# Z1. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Part 1: Formability, Weldability and Performance Evaluations of AHSS Parts for Automotive Structures

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## Objective

- Investigate the formability of advanced high-strength steel (AHSS), with emphases on loading temperature, loading paths and "secondary" deformation effects on part 'residual' strength and microstructure;
- Develop a fundamental understanding of transformation kinetics of AHSS steels by analyzing the crystallographical and morphological features of the phase transformations subject to different thermal and mechanical loading paths from forming and welding;
- Provide performance data and constitutive models for formed AHSS parts;
- Investigate the weldability of AHSS under various welding processes and parameter conditions applicable to auto production environment;
- Generate weld performance data including static strength, formability, impact strength, and fatigue life as function of welding processes and parameters;
- Investigate welding techniques for improved AHSS weld performance and benchmark the performance against the current welding practices for roll-formed and hydro-formed AHSS frame and underbody structure applications;
- Develop design guidelines on AHSS to assist rapid structure design and prototyping.

## Approach

- Investigate formability and weldability of AHSS. This task includes: forming under complex loading paths (uniaxial and biaxial); quantification of formability and weldability for various grades of AHSS based on their chemistries and corresponding thermal-mechanical process;
- Investigate the interdependency of manufacturing processes: weldability of a formed part and formability of a welded part;
- Develop transformation kinetics model and macroscopic constitutive relationships for AHSS: dual-phase (DP), transformation-induced plasticity (TRIP), and complex phase (CP).
- Systematically evaluate the effects of various welding process and process parameters on the microstructure and property of welds. Welding processes include gas metal arc welding, laser welding, hybrid laser-arc welding,

and resistance spot welding. Metallurgical and process models will be used to analyze the microstructure evolution. The properties will be measured as a function of geometry, composition, 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.

- Evaluate structural performance of formed and welded parts made of AHSS. This task will provide the automotive design engineers with accurate material performance data for design verification of AHSS structural parts.

## Recent Accomplishments

- Evaluated thru-thickness phase property variations.
- Completed a preliminary study to determine the required weld sizes in resistance spot welds of DP800 and TRIP800 steels under cross tension and lapshear loading.
- Completed high strain rate tests of TRIP800 at High Temperature Materials Laboratory (HTML) at ORNL.
- Completed quantification of retained austenite volume fraction under high rate deformation via modified X-ray diffraction technique.
- Finished initial feasibility study of using neutron source to quantify in-situ lattice strain partitioning during TRIP600 and TRIP800 deformation.

## Future Direction

- Complete the quantification of retained-austenite volume fraction on TRIP steels under shear deformation.
- Conduct bi-axial loading under different temperatures and quantify phase evolution.
- Perform in-situ phase transformation and volume fraction measurement using neutron or synchrotron source.
- Improve the multi-phase self-consistent constitutive model.
- Perform meso-scale constitutive modeling using the concept of representative volume element under different deformation mode.
- Predict structural performance of formed part made of TRIP800 with and without updated material properties.
- Continue UHSS B-Steel weldability study.

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## Introduction

This project is a collaborative effort between the Department of Energy, Pacific Northwest National Laboratory, and the United States Automotive Materials Partnership (USAMP) of the U.S. Council for Automotive Research (USCAR). The work started in October 2005.

Because of their excellent strength and formability combinations, more and more advanced high strength steels (AHSS) are being used in vehicle body structures to reduce vehicle weight and improve vehicle crash performance. Currently, the technical barriers hindering wider applications of AHSS in the domestic auto industry include: 1) The fundamental behaviors of AHSS parts subject to different thermal and mechanical loading paths (forming and welding) are not fully understood and quantified; 2) The constitutive behaviors for the formed parts are not available to CAE engineers for rapid prototyping; 3) Welding-induced complex microstructures and the effects of different welding processes and welding parameters on weld performance are not well understood. In order to address these technical barriers, this project examines key aspects of the manufacturing process that AHSS would be exposed to, and systematically evaluate how the forming and thermal histories affect final strength and ductility of the material. The goal is to provide the automotive design engineers with accurate material performance data for design verification of AHSS structural parts.

## Base Metal Mechanical Property Characterization under Different Temperatures and Strain Rates

Base material properties for TRIP800 have been characterized under different OEM manufacturing temperatures ranging from -40°C to 93°C, as well as different strain rates ranging from $10^0$/sec (Refs. 1 and 2) to 400/sec. Transformation kinetics for material points undergone high rate deformation has been quantified using a modified X-ray diffraction technique. For example, Figure 1 shows the true stress versus strain curves for TRIP800 ASTM E8 sub-sized sample under 256 inch/sec dynamic loading. The results clearly indicate the temperature dependency of the TRIP steel dynamic performance. At room temperature, the total elongation is around 33%, similar to the quasi-static results. Under higher or lower temperature, however, TRIP800 has reduced ductility under dynamic loading. This observation has also been validated by high-rate digital images taken during the deformation process, see for example Figure 2.

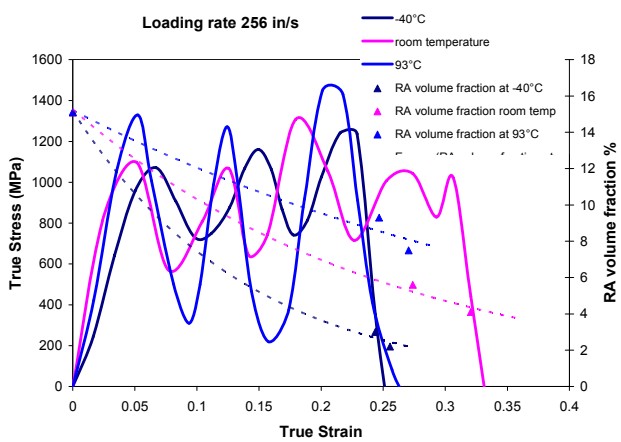


**Figure 1.** True Stress-Strain response of TRIP800 Steel at three different temperatures at ram velocity of 256 in/sec.

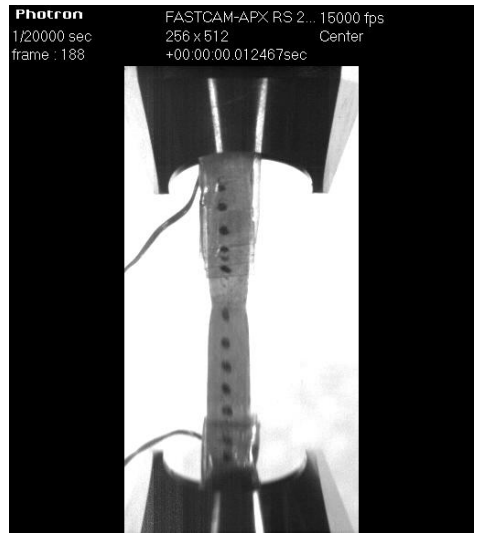


**Figure 2.** High-rate digital image of a sample right before fracture: deforming at 640 inch/sec under 93°C.

## Thru-thickness Gradient of Phase Volume Fraction for As-received Sheet

The initial thickness of the steel was 1.55 mm. We reduced the sheet thickness to 1.42mm, 1.16 mm, 0.97 mm, and 0.77 mm. The 1.16 mm and 0.77 mm thickness correspond, respectively to ¼ and ½ of the initial thickness. Figure 3 illustrates the thru-thickness phase variation for the material in as-received condition.

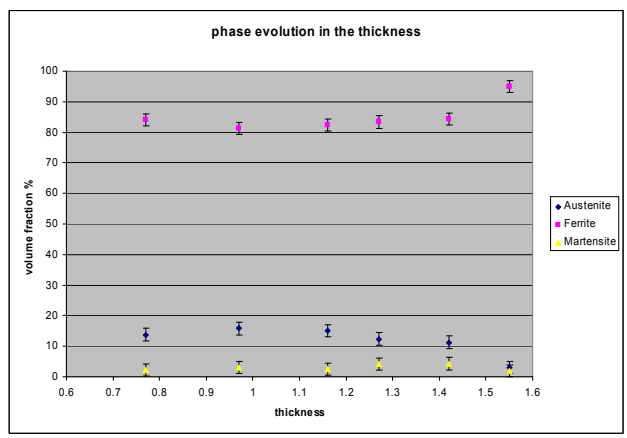


**Figure 3.** Thru-thickness phase variation of the as-received material.

A high gradient of retained austenite volume fraction exists near the sheet surface (1.55mm). This is likely due to the thermal-mechanical process undergone by the material to achieve its overall mechanical properties. In addition, there is a measurable amount of martensite in the as-received material, indicating the formation of martensite during the sheet manufacturing process. The thru-thickness phase variation leads to the thru-thickness variations of mechanical properties for the as-received sheet material. These thru-thickness property variations can lead to undesired forming behaviors such as shear fracture. More work in this area is underway to quantify the effects of thru-thickness property variations on sheet local formability/bendability.

## In-Situ Lattice Strain Partitioning for TRIP Steel during Deformation

The in-situ lattice strain data were obtained by the Rietveld analysis of the measured diffraction spectra at Los Alamos National Laboratory. See Figure 4 for TRIP590 as an example. As the applied stress increases, the tensile internal stress develops in the retained austenite (FCC) in the axial direction (L), while compressive stress builds up in transverse direction (T). The strain partitioning is initially uniform among the two phases until a stress level of 300 MPa. Above this stress level, austenite phase is taking up considerably more strain than its BCC matrix, likely going through phase transformation and provide additional transformation strain. At the applied stress level of ~550 MPa, austenite starts to diminish. As the austenite phase exhausts, the martensite phase continues to take up more strains in the longitudinal direction as expected.

Retained austenite volume fractions for deformed samples are also measured at Argonne National Laboratory using the Advanced Photon Source by high energy X-ray. Figure 5 shows the schematic of the test setup, and Figure 6 illustrates the measured change of volume fraction of FCC and BCC as well as texture for the deformed (12% strain) and un-deformed (as-received) samples.

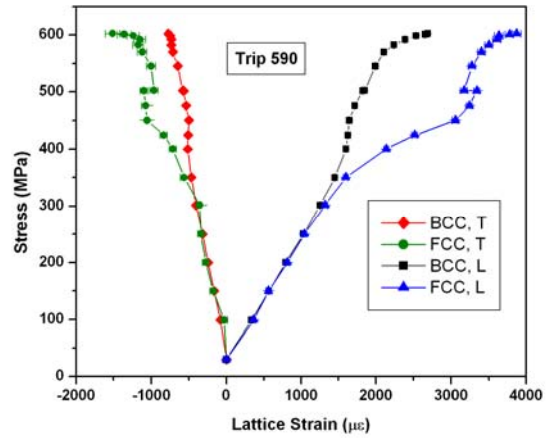


**Figure 4.** The lattice strain evolution of both retained austenite (FCC) and martensite (BCC) in TRIP590 steel during the in-situneutron measurements in SMARTS (Spectrometer for MAterials Research at Temperature and Stress).

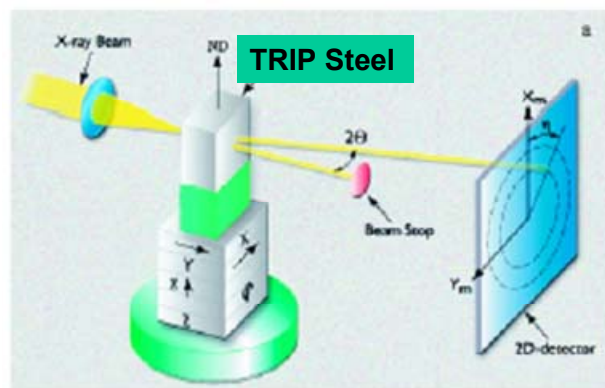


**Figure 5.** Schematic of test set up at APS.

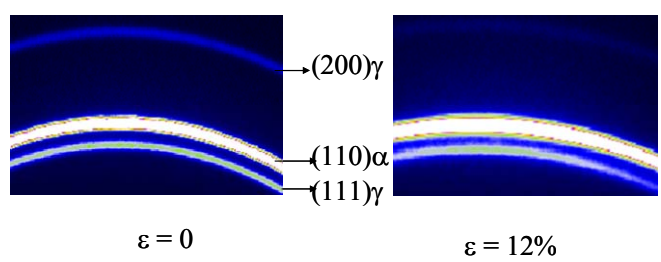


**Figure 6.** Part of Debye rings illustrating the change of volume fraction for deformed and un-deformed samples.

## Resistance Spot Welds (RSW) of DP800 and TRIP800- Effect of Critical Fusion Zone Size for Lapshear Samples

The effects of spot weld fusion zone size on failure modes, static strength, and energy absorption of DP800 and TRIP800 have been studied. Both cross tension and lapshear coupon configurations have been used (Ref. 3). See Figures 7 and 8. Under cross tension loading condition, it was found that

- The conventional weld size guidance of $4\sqrt{t}$ is not sufficient to produce nugget pullout failure mode for both DP800 and TRIP800 resistance spot welds.
- Analytical limit load based model together with micro-hardness measurements can be used to predict the critical fusion zone sizes for both DP800 and TRIP800.
- At the critical fusion zone level, both interfacial fracture and nugget pullout can be observed. Even though both failure modes offer similar distributions in terms of peak load, nugget pullout provides much higher energy absorption level than the interfacial fracture mode.
- Below the critical fusion zone sizes, interfacial fracture is the dominant failure mode with large load scatter and poor energy absorption. Above the critical fusion zone size, nugget pullout is the dominant failure mode with tightly controlled peak load and energy absorption distributions. Further increasing the fusion zone size beyond the critical size will not bring about linearly increased weld performance in terms of peak load and energy absorption.

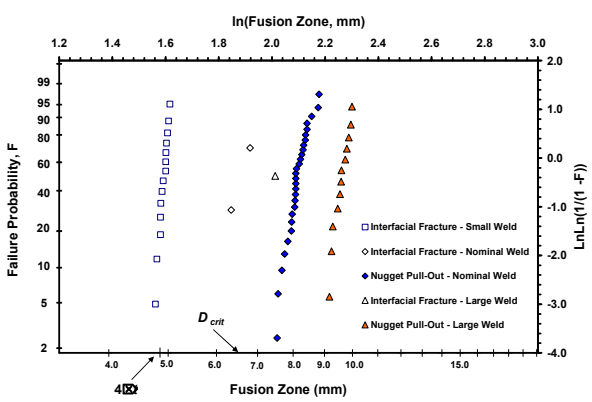


**Figure 7.** Fusion zone size distribution and its effect on failure mode for TRIP800 under cross tension.

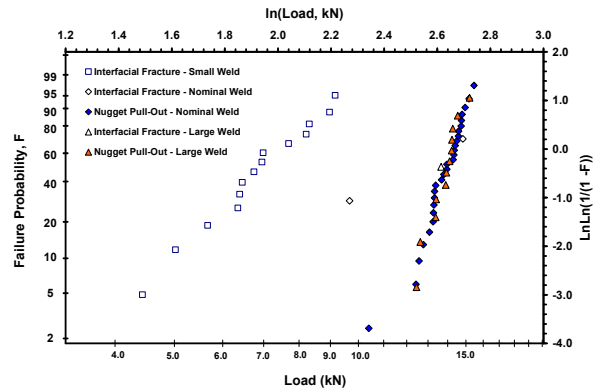


**Figure 8.** Peak load distributions for three weld populations in TRIP800 under cross tension.

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1. Khan, A.S, Liang, R., 1999. Behaviors of three BCC metal over wide range of strain rates and temperatures: experiments and modeling. *International journal of Plasticity* 15 (10), 1089-1109.

2. Khan, A.S, Kazmi, R., 2004. Quasi-static and dynamic loading responses and constitutive modeling of titanium alloys. International journal of Plasticity 20, 2233-2248.

3. Sun, X., Stephens, E.V. and Khaleel, M.A., Effects of Fusion Zone Size on Failure Modes and Performance of Advanced High Strength Steel Spot Welds, SAE 2006-01-0531.

## Presentations/Publications/Patents

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2. Sun X, EV Stephens, and MA Khaleel. Effects of Fusion Zone Size on Failure Modes and Performance of Advanced High Strength Steel Spot Welds." Accepted for publication in the research supplement of the Welding Journal, 2006.

3. Sun X, EV Stephens, MA Khaleel and Z. Feng. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Formability, Weldability and

Performance Evaluations of AHSS Parts for Automotive Structures. Presentation at USAMP AMD 2006 Sheet and Forming Offsite Meeting, Oct, 2006. Southfield, MI.

4. Feng, Z. and X Sun. Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS): Formability, Weldability and Performance Evaluations of AHSS Parts for Automotive Structures. Presentation at USAMP AMD 2006 Welding and NDE Offsite Meeting, Nov. 2006. Southfield, MI.