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Resistance Spot Welding Characteristics and High Cycle Fatigue Behavior of DP 780 Steel Sheet

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Resistance spot welding characteristics of DP 780 steel was investigated using peel test, microhardness test, tensile shear test, and fatigue test. Tensile shear test provides better spot weld quality than conventional peel test and hardness is not a good indicator of the susceptibility to interfacial fracture. The results of high-cycle fatigue behavior of spot welded DP 780 steel under two different parameters show that at high load low cycle range a significant difference in the *S-N* curve and almost similar fatigue behavior of spot welds at low load high cycle range are obtained. However, when applied load was converted to stress intensity factor, the difference in the fatigue behavior between welds diminished. Furthermore, a transition in fracture mode, i.e., interfacial and plug and hole-type at about 50% of yield load is observed.

Keywords automotive, carbon/alloy steels, mechanical testing, welding

1. Introduction

Advanced high-strength steels (AHSS) offer the potential for improvement in fuel efficiency and crash performance. Among AHSS, Dual Phase (DP) steels are gaining the widest usage among automakers (Ref 1). This is because they provide an excellent combination of strength and ductility which are controlled by the martensite volume fraction and the ferrite grain size (Ref 2, 3). At same time, they are widely available due to relative ease of manufacture.

Dual-phase steels are alloyed to control the amount and the transformation of interstitially formed austenite. The carbon contents in these steels typically range form 0.05 to 0.2 wt.% and manganese content may be up to 1.5 wt.%. Because of the relatively high carbon equivalent, high strength, etc., in comparison with low carbon steel sheet, it should be anticipated that (i) suitable welding current range shifts to the lower current side owing to high electric resistance, (ii) fully contact diameter cannot be obtained between sheets owing to spring back effect, and (iii) microstructures in the weld and heat-affected zone (HAZ) will be significantly modified during resistance spot welding.

To be able to successfully use these steels, it is important to characterize and understand the spot welding characteristics of dual-phase steels. A vehicles structural performance depends in part on the welded-joint structural integrity (Ref 4, 5). It is well known that in some vehicle safety regulated system, such as fuel system, joint performance can dramatically alter the system performance. As a means of quality control for spot welds, the automotive industry has historically used destructive tests such as peel test, to determine whether a satisfactory weld has been produced. The common criterion is that the average weld button diameter should be equal to or larger than $4\sqrt{t}$ (where t is material thickness in mm). This historical criterion works well for spot welds of low carbon steel because acceptable nugget size attributes desired nugget pullout mode of fracture having sufficient load carrying and energy absorption capability as compared to interfacial mode of fracture.

The effectiveness of this criterion for evaluating AHSS spot weld, however, has not been adequately addressed in the automotive welding community; it was simply adopted from low carbon steel practice and applied to AHSS spot welds. The importance of weld nugget size should be emphasized because the size (or diameter) of the welds controls the weld tensile strength. Studies on several high-strength steel grades and at various sheet thicknesses have shown a strong dependence (or mode) on weld size in spot weld shear-tension test (Ref 6). Rathbun et al. (Ref 2) reported that interfacial failure (IF) results in a decrease of the overload and low-cycle fatigue strength of the weld. However, Tumuluru (Ref 7) recently observed essentially the same load to failure in HDGA and HDGI despite different fracture modes and, therefore, expressed that fracture mode should not be used as the sole criteria to judge weld integrity in high strength steels. Furthermore, AHSS sheets can undergo significant fatigue damage, which is related to the reduction in sheet thickness (Ref 8, 9). Thus, it is imperative to investigate the fatigue behavior of spot welded joints in thin section AHSS for achieving a safe and reliable design. Again, some researchers (Ref 2, 10) reported that high-cycle fatigue lives were independent of the strength and microstructure of the base materials for three high strength uncoated-steels—HSLA, DP, and TRIP. They believed that the high-cycle fatigue performance is controlled by weld nugget size, sheet thickness, and corresponding joint stiffness. On the other hand, Zhang and Taylor (Ref 11) found that the number of loading cycles for a complete fatigue depends on sheet thickness and the property of material under loading.

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The purpose of this study is to examine

(1) Whether conventional nugget size guidance of $4\sqrt{t}$ can produce nugget pullout fracture mode.
(2) The effect of nugget size on static strength.
(3) Fracture mode and high cycle fatigue behavior of resistance spot-welds of DP 780 under shear-tension loading condition.

2. Experimental Procedure

2.1 Material

The material used in this study was DP780 grade steel sheet of thickness 1.2 mm with the chemical composition given in Table 1. The mechanical properties of the steel in as-received condition are given in Table 2.

2.2 Spot Welding Conditions and Test Specimen

The spot welding was performed in a 90 KVA MF-DC spot weld machine following BS1140, AFNOR welding standard. Electrodes made of class II copper alloy with flat tip ends diameter based on $2t + 3$ mm, where t is the sheet thickness, were used. A total number of eight spot welds as given in Table 3 were performed to find out acceptable nugget size ($4\sqrt{t}$, where t is the sheet thickness in mm) after peel test. Two different parameters one having relatively larger nugget diameter (6.65 mm) and other having relatively smaller nugget diameter (5.27 mm) were chosen from Table 3 to perform shear tensile and high cycle fatigue test.

2.3 Metallographic Study

Metallographic examinations were carried out using standard methods to observe the microstructural changes in weld metal and HAZ.

2.4 Microhardness Testing

Microhardness measurements were performed on metallographically polished and etched samples diagonally from one sheet base metal to the other sheet base metal through weld and HAZ using Leica Vickers Micro Hardness Tester (Model A-1170) at 200 g load as per BS 1140: 1993.

2.5 Tensile Shear Testing

Tensile shear type specimens (Fig. 1) having a length of 217 mm and width 38 mm were used to find out the maximum load sustained by various spot-welded joints.

2.6 Fatigue Testing

High cycle fatigue testing was performed for tensile shear samples (Fig. 1) in laboratory air conditions using a 50 KN RUMUL Testronic Resonant Testing Machine. The maximum dynamic load used was typically about 70% of the maximum load obtained during a quasi-static tensile test at $R = 0.1$.

3. Results and Discussion

3.1 Suitable Spot-Welding Condition for DP780 Steel Sheet

A total number of eight experiments as given in Table 3 were performed to find out acceptable spot welding parameters for DP780 grade AHSS. In general, the aim is to produce a spot weld of the required diameter, which gives plug failure on peel testing. Accordingly, acceptable parameters were found out by measuring the nugget diameter after peel test. The process parameters to produce spot-weld in DP780 without interfacial fracture (Table 3) indicate that a certain combination of weld current and weld time under constant electrode force can pass the peel test. For the welds of this study, the 1.2 mm thick DP780 steel will produce acceptable buttons ($4\sqrt{t}$) only with 200 ms weld time providing that current is 6 kA at the minimum. Similarly, the steel will necessitate weld time of

Table 2 Tensile prosperities of base metal

Material	Yield strength, MPa	Ultimate tensile strength, MPa	Total elongation, %
DP-780 Steel	585	746	16

Table 3 Spot welding parameters and corresponding nugget diameter

Welding current, kA	Welding time, ms	Applied load, daN	Nugget diameter, mm
5	200		Interfacial fracture
5	250		5.27
6	200		6.65
6	150	32	6.27
6	100		Interfacial fracture
7	200		7.22
7	100		5.43
4	250		Interfacial fracture

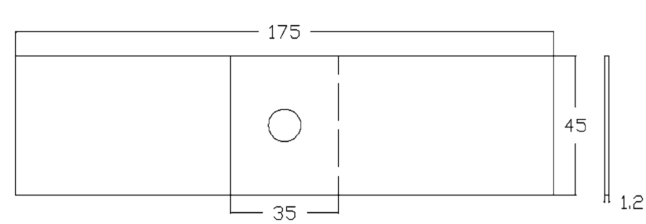

Fig. 1 Dimension (in mm) of tensile shear sample

Table 1 Chemical compositions of base metal

Elements	C	Mn	Si	P	S	Cu	Cr	Mo	Ni	Nb	Ti	Fe
wt.%	0.16	1.43	0.35	0.012	0.001	0.02	0.01	0.02	0.02	0.001	0.002	rest

250 ms to ensure the formation of acceptable button, when the corresponding current will have to exceed 5 kA. Furthermore, the well-known $4\sqrt{t}$ rule of thumb applies quite well to DP780 resistant spot welds after peel test. Similar observation was made for DP600 (Ref 12) and it was opined that the $4\sqrt{t}$ rule is valid for sheet thickness less than 1.5 mm and beyond 1.5 mm, the $5\sqrt{t}$ rule, recommended by the Japanese and German standards (Ref 13, 14) is most appropriate.

3.2 Microstructural Change

Figure 2(a) shows that the microstructure in the base metal basically consists of evenly distributed martensite within the ferrite. Martensite becomes larger and its volume fraction is higher in the HAZ than in the base metal as seen in Fig. 2(b). The weld metals are nearly full martensite (Fig. 2c). The transition region between the fusion zone and the HAZ as shown in Fig. 2(d) shows finer martensite and ferrite than those of either the base metal or the weld metal. This is due to the fact that austenitizing was incomplete in the HAZ and even when austenite grain formed grain growth was restricted by the formation of martensite and thermal cycles (Ref 8, 15). While the grains are fine in the HAZ, the resulting high density of grain boundaries constitutes obstacles to the formation of large lath martensite. Furthermore, there is insufficient time for carbon diffusion as such high cooling rates and is believed to form lath martensite or pockets of lath (Fig. 3a), and possibly some bainite as shown in Fig. 3b.

In resistance spot welding, due to the water-cooling of the electrodes, the weld cooling rates are extremely rapid. It has been shown through modeling that even at 500 °C the cooling rates in spot welding were in excess of 1000 °C/S (Ref 16).

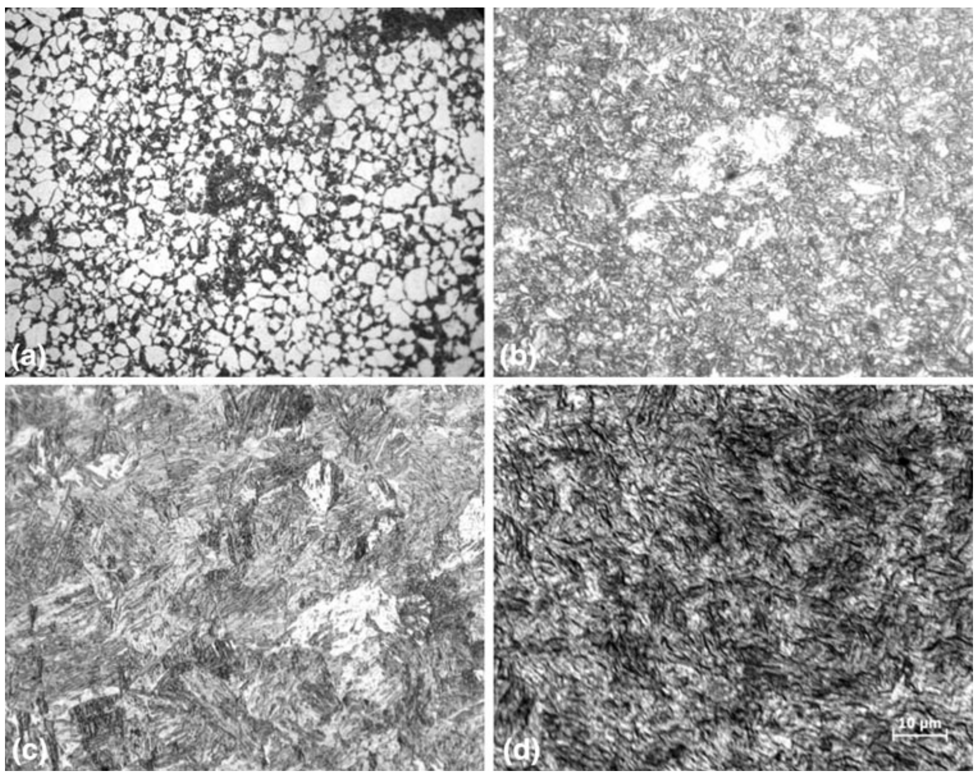

Fig. 2 Microstructures of (a) base metal, (b) HAZ, (c) weld metal, and (d) transition region between weld and HAZ

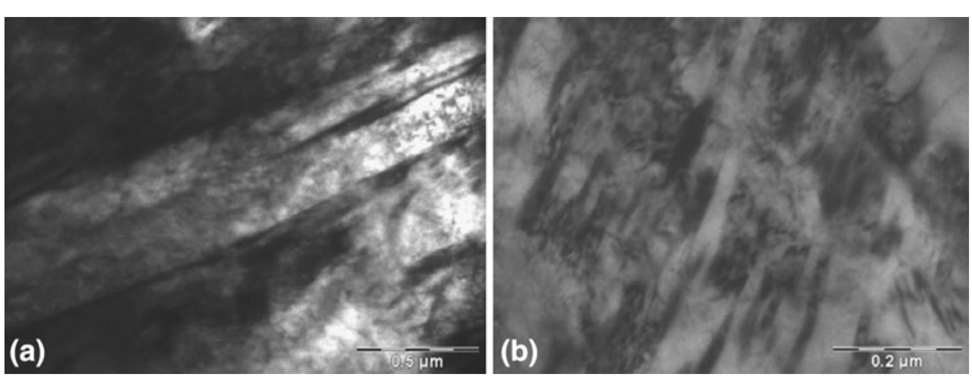

Fig. 3 TEM micrographs: (a) martensite Laths and (b) bainite laths

For steels, the critical cooling rate, required to achieve martensite in the microstructure is given by the following equation (Ref 17):

$$\text{Log } v = 7.42 - 3.13\text{ C} - 0.71\text{ Mn} - 0.37\text{ Ni} - 0.34\text{ Cr} - 0.45\text{ Mo}$$

For the DP 780 steel used in this study, the critical cooling rate turns out to be about 240 °C/S. Therefore, it is not surprising that a martensite structure is present both in the weld and in the HAZ.

3.3 Microhardness Profile

Figure 4 depicts the microhardness traverse for the DP 780 welds, which exhibited a significant hardness increase from the base metal. Due to the high content of alloying elements in the steel and high cooling rate, the hardness of weld nugget is more than that of the base metal. However, the hardness of HAZ is in-between. The higher hardness in the weld is probably attributed to the formation of martensite. Furthermore, under welding parameters studied, weld produced with 6/200 is harder than the weld produced with parameters 5/250. One possible reason for harder weld metal at higher heat input could be higher amount of deformation induced in the martensite. This is not unexpected because increasing the heat input increases the heat generation at the weld leading to higher electrode indentation induced on the weld.

3.4 Tensile Properties

Static weld strength was obtained from the tensile shear test to quantify the static load-carrying capabilities. Table 4 shows that DP 780 welds under 6/200 parameters offers higher static-load carrying capabilities than that of 5/250 parameters.

Both nugget pullout and interfacial fracture modes were observed for the tensile shear samples of DP 780 welds. All the welds under 5/250 parameters failed in interfacial fracture mode and all the welds under 6/200 parameters failed in nugget pull out mode. Results clearly indicate that even at the conventionally recommended nugget size of $4\sqrt{t}$ (minimum size), all the welds under 5/250 parameters failed in interfacial fracture mode. However, further increased the nugget size from conventional $4\sqrt{t}$ to $5\sqrt{t}$ enhances the load-carrying capabilities and failed in nugget pullout mode.

Spot welds in DP 780 may exhibit interfacial fracture (IF) modes resulting from their higher hardenability due to alloying additions. Such IF can be avoided by either reducing the weld hardness (Ref 18, 19) or alternately increasing the weld diameter for a given sheet thickness and base materials (Ref 20). However, in this study, welds having lower hardness attributed IF indicating that weld hardness is not a good indicator of the susceptibility to IF at least for DP 780 weld. Similar observation was noted in TRIP 590 welds except the presence of IF did not necessarily result in reduction in weld strength (Ref 21).

3.5 Fatigue Strength and Failure Modes

Despite the significant difference in overload weld strength for spot welded samples, the higher cycle fatigue behavior at low loads is virtually the same for all conditions (Fig. 5a). All samples tested at 70% of yield load showed interfacial fracture and at 20% of yield load showed plug and hole-type failure, regardless of whether interfacial fracture was present for that condition during overload fracture. Again, Fig. 5b shows that despite the significant difference in the low cycle behavior of the *S-N* curves for the two welds under different parameters, the high cycle fatigue behavior is the same and not influenced by the presence of interfacial fracture (Fig. 6).

The finding that interfacial fracture does not affect high cycle fatigue is not surprising. Previous studies have shown that material strength is not an important variable in high cycle fatigue; in stead other factors such as loading conditions, weld diameter, and sheet thickness control the run-out load. Thus,

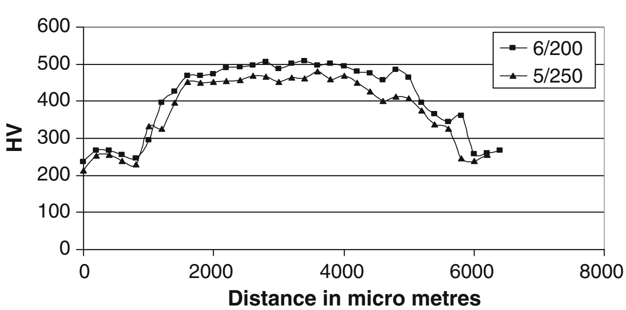

Fig. 4 Typical microhardness properties of spot welded DP780 steel with 6 kA and 200 cycles and 5 kA and 250 cycles

Table 4 Shear tensile properties of spot-welded joints

Sl. no.	Welding parameters: Welding current, kA	Welding time, ms	Load (max), KN	Yield load, KN	Type of fracture
1.	6	200	15.0	11.8	Plug and hole
2.	5	250	13.1	8.6	Interfacial

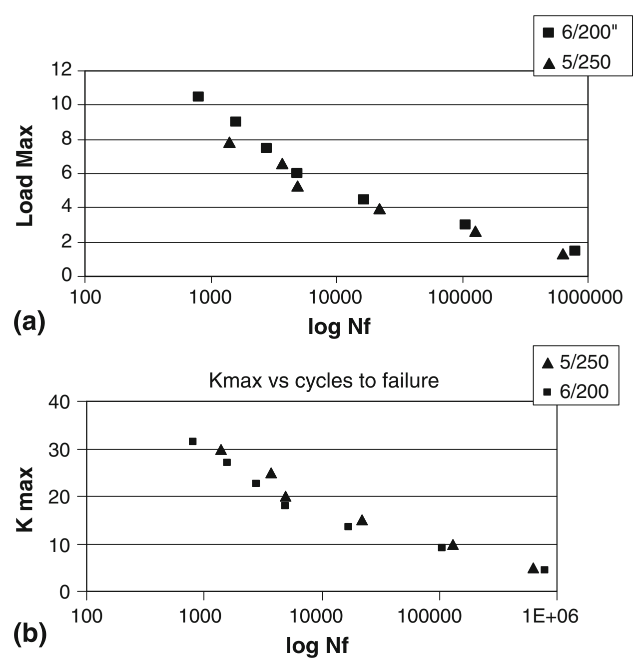

Fig. 5 (a) *S-N* curves of the spot welded specimen under two parameters (6/200 and 5/250). (b) Stress intensity factor (K_{max}) vs. no. of cycles in log scale plot for DP780

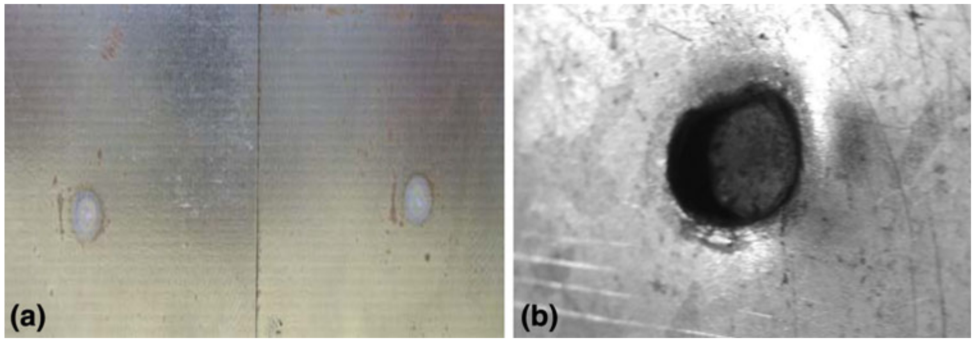

Fig. 6 Failure mode: (a) interfacial type, (b) plug and hole type

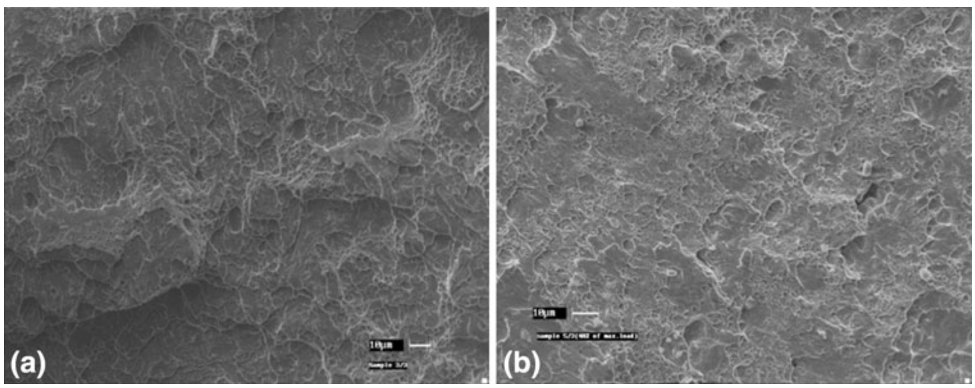

Fig. 7 SEM micrographs of fractured samples: (a) 70% yield load, (b) 20% yield load

while interfacial fracture limited the strength of the spot weld for overload failure testing, it did not affect the low load high cycle fatigue for the conditions studied in this work.

At higher load of about 60% of yield load, it is probable that crack which initiates from the interface between the two sheets (as a natural stress raiser) propagates through the hard and brittle weld metal leading to interfacial failure (Fig. 6a). This is not unexpected as higher loads develop higher stress, which can supply sufficient energy at the pre crack to propagate straight through the weld. On the other hand, precrack does not get sufficient energy at relatively lower load, i.e., about 20% of yield load and fails to propagate through the weld. Rather the crack propagates first at fusion boundary followed by the weak HAZ and base metal. The failure mechanism at lower load gives rises to plug and hole-type fracture (Fig. 6b). Thus, it can be stated that there is a transition in failure mechanism and hence the mode of fracture which changes at about 50% of yield load in case of DP 780 weld.

SEM micrographs of two different failure modes showed that there are noticeable differences in the fracture surfaces. The fracture surface of the sample at 70% yield load (Fig. 7a) showed some intergranular fracture as well, through there were large observable regions of trans-granular fracture, including cleavage facets and microvoid coalescence. Figure 7(b) shows that the 20% yield load fracture surface has predominantly trans-granular fracture regions with mainly cleavage facets in the outer layers of the weld, and microvoid coalescence in the center of the weld.

4. Conclusion

1. Conventional peel test for selecting weld parameters may not give the required spot weld quality in DP 780 steel. Rather, tensile shear tests show more consistence results regardless of the scatters of the results.
2. The maximum load-carrying capability is affected by the mode of fracture, i.e., interfacial fracture attributes lower load-carrying capability compared to plug and hole-type fracture.
3. Hardness in fusion zone is maximum and the base metal shows minimum hardness. The hardness of HAZ is in-between.
4. There is a significant difference in the *S-N* curves at high load low cycle range of welds under two different parameters. However, almost similar fatigue behavior of the welds is observed at low load high cycle ranges.
5. When applied load was converted to stress intensity factor, the difference in fatigue behavior between welds under two different parameters diminished indicating that high cycle fatigue is solely dominated by mechanical factors at least for the steel studied.
6. Fractographs of spot welds in DP 780 steel clearly revealed a transition in fracture mode, i.e., interfacial and plug and hole-type at about 50% of yield load. Above the transition, interfacial fracture and below the transition plug and hole-type fracture mode was observed.

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