ORNL/TM-2014/680
CRADA/NFE-11-03368

Improving Fatigue Performance of AHSS Welds

Oak Ridge National Laboratory

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November 2014

OAK RIDGE NATIONAL LABORATORY
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DOE EERE Vehicle Technologies Office

Improving Fatigue Performance of AHSS Welds

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Date Published: November 2014

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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1. ABSTRACT

Reported herein is technical progress on a U.S. Department of Energy CRADA project with industry cost-share aimed at developing the technical basis and demonstrate the viability of innovative in-situ weld residual stresses mitigation technology that can substantially improve the weld fatigue performance and durability of auto-body structures. The developed technology would be cost-effective and practical in high-volume vehicle production environment. Enhancing weld fatigue performance would address a critical technology gap that impedes the widespread use of advanced high-strength steels (AHSS) and other lightweight materials for auto body structure light-weighting. This means that the automotive industry can take full advantage of the AHSS in strength, durability and crashworthiness without the concern of the relatively weak weld fatigue performance. The project comprises both technological innovations in weld residual stress mitigation and due-diligence residual stress measurement and fatigue performance evaluation. Two approaches were investigated. The first one was the use of low temperature phase transformation (LTPT) weld filler wire, and the second focused on novel thermo-mechanical stress management technique. Both technical approaches have resulted in considerable improvement in fatigue lives of welded joints made of high-strength steels. Synchrotron diffraction measurement confirmed the reduction of high tensile weld residual stresses by the two weld residual stress mitigation techniques.

2. OBJECTIVES

The objectives of the project are:

- Establishing the technical basis and demonstrating the viability of innovative in-process weld residual stress mitigation technology that can substantially improve the weld fatigue performance and durability of auto-body structures.
- The developed technology will need to be cost-effective and practical in high-volume vehicle production environment.

3. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

In the not distant future, engineers need to design an auto-body structure by using the most appropriate steel and other lightweight and high-performance materials with the lightest gages possible to achieve the best fuel efficiency and greenhouse emission, while improving the performance, stiffness, strength, crashworthiness, durability, and, of course, at the lowest cost. Improving fatigue life of welds is critical in achieving this goal.

Durability is one of the primary metrics in designing and engineering automotive body structures. Fatigue performance of welded joints is critical to the durability of body structure because the likeliest fatigue failure locations are often at welds. Even in the most meticulous fatigue design, a weld may have to be placed in a high stress region, and any possible resulting fatigue crack that might result will likely preferentially initiate at the *weld stress riser* [1]. Recent studies by the Auto/Steel Partnership (A/SP) Sheet Metal Fatigue Committee, US DOE Vehicle Technologies Office's

Lightweighting Materials Program, and others [1- 5] have clearly revealed that, unlike the base metal fatigue strength, the *weld fatigue strength* of AHSS is largely insensitive to the base metal composition, microstructure, and strength, under typical welding conditions used in BIW (**Figure 1**). The lack of inherent weld fatigue strength advantage of AHSS over conventional steels is a major barrier for vehicle weight reduction through down-gauging, as down-gauging leads to increases in stresses thereby reduced durability under the same dynamic road loading conditions. In addition to AHSS, a recent comparative study [6] reveals that other lightweight alloys such as Al and Mg alloys may not offer improved weld fatigue strengths, on the "specific weight" basis.

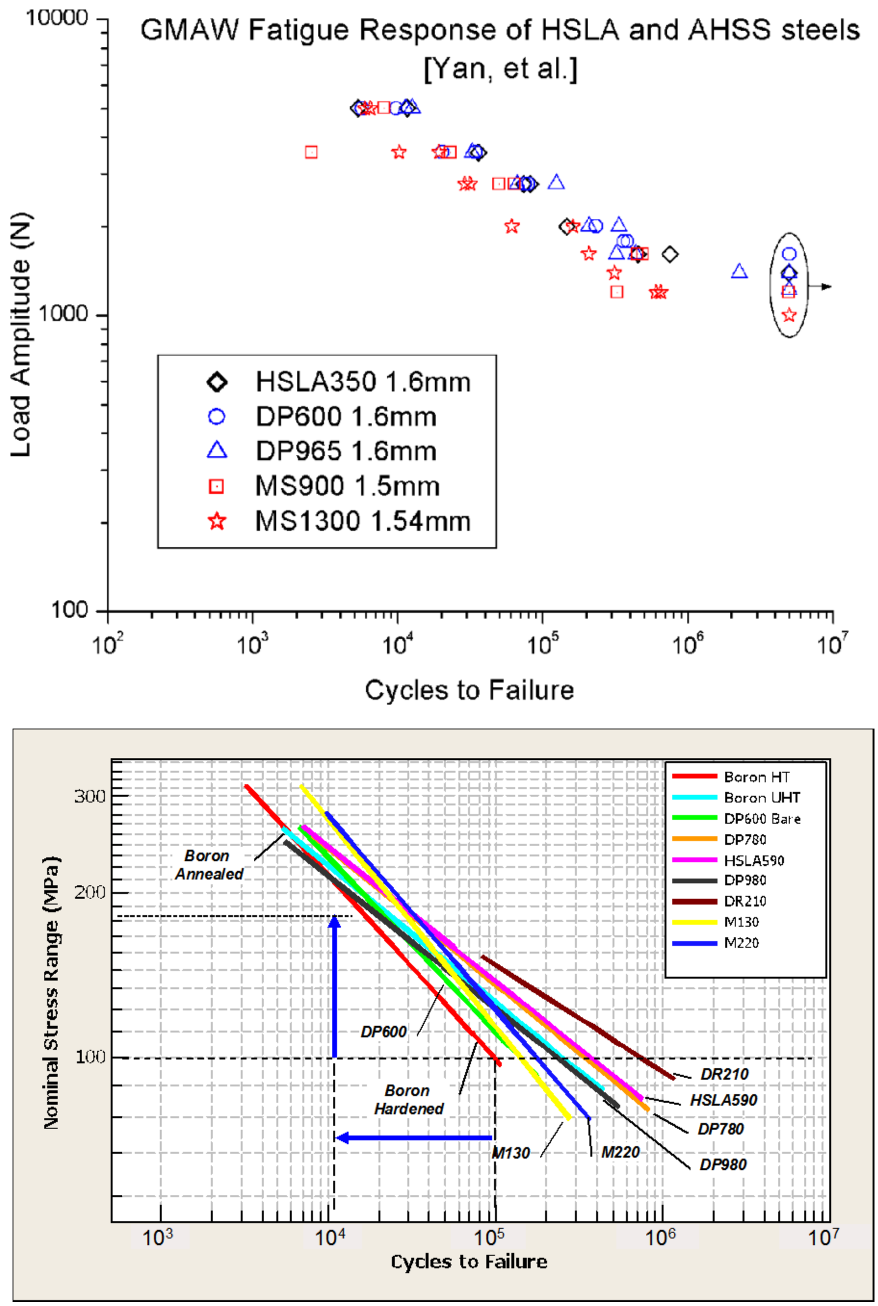


Figure 1 **S-N curves of GMAW lap weld joints of various AHSSs**. Left: from Yan et al. [2]; Right: from Feng et al. [5].

Under CRADA agreement, Oak Ridge National Laboratory and ArcelorMittal USA worked together to develop innovative technologies that can substantially improve the weld fatigue strength and the durability of autobody structures. The developed technology would be cost-effective and practical in high-volume vehicle production environment. Enhancing weld fatigue performance would close a critical technology gap that impedes the widespread use of advanced high-strength steels (AHSS) and other lightweight materials for auto body structure light-weighting. This means that the automotive industry can take full advantage of the AHSS in strength, durability and crashworthiness without the concern of the relatively weak weld fatigue performance.

4. TECHNICAL DISCUSSION OF WORK

4.1 BACKGROUND

Weld residual stresses form in a welded structure as a result of the non-uniform thermal expansion and contraction during welding operation. Weld residual stresses are typically in tension and often reach or even exceed the yield strength of material in the weld region. As the weld fatigue strength strongly depends on factors that drive the stress conditions in and around welds, the high-tensile residual stresses have a detrimental influence on the fatigue strength and durability of all types of welded structures, including auto BIW and, bridges, ships and others.

Because its broad impact, weld fatigue life is a topic for extensive research for many decades, in attempts of understanding the root causes and finding ways to improve weld fatigue life. Many good ideas have been developed, but most involving additional post-processing steps [7-9], such as laser shot peening, low plasticity burnishing, sand blast peening, coining or other means to introduce compressive stress. Although many of the post-welding stress suppressing techniques are effective in improving the weld fatigue life, they are difficult to implement due to extra cost and time in automotive industry. Because of the difficulties in improving the weld fatigue life, the auto industry takes the approach to design the weld line away from the high stress area. If this is not possible, then high strength steel will not be used. This was the reason that high strength steels, such as DP steels, were not used in chassis structure for many years until recently. It is still not fully utilized in many areas due to weld fatigue concerns. One obvious area is the tailor weld blank/structure/tube, an important light weighting technology, which often cannot be used due to weld fatigue concerns.

4.2 TECHNICAL BASIS OF THE DEVELOPED TECHNOLOGIES

Instead of utilizing the post-welding techniques to introduce compressive surface residual stresses to improve the weld fatigue strength, this project focused on developing “in-process” weld residual stress modification technologies that controls and mitigate the weld residual stresses as part of welding operation. The proposed methodology follows the proven principle that compressive residual stress in the weld region can improve the weld fatigue strength, but eliminates the added post-welding steps that can be cost prohibitive for high-volume auto-body assembly.

Two specific in-process stress mitigation approaches have been investigated and developed in this project: the proactive thermomechanical management technique and the low-temperature phase transformation technique. Both techniques have shown to be effective in suppressing the weld residual stresses in other industries mostly involving thick-section applications. However, these weld residual stress modification approaches are largely unexplored by the automotive industry. The technology development in this project considered the issues of both technical and economic nature unique to the automotive body structural welding environment are yet to be identified and addressed.

The basic technical principles of the two stress mitigation approaches are briefly described below.

4.2.1 Weld Residual Stress Control by means of Low-Temperature Phase Transformation (LTPT) Weld Filler

The Low-Temperature Phase Transformation (LTPT) technique is based on the phenomenon that martensite phase transformation in steels is accompanied with a volumetric expansion phenomenon. Special weld filler wire (which is fed into the molten weld pool and solidifies to form the weld metal region) can be formulated with its martensitic phase transformation temperatures designed much lower than the austenite decomposition temperature range of the base metal. As the weld metal undergoes the martensitic phase transformation as it cools during welding, it expands and creates compressive residual stresses in the weld toe region, which in turn improves the fatigue life of the weld. This approach was initially developed in the 1990s for thick-section welded structures for oil-gas applications. **Figure 2** shows the early work by Ohta et al that demonstrated the effectiveness of this technology for fatigue life improvement [10]. The benefits for residual stress control at the weld toe region of a girth weld on high-strength steel pipeline was shown **Figure 3**, in a different research. Today, several efforts are on-going in Europe (such as BAM in Germany), China and Japan to expand the applications of this technology for the aging infrastructures and new construction of fatigue resistance structures. For automotive AHSS, avoiding the formation of brittle martensitic phase will be one of the objectives in this project. This will be accomplished through careful design of filler metal chemistry and welding process controls.

4.2.2 Proactive Thermomechanical Management Technique

This technology is based on the principle of pro-actively altering or interrupting the “normal” differential thermal expansion and contraction sequence of welding through in-process thermal-mechanical control to create compressive residual stress in the weld region. Examples of proactive management include accelerated cooling and auxiliary heating at strategically selected locations around the weld region, identified through advanced weld process modeling. ORNL has worked with industry to apply this technology to applications in the nuclear power generation industry and aerospace industry. **Figure 4** shows an example of proactive residual stress management for stress corrosion cracking prevention for nuclear reactor internals that ORNL was involved [11]. It should be noted that the specifics of the proactive stress management are highly depending on the weld joint configurations. Application of this technology for automotive body structure applications would require additional R&D specific to thin-gage materials welding and joint configurations. If successful developed, this technology might be most desirable for high-volume production environment as it does not require the use of special filler metal and it applies for both AHSS and other lightweight materials such as Al and Mg alloys that do not involve martensitic phase transformation.

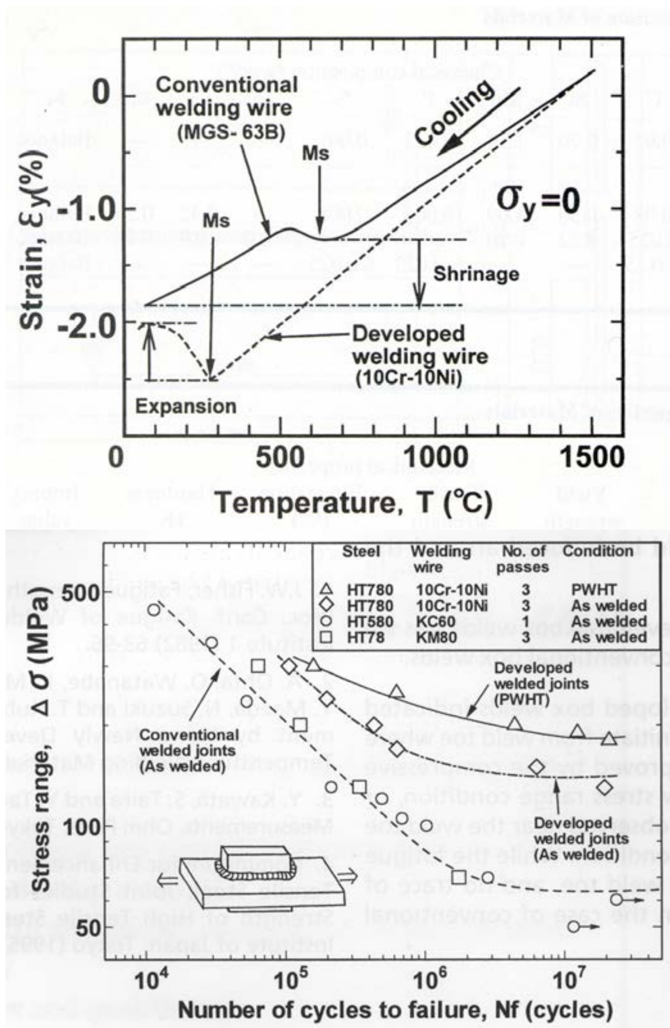


Figure 2 **Principals of LTPT and considerable improvement of weld fatigue life (Ohta et al, 2000)**

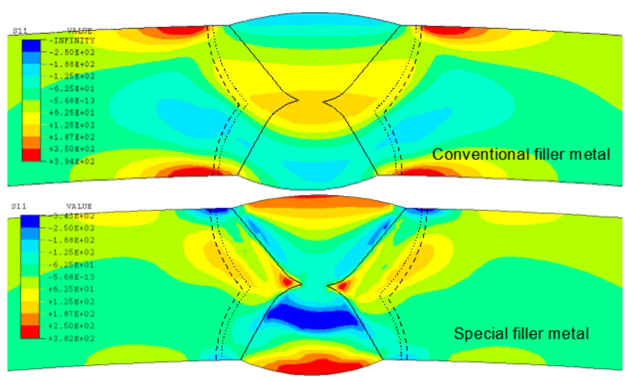


Figure 3 **Effect of LTPT filler metal on weld residual stress distributions in a high-strength steel pipeline weld (Feng et al. 2003).**

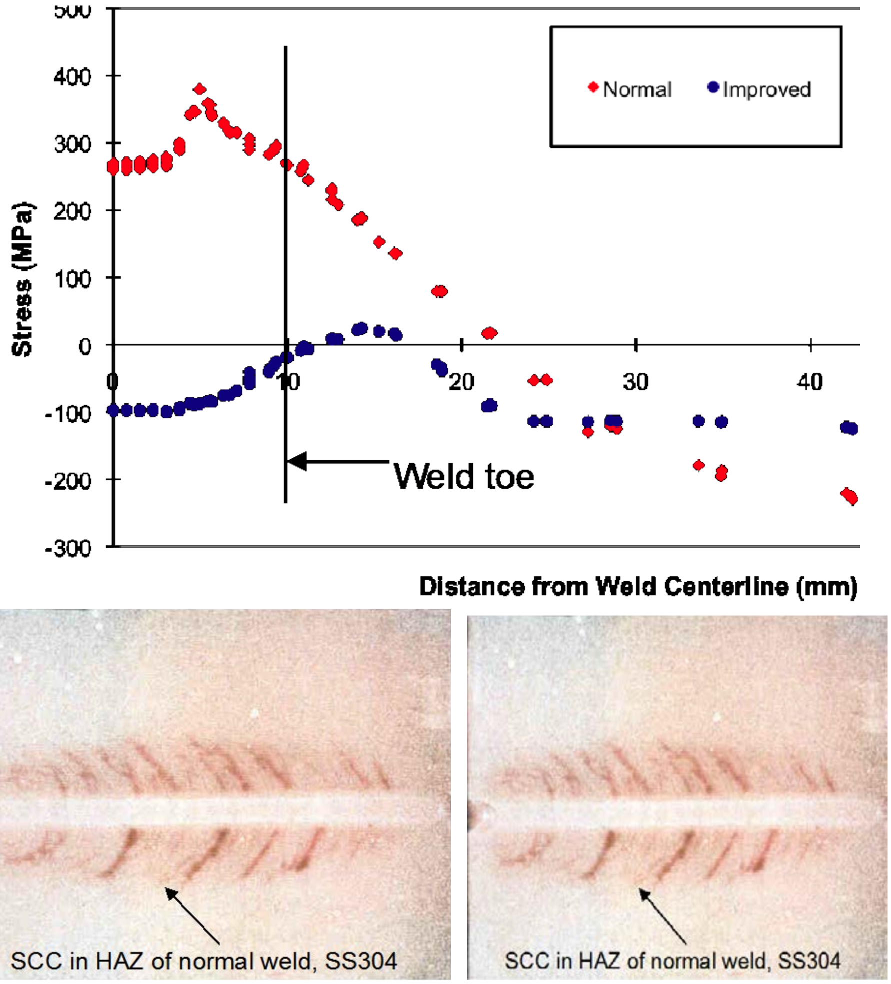


Figure 4 Creation of compressive surface residual stress through accelerated surface cooling of stainless steel (Feng et al, 1999 [11])

4.3 DESCRIPTION OF RESEARCH

This project focused on developing in-process weld technology as part of the welding operation. The overall goal of the project is developing effective ways to control and mitigate the key factors governing the fatigue life of AHSS welds, including weld residual stress, weld profile, and weld microstructure/chemistry. The joint research utilized state-of-the-art integrated computational welding engineering (ICWE), neutron/synchrotron and other advanced residual stress measurement techniques, and fatigue testing and microstructure analysis capability at ORNL and ArcelorMittal Global R&D to perform the research and development in this project.

Two specific in-process approaches were investigated in this project – the use of LTPT weld wire and the pro-active thermo-mechanical stress management. Issues of both technical and economic nature unique to the automotive body structural welding environment were identified and addressed. The project comprises both technological innovations in weld residual stress mitigation and due-diligence residual stress measurement and fatigue performance evaluation.

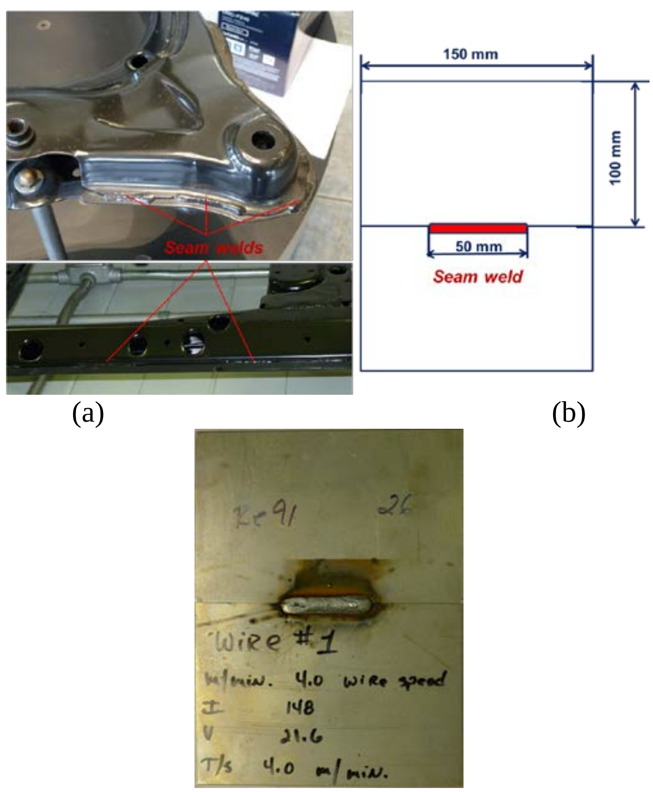
4.3.1 Design of A New Weld Fatigue Test Specimen Configuration

Major automotive original equipment manufacturers (OEMs) were surveyed to identify weld patterns representative of those in vehicle AHSS structures. Based on the survey findings, a new weld fatigue testing specimen configuration was developed with the assistance of finite element structural analysis.

Figure 5 (a) shows the typical chassis and engine motor mount structures assembled using stitches of gas metal arc seam welds. Considering the representative weld pattern, a special weld fatigue specimen configuration was designed, as shown in **Figure 5** (b). This specimen was fabricated by placing a 50-mm-long stitch weld on lap joint of two steel sheets, i.e., the most commonly used weld type in automotive structures. Moreover, the specimen contains both weld start and stop, which are the critical locations for fatigue cracking initiation. In other words, the special weld fatigue specimen configuration not only maintained the weld residual stress field representative of actual seam welds but also produced the stress/strain conditions resembling those endured by vehicle structure welds. An example of this special weld fatigue test specimen is shown in **Figure 5** (c).

4.3.2 Welding and Fatigue Testing

A robotic gas metal arc welding (GMAW) system with cold metal transfer function available at ArcelorMittal, shown in **Figure 6**(a), was used to fabricate the welds. The welding procedures and parameters in these welds for fatigue testing closely represented the typical ones used in auto-body component fabrication. The fatigue testing system at ArcelorMittal, shown in **Figure 6** (b), was modified for testing the specific weld specimen configuration to generate the S-N curves of various welds. All fatigue testing was carried out at R=0.1 and 10 or 20Hz. Additional welding and fatigue testing were also carried out at ORNL use similar welding procedures developed at ArcelorMittal

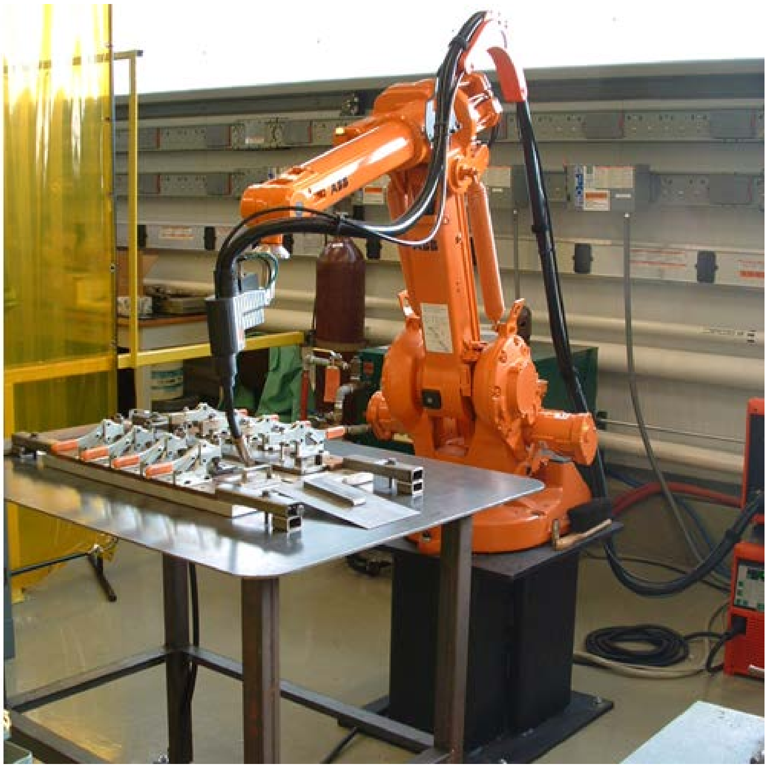


(a) (b)

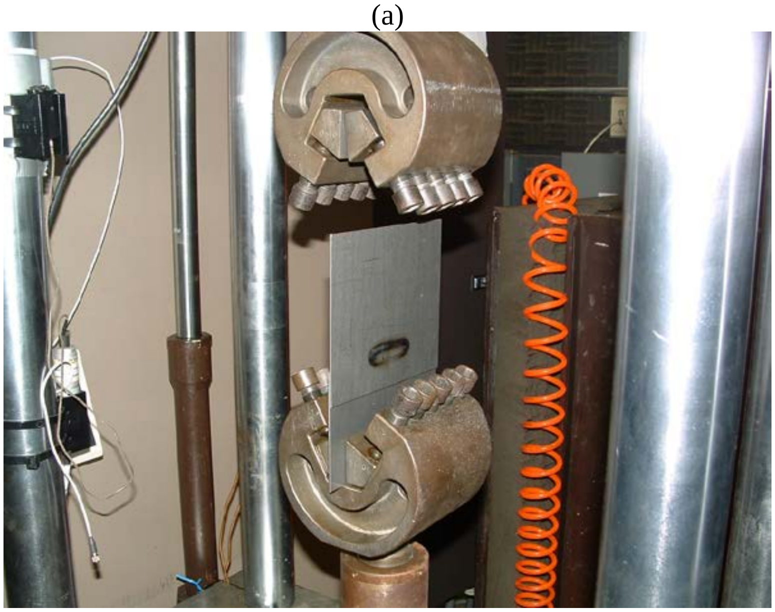
(c)

Figure 5 (a) Representative welding pattern in auto-body structures, (b) special weld fatigue

specimen configuration, and (c) appearance of actual weld fatigue testing specimen.



(a)



(b)

Figure 6 (a) Robotic welding set up and (b) Fatigue testing system at ArcelorMittal

4.3.3 ICWE Modeling for Weld Residual Stress Control

ORNL's integrated computational weld engineering (ICWE) model was used to analyze the effect of low-temperature phase transformation, and other relevant welding and geometric factors on the weld residual stress distribution. The ICWE model first calculates the transient temperature distribution during welding. The temperature history is then inputted into a martensitic phase transformation sub-model to obtain the volume change (or transformation plasticity) upon weld cooling. Finally, the temperature profile and the transformation plasticity are used in the mechanical model to predict the resulting residual stress distribution in the welded sheets. The representative lap-joint testing coupon shown in **Figure 5** was modeled. **Figure 7**(a) shows the finite element geometry and mesh of the seam weld of lap joint. The predicted temperature distributions at different times during welding are plotted in **Figure 8**. The interaction between the heat source and workpiece results in rapid heating and formation of the weld pool, indicated by the red region in **Figure 8** (a) to (c). As the heat source travels, an elongated weld pool shape is formed. As soon as the welding is completed (at time = 5 sec), the entire weld cools down rapidly. The spatial distribution of temperature is highly non-uniform, which is a major driving force for the formation of residual stresses.

With the knowledge of weld temperature distribution, the formation of residuals stress can be calculated taking into account the plasticity associated with low temperature phase transformation. **Figure 9** shows an example of the 3-D weld residual stress distribution for the case of conventional weld filler wire (ER70-S) for AHSS welding in auto-body structures. The stress concentrations near the weld start and stop locations were apparent, where fatigue crack initiation is typically observed.

Figure 10 shows the stress distributions when the tensile load is applied during the fatigue test. The applied load was 2000 lbs, corresponding to one of the load levels in the fatigue tests in the project. It is clear that that stress concentrations existed near the weld ends.

We systematically investigated the effect of low temperature phase transformation on welding residual stresses in the specially designed weld fatigue testing specimens (**Figure 6** (b)) using the ICWE model, to assist the design and selection of the LTPT weld wires. **Figure 11** presents an example of ICWE modeling results on the effects of LTPT weld wire on the residual stress in the thin sheet lap weld studied in this project. The weld residual stress distributions at the cross-section of 5 mm from the weld end are compared between a LTPT weld wire with martensitic transformation starting temperature of 200C and the conventional ER70-S weld wire. With the use of LTPT weld wire, considerable compressive transverse weld residual stresses were formed near the weld toe. The longitudinal weld residual stresses in the fusion zone were also compressive. On the other hand, the effect of LTPT was less profound on the weld root side.

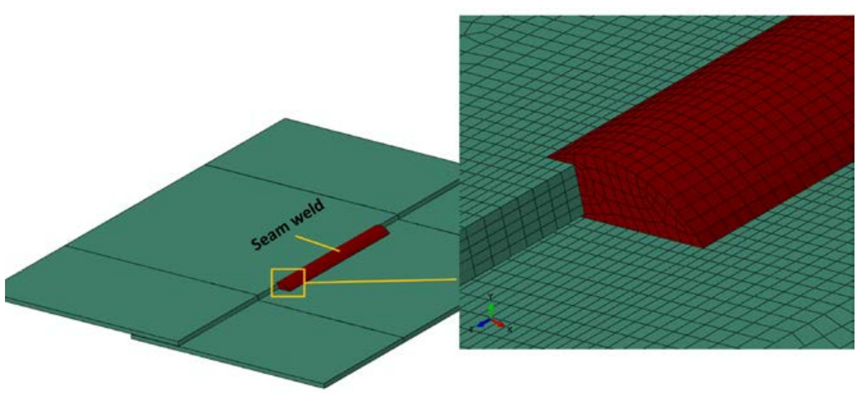


Figure 7 Finite element geometry and mesh of the seam weld of lap joint

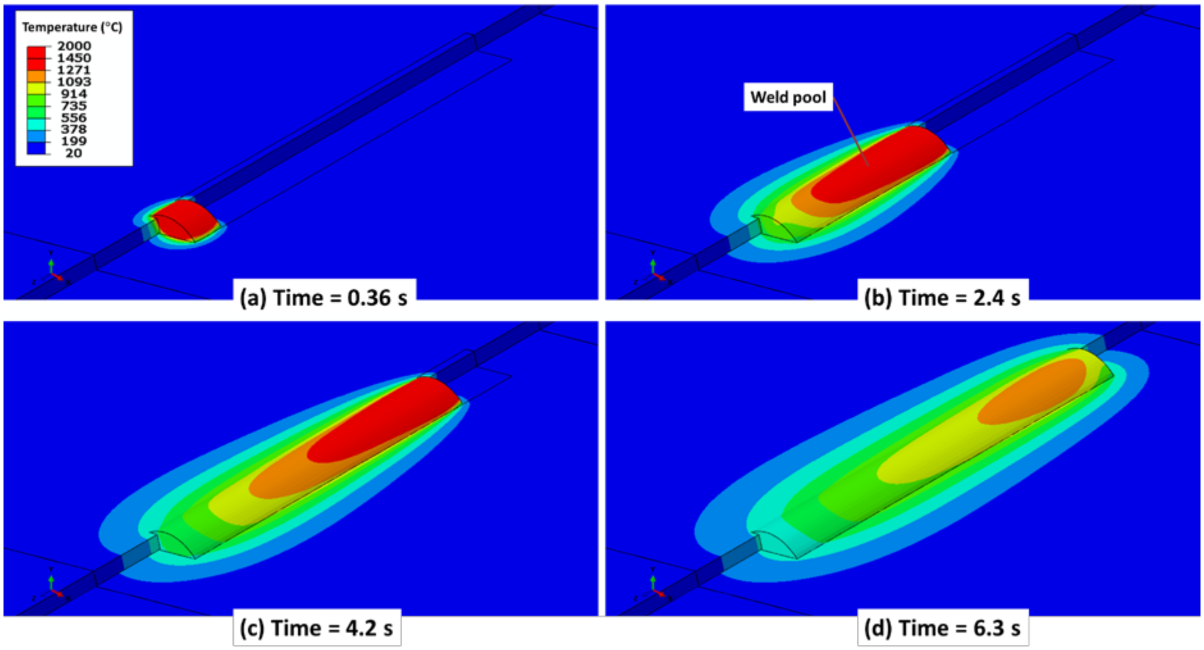


Figure 8 Temperature distribution at different times during seam welding.

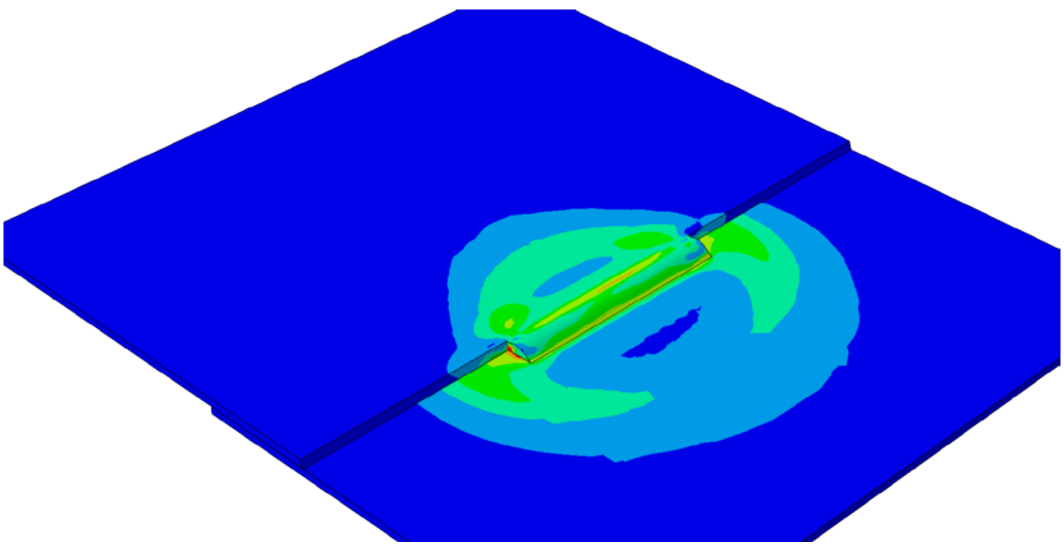
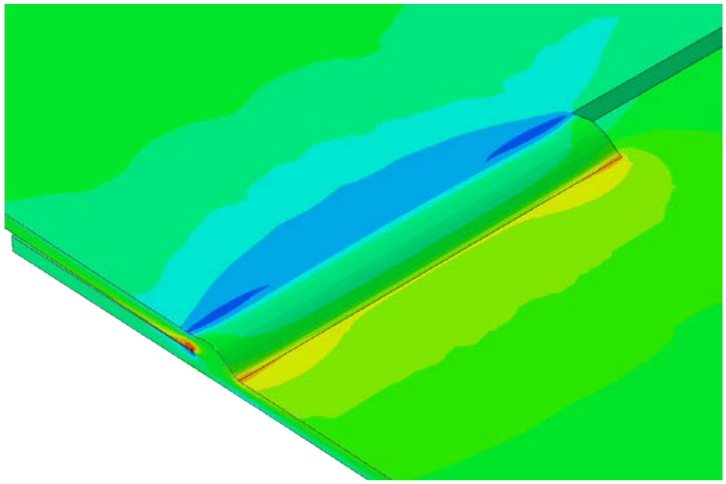
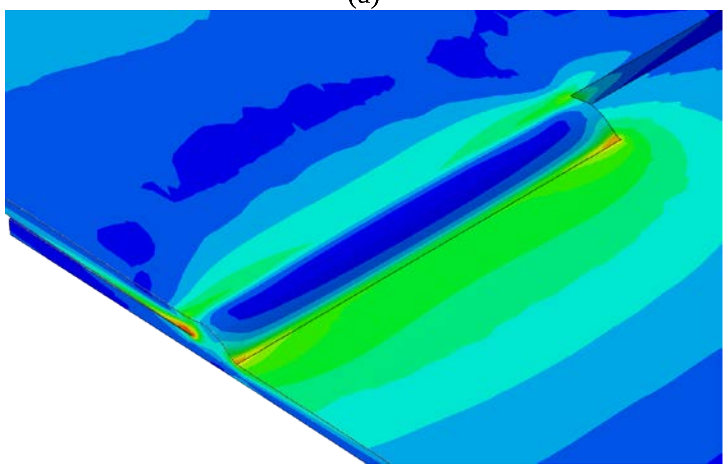


Figure 9 Contour plot of von-Mises residual stress concentration near the weld start location made with conventional weld filler metal.



(a)



(b)

Figure 10 (a) Transverse stress field and (b) Mises stress field showing stress concentrations at the root and toe of a weld near the weld start and stop locations. The 3D FEM model was cut at the cross-section near the weld stop to reveal the stresses inside the weld and sheets. Applied load level was 2000 lbs.

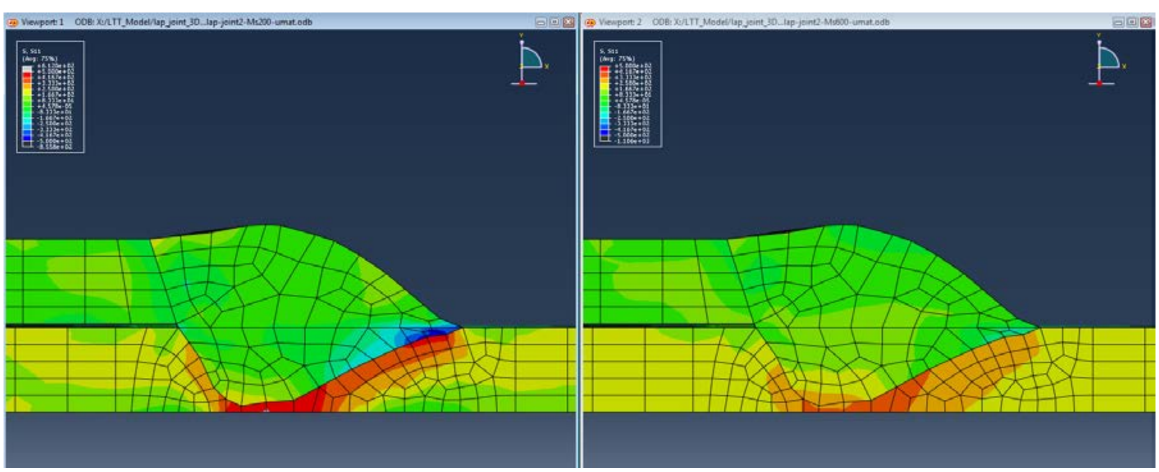


Figure 11 Comparison of transverse weld residual stress distributions at a cross-section about 5mm from the weld end. (a) LTPT wire, (b) conventional weld wire.

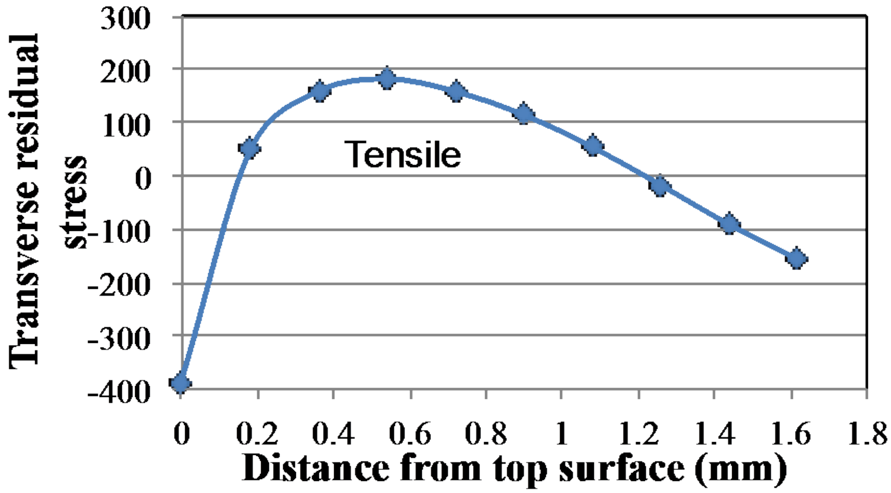


Figure 12 Distribution of transverse weld residual stresses near the weld toe from a LTPT weld wire.

4.3.4 Development of LTPT Weld Wire

The development of LTPT weld wires was carried out in several rounds.

In the first round, a total of four LTPT weld wires were produced and tested on both DP980 (2mm) and DP590 AHSS (1.8mm) AHSS. In principle, these special weld wires differ in their Cr and Ni concentration. In addition, the conventional ER70S-3 filler wire was used as the baseline for comparison. As described in previous section, ICWE modeling revealed that the weld start and stop regions of the stitch weld are high stress concentration sites under fatigue cyclic loading. The stress concentration was further compounded by the existence of the crater at the weld stop which had has less material to carry the load, thereby is particularly vulnerable to crack initiation. Indeed, failure analysis of the fatigued welds, as well as in-situ observation during fatigue testing, confirmed that the weld start and stop were the predominant fatigue crack initiation sites.

Representative fatigue testing results (S-N curves) at different loading levels are shown in **Figure 13**. Fatigue testing cycles were capped at 5 million ($5x10^6$) cycles, per testing protocol typical of automotive applications. Two special weld wires (Special Wires A and B) are presented. The conventional ER70S-3 weld wire served as the benchmark case. Also included are the data of an "improved" weld technique that was specially designed to improve the local stresses at the weld start and stop. Special Wire B had lower fatigue lives than the conventional weld wire, due to the solidification cracks in the weld start and stop region (**Figure 14**). Therefore, the development of special weld wires for residual stress mitigation must also consider other essential factors such as weldability, strength, and toughness in its chemistry formulation. On average, Special Wire A showed improvements in fatigue life over the conventional weld wire, although not as drastic as reported in the literature for thick-section welds.

Recognizing its critical role in weld fatigue live, a new improved welding procedure was developed to reinforce the weld start and stop to reduce the notch residual stresses in the regions. As shown in Figure 2, the new technique (labeled as "Improved") resulted in a considerable increase in fatigue life over the entire stress range.

In the second round, a new filler wire design considered not only the effect of LTPT on weld residual stress, but also other essential factors such as weldability, strength, and toughness in its chemistry formulation. Fatigue testing at medium load level confirmed 3-5X weld fatigue improvement with this new filler wire design, as shown in **Figure 15**. Additional testing of the new filler wire under other loading levels will continue after the completion of this project.

In the third round, the LTPT weld wire from Colorado School of Mines (labeled as EH200B) was evaluated. This LTPT weld wire again showed improvement in weld fatigue life, but less effective than the weld wire developed in the second round. As shown in **Figure 16**, on average, ~2X increase was achieved on 1.8mm thick DP980 steel sheet at applied nominal stress level of 43MPa (load level = 2100 lbs).

More interestingly, the changes in weld residual stresses via LTPT wire showed drastic changes in the dimensional changes of the thin gage steel sheet materials. This is illustrated in **Figure 17**. In this particular case, two stitch bead-on-plate welds were deposited on a 2-mm thick low carbon steel sheet. Compared to the standard reference ER70S-3 weld wire, the welded steel sheet exhibited complete reversal of the distortion direction. In the case of reference ER70S-3 weld wire, the middle section of the steel sheet was bent downward for about 10mm. To the contrary, the weld made with the new LTPT wire bent the steel sheet upward for about 15mm. This suggested the complete changes in weld residual stresses in the weld made by the new LTPT wire. The changes in weld residual stresses are being investigated by the neutron diffraction technique. It should be noted that such drastic change in distortion mode by the new LTPT wire suggests the possibility of control weld distortion by further refinement of LTPT weld wire.

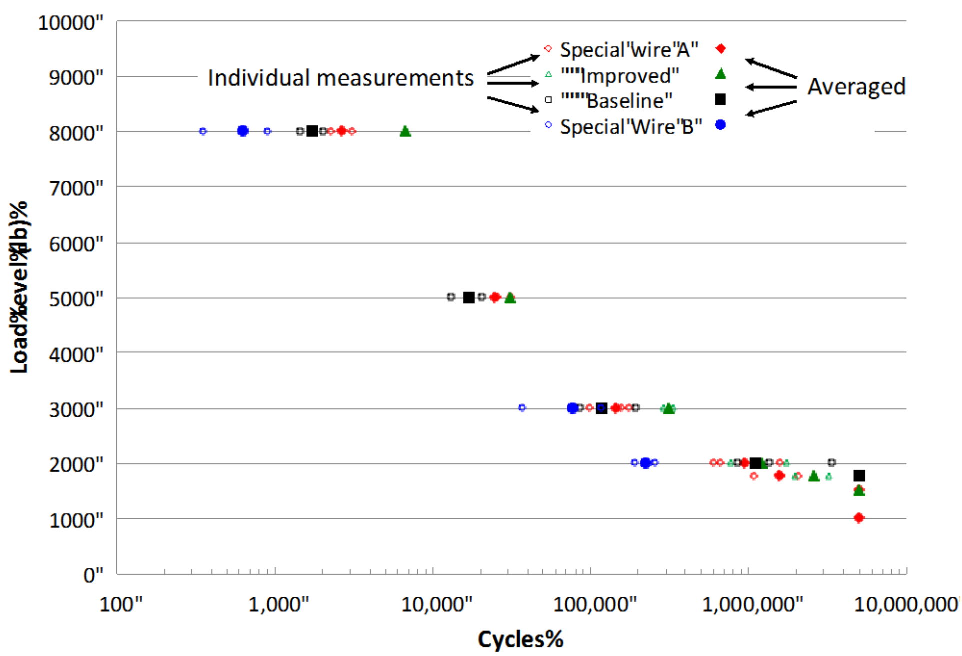


Figure 13 Weld fatigue testing results of DP590 steel

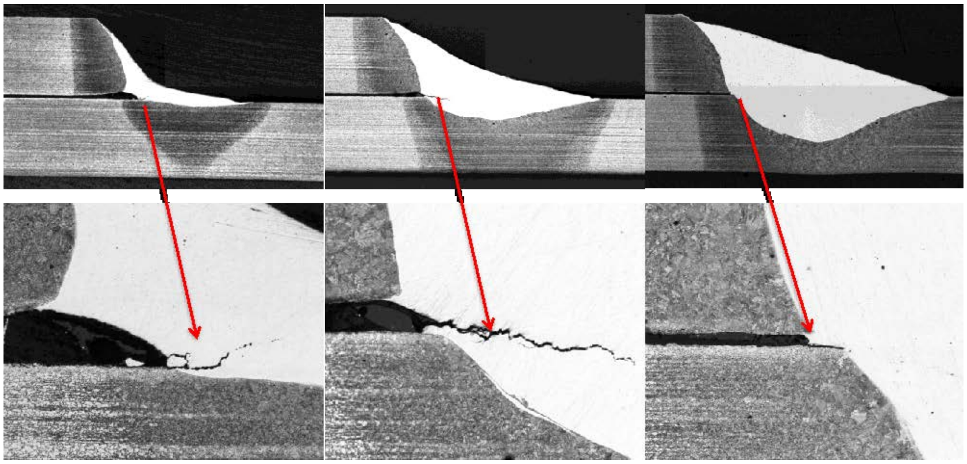


Figure 14 Weld solidification cracks at the weld stop in Special Wire B. Such cracks lead to the reduced weld fatigue lives.

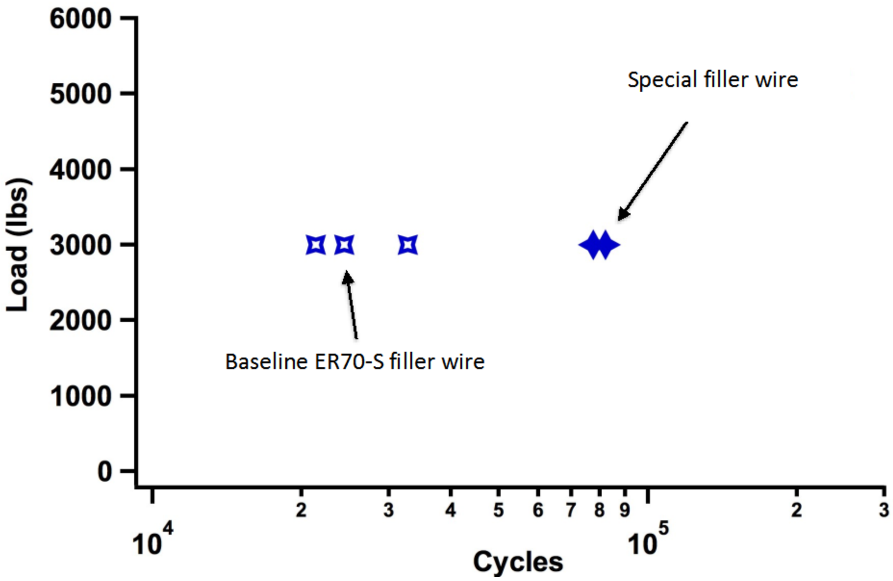


Figure 15 Comparison of weld fatigue lives of baseline ER70 weld versus the new filler wire developed in second round.

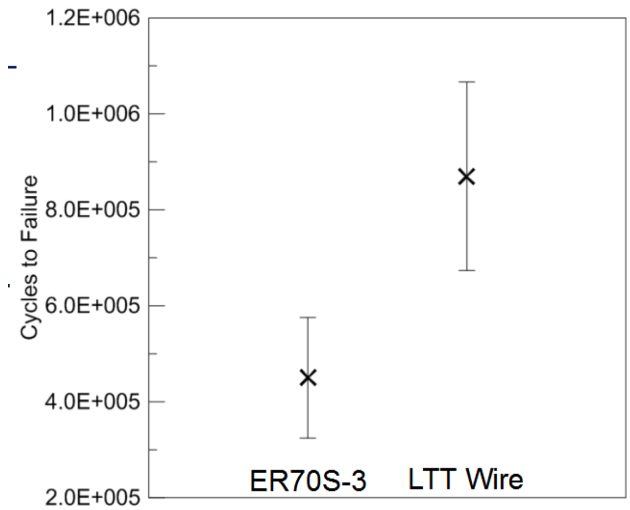


Figure 16 Fatigue testing results with LTPT wire EB200B compared with baseline ER70S-3 weld wire. Load level: 2100 lbs.

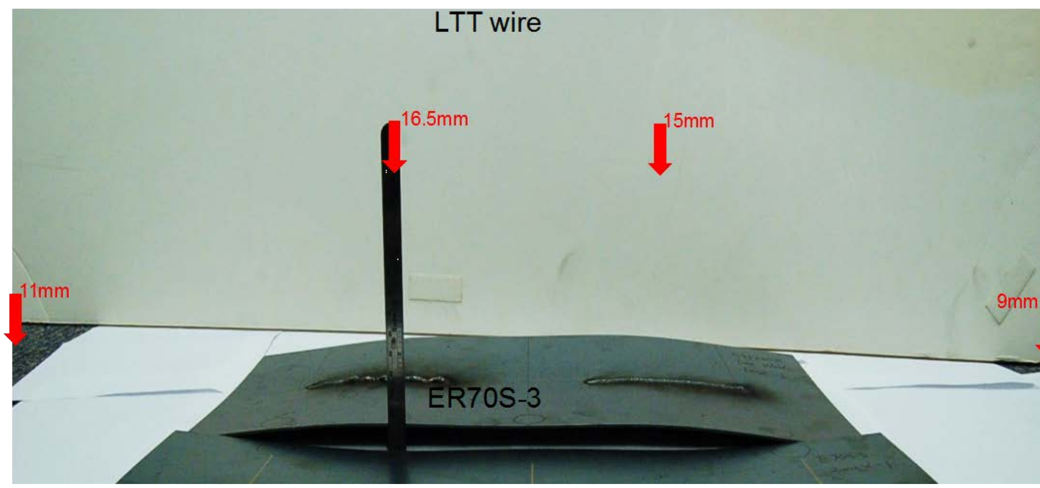


Figure 17 Reversal of distortion mode with the use of LTPT wire (EH200B).

4.3.5 Weld Residual Stress Control by Thermo-Mechanical Management

A thermo-mechanical stress management technique was developed to mitigate the tensile residual stresses in the high-stress concentration region of the stitch weld. The feasibility of this novel approach was demonstrated in laboratory environment. In laboratory set-up, significant weld fatigue life improvement was been achieved, as shown in **Figure 18** for the fatigue testing results collected so far, for both DP590 and DP980. At the low stress level which is more relevant to the durability of auto-body structures, the improvement was between 5 to 10 times over the baseline reference cases using the ER70-S filler wire which is widely used in gas metal welding of AHSS auto-body structures. In fact, at 2000 lbs, the weld specimens with stress management did not break after 10 millions cycles (marked as run-out in the figure) for DP590.

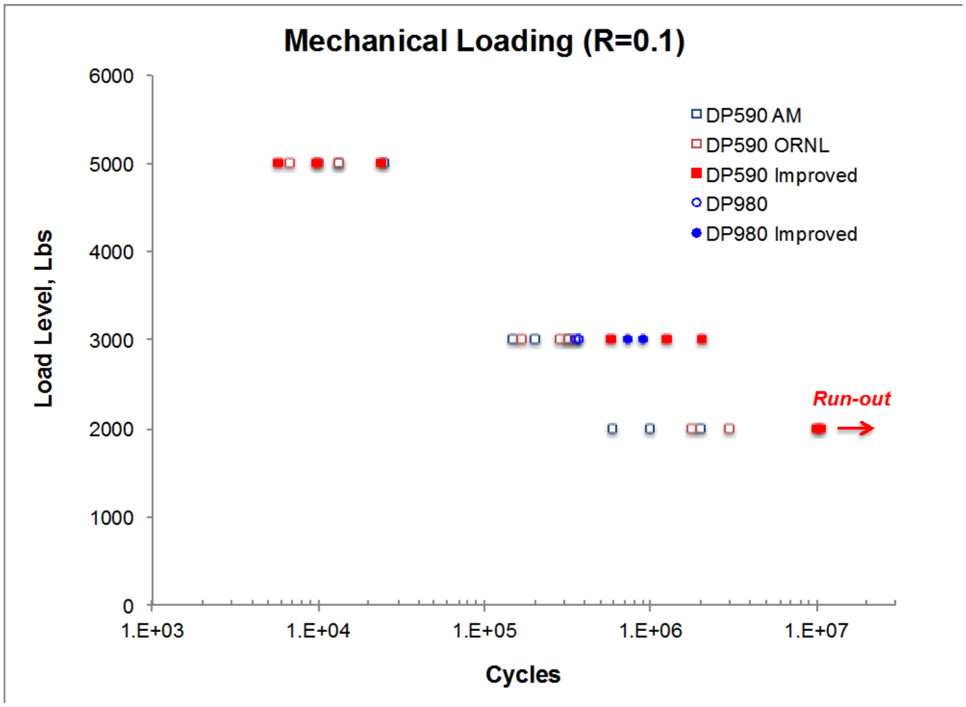


Figure 18 Improvement of weld fatigue lives through innovative thermo-mechanical stress management.

4.3.6 High-Energy Synchrotron Residual Stress Measurement

The effectiveness of weld residual stress control and mitigation techniques developed in this project was confirmed by means of high-energy synchrotron X-ray diffraction. The synchrotron measurement confirmed the substantial reductions of weld residual stresses in the region near the weld (**Figure 19**), thereby providing the technical basis for the observed drastic weld fatigue life improvement. Due to experimental difficulties, residual stresses approximately 10 mm away from the weld fusion line were obtained. New experimental setup is being devised to obtain residual stresses closer to the fusion line.

In addition, we worked on direct measurement of the weld stress evolution *during welding*, based on a unique high-temperature DIC measurement technique specifically developed for in-situ weld stress/strain measurement at ORNL (Chen et al, 2014). This new DIC technique is being applied to provide additional *direct* evidence on the role of low temperature phase transformation on the suppression of high-tensile weld residual stresses.

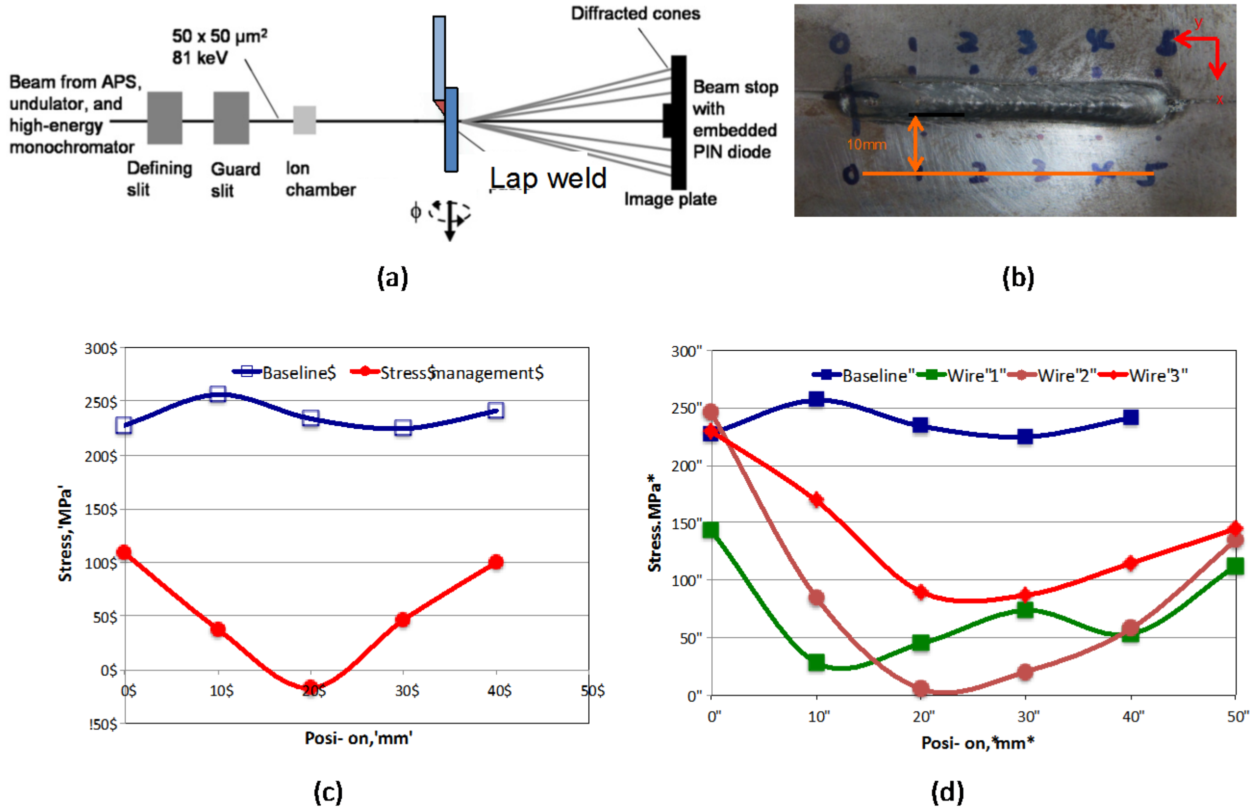


Figure 19 High-energy synchrotron residual stress measurement. Transverse residual stresses are shown. (a) Synchrotron diffraction experimental setup. (b) Measurement locations relative to the stitch weld. (c) Reduction of weld residual stresses by means of proactive thermo-mechanical stress management. (d) Reduction of weld residual stresses by means of LTT weld wires with three different LTT wires and the baseline ER70-S weld wire.

5. SUBJECT INVENTIONS (AS DEFINED IN THE CRADA)

There was no subject inventions in this project.

6. COMMERCIALIZATION POSSIBILITIES

Several weld consumables companies have expressed interests in the technology developed in this project. These interests are being evaluated to identify potential partners for technology commercialization

7. PLANS FOR FUTURE COLLABORATION

ArcelorMittal and ORNL have interests to collaborate broadly in future. This includes recent collaborations on high-strength steel development and application for hydrogen energy infrastructure and others.

8. CONCLUSIONS

Weld fatigue life has been identified as one of the key technology barriers to widespread use of lightweight materials (AHSS, Al and Mg alloys) for auto-body structure lightweighting. The technology developed in this project is expected to provide cost-effective and practical solutions to the automotive industry to address this critical issue.

Significant technical progress has been achieved in this project. 3-5X and 5-10X weld fatigue life improvements were demonstrated respectively, using the two different novel approaches to control and mitigate the weld residual stresses developed in this project. The changes of weld residual stresses could also drastically changes the welding induced distortion in thin sheet steels used for autobody structural components. High-energy synchrotron measurement confirmed the substantial reductions of weld residual stresses in the region near the weld thereby providing the technical basis for the observed drastic weld fatigue life improvement.

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