W. Evaluations of the Effects of Manufacturing Processes and In-Service Temperature Variations on the Properties of TRIP Steels

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Objective

- Develop an understanding of the effects of typical automotive manufacturing processes, such as welding and forming, on the retained properties of advanced Transformation Induced Plasticity (TRIP) steels.
- Evaluate the effects of in-service temperature variations on the properties and energy absorption characteristics of TRIP steels.
- Compare the sensitivity of mechanical properties of a range of TRIP steel grades produced by various domestic and international steelmakers.

Approach

- Develop mechanical property versus in-service temperature relationships for the available grades of TRIP steels to determine their suitable vehicle applications and allowable thermal processing histories for manufacturing. A temperature range of -40°C to 93°C is considered.
- Determine the effects of welding and forming processes on the retained mechanical properties of different grades of TRIP steels. Tensile samples are prepared from formed and/or welded parts. The samples are tested at three different temperature levels to determine the effects of primary forming on the subsequent performance and properties of TRIP steel.

Recent Accomplishments

- Demonstrated stable transformation of austenite to martensite under a temperatures range of -40°C to 93°C for TRIP steel materials.
- Completed base metal characterization (mechanical properties and chemical composition) for all four TRIP steel populations.
- Performed experiments to quantify the effect of primary forming processes on the retained austenite volume fraction.
- Completed a preliminary study to determine the required weld sizes in resistance spot welds of TRIP 800 steels.
- Held a mid-year technical review meeting with project participants from Ford, GM and DCX.
- Presented project results at the annual project review of steel projects funded by DOE. The meeting was sponsored by DOE and the Auto Steel Partnership.

Future Direction

- Complete the quantification of retained austenite volume fraction by performing microstructure characterization on deformed TRIP steels.
- Follow Phase II proposed approach to model the kinetic transformation of retained austenite to martensite under different thermal-mechanical loading paths and to develop a micromechanical model to aid in the performance prediction of TRIP steels. Validate the models by performing welding and forming experiments.

Introduction

This project is a collaborative effort between DOE, Pacific Northwest National Laboratory (PNNL), and the USAMP of the U.S. Council for Automotive Research (USCAR). The work started in July 2004.

Because of the excellent strength and formability of "Transformation Induced Plasticity" (TRIP) steels, they offer the potential for reduced vehicle weight and improved vehicle crash performance. The enhanced ductility of TRIP steels is the result of a phase transformation, therefore, thermal cycling, forming, and welding could be expected to impact the final microstructure, and thus final material properties. Although the combination of strength and energy absorbing capabilities of TRIP steels make them attractive, their sensitivity to thermal processing and in-service temperature variations has not been sufficiently established. In order to introduce TRIP steels into critical areas of the body structure (such as crash energy management areas), the automotive OEM's must know what the retained properties of the material are after exposure to a range of manufacturing and in-service conditions.

This project examines key aspects of the manufacturing process that TRIP steels would be exposed to, and systematically evaluate how the forming and thermal histories affect final strength and ductility of the material. The project evaluates in-service temperature variations, such as under hood and hot/cold cyclic conditions, to determine whether these conditions influence final strength, ductility and energy absorption characteristics of several available TRIP steel grades. As part of the manufacturing thermal environment evaluations, stamping process thermal histories are included in the studies. As part of the in-service conditions, different loading rates are also included.

At the completion of the study, a thermal history/material property relationship is established over a full range of expected thermal histories and selected loading rates. Establishing these relationships will allow OEM designers to select TRIP steels for proper vehicle applications, and to specify manufacturing process conditions that yield reliable final material property levels.

Base Metal Mechanical Property Characterization under Different Temperatures

Since TRIP steels are relatively new for the automotive OEMs, there are many uncertainties on the feasibility of this class of steel in the domestic automotive industry and whether the desired phase transformation and enhanced ductility will occur under different manufacturing and operating temperatures.

Another issue with this class of steel is the supplier dependency. These steels are so called "performance-based steels", which means that each supplier could basically 'cook' their recipes differently to achieve the same strength and ductility requirements with different steel chemistry and thermal-mechanical processing. This puts a lot of strain on OEM manufacturing engineers. Because of the lack of fundamental understanding of these steels, each material batch would need extensive characterization and forming and welding trials. This would significantly prolong the material insertion process. Also, as shown previously by the U.S. Council for Automotive Research (USCAR) Joining Team, there is a lack of weld acceptance criterion on spot welds. Welding engineers have to go to great length and use some very exotic welding schedules to achieve the current weld acceptance criterion without knowing the actual benefit on weld performance.

In order to answer these feasibility questions, four TRIP steel materials from different suppliers were obtained and tested at -40°C, room temperature and

93°C. The four suppliers are from North America, Europe and Asia. Material B is a TRIP700 grade, and the remaining three are TRIP800. The chemistry compositions for the four steels are shown in Table 1. Materials A and C have very similar composition and are both CMnSi TRIP steels. Materials B and D are both CMnAl TRIP steels.

Table 1. Steel chemistry comparison (weight percent).

	C	*Mn*	*Si*	*P*	*Al*	*S*
Material A	0.191	1.83	1.17	0.009	0.032	0.003
Material C	0.18	1.75	1.62	0.014	0.03	0.002
Material D	0.20	2.21	0.07	0.013	1.41	0.002
Material B	0.22	1.64	0.046	0.012	1.51	0.001

Figure 1 shows the room temperature stress versus strain behaviors for three TRIP800 as-received base materials. Even though they are all TRIP800, the mechanical properties of these steels can vary quite significantly. Materials A and D have very similar and consistent behaviors, with total elongation around 27%. Material C has the similar initial yield level as materials A and D, however, it does not have the typical 'elongation at yield', the so-called EAY point. In addition, its transformation rate and therefore initial work hardening is higher, and it has relatively low ultimate elongation.

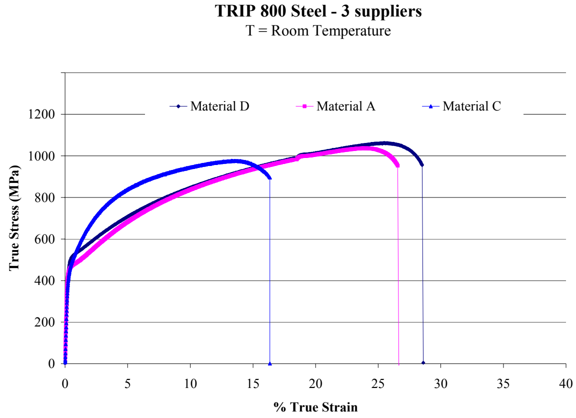


Figure 1. Base material room temperature stress versus strain curves.

Figures 2 and 3 show the stress versus strain curves for three TRIP800 materials tested at 93°C and -40°C, respectively. Slightly higher elongations were observed for all the three materials at 93°C with small degrees of strength reductions compared to their room temperature behaviors. At -40°C, materials A and D have much higher initial work hardening rate and lower total elongation compared to their room temperature behavior. Material C's stress versus strain behavior is less sensitive to test temperature which suggests that it has lower level of initial retained austenite in its microstructure.

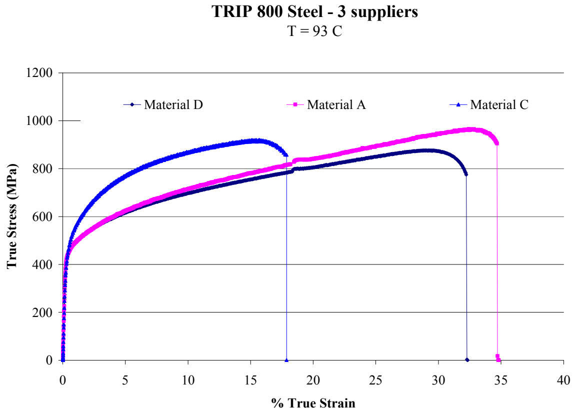


Figure 2. Base material stress versus strain curves under 93°C.

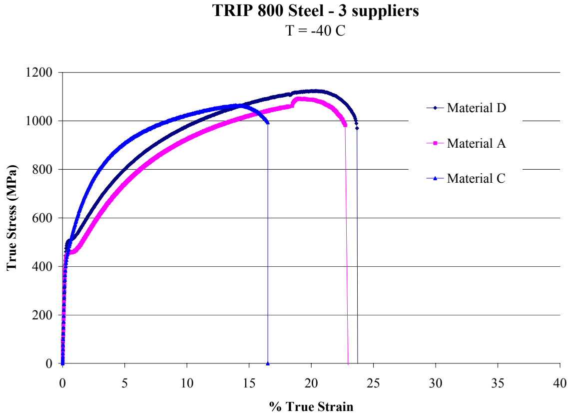


Figure 3. Base material stress versus strain curves under -40°C.

Figures 4 and 5compare the different stress versus strain behaviors for materials A and D at different test temperatures and the transformation kinetics of retained austenite (RA) as measured by electron back-scattered diffraction (EBSD). The as-received austenite volume fraction is about 8% for material A and 17% for material D.

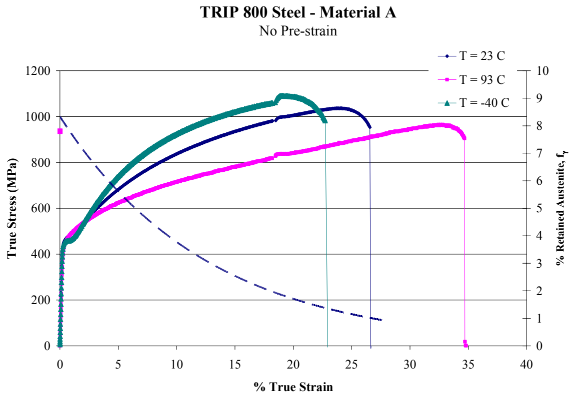


Figure 4. Stress vs. strain curves for material A under different test temperature and RA volume fraction evolution during deformation.

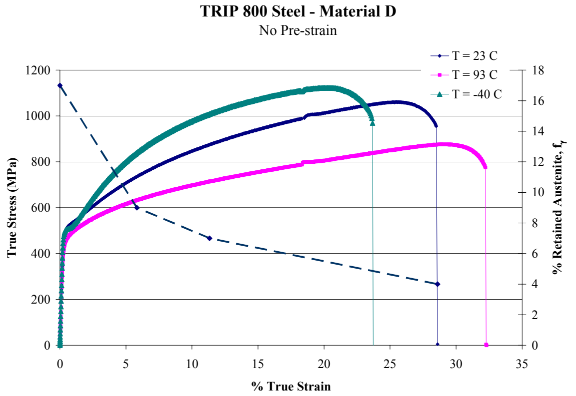
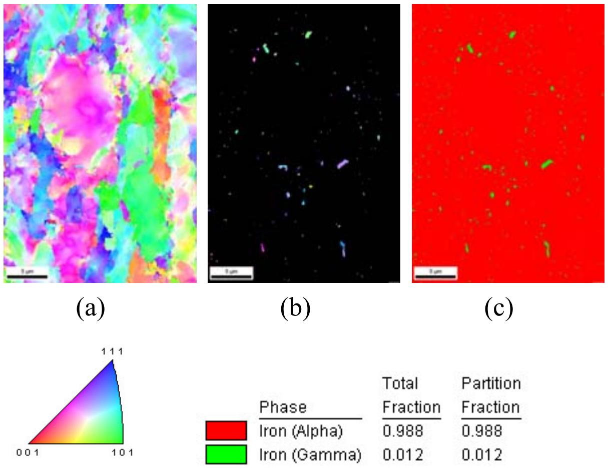


Figure 5. Stress vs. strain curves for material D under different test temperature and RA volume fraction evolution during deformation.

Figure 6 shows the typical EBSD measurement for material A at fracture. Its retained austenite volume fraction is only about 1%. The detailed transformation kinetics under different deformation temperature are still under investigation. The second phase of this project will focus on modeling of the transformation kinetics and provide automotive engineers with appropriate constitutive laws describing various grades of TRIP steels based on different chemistry compositions and associated thermal-mechanical processes.



	Phase	Total Fraction	Partition Fraction
🟥	Iron (Alpha)	0.988	0.988
🟩	Iron (Gamma)	0.012	0.012

Figure 6. Typical EBSD measurements for Material A at fracture. (a) The total data orientation map; (b) the retained austenite orientation map; and (c) the retained austenite phase map.

Effects of Primary Forming and Different Loading Paths on Stress-Strain Behaviors

In this section, the effects of pre-straining or primary forming on subsequent stress versus strain characteristics are studied. Three pre-strain levels were considered: 5%, 10% and 15%. Pre-straining was carried out by stretching a large sheet of sheet material under plane-strain condition. Sub-sized ASTM E8 specimens were then prepared from the pre-stretched sheet and subjected to subsequent tensile testing at different temperatures (Figure 7).

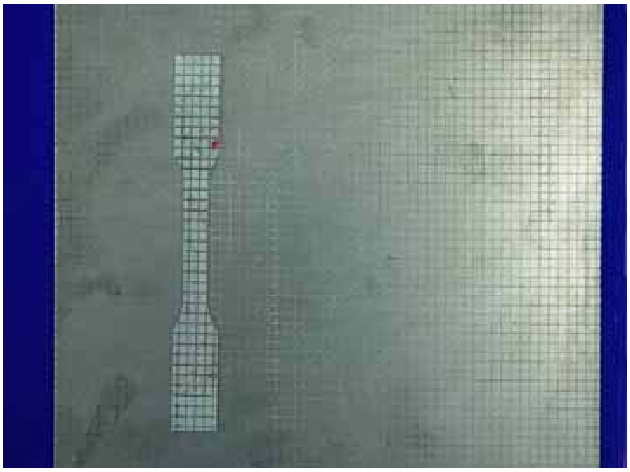


Figure 7. Pre-straining of tensile samples.

It should be noted that since the pre-straining is performed under plane-strain condition, more austenite should have transformed into martensite compared to the uniaxial samples at the equivalent strain levels. Pre-straining allows retained austenite to partially transform into martensite. Depending on the pre-strain levels and temperatures at which pre-straining is performed, materials of completely different microstructure and therefore different stress/strain characteristics will be generated. For example, Figure 8 illustrates the effects of room temperature pre-straining on material A. The pre-strained samples all have lower strengths in comparison to the strength of the non-pre-strained samples at the equivalent strain level. This indicates possible softening/aging response with tendency for strain localization. The final elongation values plus the corresponding levels of pre-strain are slightly higher than that of the non-pre-strained samples at room temperature testing. This is consistently observed for all the four materials studied.

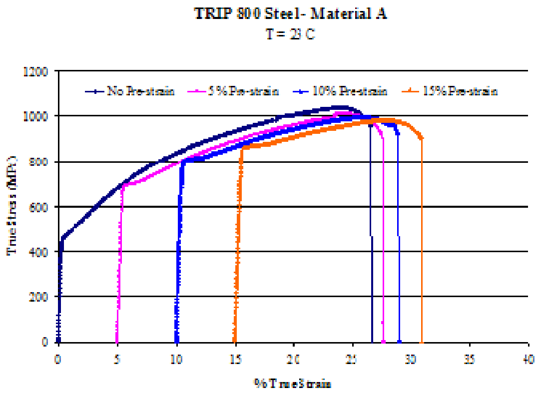


Figure 8. Effects of pre-straining on stress versus strain characteristics for Material A.

Figures 9 and 10 show the effects of room temperature pre-straining on the subsequent tensile behaviors at 93°C for material D and -40°C for material B. Consistent behaviors are observed for all other materials.

At 93°C, samples with room-temperature pre-strains have considerably higher initial yield levels than samples without pre-strains. This is because faster transformation occurs at room temperature than at 93°C (see Figures 4 and 5). Hence, the volume fraction of martensite in the pre-strained samples at any strain level is higher than those without pre-strains. More martensite in the pre-strained samples also renders the samples to have less total ductility at 93°C.

Completely different pre-straining effects are observed for samples tested at -40°C (see Figure 10 for material B). Since the samples are pre-strained at room temperature, less austenitic transformation occurs for the pre-strained samples than those tested at -40°C at the same strain levels. Therefore, the pre-strained samples have lower initial yield strength, more prominent Luders Band, and inhomogeneous shear deformation. The total ductility levels of the pre-strained samples are higher than those without pre-strain.

The effect of automotive paint bake was also examined for material B (see Figure 11). Minimal influence is observed on the samples' ultimate

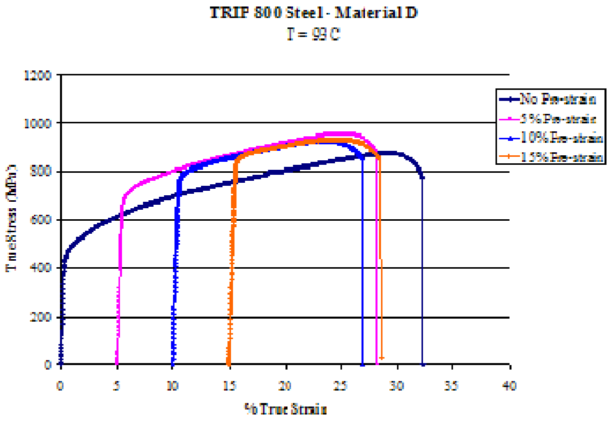


Figure 9. Effect of room temperature pre-straining on tensile properties under 93°C for Material D.

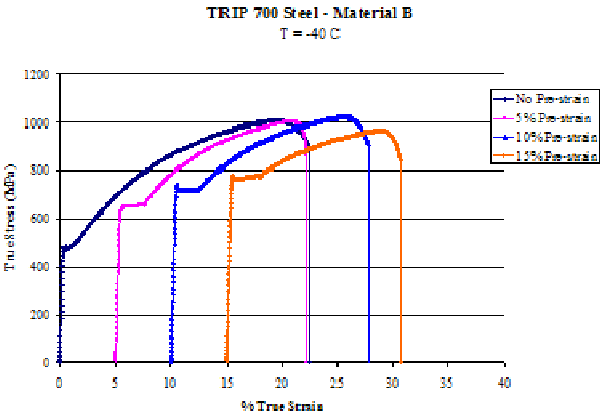


Figure 10. Effect of room temperature pre-straining on tensile properties under -40°C for material B.

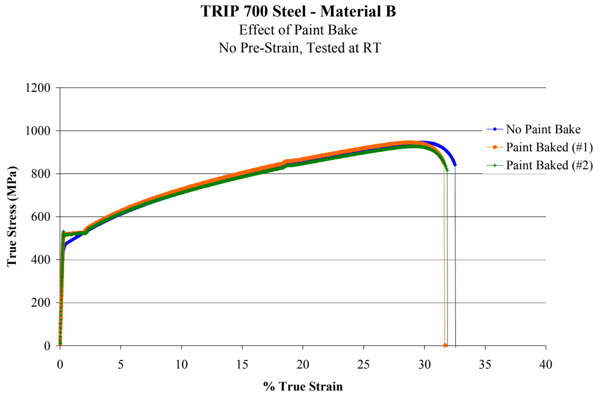


Figure 11. Effect of paint bake on base material properties.

tensile strength (UTS) and elongation. There is only a slight positive bake hardening effect on initial yield level for material B.

Resistance Spot Welds (RSW) of TRIP800-Effect of Fusion Zone Size

The effects of fusion zone size on failure modes, static strength and energy absorption of resistance spot welds of TRIP800 are also studied. The main failure modes for spot welds are nugget pullout and interfacial fracture. Partial interfacial fracture is also observed. Static weld strength tests using cross tension samples were performed on three joint populations with controlled fusion zone sizes. The resulted peak load and energy absorption levels associated with each failure mode were studied for all the weld populations using statistical data analysis tools.

Figures 12 and 13 show the effects of fusion zone size and weld failure mode on the peak load and total energy absorption of the RSW samples. The large slopes in Figures 12 and 13 for the TRIP800 small population indicate large scatters in peak load and energy absorption for the welds that failed by interfacial fracture. On the other hand, the much tighter slopes for the pullout welds in TRIP800 nominal and large populations indicate that welds failing by nugget pullout have well-controlled peak loads and energy absorption distributions with less performance variations. It is also interesting to note that even though the smallest weld in the TRIP800 large population failed by interfacial fracture mode, its peak load and energy absorption levels are comparable with the welds that failed by nugget pullout. In addition, the two interfacial fracture welds in the TRIP800 nominal population also indicate a large scatter in peak load and energy absorption. Note that the peak load and energy absorption levels for the TRIP800 nominal and large populations are about the same. This can be attributed to the significant weld indentation and expulsions for the TRIP800 large population.

The results in this study show that spot welds with fusion zone size of $4\sqrt{t}$ (t being the sheet thickness in *mm*) can not produce nugget pullout mode for the TRIP800 material examined. The critical fusion zone size for nugget pullout should be derived for individual materials based on different base metal properties as well as different heat affected zone (HAZ) and weld properties resulted from different welding parameters.

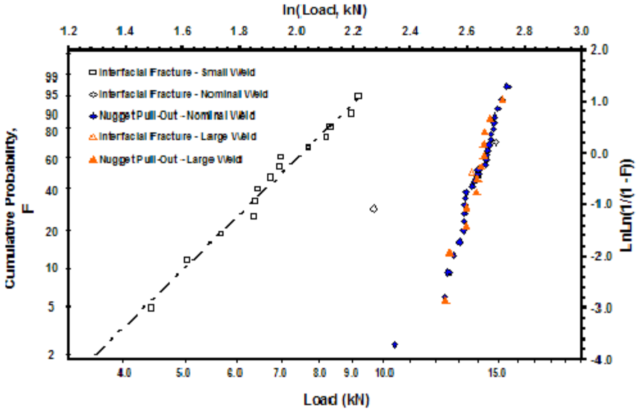


Figure 12. Peak load distributions for three weld populations in TRIP800.

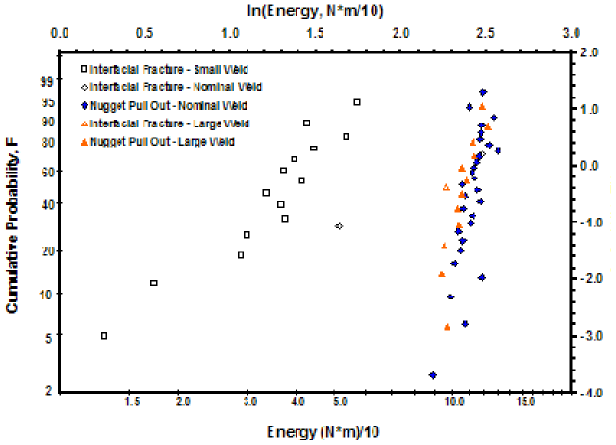


Figure 13. Distributions of energy absorption level for three weld populations in TRIP800.

Conclusions

- TRIP steels are performance-based steels; therefore, different suppliers have different chemistries and surface coatings on the same steel grade resulting in different base material properties.
- Four TRIP steels (TRIP 700 and three TRIP 800) manufactured by various domestic and international suppliers were evaluated.
- For the four TRIP steels tested, retained austenite transformation is stable under temperature range tested: -40°C to 93°C.
- Different pre-straining levels (i.e., primary forming processes) and test temperatures influence the yield strength and total elongation.
- Automotive paint bake has very little effect on the stress versus strain behaviors of TRIP steels.
- The critical fusion zone size for nugget pullout for TRIP800 should be derived for individual materials based on different base metal properties as well as different heat affected zone (HAZ) and weld properties resulted from different welding parameters.

Presentations

- Sun X, EV Stephens, and MA Khaleel. 2005. *"Effects of Manufacturing Processes and In-Service Temperature Variations on the Properties of TRIP steels - Concept Feasibility Study."* Presented by Moe Khaleel, Xin Sun and Elizabeth Stephens (Invited Speaker) at A/SP annual program review with DOE, Southfield, MI on September 21, 2005. PNNL-SA-46610.

- Sun X, EV Stephens, and MA Khaleel. 2005. *"Effects of Manufacturing Processes and In-Service Temperature Variations on the Properties of TRIP steels - Concept Feasibility Study."* Presented by Xin Sun and Elizabeth Stephens at Semi-Annual Program Review, Southfield, MI on March 10, 2005. PNNL-SA-44524.