Experimental Study on Dissimilar Spot Welded Joints of DP590 and IFHS Steels

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***Abstract*: Resistance spot welding (RSW) is a predominant joining process in automotive industry. Typically, there are about 2000–5000 spot welds in a modern vehicle. The most important features of RSW process are high production rate and its suitability for automation. In automotive body, the majority of welds are between two dissimilar thicknesses and dissimilar grades of steels. As the different metals have different metallurgical responses to the temporal conditions of welding, it creates asymmetric weld nugget which subsequently affects the mechanical performance. Evaluation of mechanical performance of steel resistance spot welds under quasi-static and fatigue loading conditions are important characteristics in respect of vehicle crashworthiness. Integration of Advanced High strength Steel (AHSS) into the automotive structure has brought renewed challenges for achieving acceptable welds.**

The current study investigates RSW of dissimilar joints of high strength and advance high strength steels including high strength interstitial free (IFHS), dual phase (DP590) steel sheets. The microstructure and mechanical properties of these dissimilar RSW welded steel sheets are characterized using metallurgical techniques and tensile shear and fatigue loading condition.

Keywords: RSW, AHSS, Microstructure, Mechanical performance.

1. INTRODUCTION

Advanced High Strength Steels (AHSS) are characterized by improved formability and crash worthiness compared to conventional steel grades **[1]**. Dual-phase (DP) steel is one of the most common AHSS grade steels. The higher initial rate of work hardening with excellent uniform elongation combines to give DP steels a much higher ultimate tensile strength (UTS) and a lower ratio of yield strength (YS) to UTS than conventional steels. These characteristics have made DP steels attractive for automotive industry. Interstitial free (IF) steel having excellent formability and weldability, is being used as structural material in automotive industry during the last few decades. However, dissimilar resistance spot welding can be more complex than similar welding due to different thermal cycle experienced with each metal. Furthermore, during service in automotive structure, spot welds are subjected to complicated static and dynamic loading histories. Thus performance of resistance spot dissimilar welded joints has become an important issue for safety and reliability of the vehicle. Despite of various application of dissimilar RSW, reports in the literature in dealing with mechanical performance of DP steel and IF steel are limited. Development of microstructure during RSW is significantly affected by base metal (BM) chemistry, initial microstructure of BM and the high cooling rate **[2]**. It is reported that the cooling rate in RSW changes approximately from 3000°C/s for 2.0 mm thickness to over 10^5 C/s for thicknesses less than 0.5 mm **[3].** This high cooling rate is sufficient to produce martensite in fusion zone of DP steels and even in low carbon steels.

Generally, the failure of resistance spot weld (RSW) occurs in two modes: interfacial failure (IF) and pullout failure (PF). RSW of AHSS exhibits higher tendency to fail in interfacial failure mode than low carbon and HSLA steels **[2-7]**.

Pouranvari and Marashi [**8**] presented a comparative study of the transition from interfacial failure to pullout failure for similar and dissimilar resistance spot welds of low carbon and DP600. It is observed that there are three distinct failure modes during tensile-shear test of dissimilar DP steel and low carbon steel- interfacial, pullout and partial thickness–partial pullout. Contrary to general expectations, failure is commenced from stronger side, DP600. However, excessive welding current and welding time cause severe expulsion and severe electrode indentation and ultimately results in reduction in peak load and energy absorption.

Hardness of the fusion zone is a key metallurgical factor in determining weld ductility and failure mode transition **[16-18]**. The hardness of the fusion zone is governed by volume fraction of its microconstituents and their individual hardness.

Notch is inherently present in the RSW at the edge of the nugget. Notch geometry affects failure modes of the weld **[9]**. In the case of sharp notches at the edge of the nugget, the stress concentration in front of the notch tip is very high **[10]**, leading to the preferential occurrence of the interface failure mode. In the shear tensile test, the driving force for the interfacial failure mode is the shear stress at the

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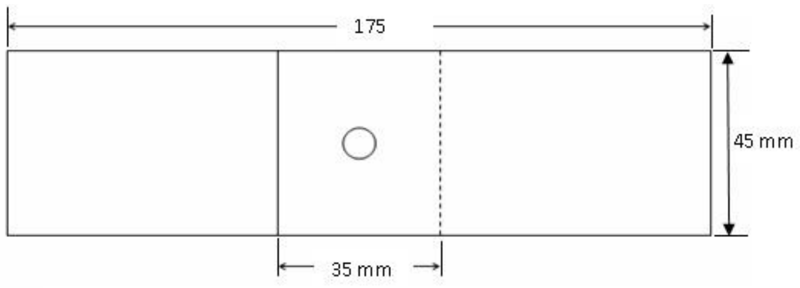
interface of two sheets which depends on the area of the weld nugget in the sheet/sheet plane. The resistance against the interfacial failure of the spot welds is determined **[11]** by the fusion zone hardness.
Vural et al. **[12]** presented that when as current is increased, nugget diameter increases until a critical current value. After exceeding this critical value, the nugget diameter decreases because of expulsion. Thus, the fatigue life increases as nugget diameter increases. This result is similar to the results of tensile-shear tests.
Long and Khanna **[13,14]** observed that at high load and low cycles, in a shear tensile sample fatigue crack initiated outside the weld nugget for HSLA350 while in DP600 and TRIP 600, crack initiated closer to the weld nugget. The crack propagates along the workpiece interface for a short distance and then it propagates perpendicular to the workpiece interface to complete fracture. For the case of low load and high cycles, the crack was seen directly propagated perpendicular to the workpiece interface from the HAZ area of weld nugget.
S.-H. Lin et al. **[15]** found that failure to be dominated by the through thickness cracking. The fatigue crack is considered as a kinked crack with respect to the original notch tip. The fatigue crack appears to be initiated close to the notch tip along the nugget circumference, then propagates through the sheet thickness. Then the kinked crack was seen to propagate into the weld nugget and to go through the sheet thickness.

2.1. WELDING EQUIPMENT AND PARAMETERS
Spot-welding is carried out on shear-tensile sheet samples CEA make interfaced with a Mechelonic Engineer software. A cold water circulating system is used to maintain the temperature of the truncated cone electrodes (RWMA Group A, Class-2 Cu-Cr-Zn type) at 18^{O}C. Experiment is done in two sets. Electrode tip diameters of 6mm of both electrodes for experimental set I (S1) and 8 mm and 6mm for experimental set II (S2) are used for the experiments based on BS1140 specification.
To get larger nugget diameter current had to be increased but it causes expulsion so in second set (S2), preheat is adopted to increase the total heat input in both sheets and subsequently to get bigger nugget diameter.

Table: 1

Welding current = 7 kA Welding time = 14 Cycle = 280 ms; Electrode pressure = 4 bar Squeeze Time = 23 Cycle = (23 x 20)ms = 560ms	
Experimental Sets	Parameter
S1	For DP steel Electrode Tip Diameter = 6mm For IFHS steel Electrode Tip Diameter = 6 mm; Hold time = 10 Cycle
S2	For DP steel Electrode Tip Diameter = 8mm For IFHS steel Electrode Tip Diameter = 6 mm; Preheat current = 5.5 kA Preheat time = 7 Cycle Hold time = 6 Cycle



Shear Test Sample as per BS 1140

A weldability test is conducted to determine weld lobes which produce acceptable weld quality as determined by AWS standards.

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2.2. Mechanical Testing and Microstructure

To evaluate mechanical testing, Mechanical properties of the spot welded joints of DP590/IFHS steels are evaluated by measuring the peak load to failure during overlap tensile shear testing using two different parameters given in Table 1. Tensile tests are carried out on a 100kN universal testing machine of Servo-Electric Instron8862. Samples are monotonically loaded and the displacement data are simultaneously recorded. Tests are terminated when two parts of the samples are completely separated. Detailed examination of failure mechanism is also examined by interrupting the loading cycle during overlap shear testing.

Fatigue tests are carried out only on the same tensile shear samples, using the average value of breaking load obtained in the tensile shear test. Fatigue tests are performed on a 50kN Testronic Rumul Resonant Testing Machine. The test is first performed applying a maximum load of 20% to 80% of the tensile breaking load at a constant R-ratio (of 0.1) in tension-tension mode. The tests are continued up to failure and the number of cycles to failure (N) was recorded. From this data, maximum load with number of cycles to failure curve is plotted for different joints.
Microhardness values were taken on the polished surface of the specimens using Vicker's micro hardness testing machine (Model: LM-248AT, manufactured by Leco, load range: 5gf-2kgf) at 100gf load for a dwell time 10 seconds.

3. RESULT & DISCUSSION

3.1. Microstructural Observation of Weld Joints:

The macroscopic view of a typical DP590/IFHS RSW joint under the welding current 7.0 kA, welding time 14 cycles is shown in **Fig. 1 and 2.** It is seen the joint consists of three distinct regions:

(i) **Fusion Zone (FZ) or Weld Metal (WM):** This zone is melted during welding and is resolidified showing a cast structure. Macrostructure of the weld nugget consists of columnar grains with lath martensite. In IF side weld metal, some amount of martensite and widmanstätten ferrite are observed. Martensite is observed in IF side weld metal may be present due to dilution during welding. There is less amount of carbon present in IF base metal. During welding, some amount of carbon present in DP may be got transferred into IF side making it to have more carbon content. In turn, these carbon rich regions may have transferred into martensite.

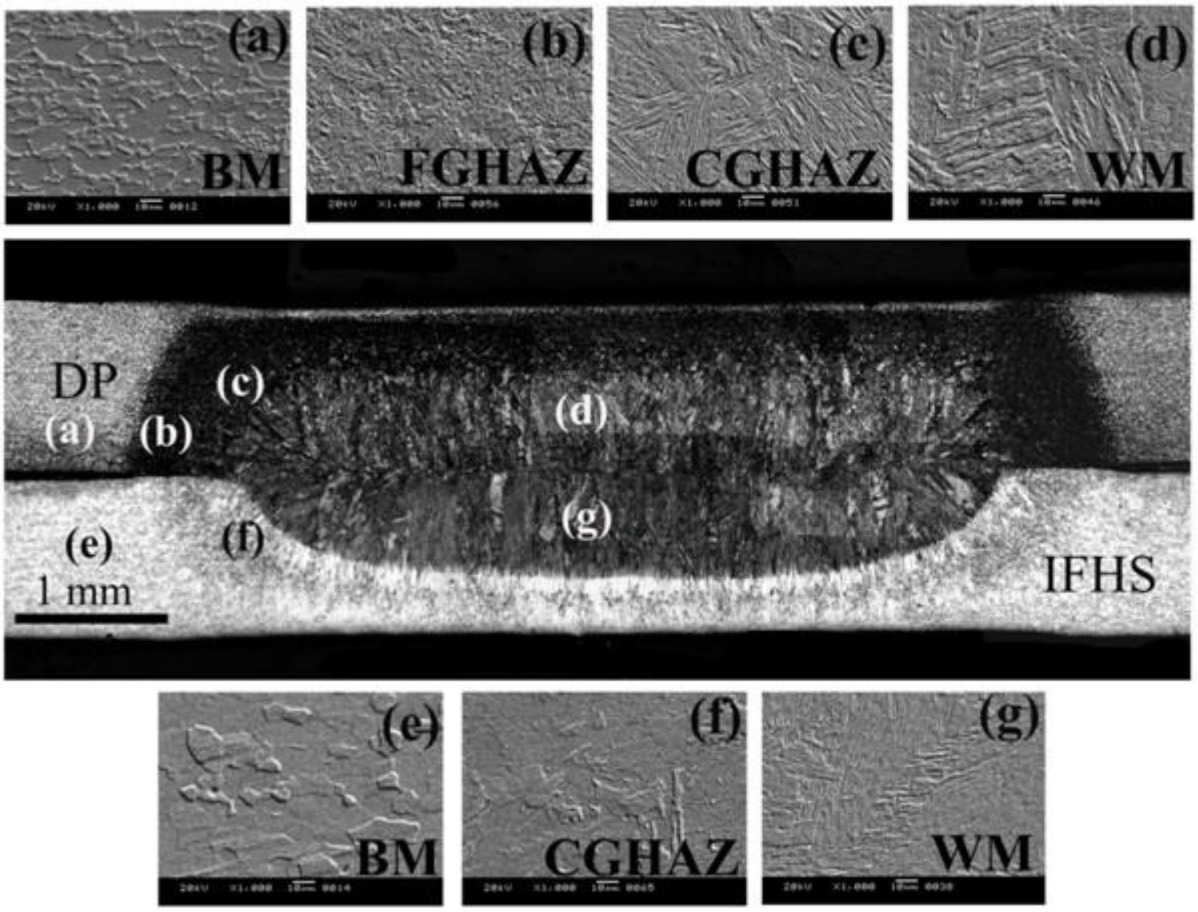

Fig.1. Macrostructure of sample S1 indicating different regions of DP side:
(a) Base metal (BM) (b) fine grain HAZ (FGHAZ) (c) coarse grain HAZ (CGHAZ) (d) weld metal (WM),
IF side: (e) base metal (BM) (f) coarse grain HAZ (CGHAZ) (g) weld metal (WM).

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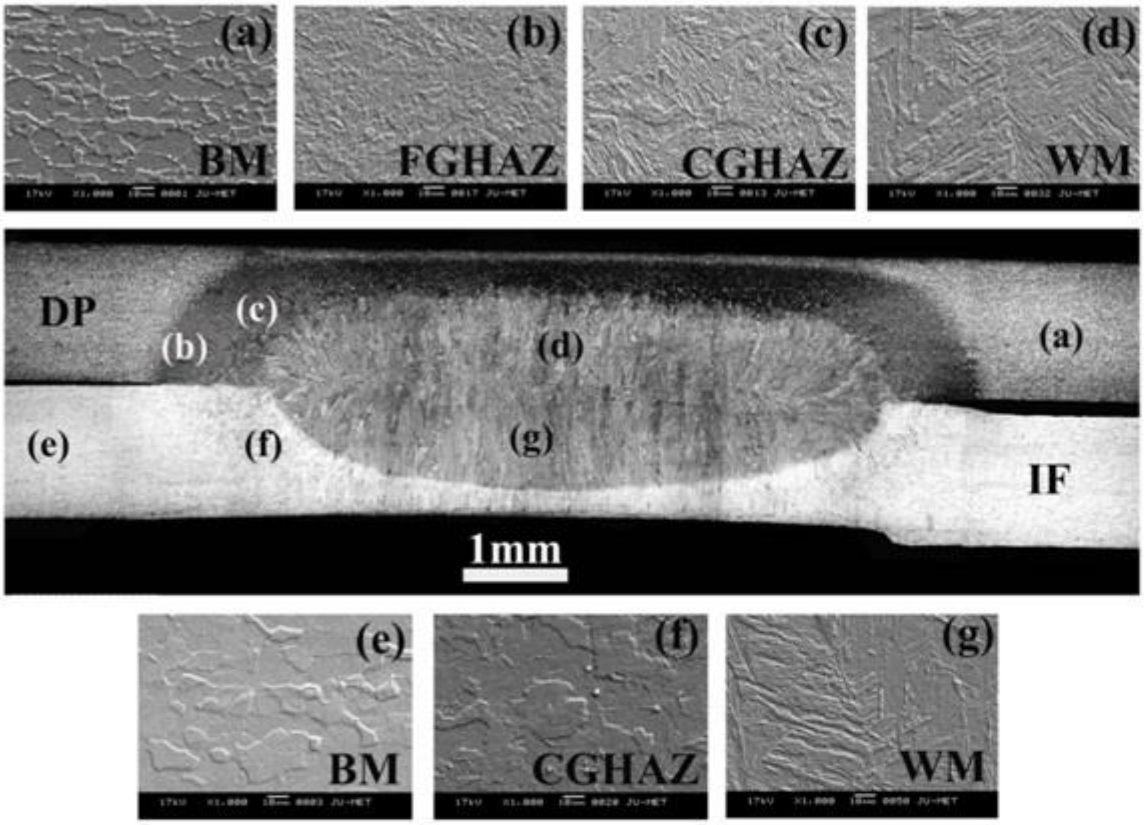

Fig.2. Macrostructure of sample S2 indicating different regions of DP side:
(a) Base metal (BM) (b) fine grain HAZ (FGHAZ) (c) coarse grain HAZ (CGHAZ) (d) weld metal (WM),
IFHS side: (e) base metal (BM) (f) coarse grain HAZ (CGHAZ) (g) weld metal (WM).

(ii) **Heat affected zone (HAZ):** It is not melted but undergoes microstructural changes. HAZ can be divided into two regions namely (a) coarse grain HAZ (CGHAZ) (b) fine grain HAZ (FGHAZ). In IFHS side, CGHAZ and FGHAZ regions are not distinct due to lesser rich chemistry than DP590. As DP590 being AHSS grade of steel contains more than one phase, FGHAZ in DP590 is divided into another type of HAZ called intercritical HAZ (ICHAZ).

(iii) **Base metal (BM):** It remains thermally unaffected.

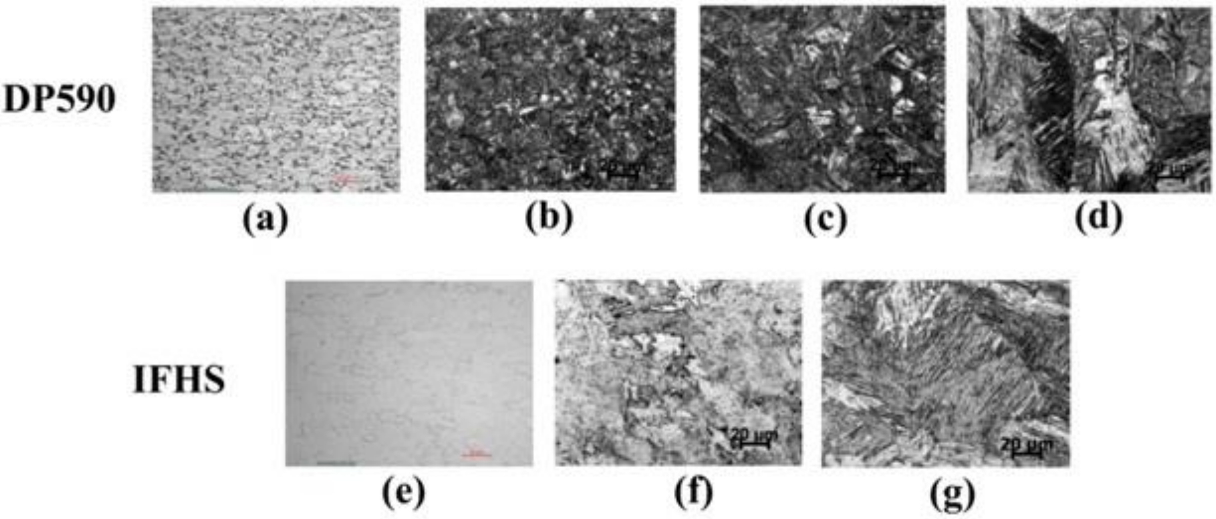

Fig.3. Microstructure of different zones indicating different regions of DP side: (a) base metal (BM) (b) fine grain HAZ (FGHAZ) (c) coarse grain HAZ (CGHAZ) (d) weld metal (WM),
IF side: (e) base metal (BM) (f) coarse grain HAZ (CGHAZ) (g) weld metal (WM).

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Microstructure of fusion zone is depends on chemical composition and rate of cooling during RSW process. Chemical composition of fusion zone is affected by the chemical composition of base metals involved in the joint and the mixing of them. In the case of dissimilar metal welding, the melting is different for each sheet. DP590 steel sheet with higher electrical resistivity exhibits higher bulk electrical resistivity and results in higher contribution in the volume of melted zone. Therefore, nugget size is asymmetrical, larger at DP side than IF side. In order to make it uniform and large in size, electrode of greater diameter (8mm) is used in DP side to reduce the current density and preheated both sheets before welding. As current passes from bigger to smaller diameter, current density increases at the lower side of the sheet, and tends to increase more melted IF. Due to preheating, overall nugget size increases.

3.2. Microhardness Profile

The microhardness plot of the combination of DP590/IFHS with similar electrode and dissimilar electrode is shown in Fig. 4

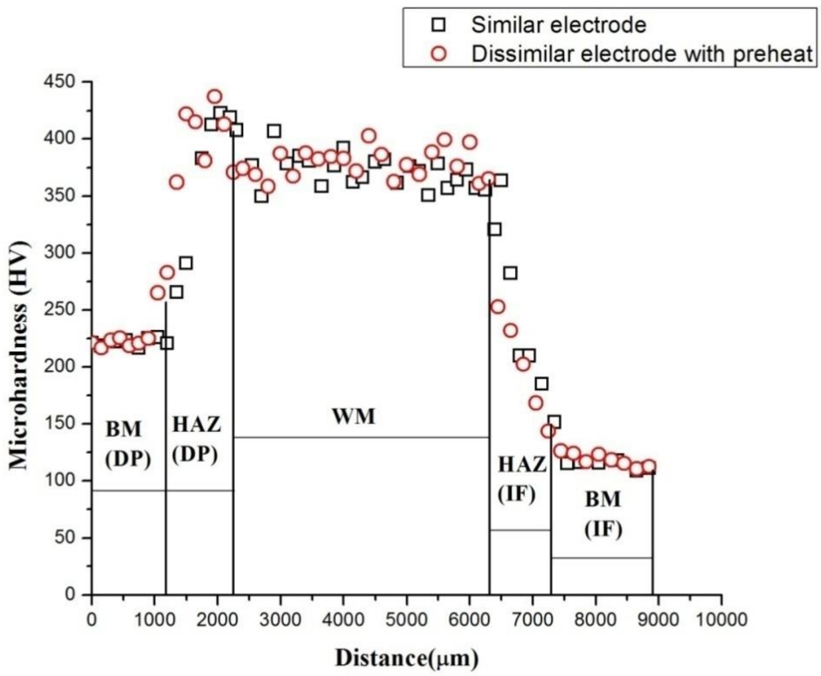

Fig.4. Microhardness distribution in DP590/IFHS joint.

It is observed from Fig.4**.** that microhardness of the fusion zone (FZ) is clearly more than the base metals. Fusion zone hardness increases due to formation of lath martensite due to very high cooling rate. In IFHS side, weld metal hardness increases, even when there is less amount of carbon present in base metal. The probable reason may be due to dilution effect. At the interface region, carbon may diffuse into IF portion from carbon rich DP portion. This may cause increase in hardness of the interface region. As martensite and widmanstätten ferrite is found, hardness increases. Due to different base metal compositions of DP590 and IFHS, dilution occurs in the fusion zone.

3.3. Performance under Quasi-Static Loading

To evaluate mechanical performance and failure mode of the spot welds, shear tensile tests are performed. Breaking load (maximum load in the load–displacement curve) and failure energy (the area under the load–displacement curve up to the breaking load) are determined from the load–displacement curve.

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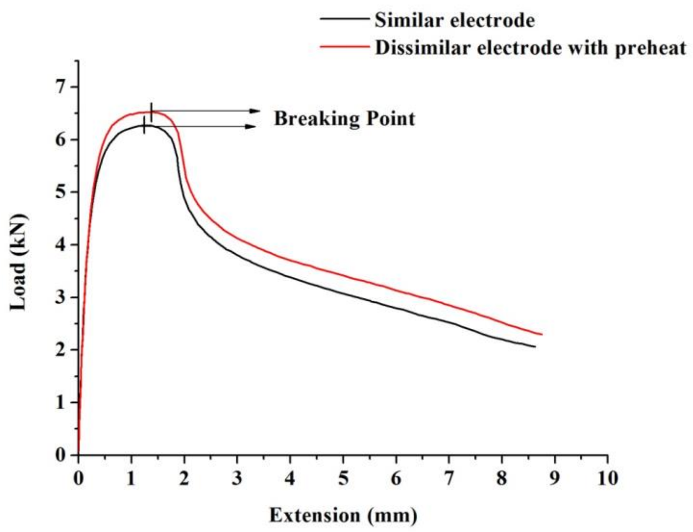
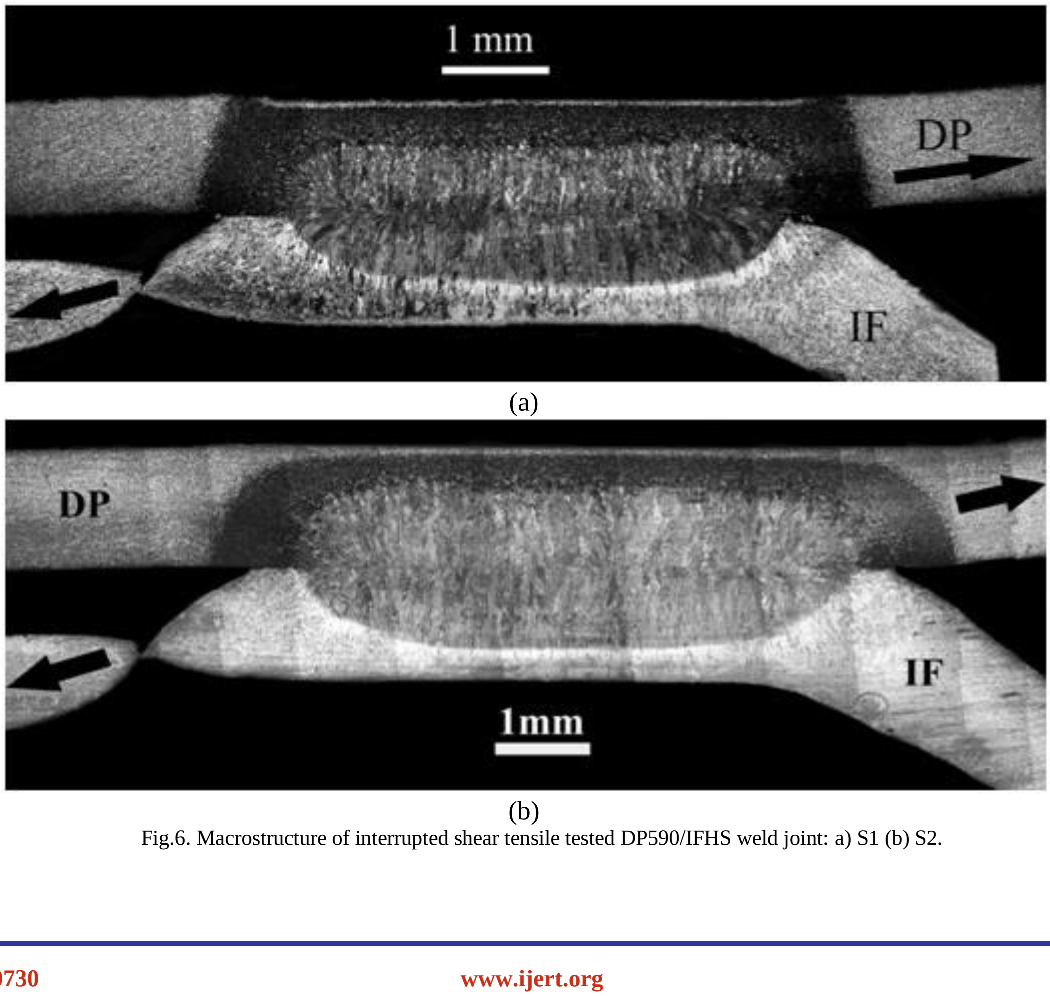


Fig.5. Plot of load with extension for S1 and S2 samples.

The amount of failure energy is calculated by measuring the area under the load–displacement curve up to the breaking load using the following equation **[1]:**

$$\text{Failure energy} = \int_0^{X\max} F\,dx = \sum_{n=1}^{N} F(n)[X(n) - X(n-1)]$$

It may be noted that the tensile shear strength of spot welds depend on the nugget size, sheet thickness and base material strength. It is observed that the maximum tensile load in lap shear tensile joints increases with increasing nugget diameter. In both cases, plug type i.e. pullout failure was obtained where the weld button remained intact in stronger sheet (DP590) and a hole was created in the weaker sheet (IFHS). Necking occurs in base metal of the IFHS steel sheet because of the difference between UTS of sheets. The UTS of DP590 is almost 65% more than IFHS. The location of the failure is governed by microhardness profile characteristics of the weld. Necking occurs where hardness has its lowest value. As the base metal of IFHS sheet has the lowest hardness, necking is initiated from the base metal.



(a)

(b)

Fig.6. Macrostructure of interrupted shear tensile tested DP590/IFHS weld joint: a) S1 (b) S2.

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3.4. Fatigue Performances

Fatigue performance of spot welded joints is evaluated to determine the number of cycles to failure as a function of load amplitude and maximum load. The lap shear fatigue test results **(Fig. 7)** indicate that the endurance limit of 2x10^6 cycles is obtained at load amplitudes of 0.55kN and 0.57kN (fatigue endurance strength) for nugget diameters of 4.74mm (S1) and 5.4mm (S2) respectively.

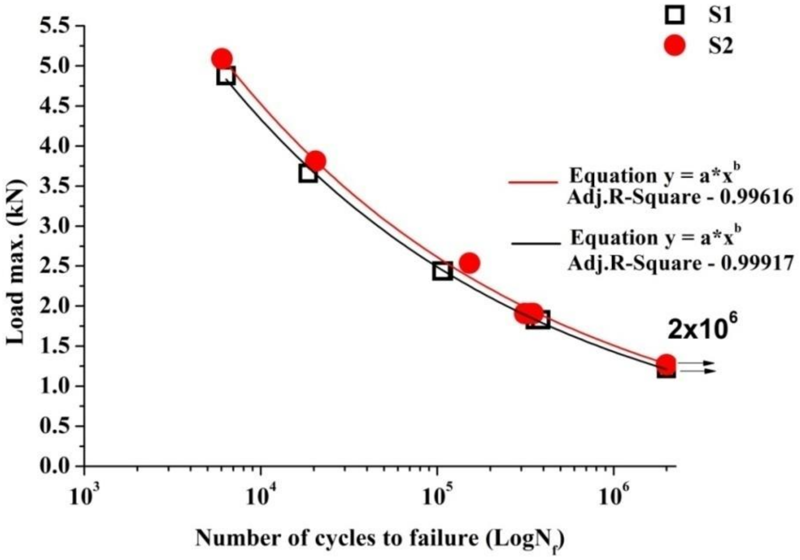

Fig. 7. Plot of maximum load with number of cycles to failure curve of DP590/IFHS joint for S1 and S2.

In RSW, notch is inherently present at the edge of the fusion zone. In front of the notch tip stress concentration is very high. This notch usually acts as stress raiser for initiation of the fatigue crack. The geometry of the notch in S1 and S2 are shown in Fig.8. During spot welding, a partially bonded interface, known as corona bond, presents ahead of the notch and ends up to the fusion zone

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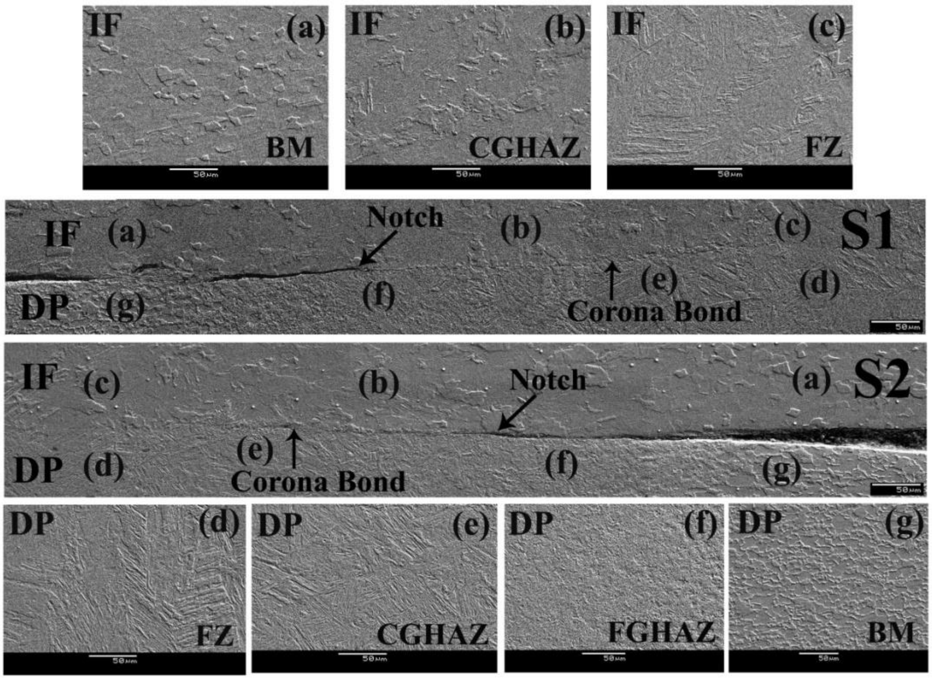

Fig.8. Corona bond is shown in both samples with different microstructure zones.

Another factor that contributes to the brittleness is the microstructure itself. The rapid cooling results with a martensitic structure in a weld nugget because of the higher level of carbon and other alloying elements. The presence of hard martensite facilitates easier propagation of cracks and generates failure.

It is known that there is a direct relationship between fatigue strength and weld nugget size. Increase in fusion

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zone size results in increase fatigue strength. In S2, heat input is higher than S1, so the fusion zone size increases in S2. Fatigue strength also increases in S2. Variation of acting frequency with number of cycles to failure is plotted at high load low cycle regime and intermediate load high cycle regime for both S1 and S2. In **Fig.9** and **Fig.10** it is seen that drop in test frequency occurs earlier in S1 for both high cycle and intermediate cycle loading. This indicates that S2 samples are able to retain its stiffness for higher number of cycles under applied load, in comparison with S1.

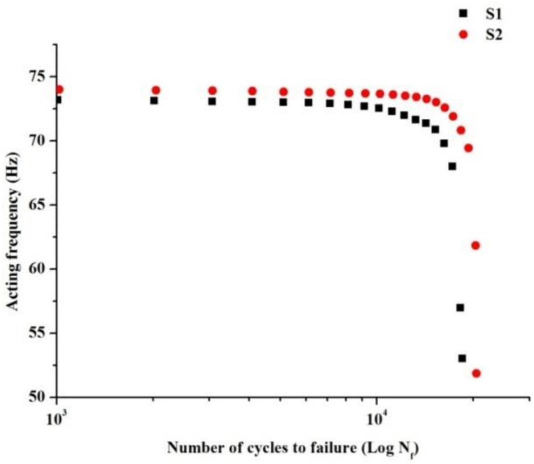

Fig.9. Plot of acting frequency with no. of cycles failure plot of S1 and S2 samples at an applied fatigue load equal to 60% of static failure load.

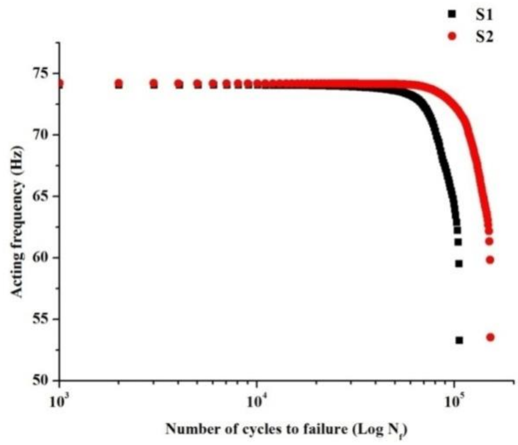

Fig.10. Plot of acting frequency with no. of cycles failure plot of S1 and S2 samples at an applied fatigue load equal to 40% of static failure load.

4. CONCLUSION

1.The shape of the weld nugget is asymmetrical in S1. The fusion zone size and the depth of penetration of DP590 side are larger than that of the IFHS side. Differences in the electrical resistivity and thermal conductivity of two steel sheets lead to an asymmetrical weld nugget in dissimilar metal joints. Lower electrical resistance and higher thermal conductivity of IFHS compared to DP590 leads to smaller fusion zone size in the former. Dissimilar electrode tip diameters (S2) are used to make the nugget symmetrical.

2. Shear tensile load bearing capacity of higher heat input parameter (S2) is relatively better than lower heat input parameter (S1) because of the larger nugget diameter of the former. Typical pullout failure by necking of weaker side base metal (IFHS) was observed in both cases.

3. Fatigue performance is observed to be influenced by the fusion zone size. Hence, S2 samples with larger nugget diameter and higher failure load, performs better than the S1 sample. At high load, kinked crack initiates from CGHAZ/FZ boundary and at low load, kinked crack initiates from FGHAZ/CGHAZ boundary. It subsequently propagated through the thickness of the loading members. Endurance limit was obtained at 1.22kN for S1 and 1.27kN for S2 (20% of the breaking load of shear tensile test).

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