# A Comparative Study on Fatigue Performance of DP590 and DP780 Spot Welded and Weld Bonded Steel Sheets

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## ABSTRACT

The automotive companies are quickly changing their material bill from low strength formable grades to advanced high strength steels (AHSS) in response to the global call for preserving a green environment and enhanced passenger safety. As compared to low carbon formable steels, the AHSS steels are relatively difficult to weld by the traditional processes and the joint performance is below expected levels. Thereby conventional manufacturing processes are being challenged, and new processes with improved service performance are being increasingly explored. Fatigue performance of material joints is a key design input and indicator of the performance of automobiles during service, particularly for AHSS.

In this paper, primary joining process such as spot welding and emerging hybrid joining process such as weld-bonding were carried out on two commercially available AHS dual phase (DP590, DP780) automotive steels. Two dimensional spot welding lobes were developed for each of the steels following nugget diameter criteria of $4\sqrt{t}$ to $5.5\sqrt{t}$, where t is the thickness of the sheets. By selecting two sets of parameters from the lobes, spot-welding was carried out on shear-tension sheet samples with an AC type resistance spot welding machine. Weld-bonding was done by applying a thin layer of high strength epoxy based structural adhesive followed by spot welding on two overlapping sheet samples. Static shear tensile and fatigue properties under tension-tension mode for all the spot welded and weld-bonded joints of DP590 and DP780 steels were evaluated and compared.

**Key words:** Weldability Lobe, DP Steels, Weld Bonding, Shear Tensile strength, High Cycle Fatigue performance.

## 1.0 INTRODUCTION

The automotive industries are quickly changing their material from low strength formable grades to advanced high strength steel (AHSS) in response to the global call for preserving a green environment and enhanced passenger safety. Among the AHSS, the dual phase (DP) steels have shown promise of fulfilling all their needs. As a result, DP590 and DP780 steels are being used in large volumes in the latest vehicles.

With the introduction of 590 MPa DP steel, the automotive industries have realized that DP steel has good formability without sacrificing strength [1]. This combination of high ductility (hence formability) and high strength, which comes from the unique microstructure i.e. martensite in a soft ferrite matrix, can allow thinner steels to be used in automotive bodies. With further development and commercialization of DP steels with minimum tensile strength of 780MPa and 980MPa, many automotive industries are targeting to use these two steel too [2,3].

Spot welding is a popular joining method in thin sheet metal manufacturing, especially in automotive industry. Although other fusion welding methods such as laser beam welding, gas metal arc welding etc. are being used in automotive manufacturing, spot welding still remains the most important joining method due to its low cost and high robustness.

Spot weld quality is usually measured in view of the performance requirements of a weld. They can be either quantitative or qualitative. In general, weld performance characteristics should refer to both static and dynamic strength. However, DP steels can undergo significant fatigue damage which is related to the reduction in sheet thickness [4,5]. Thus, it is imperative to investigate the fatigue behaviour of spot welded joints in thin section DP steels for achieving a safe and reliable design.

Since suitable amounts of ferrite and martensite in DP steels may be produced from a combination of heat-treating parameters, composition of DP steels may vary significantly from one steel maker to another. Again, various micro-structures and sets of properties can also be generated from a single composition. However, the role of chemical composition on spot weld quality is not yet entirely clarified with same grade of DP steel and also, the mechanical properties of the as received steels influence weld fracture [6].

It was indicated that the conventional recommendation (based on the sheet thickness) for weld sizing in order to ensure pull-out failure mode of welds are not dominant for AHSS welds [7]. Furthermore, recent investigation on the transition criteria from interfacial to pull out mode in AHSS spot welds during tensile shear test has introduced critical fusion zone (FZ) size as new weld quality criteria. The critical FZ size was reported to increase in the order of DP600, DP980 and DP780. However, no direct relationship was found between the tensile strength of base metal and critical FZ size [7]. According to sen et al [8] for weld made on DP600, the weld failure mode is closely linked with both load bearing capacity and energy absorption capability. However, complete assessment of RSW failure analysis depends on the fatigue failure behaviour of welds besides overload failure. The FZ size was reported as the main controlling factor in determining the fatigue strength of RSWs [9]. Developing a spot weld size criterion based on fatigue strength is required to ensure reliable service of the weld during the vehicles lifetime. Furthermore, interfacial fracture does not necessarily lead to decrease in strength as compared to button pullout mode. While interfacial fracture does affect low cycle to failure behaviour, but there was no effect on high cycle fatigue [10].

From the geometrical point of view the spot weld forms an external cracks, where the nugget plays the role of a ligament. This geometric singularity would bring about stress concentration and accompanying excessive local deformation. Since adhesive bonding offers more uniform distribution of stresses, increased fatigue life, weight savings, and reduced corrosion between dissimilar materials, a new hybrid welding process (i.e. weld-bonding process), has been attempted in this case, resistance spot welding is done in parts that have been joined fix by adhesive bonded. The process is reported to improve joint performance [11].

Since the RSW process is the primary joining method used in automotive production, a detailed understanding of the metallurgical changes and their effects on the mechanical performance of AHSS welds is required for safe integration into the automotive architecture. Recent publications detailing microstructure and mechanical properties of resistance spot welded AHSS have focused exclusively on a single grade of steel. For example, marya et al [12] examined the effects of RSW process parameters on the failure mode during tensile shear testing of DP steels. Similarly tong et al [13] examined the mechanical properties of spot welded DP steels and their influence on failure behaviour. The current literature, however, fails to critically compare the microstructure and mechanical properties of spot welded DP steels in various grades. Furthermore, weld bonded joints have been compares with resistant spot welded joints with regard to both static and dynamic strength of DP steels.

## 2.0 EXPERIMENTAL PROCEDURE

### 2.1 Material

Test materials comprising of 1mm thick DP590 and DP780 steel sheets, sourced by Tata Steel, were used for investigation. The chemical composition, carbon equivalent and mechanical properties of the steels are given in **Table 1**. Details of the adhesive used for weld bonding are given in **Table 2**.

### 2.2 Spot welding

Spot-welding was carried out on shear tensile and weld bonded sheet samples with a CEA make PPN53 RATIA73 IQ1 AC type resistance spot welding machine of 50KVA rating (at 60 % duty cycle) interfaced with a Pegasus software. A cold water circulating system maintained the temperature of the truncated cone electrodes (RWMA Group A, Class-2 Cu-Cr-Zn type) at 18°C. Electrode tip diameter of 6mm was used for the experiments based on BS1140:1993 specification. Details of welding parameters are given in **Table 3**.

**Table 1: Chemical composition and mechanical properties of DP590 and DP780 steel sheet**

| Grade | Chemical Composition | | | | | | Mechanical Properties | | | Thickness of sheet (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | S | P | CE | YS (MPa) | UTS (MPa) | %E1 | |
| DP590 | 0.09 | 0.9 | 0.35 | 0.009 | 0.012 | 0.15 | 371 | 621 | 25 | 1.0 |
| DP780 | 0.1 | 1.78 | 0.33 | 0.007 | 0.012 | 0.20 | 461 | 843 | 17 | 1.0 |

Note: CE = C + (Si/30) + (Mn + Cu + Cr)/20 + (Ni/60) + (Mo/15) + (V/10) + 5B

**Table2 : Main characteristics of adhesive used**

| Adhesive | Chemical base | Shear Strength | Working time | Curing |
|---|---|---|---|---|
| E | One part adhesive | 25MPa | 30 - 45 min | 180°C , 60 min |

**Table 3 : Details of welding parameters used**

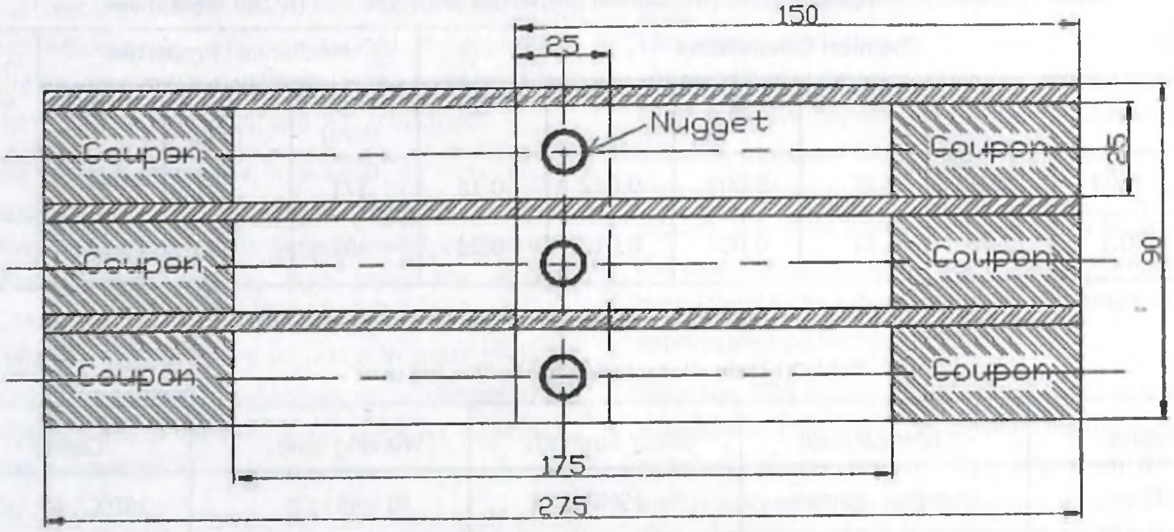
| Electrode Tip Diameter = 6mm; Electrode pressure = 4.4 bar<br>Squeeze Time = 23cycle = (23 x 20)ms = 560ms;<br>Hold time = 10cycle = 200ms; Off time = 99cycle = 1980ms | |
|---|---|
| Grade | Parameter |
| DP590 | Weld Current = 9.3kA<br>Weld Time = 6 cycles = 120ms |
| | Weld Current = 7kA<br>Weld Time = 14 cycles = 280ms |
| DP780 | Weld Current = 8kA<br>Weld Time = 6 cycles = 120ms |
| | Weld Current = 9 kA<br>Weld Time = 8 cycles = 160ms |

### 2.3 Weld-bonding

For weld bonding two 150 mm x 90 mm size sheets were used as shown in **Fig.1**. The surface of the sheets was cleaned using acetone. An epoxy based adhesive (**Table 2**) of 0.4 mm thickness was applied on one of the sheet surfaces (only overlapping area of 25 mm wide as per ASTM D1002) with the help of a spatula and then the other sheet was placed over it and pressed lightly. For maintaining an adhesive layer thickness of < 0.4 mm, a spacer of the same thickness was used. Spot welding was carried out immediately and the assembly was subjected to curing at 180°C for 45 minutes in a muffle furnace. Tensile shear test pieces of dimension 175 mm x 25 mm (**Fig.2**) were extracted from the above assembly. The same sample dimension was used for fatigue testing.

### 2.4 Tensile test

Lap shear tensile and fatigue tests were carried out using two different parameters, i.e. the minimum and maximum nugget diameter, determined from the weldability lobes of the two steels. Tensile shear tests were made producing lap joint of two sheets of dimension 175 mm x 45 mm with an overlap of 35 mm x 45 mm, as per BS 1140: 1993. Tensile shear test sample is shown in **Fig.3 & Fig. 4**. Static tensile shear was performed on the steels using both folded and un-folded samples (**Fig. 3 & Fig. 4**). Folding was done for better alignment and improved stiffness of the tensile test pieces. Tensile tests were carried out on a 100kN servo-electric machine (Instron 8862). The samples were monotonically loaded and the displacement data was simultaneously recorded. The tests were terminated when two parts of the samples were completely separated.



All dimensions are in mm

**Fig. 1 : Weld-bonding sheet size**

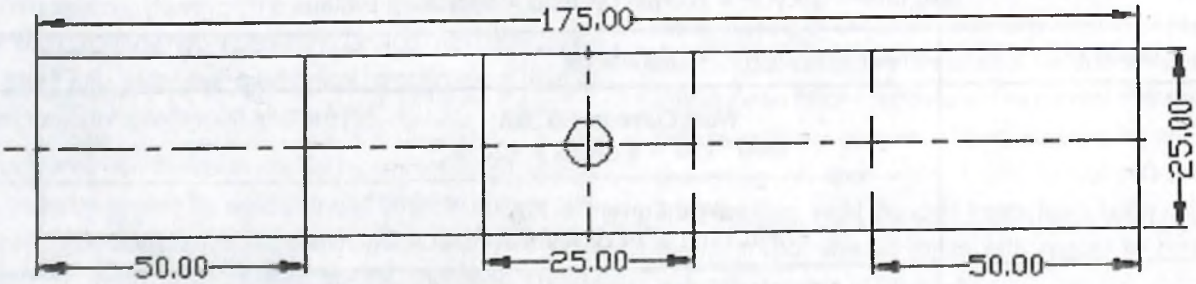


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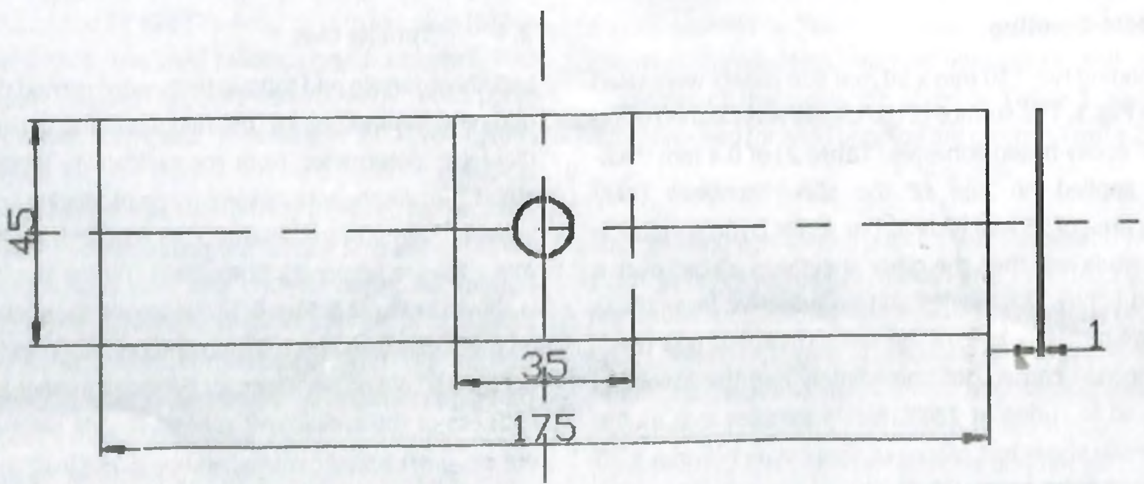
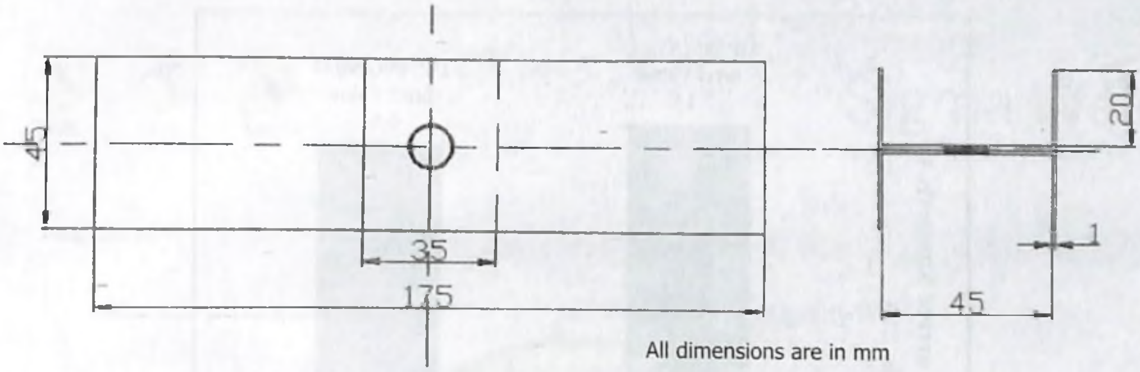
**Fig. 2 : Weld Bonded sample as per ASTM D1002**



All dimensions are in mm

**Fig. 3 : Tensile Shear Test of unfolded Sample as per BS 1140:1993**



All dimensions are in mm

Fig.4 : Tensile Shear Test of folded Sample as per BS 1140:1993

### 2.5 High cycle fatigue test

FFatigue tests on the same tensile shear samples were carried out on a 50kN Testronic Rumul resonant testing machine. Both folded and un-folded samples were used. Again, folding was done for better alignment and higher stiffness of the test pieces as preferred for resonance fatigue testing. The test was first performed applying a load range from of 20% to 80% of the tensile load at a constant R-ratio of (0.1) in tension-tension mode. The load amplitude (S) and minimum load value was calculated by using the R-ratio value. The tests were continued up to failure and the number of cycles to failure (N) was recorded. From this data, S-N (Load amplitude vs Number of cycles to failure) curves were plotted for different joints.

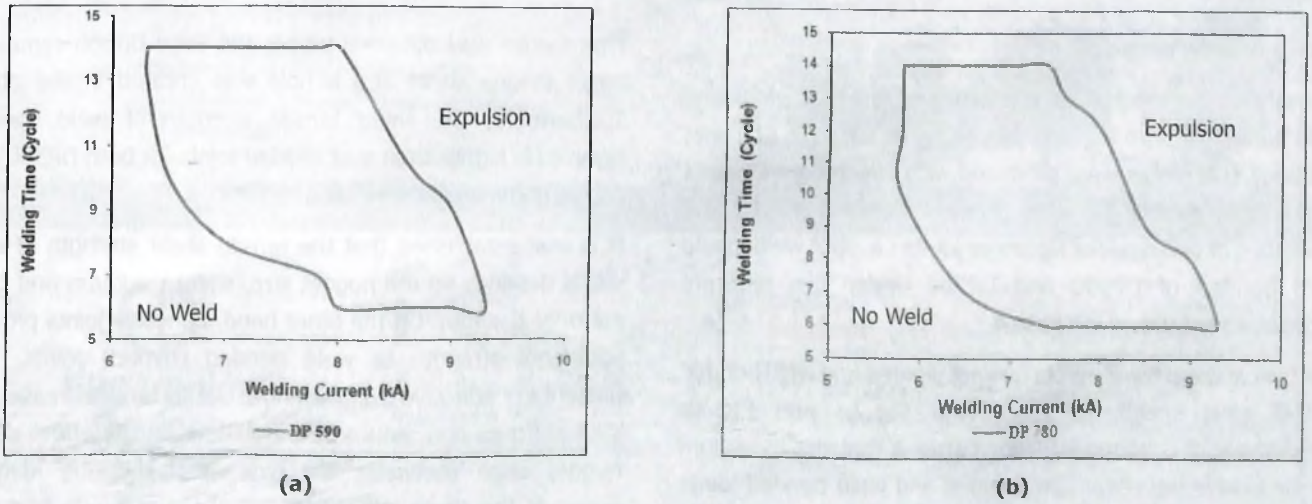
## 3.0 RESULTS AND DISCUSSION

### 3.1 Weldability lobe

Two dimensional weldability lobes were developed for each of the steels considered. Details of welding parameters applied, which include electrode pressure, squeeze time, welding current, welding time, and electrode tip diameter are given in **Table 3**. The nugget diameters after peel-off test are also given. Weldability lobes for both DP590 and DP780, as shown in **Fig.5**, were generated on the basis of minimum nugget diameter criteria of $4\sqrt{t}$ for DP steel, where t is the thickness of the sheet.

The weldability lobes of DP590 and DP780 (**Fig.5**) show significant difference in terms of minimum current requirement for nugget formation. The current required to generate acceptable nuggets is less in DP780 steel as compared to DP590 steel, due to higher resistivity.

Again, the carbon equivalent (CE) values can be related with the welding range as shown in **Fig.6**. Lower the CE, more is the current requirement with wider current range. As material resistivity is directly related with CE, a richer chemistry requires lower current for welding. Materials with higher CE heat up rapidly to form weld nuggets and excessive currents may cause expulsion. Hence DP780 requires lower current for producing acceptable weld nuggets.



(a) (b)

Fig. 5 : Weldability lobe of (a) DP590 and (b) DP780 steel sheet.

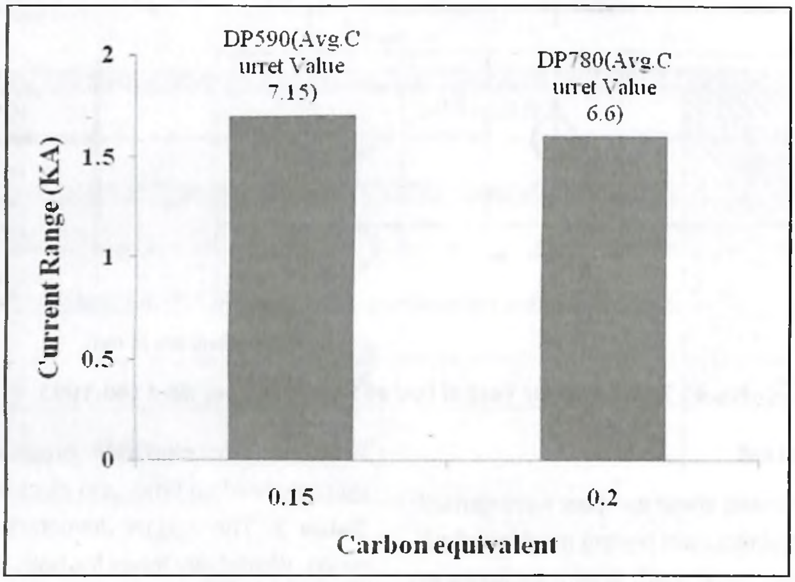


**Fig. 6 : Current range vs Carbon Equivalent**

**Table 4 : Testing conditions and tensile test results of spot welded joints**

| Steel Grade | Sheet Thickness (t in mm) | Parameter | Nugget Diameter (mm) | Spot welded (kN) | Weld Bonded (kN) |
|---|---|---|---|---|---|
| DP 590 | 1 | Welding Current = 9.3 kA<br>Welding Time = 6 Cycle = 120 ms | 5.52 | 11.69 | 14.38 |
| | | Welding Current = 7 kA<br>Welding Time = 14 Cycle = 280 ms | 5.82 | 12.45 | 15.19 |
| DP780 (Folded) | | Welding Current = 8 kA<br>Welding Time = 6 Cycle = 120 ms | 4.76 | 10.92 | 15.32 |
| | | Welding Current = 9 kA<br>Welding Time =8 Cycle = 160 ms | 5.14 | 12.74 | 16.00 |

### 3.2 Tensile property

To evaluate the mechanical properties of the spot welds and weld bonds (i.e. hybrid joint comprising of adhesive and spot welding), test pieces were produced with selected parameters within the weldability lobe as given in **Table 3**. Mechanical properties of two types of lap shear joints i.e. spot welded and weld bonded of DP590 and DP780 under two different parameters are shown in **Table 4**.

The typical shear tensile plots for spot welded and weld bonded DP590 steel sheets are shown in **Fig.7a** and **Fig.7b** respectively. It is observed from **Table 4** that the maximum tensile load in lap shear spot welded and weld bonded joints increases with increasing nugget diameter. For both the specimen geometries (i.e. spot welded and weld bonded), plug type failure was obtained where the weld button remained intact in one sheet and a hole was created in the other. Furthermore, the shear tensile strength of weld bonded samples is higher than spot welded joints for both DP590 and DP780 under identical welding conditions.

It is well established that the tensile shear strength of spot welds depends on the nugget size, sheet thickness and base material strength. On the other hand, adhesive joints provide additional strength to weld bonded (hybrid) joints. The presence of adhesive over the entire overlap area increases the joint stiffness and reduces the notch sensitivity effect at the nugget edge (between the two sheets) during loading. However, the stress intensity factor at the notch tip becomes active only after the nugget gets delaminated. The adhesive

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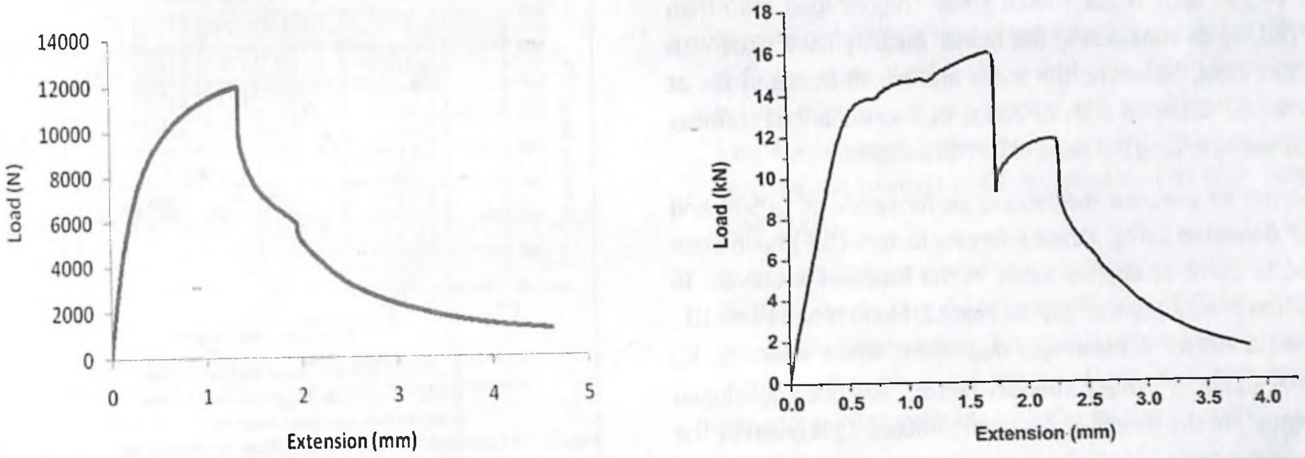


(a) Shear tensile curve for spot welded DP590 steel sheet

(b) Shear tensile curve for weld bonded DP590 steel sheet

**Fig.7 : (a) Shear tensile curve of spot welded and (b) Shear tensile curve of weld bonded DP590 steel sheets**

also ensures Mode-II (shear) loading, as against mixed mode loading in case of spot welds. These are the reasons why the shear tensile strength of weld bonded samples is found to be higher than spot welded joints for identical material and welding conditions.

### 3.3 Fatigue performance

Fatigue performance of spot welded and weld bonded joints has been evaluated to determine the number of cycles to failure as a function of load amplitude and load ratio. The load amplitude against number of cycles to failure has been plotted for spot welded joints for the steels **(Fig. 8)**, to evaluate the endurance limits of the joints. The load ratio against no. of cycles to failure has also been plotted **(Fig.9)** to understand comparative fatigue performance of DP590 and DP780 steel welds.

The lap shear fatigue test results of the two steels with two different spot size (**Fig 8** and **Fig.9**) indicate that in DP590 steel the endurance limit of $10^6$ cycles is obtained at load amplitudes of 1kN and 1.12kN for nugget diameters of 5.52mm (9.3kA, 6 cycles) and 5.82mm (7kA, 14 cycles) respectively. Whereas, in DP780 steels, the endurance limit of $10^6$ cycles is attained at load amplitudes of 0.98kN and 1.15kN for nugget diameters of 4.76mm (8kA, 6 cycles) and 5.14mm (9kA, 8 cycles) respectively. From this result, it can be concluded that the fatigue strength marginally increases with increase in nugget diameter for both DP590 and DP780 spot welded joints.

It is observed from **Fig.9** that for a given load ratio, DP780 spot welded joint shows better fatigue performance than DP590 spot welded joint .The result is contrary to convention

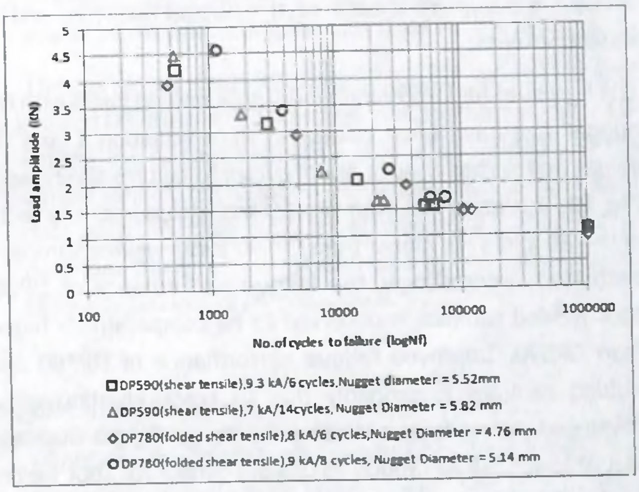


**Fig. 8 : Plot of Load amplitude vs No. of cycles to failure**

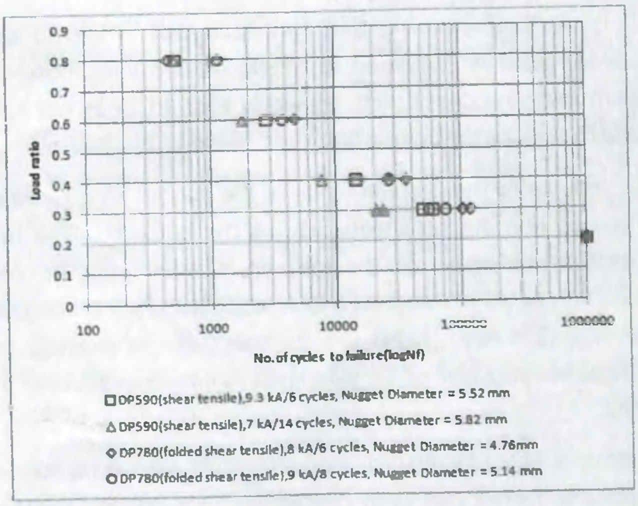


**Fig. 9 : Plot of Load ratio vs No. of cycles to failure**

i.e. DP590 spot welds should show higher load ratio than DP780 welds considering the higher ductility associated with DP590 steel. However, the more number of stress cycles at each load obtained with DP780 is due to enhanced stiffness attained by folding the sides of DP780 samples.

In order to evaluate the fatigue performance of DP590 and DP780 welded joints, stress intensity factors (SIF) have been used in place of applied loads in the fatigue-life curves. In addition to equations for SIF for Mode I, Mode II and Mode III, an equation for a maximum equivalent stress intensity, $K_{eq}$ (initial equivalent stress intensity factor), has been developed recently. For the tensile-shear configuration, $K_{eq}$ is given by the expression [14].

$$K_{eq}^{ts} = 0.694 \frac{F}{d\sqrt{t}} \quad \text{........ (1)}$$

where F = maximum shear load, d = nugget diameter, and t = sheet thickness;

The $K_{eq}$ values for DP590and DP780 spot welded joints with two nugget size have been calculated from equation 1 and the values are plotted against no. of cycles to failures as shown in **Fig 10**. It is observed from **Fig.10** that stress intensity factor of DP780 joints are higher than DP590 joints welded sample at each load. Interestingly, the fatigue performance of DP780 spot welded samples is observed to be comparatively higher than DP590. Improved fatigue performance of DP780 spot welded samples is probably due to crack blunting effect developed during fatigue loading. However, **Fig.10** illustrates that at lower SIF all fatigue values are similar for spot welded joints of different sizes. Therefore, the high-cycle fatigue performance is independent of microstructure and strength and fatigue performance is controlled almost exclusively by sample geometry.

It is worth mentioning that HAZ softening in DP780 spot welded joint as compared to DP590 welded joint, observed from micro-hardness plots shown in **Fig. 11** does not have much effect on the fatigue life.

In spot welds the circumference of the nugget lying between the two overlapping sheets acts as the notch tip. The HAZ being located away from the notch tip, is certainly not the crack initiation point. Although at a later stage the crack propagates through the HAZ (along the thickness of the sheets), the composite structure of the joint ensures minimum effect of the HAZ.

Like spot welded joints, the load amplitude against number. of cycles to failure has been plotted for weld bonded joints in

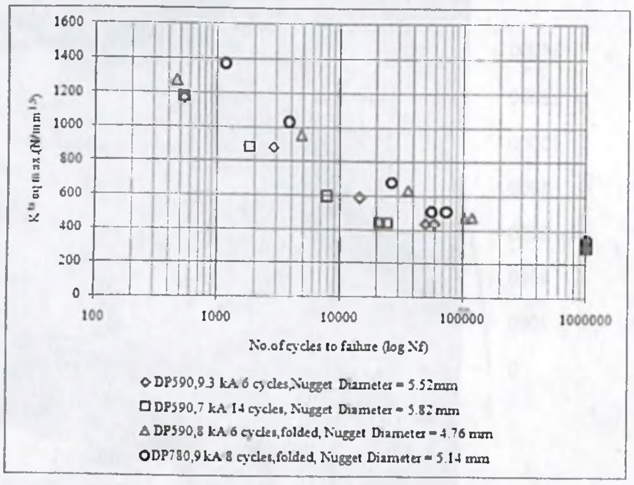
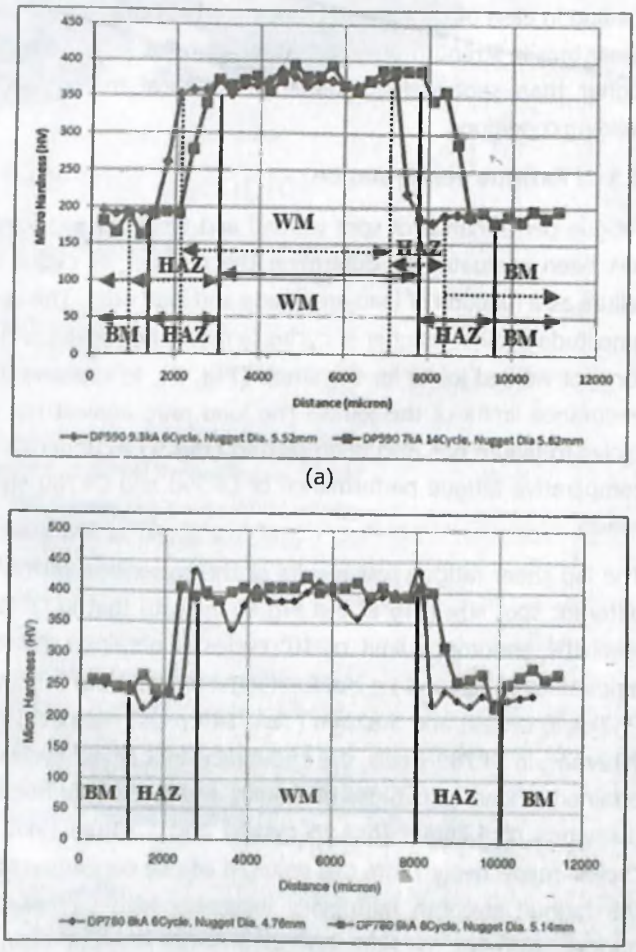


**Fig. 10 : Plot of initial equivalent $K_{eq}$ with No. of cycles to failure in shear tensile mode**



(a)

(b)

**Fig.11 : Micro hardness plot of (a) DP590 (b) DP780 steels at two different parameter.**

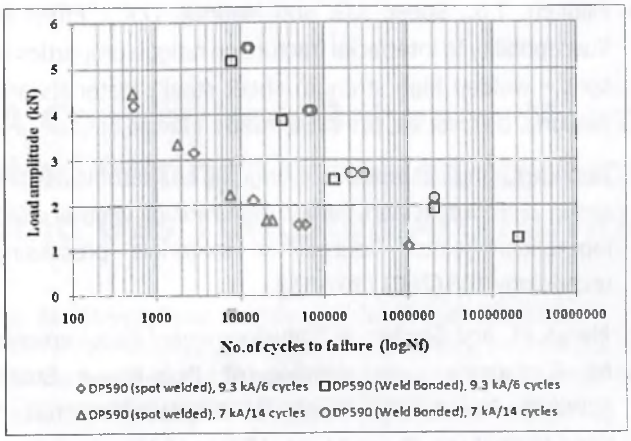


Fig. 12 : Plot of Load amplitude vs No. of cycles to failure

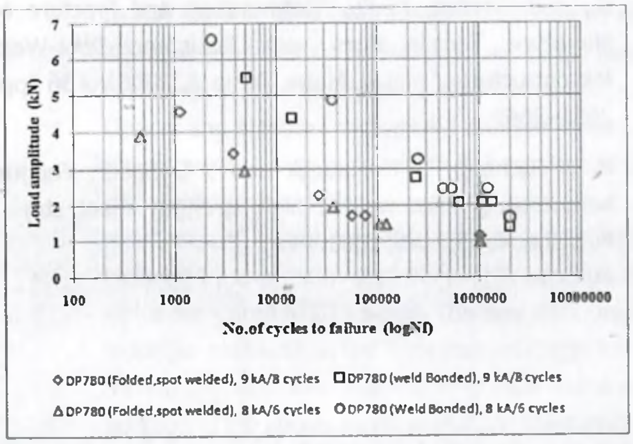


Fig. 13 : Plot of Load amplitude vs No. of cycles to failure

**Fig. 12** and **Fig. 13** respectively. In order to compare the fatigue performance of DP590 and DP780 weld bonded joints with spot welded joints, data of spot welded joints has been superimposed in **Fig. 12** and **Fig. 13.**

Spot welded DP590 steel with nugget diameter of 5.5-5.8mm resulted in a fatigue limit ($10^6$ cycles) of 1-1.15kN. In hybrid weld-bonds, using the same spot welded parameters, higher fatigue limit of 1.94-2.19kN (**Fig.12**) was obtained even at greater number of cycles ($2x10^6$). Again, spot welded DP780 steel with nugget diameter of 4.76-5.14mm have fatigue limit of 1-1.15kN. The corresponding weld bonded samples were able to withstand $2x10^6$ cycles at load amplitude of 1.38-1.64kN (**Fig.13**). The improved fatigue life of weld bonded sample can be attributed to better stiffness of the joint, uniform transfer of load over a large overlap section, and delayed delaminating of the adhesive layer. The adhesive also covered the notch tip and reduce the initial stress intensity factor, thereby further causing delayed crack initiation under cyclic loading.

## CONCLUSION

1. Shear tensile failure load of resistance spot welded DP780 is higher than DP590. In weld-bonded DP steels with 0.4mm thick structural adhesive, the shear tensile failure load is significantly higher than spot welds. However, more difference is realised in DP780 steel (4 kN) than DP590 steel (3 kN).
2. In general, fatigue performance of spot welded DP780 and DP590 steels are similar, although DP780 shows marginally better values than DP590 steel. Larger nugget diameter for the same grade of DP steel also shows superior performance than smaller nugget diameter.
3. Endurance limit of weld-bonded DP sheets is higher than spot welds by about 1kN at low load amplitudes, and up to 3kN at high load (>40%) amplitudes. Improved fatigue properties due to adhesive layer is mainly derived from the overall increase in strength and stiffness of the joint.
4. The calculated stress intensity factor(SIF values) for spot welded DP780 and DP590 steels indicate that at lower SIF values, the fatigue behaviour of all spot welded joints is almost similar; but at higher SIF values there is significant difference in the fatigue performance. This factor overrides the effect of microstructure, and influence the fatigue behaviour of DP spot welds.

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