

# Resistance Spot Welding of Coated High-Strength Dual-Phase Steels

*New car models will  
be safer, lighter, and  
more fuel efficient as  
advanced high-  
strength steels are  
introduced into  
production*

BY MURALI D. TUMULURU

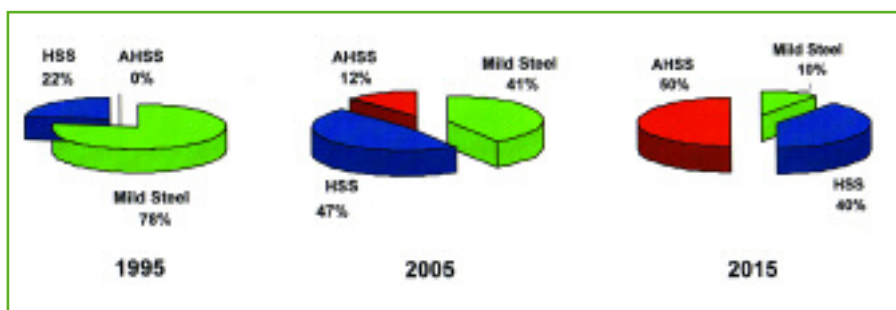


Fig. 1 — The pie charts show the evolution of automotive body structure in the usage of advanced high-strength steels. Courtesy of J. Shaw, United States Steel Corp., Automotive Center, Troy, Mich.

Automotive companies are constantly seeking ways to improve the fuel efficiency of their vehicles and to build vehicles from materials that offer improved occupant safety.

Any material intended for automotive use must be easily formable, weldable, coatable (for corrosion protection), and repairable.

One such class of materials that shows promise of fulfilling all these needs is dual-phase steel. As a result, dual-phase steels with a minimum tensile strength of 590 MPa have found their way into several 2004 and 2005 model vehicles (Refs. 1, 2).

With the use of 590 MPa dual-phase steel in automotive bodies, the automotive companies realized that dual-phase steels have excellent formability without sacrificing strength (Ref. 3). This combination of high ductility (hence formability) and high strength can allow thinner steels to be used in automotive bodies, thus providing improved fuel economy for vehicles. Further, the high energy-absorption capability that dual-phase steels possess can offer improved occupant protection. Therefore, it is no surprise that

590 MPa dual-phase steel found several applications in 2004 and 2005 model year automotive bodies.

Dual-phase steels are considered advanced high-strength steels (AHSS) to distinguish them from the conventional high-strength steels (HSS). The HSS types include high-strength low-alloy steels and carbon-manganese steels of tensile strengths up to 440 MPa. While AHSS was not used at all up to 2001, the AHSS content in 2005 models is about 12% — Fig. 1.

## Use of AHSS to Grow

Based on the expressed objectives of various automotive companies to build more fuel-efficient and safer cars, and the trends in steel usage to meet the increasingly stringent government requirements, it is anticipated that AHSS usage in automotive bodies will climb to 50% by 2015 (Ref. 4).

Although the technology of dual-phase steels is not new, and 590 MPa dual-phase steel has been available since 1979 (Ref. 3), their uses in automotive applications prior to 2000 was virtually nonexistent.

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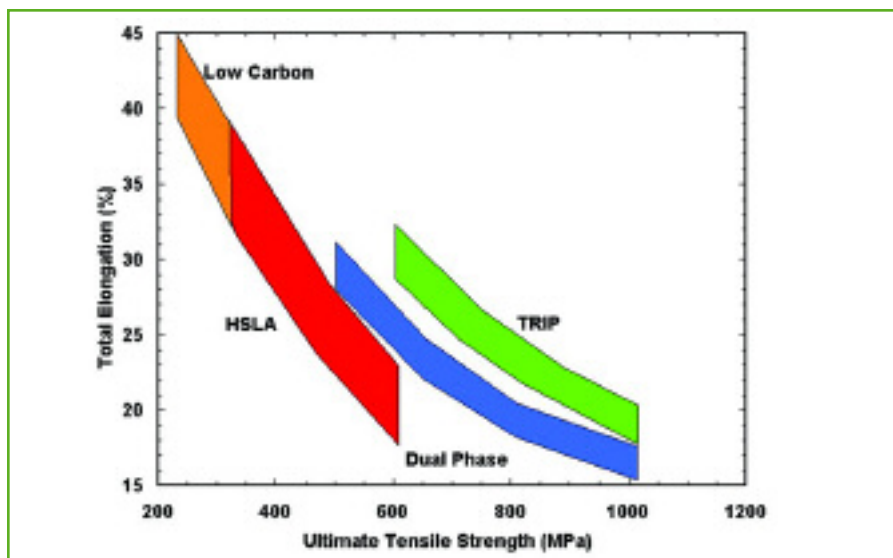


Fig. 2 — A plot showing the relationship between strength and elongation for various sheet steel grades used in automotive applications. TRIP is transformation-induced plasticity steel.

The increased demand to improve Corporate Average Fuel Economy (CAFE) standards and the tightening of roof crush-strength requirements to better protect occupants in roll-over situations, sparked a renewed interest for the automotive companies to look at dual-phase steels to enable them to meet these increasingly rigorous standards. It can be seen from Fig. 1 that the present use for AHSS in automotive bodies is limited to dual-phase steels with a minimum tensile strength of 590 MPa. With the development and commercialization of dual-phase steels with minimum tensile strengths of 780 and 980 MPa, many automotive companies are aggressively targeting the use of these two steel grades into the models to be launched in 2007 and later (Refs. 5, 6).

For steels, as their strength increases, the ductility (as measured by elongation) drops. However, from Fig. 2 it is apparent that even at strength levels of 780 MPa, dual-phase steels possess elongation values as high as 25% and 980 MPa grade features elongation values as high as 18%. This combination of high strength and high ductility comes from the unique microstructure and characteristics that this grade possesses.

### Features of Dual-Phase Steels

Some of the characteristics that make dual-phase steels attractive for automotive applications include the following:

- They achieve strengthening through a phase transformation, namely the transformation of austenite to martensite.
- Depending on the strength level, they contain 10% to 40% martensite in a soft ferrite matrix.

- To achieve higher strength, more martensite is required in the steel. Therefore, as the strength of the steel increases, the amount of martensite in the steel increases (Fig. 3).

- Dual-phase steels possess high strength with high elongation when compared to conventional HSS.

- Dual-phase steels do not exhibit yield point elongation. Yield point elongation or discontinuous yielding causes Luder bands (or stretcher strains) and surface appearance problems.

- Dual-phase steels possess high strain hardening (high  $n$ -value), which indicates excellent formability.

- They have a low plastic strain ratio value  $r_m$ . It is the ratio of the width strain to the thickness strain. Low  $r_m$  indicates poor deep drawability. This means dual-phase steels are not good candidates for applications that require deep drawability.

- They are bake hardenable (strain aging at elevated temperature). Bake hardening provides an increase in strength after the paint bake cycle that welded automotive bodies undergo.

### Spot Welding Concerns

Resistance spot welding is the main method of joining used in the automotive industry with each vehicle containing several thousand welds. To be able to successfully use these steels, it is important to characterize and understand the spot welding behavior of dual-phase steels. For body-in-white applications, to provide corrosion protection, dual-phase steels are used with either galvanized (zinc-iron alloy) or galvanized (pure zinc) coating.

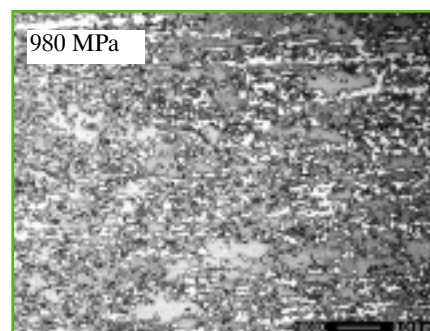
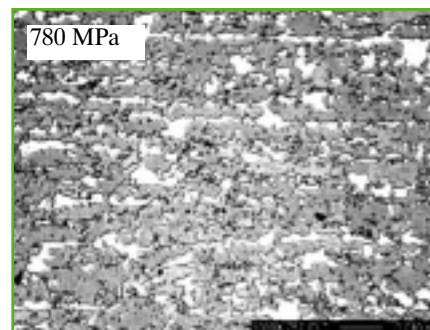
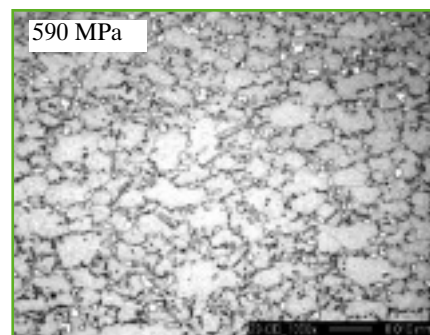


Fig. 3 — Photomicrographs of the as-received base metal microstructures for the three dual-phase steel grades. The white islands are martensite distributed in soft ferrite phase (gray areas).

Resistance spot welding behavior of coated 590 MPa dual-phase steel has previously been the focus of research (Refs. 7–9). This understanding led to the successful implementation of 590 MPa dual-phase steel into automotive production. With the availability of 780 and 980 MPa steels, there is a need to understand the resistance spot welding behavior of these steels. Therefore, resistance spot welding studies were undertaken to examine the welding behavior of 590, 780, and 980 MPa dual-phase steels. Another purpose of the study was to determine whether these higher-strength grades could be welded with simple, easy-to-use welding parameters.

### Materials and Procedure

Commercially processed coils were used in this study. Examples of tensile properties of 590, 780, and 980 MPa dual-

phase steels are provided in Table 1. The tensile properties of draw-quality special-killed (DQSK) steel are provided for comparison. The DQSK steels are low-strength steels that are used in automotive bodies—Fig. 1. Typical alloying elements, their ranges, and the reasons for adding them in dual-phase steels are shown in Table 2. All steel coils were produced through intercritical annealing of cold rolled sheets (Fig. 4) and hot-dip coated. The nominal coating weights for all the coils used were 45/45 g/m<sup>2</sup> (i.e., same coating weight on both surfaces of the coils). These coating weights are typical of current commercial automotive use. The steel sheet thickness for all three grades was 1.6 mm. To examine the effects of welding current and button size on the weld tensile strength in 780 MPa grade sheets from 2.0-mm-thick coil were also used. All welding was performed using a Taylor Winfield pedestal-type welding machine equipped with an AC power source. Resistance Welding Manufacturers Association Class 2 (copper-chromium) electrodes were used to make test welds. Both truncated cone electrode tips with 45-deg included angle- and ball-nosed tips were used. The welding machine details and parameters used in this study are shown in Table 3.

## Characterizing Welding Behavior of Steels

To characterize the welding behavior of the steels, useful current ranges and static weld tensile tests were performed. The useful current range is the difference between the welding current required to produce a minimum button size ( $I_{\min}$ ) and the current that causes expulsion of weld metal ( $I_{\max}$ ). In this study, the minimum button size was defined as  $4(t)^{1/2}$ , where  $t$  is the nominal sheet thickness. The use of  $4(t)^{1/2}$  as the minimum button diameter, where  $t$  is the nominal sheet thickness, is generally used in the automotive and steel industries.

The procedure to determine current range is described in detail in Ref. 10. Peel test coupons measuring 140 × 50 mm were used in the current range determination—Fig. 5. The coupons were overlapped by 25 mm and a shunt or anchor weld was made on one side of each coupon pair. On the other side, 35 mm from the edge, test welds were made. The test welds were peeled open and the button sizes were measured using calipers. The current range is useful because it provides a range of welding currents over which welds with buttons of acceptable size can be produced. Prior to determining the current range, the electrode tips were conditioned by making 250 welds. Current ranges were then determined by first determining the

**Table 1 — Tensile Properties of Dual-Phase Steels**

Steel Grade	Yield Strength, MPa	Ultimate Tensile Strength, MPa	Total Elongation
590*	370	620	25%
780	465	835	17%
980	600	1040	14%
DQSK*	170	300	45%

\*Provided for comparison.

**Table 2 — Hot-Dip Coated Dual-Phase Steel Composition Ranges**

Alloying Element (Wt-%)	Influence and Reason For Adding
C (0.06–0.15)	1. Ferrite stabilizer 2. Strengthens martensite 3. Determines the phase distribution
Mn (1.5–2.5)	1. Ferrite stabilizer 2. Solid solution strengthener of ferrite 3. Retards ferrite formation
Cr, Mo (each up to 0.40)	1. Austenite stabilizer 2. Retards pearlite and bainite formation
V (up to 0.060)	1. Austenite stabilizer 2. Precipitation strengthener 3. Refines microstructure
Nb (up to 0.04)	1. Austenite stabilizer 2. Reduces $M_s$ temperature 3. Refines microstructure

**Table 3 — Welding Machine Details and Conditions**

Manufacturer	Taylor Winfield Corp.
Type	Pedestal Type
Transformer	100 kVA
Controller	TrueAmp IV
Electrode Face Diameter	7-mm truncated tip for 1.6-mm and 8-mm dome-shaped tip for 2-mm 780 MPa steel
Electrode Force	4.2 kN for 590 and 5.3 kN for 780 and 980 MPa steels
Squeeze Time	30 cycles
Weld Time	18 cycles for 1.6-mm and 23 cycles for 2-mm sheets
Hold Time	10 cycles
Preheating	None
Postheating	None

lowest welding current that produced the minimum acceptable button size. Then, the current was gradually increased until weld metal expulsion resulted.

## Determining Weld Quality

Weld shear-tension and cross-tension strengths were determined to assess the load-bearing ability of the welds. For shear-tension strength determination, 140- × 60-mm samples were sheared and a single spot weld was made at the center of an overlapped area that measured 45 mm—Fig. 6. For cross-tension tests, the test

coupons used were 150 mm long × 50 mm wide—Fig. 6. Two coupons were placed at 90 deg to each other and a spot weld was made at the center of the overlapped area. Prior to making the weld test samples, the electrode tips were stabilized as described in Ref. 10 by making 250 welds on flat panels. Per Ref. 10, all shear and cross-tension test samples were prepared with a specified weld size of 6.7 mm, which was slightly higher than 90% of the electrode face diameter. Weld sizes were verified prior to the tensile tests on each grade. Weld sizes measured after the tensile tests agreed well with the specified weld size. Tensile

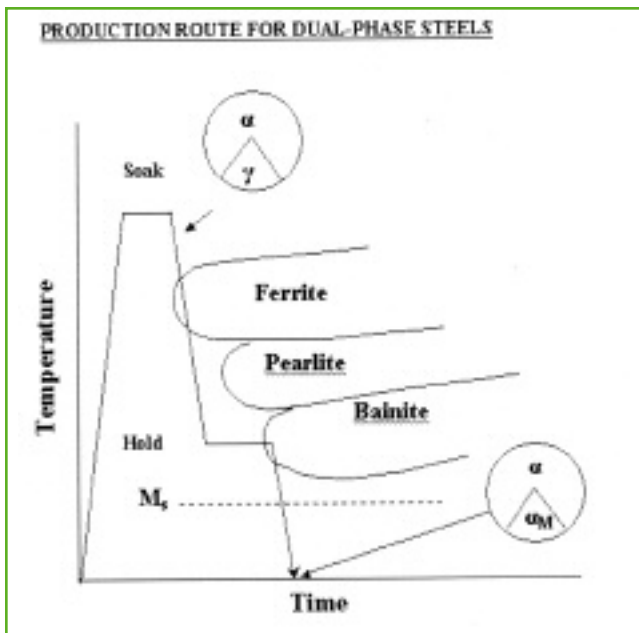


Fig. 4 — Sketch of a continuous cooling diagram showing the production route typically used for the production of dual-phase steels.

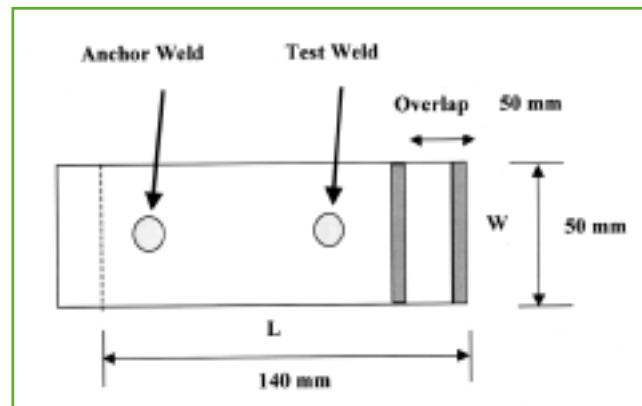


Fig. 5 — Sketch showing the dimensions of a peel test coupon used to determine welding current ranges.

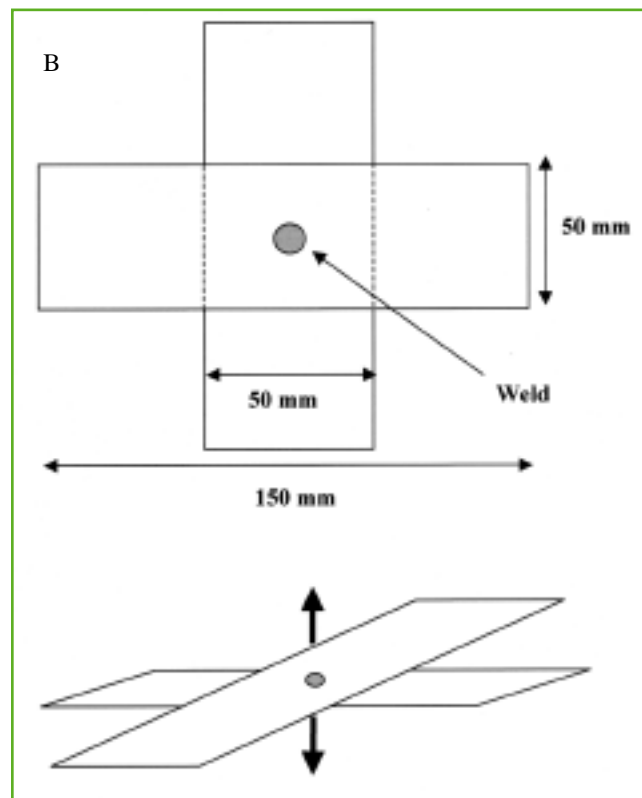
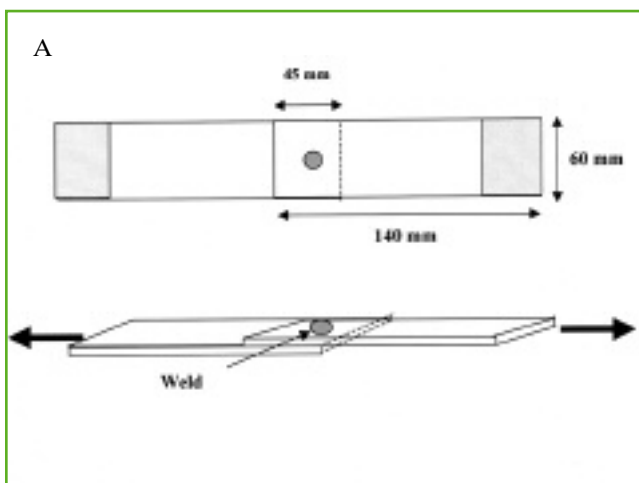


Fig. 6 — Sketches showing the dimensions of shear-tension and cross-tension test coupons. The arrows in the sketches show the direction of the application of tensile stress during the test. A — Shear-tension test coupons; B — cross-tension test coupon.

tests were carried out per the procedure outlined in Ref. 10. Additional details on the testing methodology can be found in this reference.

Fracture appearance of the welds was determined on all weld tensile test samples after the tests. Weld tensile test fractures were classified as full button pullout, interfacial fracture, or partial interfacial fracture. In full button pullout fracture mode, the entire weld nugget pulls out from the sheets by fracture occurring outside of the weld area. In interfacial frac-

ture, the entire weld fails through the plane of the weld. In partial interfacial fracture, part of the weld nugget fails through the plane of the weld and some portion of the weld pulls out as a partial button.

Weld and heat-affected zone microstructures were examined to check for any imperfections such as pores and cracks and to provide an understanding of the tensile properties of the weld. Weld microhardness profiles were determined by making hardness measurements at 0.4 mm spacing along a diagonal in a weld cross section.

## Results and Discussion

Figure 7 shows a plot between welding current and the button sizes for all three grades of dual-phase steels. A welding force of 4.2 kN was used for 590 MPa steel while 5.3 kN was used for the 780 and 980 MPa steels. Figure 7 shows that a current range of 2.2 kA was obtained for the 590 and 780 grades, and 2.5 kA for the 980 MPa grade. These current ranges are considered broad and show that there is a wide current range to successfully weld

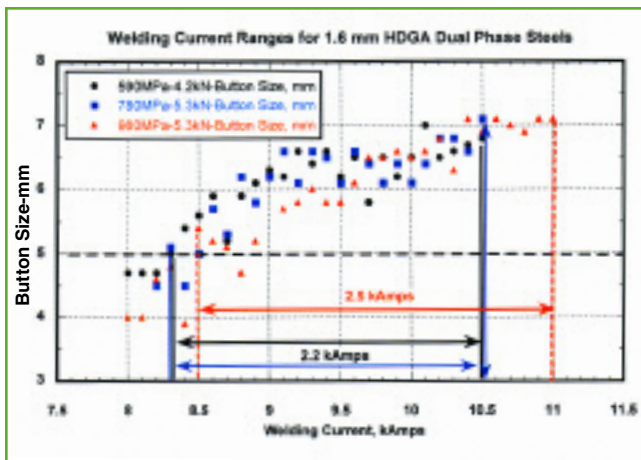


Fig. 7 — Welding current range plot for the three dual-phase steels studied.

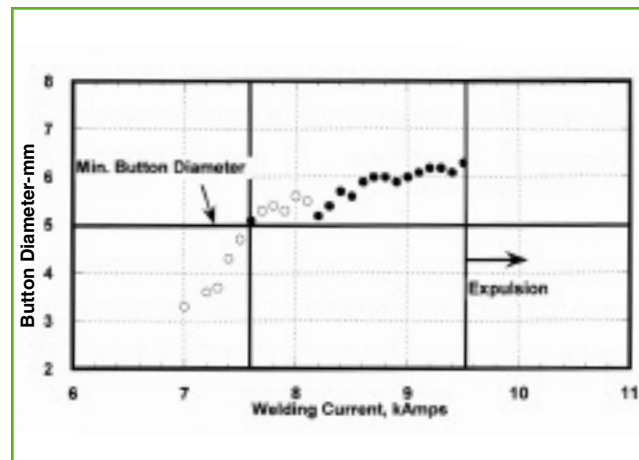


Fig. 8 — Welding current range plot for 1.6-mm 980 MPa dual-phase steel shown to indicate the fracture appearance in peel tests. Open circles in the plot refer to interfacial fractures in the test samples.

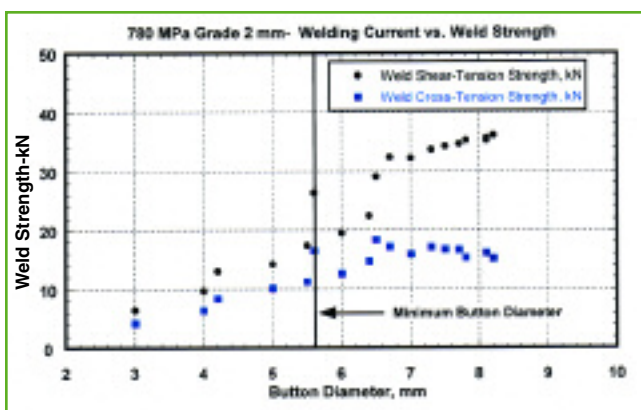


Fig. 9 — Weld shear- and cross-tension plots as a function of button diameter for 780 MPa dual-phase steel.

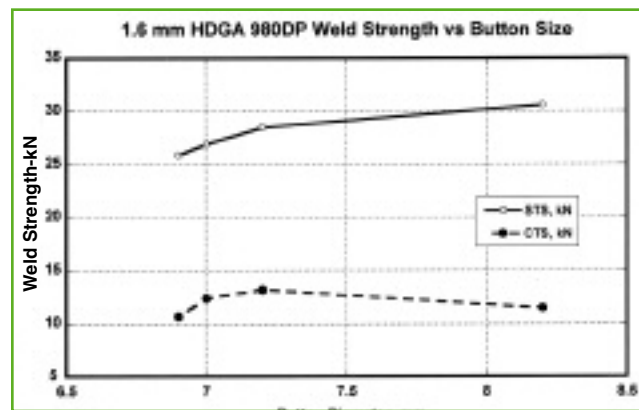


Fig. 10 — Weld shear- and cross-tension plots as a function of welding current for 980 MPa dual-phase steel.

these dual-phase steels. From Fig. 7 it is interesting to note that at any given welding current, the button sizes were clearly the smallest for the 980 MPa grade compared to the 590 and 780 MPa grades. Although not as distinct as those of 980 MPa grade, in general, it appeared that the weld sizes were slightly smaller for 780 compared to 590 MPa grade. One possible reason for smaller weld sizes seen at any given welding current as the base material strength goes up may have to do with the weld nugget growth. However, this needs further studies.

Figure 8 shows the current range plot from a second test done on 980 MPa steel to examine the fracture appearance of welds in the peel samples used. Two observations can be made from Fig. 8. The first one is that, as the welding current was increased, the weld size also increased. This is no surprise because increasing the welding current increases the heat generation at the sheet interface. In resistance spot welding, heat generation is provided by  $I^2Rt$ , where  $I$  is the welding current,  $R$  is the total resistance, and  $t$  is the time of

welding. The second observation is that as the weld button size increased beyond the minimum button size, the welds showed a full button pull out fracture mode upon peeling the coupons.

Figure 9 shows the relationship between the button diameter and the weld strength of the 780 MPa steel. It can be seen that as the button diameter is increased, both the shear-tension and cross-tension strengths went up. This is because larger welds have higher load-bearing ability. Figure 10 also shows the same effect of weld size on weld strength for the 980 MPa steel. In the results shown in Figs. 8–10, tests were terminated when weld metal expulsion was experienced. In Fig. 10 for example, 8.2 mm was the largest button size that could be achieved without expulsion.

An interesting observation that can be made from Fig. 9 is that as the button diameter increased, the increase in the shear-tension strength was much more rapid than that of the cross-tension strength. In fact, there was no increase in the cross-tension strength at button sizes

beyond the minimum button size. The reasons for the significant difference between the shear-tension and cross-tension strengths at larger button sizes may have to do with the type of stress the welds are subjected to in the shear- and cross-tension tests.

Chao showed that in shear-tension testing, even though the weld is subjected to a shear load, due to the rotation of the sample the weld is aligned with the loading axis. As a result, the weld experiences a tensile load and undergoes a tensile overload failure (Ref. 11). Therefore, the weld shear-tension strength depends upon the tensile strength of the base material. In the case of a cross-tension test, the weld specimen is subjected to bending loads and is sheared off when overload occurs. Therefore, in a cross-tension test the fracture mechanism is by shear even though on a macroscopic scale the loading mode is tensile. Shear failure is dependent on the shear strength of the base material. The shear strength of steel is about 50% to 60% of its tensile strength. Therefore, weld cross-tension strength tends to be

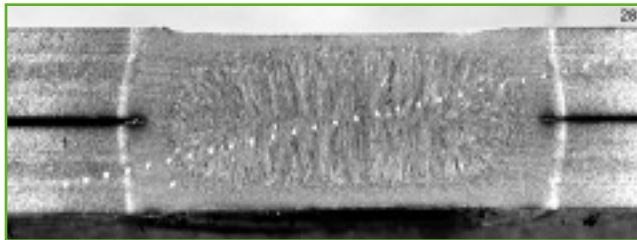
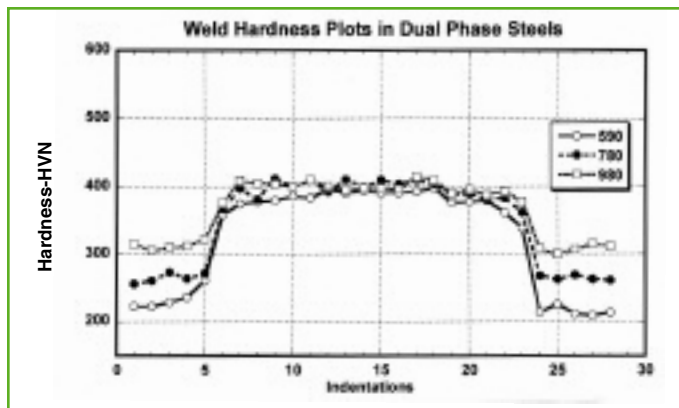


Fig. 11 — A plot of hardness distribution across the weld, the heat-affected zone, and base metals for 590, 780, and 980 MPa steels. The bottom photograph shows the location of hardness indentations.

much lower than its shear-tension strength.

Figure 11 shows the microhardness distribution for welds in all three strength levels. While hardness of the base material increases as its strength increases, the weld hardness distribution in 780 and 980 MPa steels is similar, and the average hardness for both the steels is around 415 VHN. The average hardness for the 590 MPa steel is around 380 VHN, which is only slightly lower than those of the 780 and 980 MPa steels. The reason for the similarity in weld hardness between the 780 and 980 MPa steels is due to the presence of untempered martensite in the weld and the heat-affected zones — Fig. 12. Even at 500°C, cooling rates of 1000°C/s were estimated in a 2-mm steel resistance spot weld (Ref. 12). Recent calculations showed that for 2-mm-thick steel, the overall cooling rate from melting to ambient was about 2000°C/s (Ref. 13). Calculations showed that the cooling rate required to form martensite in these steels is about 250°C/s (Ref. 14). Due to the extremely rapid cooling that resistance spot welds undergo, it is not surprising to see untempered martensite in the welds. The hardness of martensite is controlled by the carbon content present. Both 780 and 980 MPa steels contain similar levels of carbon. Due to a lower carbon content required to achieve the required strength level in 590 MPa steel, the weld showed

lower hardness compared to welds in 780 and 980 MPa steels. However, the microstructural constituents in all three grades were similar.

For simplicity, weld fractures were classified in this study either as full button pullout or interfacial fractures. Other types of fractures that are seen sometimes in high-strength steels include partial interfacial and partial thickness fractures.

Work at United States Steel Corp. has shown a dependence of fracture mode on sheet thickness, weld size, and steel tensile strength. Weld tensile tests in this study showed that full-button pull out fracture mode was seen in 980 MPa grade when the weld size is large. However, even when interfacial fractures were seen, the load-bearing ability of the welds was still high. Therefore, fracture mode alone is not a good indicator of weld integrity and performance.

## Conclusions

Based on the resistance spot weld evaluations done on 590, 780, and 980 MPa dual-phase steels, the following conclusions can be drawn:

1. Welds with no imperfections were obtained in all three of the steel grades studied, which suggested that dual-phase steels possess good weldability and could be welded with simple, easy-to-use welding parameters.

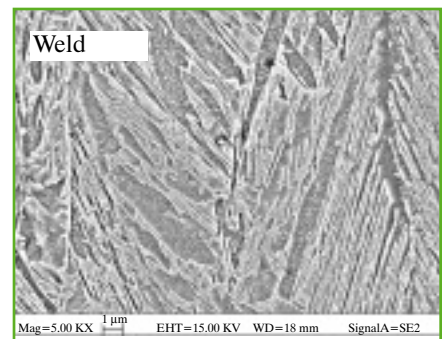
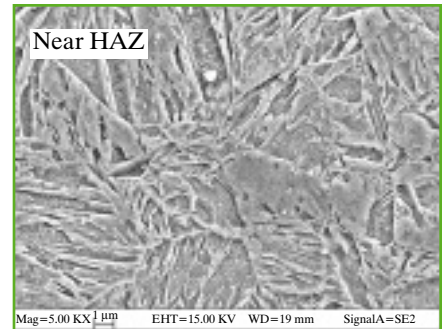
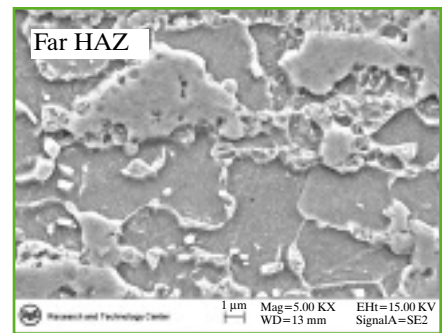


Fig. 12 — Weld and heat-affected zone microstructures in dual-phase steels. Both the weld and the near heat-affected zones showed martensite. The heat-affected zone area consisting of martensite was quite wide. The far heat-affected zone, which was narrow, showed areas of ferrite and tempered martensite.

2. Similar welding behavior can be expected with all three DP steels studied. All three DP steels showed wide welding current ranges to achieve acceptable weld sizes.

3. Fracture appearance alone should not be used to judge weld quality in dual-phase steels.

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