cross-section of SPR and RSW joints and EDS point mapping starting from DP side.

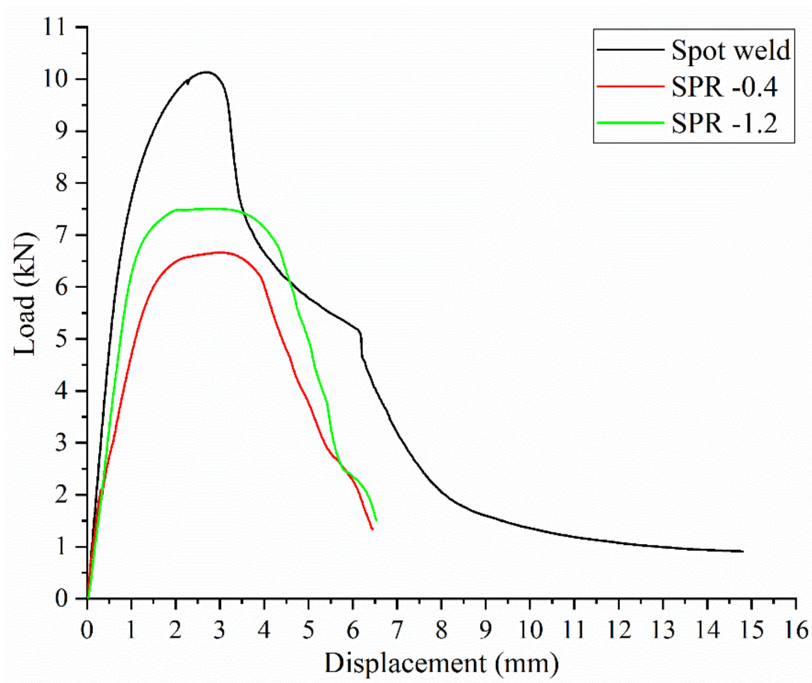


Fig. 5. Static tensile strength of DP+IF joints(SPR and RSW).

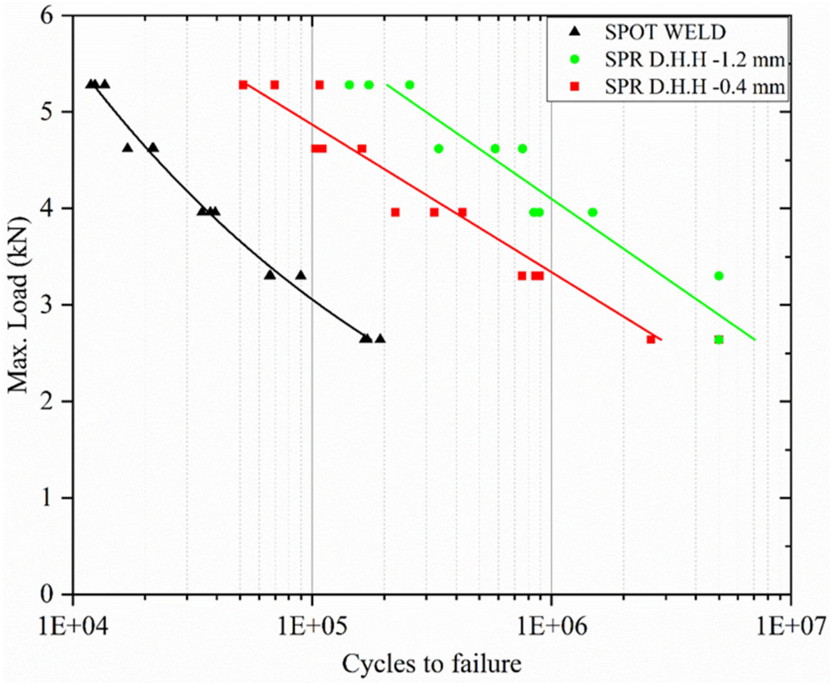


Fig. 6. F-N curve for DP-IF joints 3.4 Fractography of Riveted joints.

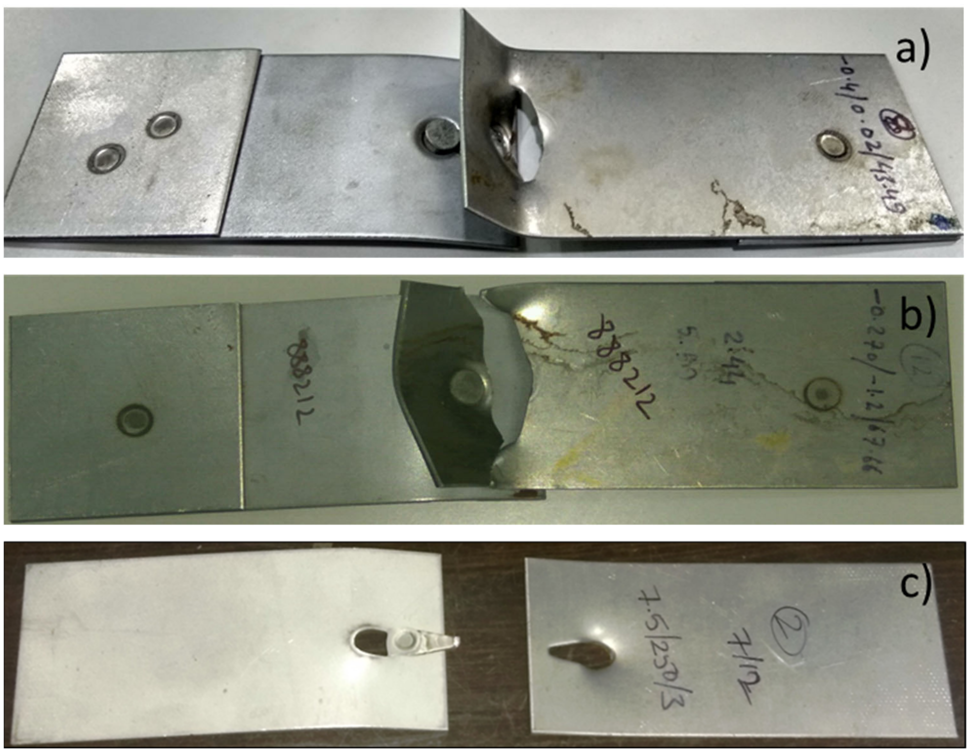


Fig. 7. As received fatigue failure images of self-piercing riveted and resistance spot welded coupons.

The fatigue failure modes in self-piercing riveted lap shear coupons are majorly affected by desired head height. SPR-0.4 failed through the combination of rivet pull out and eyebrow cracking on the top sheet (fig. 7a) rather than SPR-1.2 which failed through eyebrow cracking only on the upper sheet (fig 7b). The upper sheet is the weaker link in the riveted joint[21] Less interlock in SPR-0.4 is the reason for rivet pull out in the coupon compared to SPR-1.2. The same is reflected in fatigue life. In both SPR joints, sheet bending is observed in both sheets. Spot welded joint failed in desirable rivet pull out mode in both sheets around HAZ area as shown in fig 7c. Crack initiation and propogration followed by sheet tearinghas explored deeper in the later stage of this study.

Fractorgaphic Analysis of SPR Joint

To study the fatigue crack mechanism, intermittent fatigue loading was done. Fatigue test at a load of 3.96kN was stopped at 433000 cycles which is ~50% of the total life at this load. An eye brow crack was observed on the DP steel side which was carefully sectioned and analyzed. Region A in figure 8a shows the crack initiation points exactly at the middle of the sheet with ratchet marks started from the crack initiation point. The fatigue crack initiated from the faying surface of the DP590 sheet due to stress concentration and micro crack nucleation resulted from fretting below the rivet head resulted from bending and unbending of the sheet at the interface. Rivet pressing is shown in the figure 3b. Ratchet marks at crack initiation were joined together to form river marks emanating from the crack initiation point which is shown in figure 8c. In figure 8b the region marked shows the debris formed due to rubbing between the sheets after early crack initiation stage. Fatigue fracture striations were observed as shown in figure 8d along the river lines marked by dotted lines. Strain hardening due to large deformation in the bottom sheet makes the bottom sheet strongbut the stress concentration due to rivet head pressing causes fatigue failure in the top sheet. Strain hardening and high compressive residual stress[22] suppresses the fatigue crack in the bottom sheet. Stress concentration in the top sheet below the rivet head is the causal factor for fatigue failure.

Fractography of Spot Welded Joint

In spot welded sheet at 3.96kN load and 38094 cycles, an eyebrow crack was observed on the DP590 steel sheet and desirable rivet pullout was observed in IF side. Crack initiates at different points of the sheet width at the interface between the sheets. The river marks from different crack initiation were observed to be overlapped as shown in the figure 9b, 9c. More than one crack initiation point suggest the presence of weak microstructure could act as a potential crack initiation zone. The propagation front is clearly visible which shows the crack propagated both in the width and thickness direction simultaneously. The striation along the river marks are not clear in the spot weld due to the overlap of different crack initiations.Compared to self-piercing riveting, the crack initiation point is clearly visible without debris. The debris formed in the SPR sheet is due to the detachment of the rivet inter lock during continuous loading.

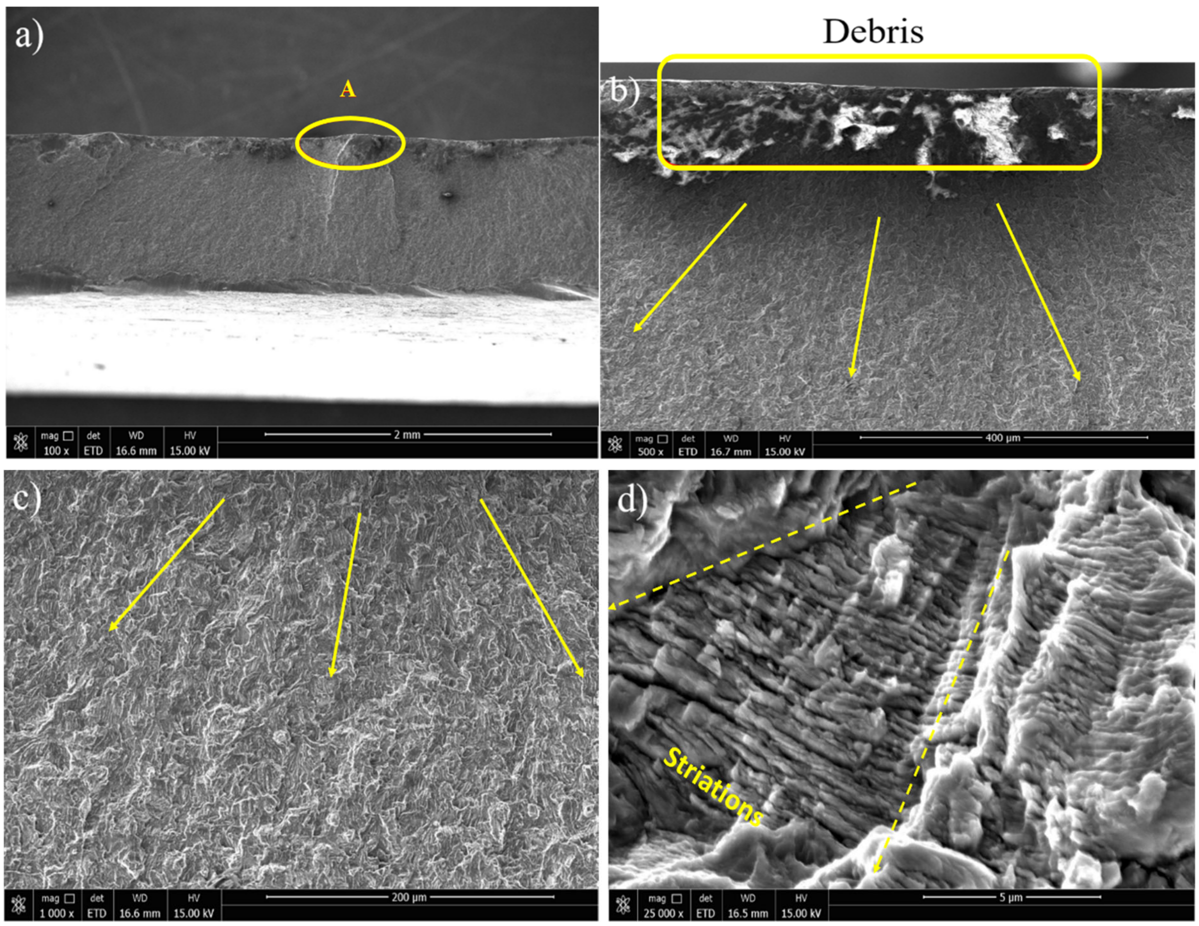


Fig. 8. Failure analysis of SPR joints (Fatigue fracture surface at 3.96kN load).

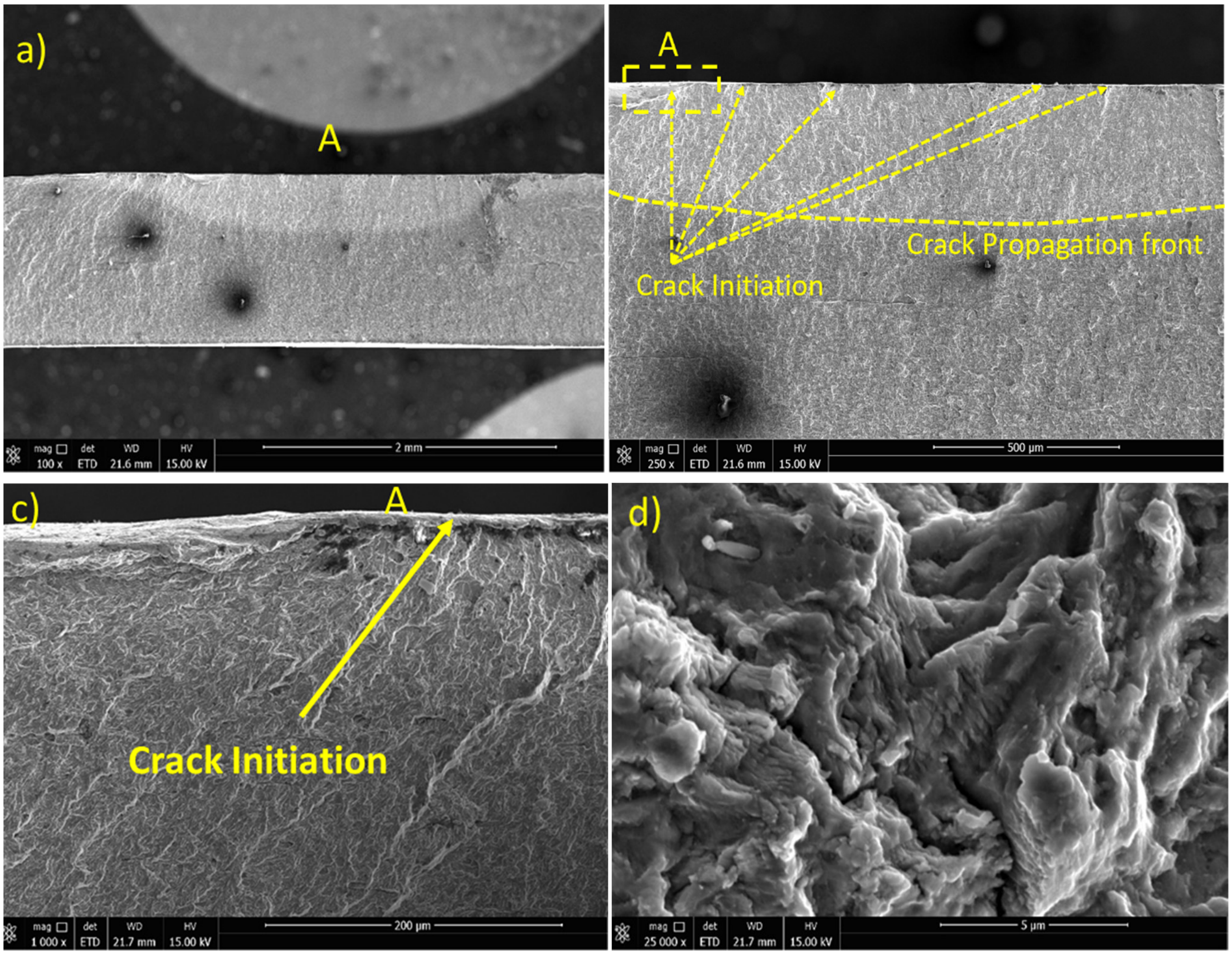


Fig. 9. Failure analysis of spot welded joints(Fatigue failed sample through eyebrow crack at 3.96kN and 38094 number of cycles).

Microhardness Values on Spot Welded Joint

The fracture surface analysis clearly shows the detached or loosened interlock that led to fretting and microparticle (oxide/debris) formation at the faying surface. Microcracks nucleates at the surface due to the fretting behaviour in the SPR sheets. Eccentric loading during fatigue resulted in stress concentration below the rivet head at the center of the sheet accelerates the nucleation of the micro-cracks as demonstrated in the figure below. But in the case of resistance spot welding, the crack initiated along a boundary concurrently. The Microhardness evaluation on the DP590 side in figure 10 shows the soft regions with hardness value 170HV – 200HV near the heat-affected zone and notch/corona bond region. At higher magnification, the presence of tempered martensite is observed along the regions 2 and 3. In the region marked as 2, the fatigue crack is visible which propagates through the tempered zone. The analysis confirms that crack initiated from the notch and propagated through soft tempered zone.Even though notch encounters brittle martensite with hardness value of 300HV-350HV at the nugget region crack propagates in the direction perpendicular to loading direction. The corona bond in the region near to nugget prevents the notch crack from propagating into fusion zone. The fatigue kink crack in the soft region of the DP590 steel side[23] HAZ Softening phenomenon in the Fine Grain HAZ (FGHAZ) makes the DP590 steel prone to fatigue crack along this region as show in the schematic figure 10a and figure 10b.

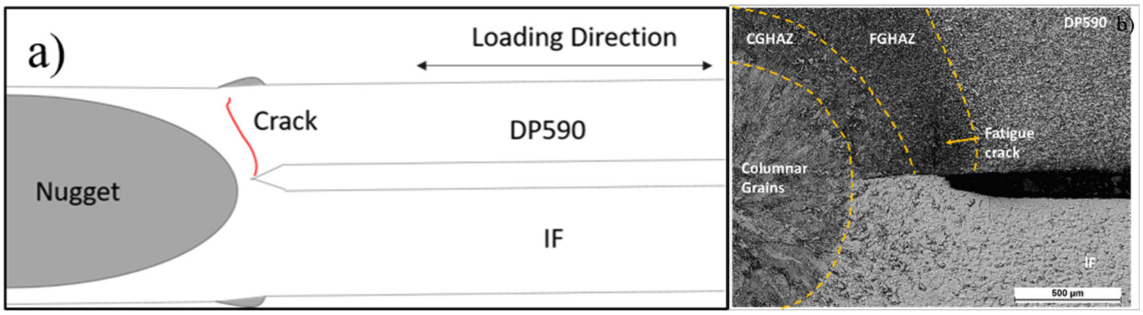


Fig. 10. (a) Schematic of fatigue loading direction and crack (b) HAZ and fatigue crack.

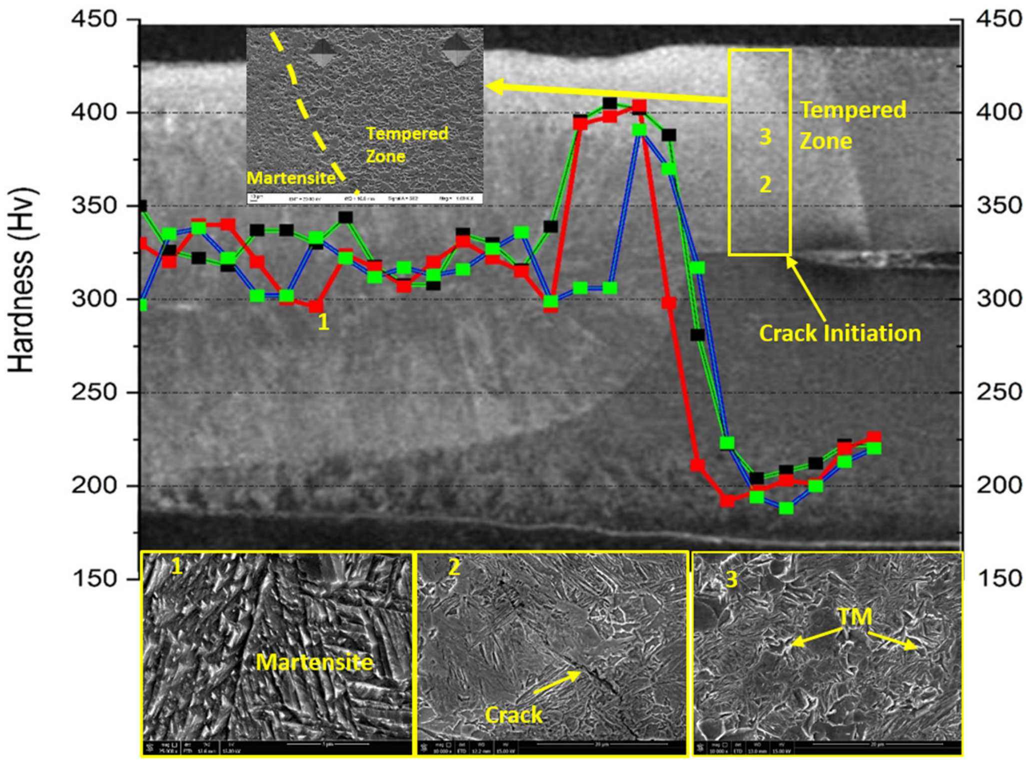


Fig. 11. Cross section of the fatigue samples at 3.96kN, 18500 cycles.

Conclusions

From the present research work on DP590 and IF steel joined using Self Piercing Riveting and Resistance Spot Welding, following conclusions are drawn,

1. Dissimilar sheet of DP590 and IF steel with 1mm and 1.4mm thickness joined using SPR and RSW processes. Both joints haveshown reliable mechanical properties with littlescatter.
2. IF steel side was found to have a larger nugget size. The difference in steel chemistry is not a significant factor for nugget formation in spot welding of dissimilar steels. Dissimilarity in thickness was a key factor ingoverning the nugget size.
3. Spot welded joint is 26% superior in lap shear strength compared to the SPR joints. Top sheet piercing in the SPR process reduced the load-bearing and reduces the tensile strength of the joint. SPR with -0.4mm head height has shown lower tensile strength due to less interlocking of the rivet in bottom sheet compared to SPR with -1.2mm head height. Tensile failure in spot welding occurs along the tempered area of the heat-affected zone.
4. SPR process is more reliable in cyclic loading conditions compared to spot welding process in DP590 (1mm) – IF (1.4mm) combination. Residual stress and strain hardening due to riveting process improved the fatigue performance of the SPR joint compared to RSW joint.
5. SPR joint has shown single crack initiation point where as in spot weld a single point of crack initiation is not observed as crack propagates from the notch. The tempered martensite zone was observed in the DP590 is a soft region with hardness value 170HV - 200HV for crack propagation. The crack initiates and propagates through a boundary along the tempered zone. This soft region reduces the fatigue strength of the spot welds.

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Address correspondence to: Akhil Kishore V T, *Department of Metallurgical and Materials Engineering, National Institute of Technology Karnataka, Suratkal, Mangalore – 575025.*
E-mail: akhil14247@gmail.com