Z2. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Task 2 - Weldability and Performance Evaluations of AHSS Parts for Automotive Structures

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Objective

- Develop fundamental understanding and predictive capability to quantify the effects of welding and service loading on the structural performance of welded AHSS auto-body structures.
- Investigate the weldability of AHSS under various welding processes and parameter conditions applicable to auto production environment.
- Investigate welding techniques and practices to improve AHSS weld performance and benchmark the performance against the current welding practices.
- Generate weld performance data including static strength, impact strength, and fatigue life as function of welding processes/parameters, and steel grade and chemistry.
- Develop design guidelines and CAE methodology to assist rapid structure design validation and prototyping of AHSS parts, to achieve maximum vehicle weight reduction through intelligent selection and utilization of AHSS based on the fitness-for-purpose principle.

Approach

- Conduct comparative welding experiments on various AHSS including HSLA, dual-phase (DP), and transformation-induced plasticity (TRIP) boron steel to develop the correlation among the joint properties, welding process conditions, and steel chemistry.
- Characterize and rank the factors controlling the weld geometry, weld microstructures and weld joint performance.
- Develop an integrated thermal-mechanical-metallurgical welding process and performance modeling methodology to accurately predict the microstructure and mechanical property gradients in the weld region; use the experimental data to validate the integrated model.

Accomplishments

- Generated baseline gas metal arc weld performance data (static tensile strength and fatigue life) for a number of AHSS including HSLA590, DP600, DP780, DP980, TRIP780, M130, M220 and Boron Steels.
- Proposed two design parameters (normalized static joint strength and joint efficiency) to quantify the benefit of AHSS under static loading conditions.
- Established the strong correlation between weld joint efficiency and the HAZ softening under static loading condition.
- Revealed the dependency of weld fatigue life as function of steel grade and chemistry.
- Determined the negligible influence of HAZ softening on the weld fatigue life.
- Demonstrated the feasibility of improved weld fatigue life through adjustment of welding conditions.

Future Direction

- Continue to identify key factors controlling the weld joint performance under static and fatigue loading conditions.
- Investigate the weld joint performance under impact loading conditions.
- Develop the integrated thermo-mechanical-metallurgical modeling framework.
- Investigate welding techniques and practices to improve weld fatigue performance.
- Develop design guideline and CAE analysis methodology to assist rapid design and prototyping of AHSS structures.

Introduction

This project is part of joint research at Oak Ridge National Laboratory (ONRL) and Pacific Northwest National Laboratory (PNNL) on "Characterization of Thermo-Mechanical Behaviors of Advanced High-Stress Steels (AHSS)." This joint program aims at developing fundamental understanding and predictive modeling capability to quantify the effects of auto-body manufacturing processes (forming, welding, paint baking, etc) and in-service conditions on the performance of auto-body structures made of AHSS. ORNL's research (designated as Task 2 in this joint program) focuses on welding of AHSS. In late part of the program, the interdependency of manufacturing processes – weldability of a formed part and formability of a welded part, will be investigated.

The automotive industry is aggressively pursuing insertion of AHSS in automotive body structures for crashworthiness and weight reduction. However, welding AHSS for automotive structure applications presents some unique technical challenges to the steel suppliers and end-users. Data available so far have indicated that welding AHSS with practices developed for the conventional mild steels may not be the preferred approach to bring the full benefits of AHSS. Because of their higher carbon and alloying element contents, AHSS as a whole are more sensitive to the thermal cycle of welding than mild steels. Consequently, the weld region of AHSS generally exhibits greater variations in microstructure and mechanical properties that are highly dependent on welding conditions and type of steel. As the properties of AHSS often require an orchestrated optimization of steel chemistry control and advanced steel processing route by steel maker, the microstructure changes in the weld region often result in different performance characteristics than the optimum base metal microstructures. As higher grades of AHSS (DP800, boron steel, TRIP 780 and above) are being developed and available for auto-body applications, the property degradation penalty due to welding is more profound, and must be adequately dealt with by both the steel makers and auto end-users.

It is important to recognize that the steel chemistry and steel processing route are only two of the many variables that govern the performance (static strength, fatigue life, impact properties, etc) of a weld joint in an auto structure. The geometric features of a weld (such as the weld surface profile and weld size) also play an important role. Furthermore, the welding processes and parameters need to be selected carefully to match the metallurgical characteristics of a given AHSS; and different types of AHSS may require different welding conditions to realize the benefits of the steels.

To the end-users, making the strongest weld is certainly desirable. However, the real engineering challenge is more than that it seeks to answer the question of "how to specify a weld to meet the target performance specifications of a welded component in the most cost-effective way". It involves more than merely selecting the "best" steel in the market – in many cases, the specification could be met by using a less-expensive steel together with intelligent specification and control of weld geometric attributes and welding conditions, to achieve the total cost-effectiveness. It would be highly desirable if the quality and performance characteristics of the AHSS welds could be accurately specified in the design stage, resulting in significant cost-savings and shortening of the design cycle.

The goals of this program are two-fold. First, it is to develop a fundamental understanding of the welding effects on the microstructure and the associated property changes in AHSS weld joints, and to develop the predictive capability that quantitatively relate these microstructure and property changes to the steel chemistry and welding process conditions. With the developed fundamental understanding, we also seek new welding techniques and practices to improve the structural performance of AHSS welded auto-body components. Second, it aims at addressing the weldability and performance of AHSS from the end-user's perspective by developing a systematic approach that enables the product design engineers to reliably and cost-effectively design AHSS welds, to meet the performance design targets of welded components. In this aspect, we plan to consolidate the effects of welding on AHSS into weld performance data and design guidelines or CAE design methodology, which take into account of the weld property variations and the best-in-class welding practices, for use in the design stage to achieve vehicle weight reduction through intelligent selection and utilization of various AHSS

This research will focus on welding of AHSS for chassis and underbody applications. The proposed work scope includes both seam welds in making the hydroformed and roll-formed tubes, and attachment welds for assembling parts. The effects of welding process and parameters on the microstructure and property of welds will be systematically evaluated. Welding processes under consideration are gas metal arc welding (GMAW), laser welding, and resistance spot welding (RSW). The microstructure evolution will be studied by means of advanced materials characterization techniques. Metallurgical and process models will be used to analyze the microstructure evolution. The weld performance properties will be measured as a function of weld geometry, steel composition, welding process and process parameters. A performance evaluation procedure will be developed that allows for quantifying the performance improvement, weight and cost savings associated with use of AHSS. At the end of program, guidelines to design and quantify weld performance for AHSS automotive structure applications will be delivered.

FY 2006 was the first year of this program. The research in FY2006 focused on obtaining the baseline knowledge and understanding about the static strength and fatigue life of AHSS welds. To this end, we investigated a wide range of AHSS types and grades most interesting to the US automotive industry.

We started the program with a series of discussions and meetings with auto OEMs and steel suppliers to refine the program work scope for the next 12 to 18 months. This work scope was developed based on the research needs and issues facing the automotive industry in application of AHSS and the availability of AHSS from steel suppliers. We also met with the A/SP Joining Technologies Team to discuss the goals and research plan of this program, and to have a better understanding of various welding and high-strength steel programs under A/SP. We agreed to meet with the A/SP Joining Technologies Team on a regular basis for information exchange and update of research progress. Recently, the interactions with A/SP have been expanded to other A/SP committees such as the Sheet Steel Fatigue Team and the Lightweight Chassis Structures design team.

From these interactions, an industry advisory committee was formed for this program which consisted of representatives from the Big-Three (DaimlerChrysler, Ford and GM), and fives steels suppliers (Mittal Steel, US Steel, SeverStal, AK Steel, Dofasco).

Steels

Steels selected for the study included five types of AHSS: high-strength low-alloy (HSLA), dual-phase (DP), transformation induced plasticity (TRIP), martensite, and boron steel. In addition, mild steel was used as the baseline steel for comparison. The steel selection matrix also included different surface conditions: uncoated (Bare), hot-dipped galvanized (GI), and hot-dipped galvannealed (GA) coatings.

The FY2006 research concentrated on 2-mm thick steels. Eventually, the program will expand to thicknesses ranging from 1.5 to 8.5 mm, which would cover the typical materials thicknesses for passenger vehicles, light trucks, and SUVs. The heavier gauges steels used in light trucks and SUVs may offer the biggest light-weighting opportunities. According to the automotive industry, the light trucks and SUV currently use less AHSS in the body structures than the passenger sedans. Furthermore, for the same percentage gauge reduction, a heavy gauge section would offer more absolute weight reduction than a thin gauge section.

The program received strong support from the steel suppliers. So far, a total of 22 grade-gauge-coating steel combinations were received from six steel companies: Mittal Steel, US Steel, AK Steel, Dofasco, Severstal, and ThyssenKrupp. They are listed below:

- Group 2 (350 MPa ~500 MPa)
  - 1.5mm HSLA Bare
  - 1.5mm Mild Steel Bare (2 suppliers)
  - 2.0mm DR210 Bare
- Group 3 (500 MPa~ 800 MPa)
  - 2.0mm DP600 Bare
  - 1.8mm HFT590 Bare, 1.6mm 590R GA, 1.8mm DP590Bare
  - 1.7mm DP600 HDGI, 1.6mm DP600 GA, 2.0mm DP600 HDGI
  - 2.0mm HSLA590 Bare
- Group 4 (>800 MPa)
  - 1.4mm DP780 GI, 1.6mm DP780 EG, 2.0mm DP780 Bare
  - 1.5mm TRIP780 GA
  - 1.5mm Boron HT Bare, 1.5mm Boron UHT Bare, 2.0mm Boron HT Bare, 2.0mm Boron UHT Bare
  - 2.0mm DP980 Bare
  - 2.0mm M130 Bare, 2.0mm M220 Bare

We will continue to work with the OEMs and steel suppliers to obtain additional heavier gauge materials for future studies.

Welding

Based on the input from the industry, it was decided that the FY06 and part of FY07 activities would focus gas metal arc welding (GMAW), since it is the commonly used joining process for attachment welds and structure welds for heavy gauge underbody and chassis assembly parts. The selection of GMAW process also considered the fact of on-going studies on resistance spot welding and other welding processes in the USCAR program.

All welds were made in the lap joint configuration, the most common type of weld for attachment and structure joining with the GMAW process. All welds were fabricated with a robotic system (OTC Robot Almega) at AET-Integration, Inc.

ER70-S3, a filler metal commonly used by the auto industry, was used in this study. This filler metal may present a strength under-match for some higher strength AHSS, i.e., the tensile strength of weld metal is lower than that of the base metal. However, as shown in later part of this report, the degree of under-match was not sufficient to cause failure in the weld metal. All welds investigated so far failed outside the weld metal, either in the base metal or the heat-affected zone (HAZ). This was due to the fact that the “structural” strength of a lap joint not only depends on the weld metal strength, but also on the weld geometry that can greatly influence the stress distribution in the weld region (weld metal and HAZ).

In order to evaluate the intrinsic microstructural differences in the weld region of different AHSS, all welds were made with the same welding heat input level. In keeping the same sheet thickness, same joint configuration and same welding heat input in our experiments, all weld joints would experience the same welding thermal history. Therefore, the microstructure differences in the weld region in this study can be solely attributed to the chemistry of different steels. The potential complications of steel phase transformation behavior in welding due to different thermal histories can be avoided in our comparative study

Welding parameters representative to current practices in the automotive industry were adopted in the study. Specifically, the welding speed, which controls the welding productivity, was set at 50 in/min. The welding current and voltage were 230A and 24V, respectively. Other process parameters such as welding torch angle, etc, were adjusted to obtain a consistent weld profile (toe angle and radius, etc.) for different steels. Figure 1 shows the weld profiles of different AHSS produced with the above baseline welding parameters.

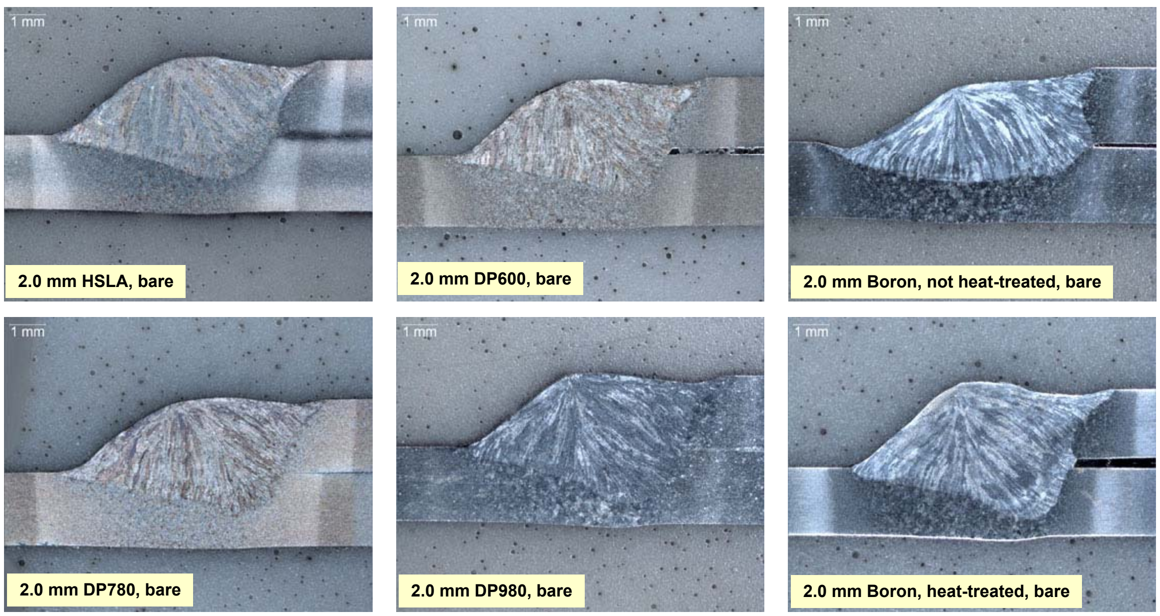

Figure 1. Cross-section view of weld profiles among different AHSSs.

Maintaining consistent weld profile was an important consideration in evaluating the performance of different steels. It minimizes the complications of weld stress variations due to weld geometry differences. By maintaining consistent welding thermal history and weld stress profile, it was then possible in this study to correlate the weld structural performance (static strength and fatigue life) to the intrinsic microstructural differences in the weld region of different steels.

It is noted that the welding conditions used in our comparative study may not be optimal for AHSS. The welding process improvement/optimization for AHSS will be an important direction of our future research in this program

Results and Discussions

Static Tensile

Figure 2 summarizes the static tensile testing results of 11 different steels. For each type of steel, the ultimate tensile strength of both the lap joint weld and the base metal are provided. In the figure, the steels are arranged based on their base metal strength. Note that the base metal strengths shown in the figure are the actual measured values from the tensile test, and they are higher than those in the steel specification. This reflects a common practice of steel suppliers to ensure their products meet or exceed the minimum specified values for a given steel designation.

As shown in Figure 2, as the base metal strength increases, the lap joint weld strength generally increases. The benefits of AHSS (in terms of static tensile strength) over mild steels can be measured by the normalized static joint strength (NSJS) – the ratio of the static weld strength of AHSS to that of the baseline reference mild steel (DR210 in this case). For example, DP780 steel has a NSJS of 209%, which means its static tensile strength is about twice that of DR210. Among all AHSS studied so far, the boron steel has the highest NSJS, about 2.5 times of that DR210.

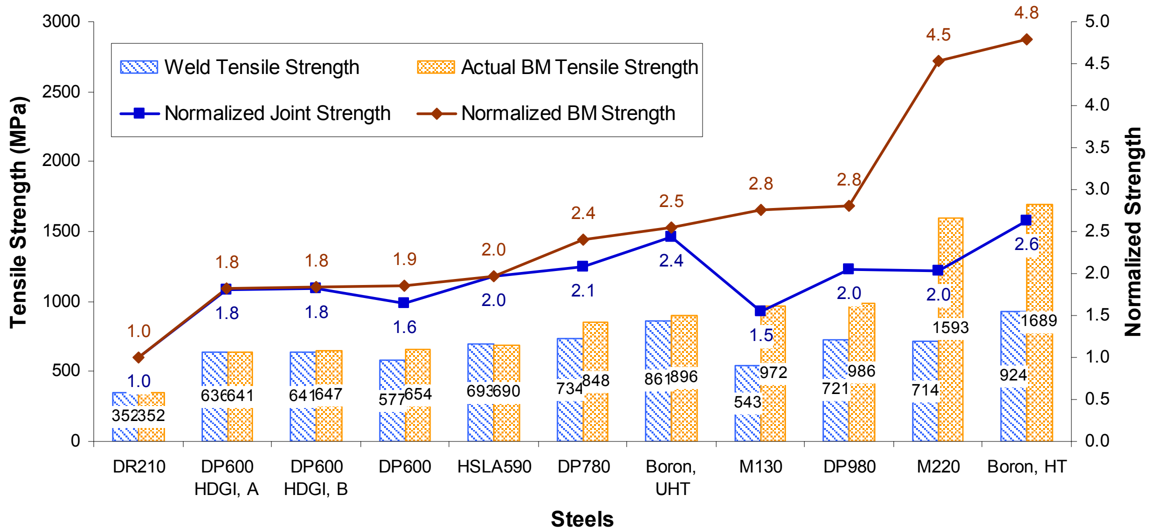

Figure 2. Comparison of lap joint static tensile strength and base metal tensile strength among different AHSS. All steel sheets were 2.0mm. The joint strength is normalized to that of DR210 (baseline reference mild steel).

NSJS can be considered as a measure for weight reduction potential of high-strength steel in replacing the mild steel while maintaining the same static joint tensile strength.

It is important to note that NSJS of AHSS does not always follow the increase in base metal strength. As shown in Figure 2, for steels on the low strength end of AHSS spectrum (DP600, DP780, and HSLA590 in this study), the weld joint strength is about the same as the base metal steel. This means that welding does not adversely penalize the strength gains of these types of AHSS. On the other hand, for steels with primarily martensitic base metal microstructure (DP980, M130, M200, heat-treated hardened boron steel), the static strengths of the lap welds are considerably lower than those of the base metal. For example, for the hardened boron steel, its base metal tensile strength (1689MPa) is 4.8 times of DR210's (352MPa). However, its weld joint strength (924MPa) is only 2.5 times higher. This means that the microstructure changes in the weld region caused by the thermal cycles of GMAW could severely diminish the potential gains of static tensile strength of these steels.

The degree of welding induced penalty to the static tensile strength of AHSS can be measured by the joint efficiency (JE). JE is defined as the ratio of the weld strength to the base metal strength of the same steel. The joint efficiencies of the 11 steels studied in this program are given in Figure 3. For the steels investigated in this program, AHSS with nominal tensile strength below 800MPa (the Group 3 AHSS) maintains relatively high joint efficiency (minimal welding induced penalty). On the other hand, higher strength Group 4 AHSS (800MPa and above) exhibit considerable joint efficiency reduction. This drop in joint efficiency is caused by the significant microstructure changes in the HAZ (HAZ softening), as revealed by the microhardness measurement.

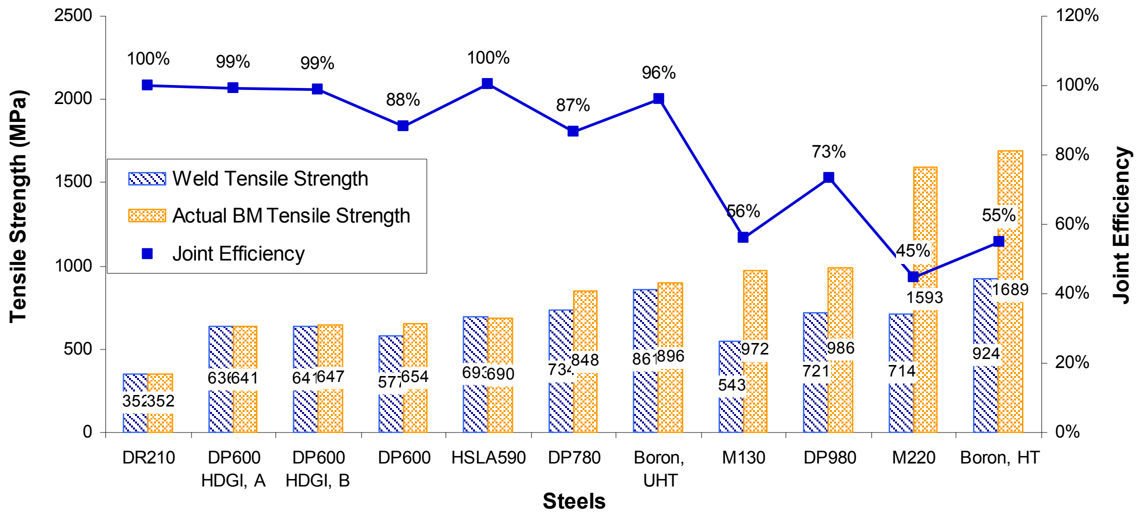

Figure 3. Joint efficiency of different AHSS. The joint efficiency is the ratio of weld strength to the base metal strength. Steel sheet thickness: 2.0mm.

HAZ Softening

Microhardness mapping was performed to better understand the microstructural changes in the weld region. The microhardness map was constructed from 6000 to 8000 automated microhardness measurements with spatial resolution of 0.15 to 0.2 mm, and covers the different regions of a weld joint (weld metal, HAZ, and adjacent unaffected base metal). Figure 4 presents the microhardness distribution of the hardened boron steel weld.

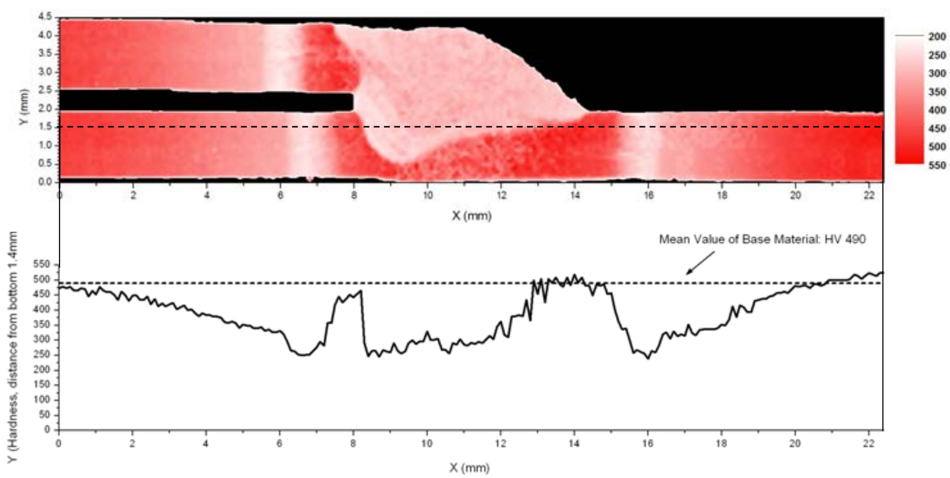

Figure 4. Weld region microhardness mapping of hardened boron steel. The line plot is taken along the dashed line in the microhardness map.

The boron steel weld exhibits highly non-uniform microhardness distribution. Considerable softening (as low as 45% of the base metal hardness) occurs in the intercritical region of the HAZ that is about 1-mm away from the weld fusion line. Because of the high hardenability of boron steel, the coarse grain HAZ adjacent to the fusion line transforms back to martensitic microstructure on cooling, thereby essentially recovering to the hardness of the base metal which also has martensitic microstructure.

Figure 5 compares the microhardness distributions in three AHSS: HSLA590, DP980 and hardened

boron steel. For comparison purpose, the microhardness of each weld was normalized with respect to its mean base metal microhardness microhardness. A normalized value of 1.0 in the plot means the hardness is the same as the base metal. The normalized microhardness maps clearly reveal the different degrees of HAZ softening of the three AHSS. The low-strength grade HSLA590 shows minimal HAZ softening. DP980 exhibits a noticeable level of HAS softening: a wide softening region with hardness only about 65% of the base metal DP980. The ultra-high strength boron steel develops the most severe HAS softening.
The minimum hardness in the softening region was only about 45% of the base metal value. The drastic differences in joint efficiency of different AHSS can be related to the extent of HAZ softening in these steels.

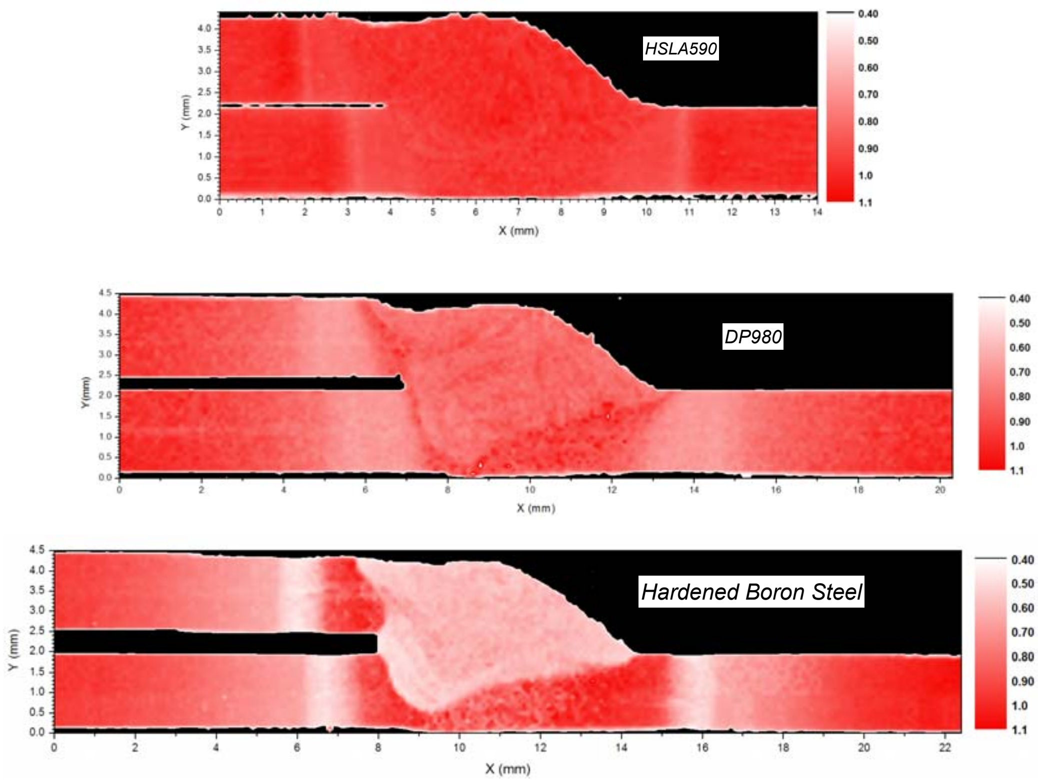

Figure 5. Comparison of microhardness distributions in three AHSS. The microhardness has been normalized with respect to the respective base metal microhardness. Mean base metal hardness: HSLA 590: 240Hv; DP980: 280Hv; Hardened boron steel: 490Hv.

Correlation between Static Tensile Strength and HAZ Softening

Figure 6 shows the failure locations of 6 AHSS welds during the static tensile test. As the base metal strength increases, the failure location generally shifts from the root of the weld (where geometric stress concentration exists) to the softened region in HAZ where the materials strength decreases. Such shifting in failure location correlates well to the observed joint efficiency reduce tion of the ultra-high strength steels (DP980, boron and martensitic steels) showing in Figure 3.

Figure 7 provides the side-by-side comparison of the failure location and the microhardness distribution in DP90 steel. Clearly, the DP90 weld failed in the softened region in HAZ. Therefore, the weld-strength of the ultra high-strength steels is governed by the softened region in HAZ, not by the base metal strength.

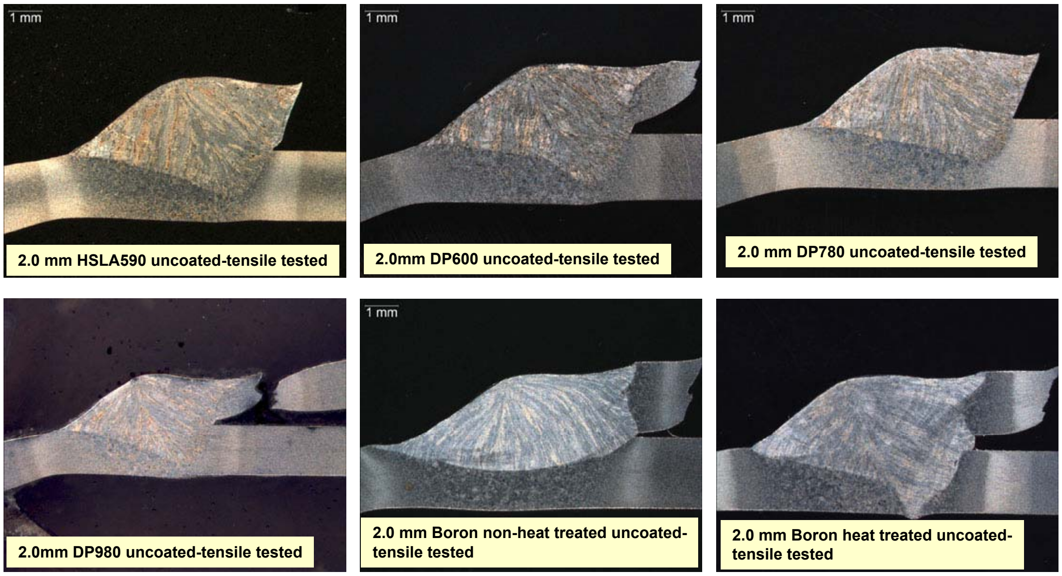

Figure 6. Failure locations of AHSS weld under static tensile loading.

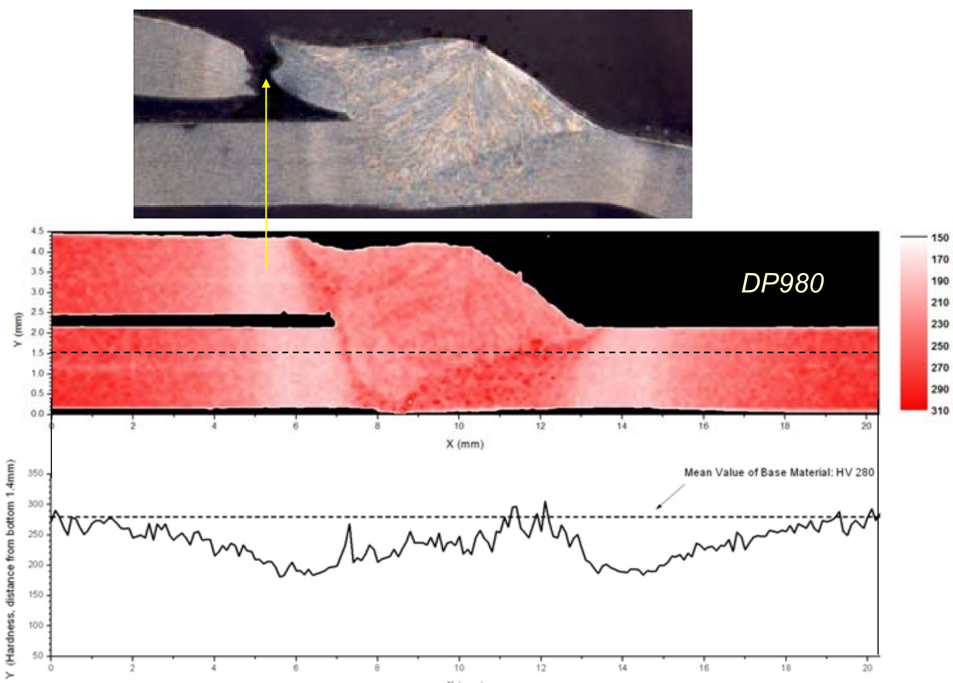

Figure 7. Failure location during static tensile loading correlates to HAS softened region in DP980.

Fatigue Life of AHSS Weld

Figure 8 compares the lap weld fatigue lives of 9 different uncoated AHSS: heat-treated hardened boron steel (Boron HT), unhardened boron steel (Boron UHT), two martensitic steels (M220 and M130), three DP steels (DP980, DP780, DP600), HSLA590, and DR210. The fatigue tests were conducted in constant load amplitude mode (R=0.1). For clarity, only the statistical regression lines were plotted. There are noticeable differences in fatigue lives among the different steels. For example, at 100MPa nominal stress range, the mean fatigue life of DR210 weld is about 8 times longer than that of the hardened boron steel weld.

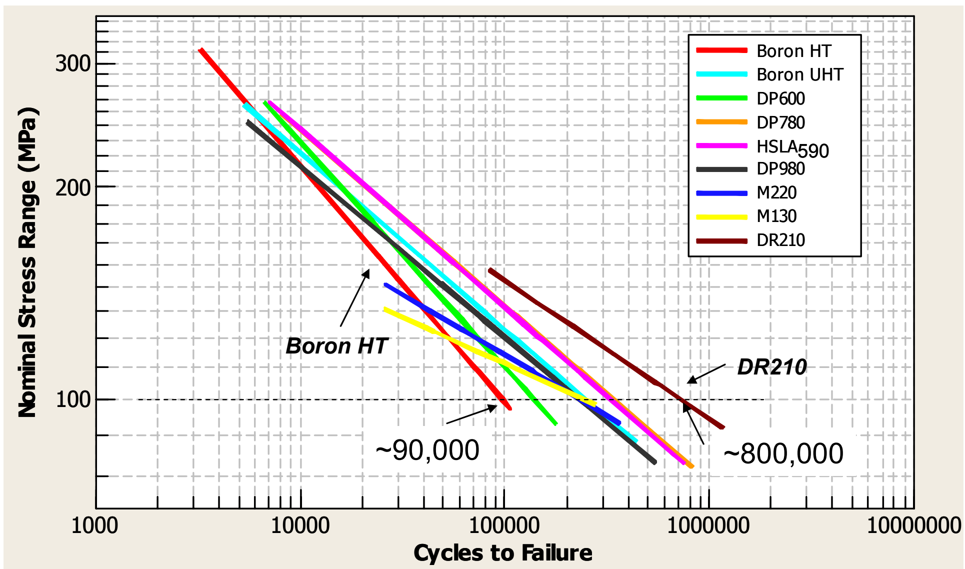

Figure 8. Comparison of fatigue S-N curves of different AHSS made under same welding conditions and having consistent weld profile. The regression curves are shown. R=0.1. Steel sheet thickness: 2 mm.

Figure 9 shows the failure locations of 6 different AHSS during the fatigue test. Contrary to the static tensile loading case, the fatigue failure initiated either at the weld toe or weld root, and none was in the softened region of HAZ. This suggests that the HAZ softening does not contribute to the fatigue crack initiation and propagation (thereby the fatigue life), at least for the steels investigated so far.

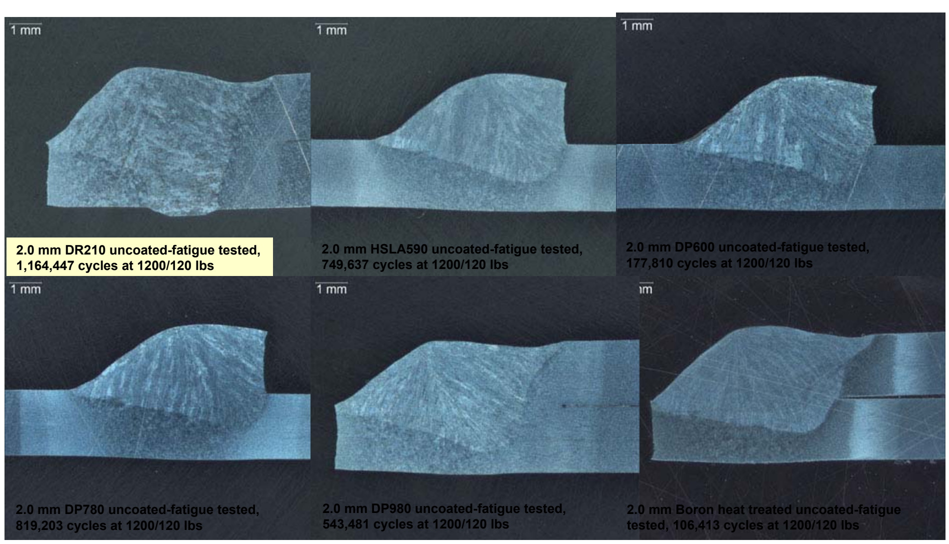

Figure 9. Failure locations in fatigue testing.

Finally, Figure 10 shows our preliminary attempts to improve the fatigue life of AHSS welds. By reducing the welding speed from 50 in/min to 40 in/min (still within the welding speed window commonly accepted by the industry) and maintaining the same welding heat input, the fatigue life of DP600 increased over 20 times. The fatigue life of the DP600 weld made with the baseline welding condition was among the worst of all the steels investigated (see Figure 8). The improved welding practice resulted in fatigue life far better than the best weld (DR210) made with the baseline welding condition.

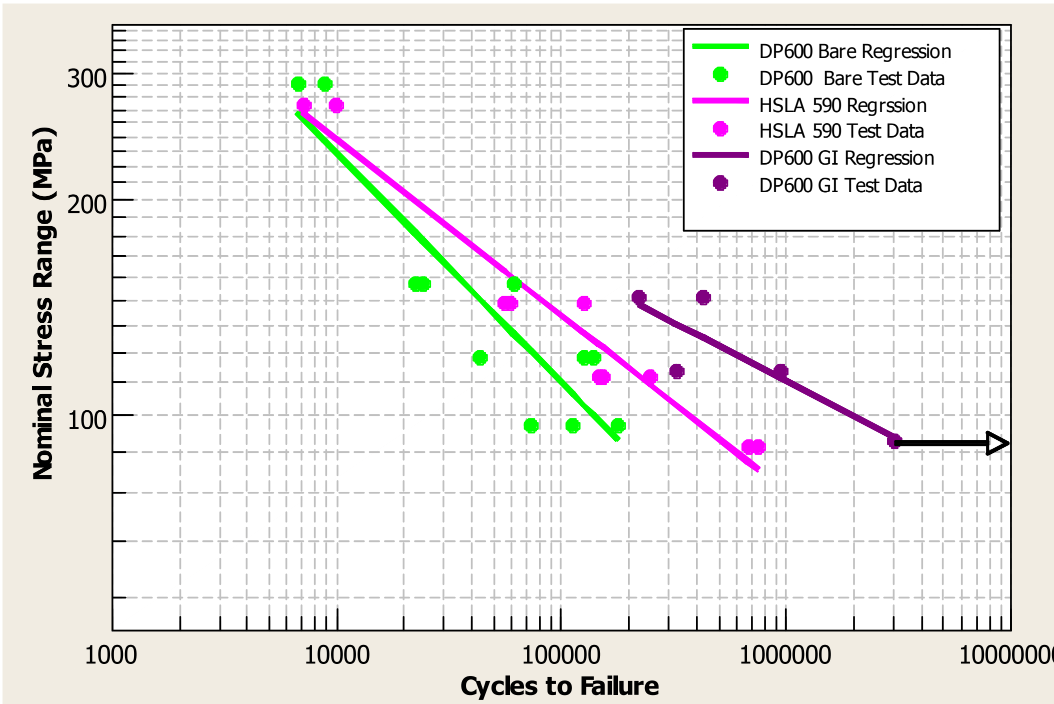

Figure 10. 20X improvement in fatigue life of DP600 steel. Both the regression lines and the actual testing data are shown. DP600 Bare and HSLA 590 were made at the baseline.

We will further investigate the fundamental causes/mechanisms leading to the above drastic fatigue life improvement in FY2007 and FY2008 to determine whether they are related to the weld profile changes, the microstructural changes, or both. If the microstructure is an important factor, then what type of microstructure would lead to better fatigue life? More detailed modeling analysis, microstructure characterization and additional special welding tests are planned in FY2007 and FY2008 to understand the key factors controlling the weld fatigue life.

Conclusions

In FY2006, the first year of the program, we have developed baseline knowledge about the static tensile strength and fatigue life of GMAW lap weld joints for a wide range of AHSS (HSLA, DP, TRIP, martensitic, and boron steels). It was found, for the steels and welding conditions investigated herein, that:

1. The static tensile strength of GMAW lap weld increases as the base metal steel strength increases. However, the joint efficiency decreases considerably for ultra-high strength steels (DP980, boron and martensitic steels) due to the profound HAZ softening in these steels. The lower grade AHSS without HAZ softening maintains their high joint efficiency.
2. Steel grade dependency of weld fatigue life has been confirmed. The HAZ softening does not appear to be a major factor influencing the weld fatigue life.

3. It is feasible to drastically improve the weld fatigue life of AHSS by manipulating welding process conditions. The fundamental causes/mechanisms leading to the observed fatigue life improved require further investigation.

Presentations/Publications/Patents

None in FY2006, but several presentations and publications have been accepted in FY2007.