Characterization of Thermo-Mechanical Behaviors of Advanced High Strength Steels (AHSS)

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Project Goal and Objective

- **Ultimate Goals:**
  - Meet DOE goal on weight reduction by promoting more widespread use of Advanced High Strength Steels (AHSS) in vehicle structures.
  - Accelerate development and adoption of AHSS in auto-body structures
- **Objectives:**
  - Develop fundamental understanding and predictive modeling capability to quantify the effects of auto manufacturing processes (forming, welding, paint baking, etc) and in-service conditions on the performance of auto-body structures made of advanced high-strength steels (AHSS)
  - Establish the technical basis to fully realize the advantages of AHSS intensive structures in fuel efficiency and structure crash safety
  - To provide performance data and constitutive models for formed and welded AHSS parts.

Technical Barriers

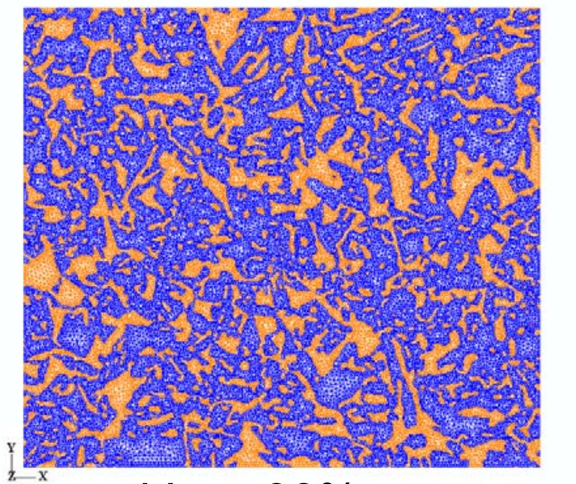
- There exist wide range of grades and types of AHSS and they continue to evolve:
  - The constitutive behaviors for AHSS parts are not available to CAE engineers for rapid prototyping;
  - Lack of quantitative understandings and predictive capabilities on the effects of 2nd phase particles on the overall stress versus strain behaviors of AHSS.
- The behaviors of AHSS parts subject to different thermal and mechanical loading paths (forming and welding) are not fully understood and quantified:
  - Forming induced failure under different loading paths: biaxial stretch, plane strain, stretch bending, etc.
  - Welding induced complex microstructure changes.
- Lack of application guidelines for effective and optimal use of AHSS in auto body structures

Technical Approach

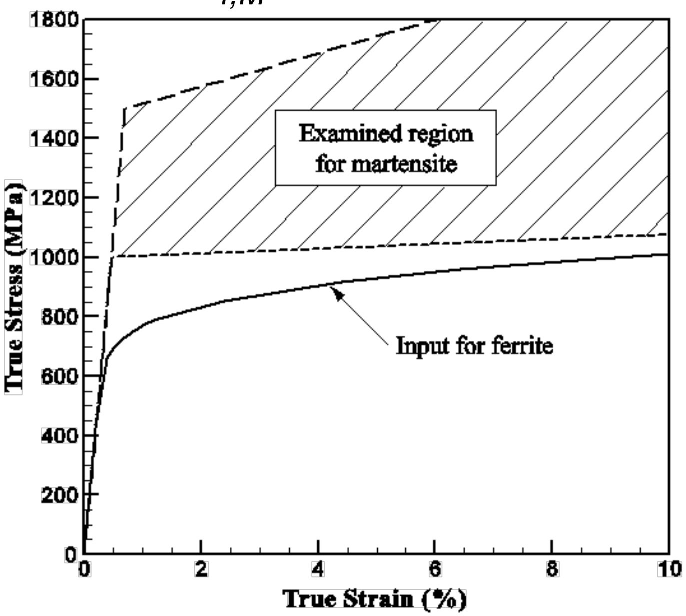
- Forming and base material property characterizations – PNNL
  - Quantify the base material performance under different loading paths, loading rates and loading temperatures
  - Quantify the effects of loading mode, rate and temperature on transformation kinetics
  - Evaluate structural performance of formed and welded parts made of AHSS
  - Develop transformation kinetics model and macroscopic constitutive relationships for TRIP steels
  - Develop macroscopic constitutive model to simulate the stress vs. strain behavior of AHSS: TRIP + DP
  - Develop micromechanics model to predict AHSS failure modes under different loading conditions

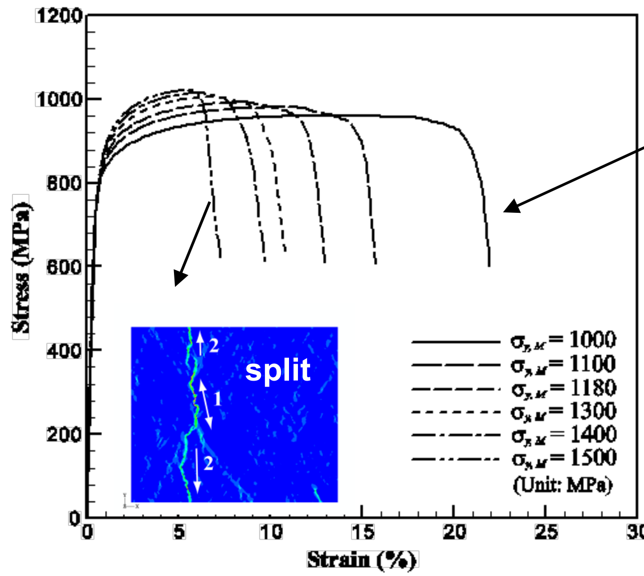
- Welding – ORNL
  - Develop a fundamental understanding of microstructure transformation kinetics of AHSS steels during welding
  - Develop integrated thermo-metallurgical-mechanical predictive models for the performance of welded AHSS parts
  - Investigate the weldability of AHSS under various welding processes and parameter conditions applicable to auto production environment
  - Investigate welding techniques for improved AHSS weld performance and benchmark them against the current welding practices for roll-formed and hydro-formed AHSS frame and underbody structure applications
  - Generate weld performance data including static strength, formability, impact strength, and fatigue life as function of welding processes and parameters

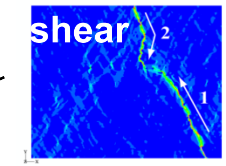
Forming and Basic Material Properties Accomplishments -- Effects of Martensite Mechanical Properties on Behaviors of DP980



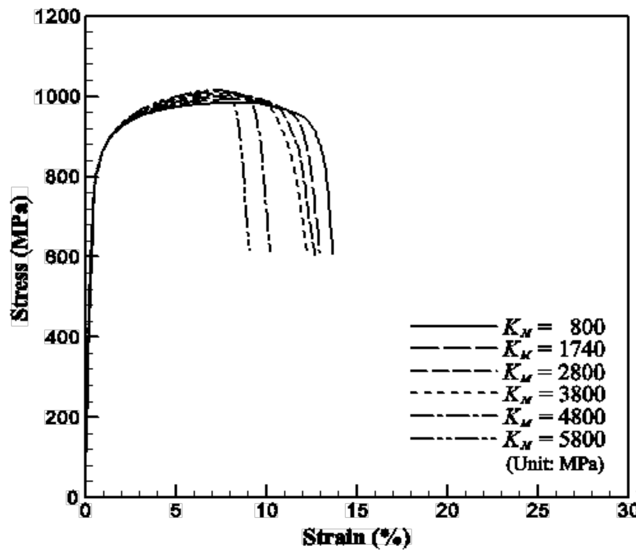
$V_{f,M}$ = 38%







Effects of the initial yield strength of the martensite with K_M = 1740 MPa



Effects of the hardening rate of the martensite with $\sigma_{y,M}$ = 1180 MPa

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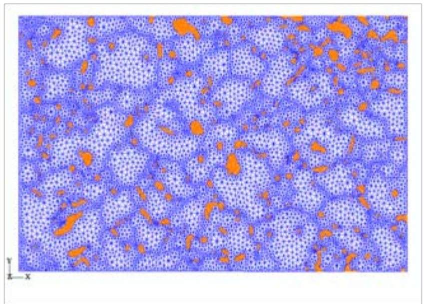
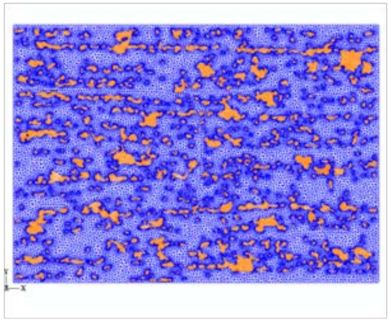
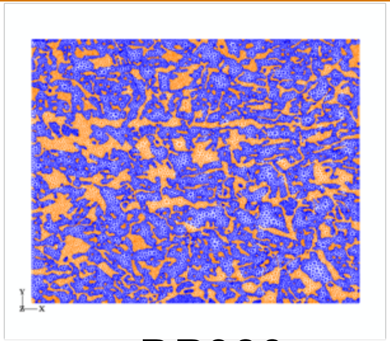
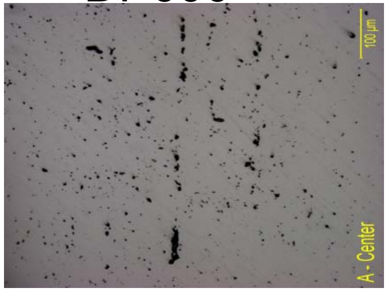
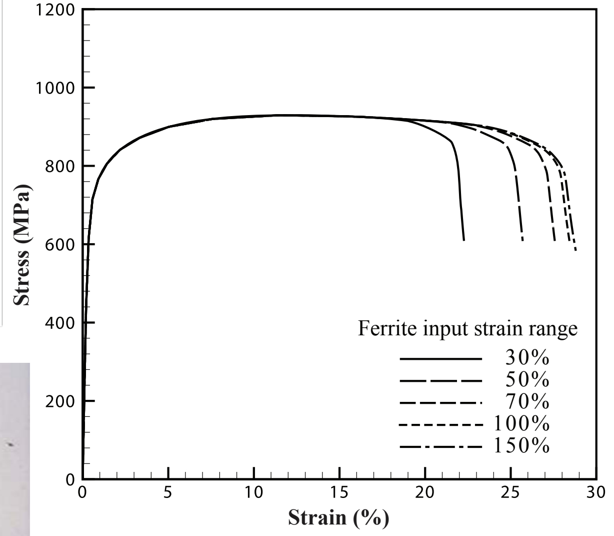
Forming and Basic Material Properties Accomplishments -- Effects of Martensite Volume Fraction and Ferrite Ductility on Ductility of DP Steels

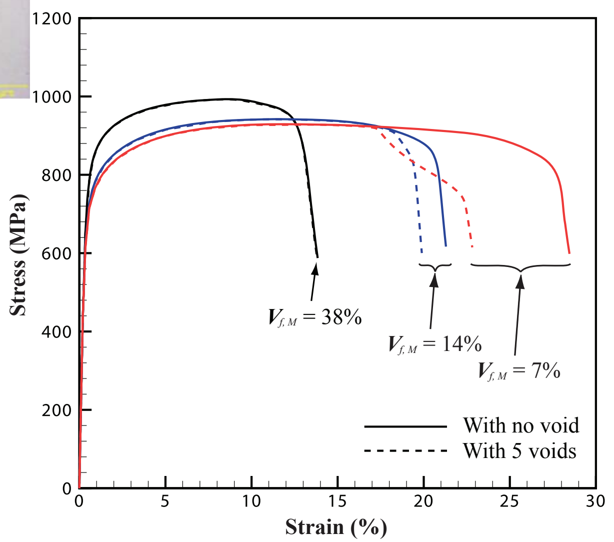




DP600 DP780 DP980



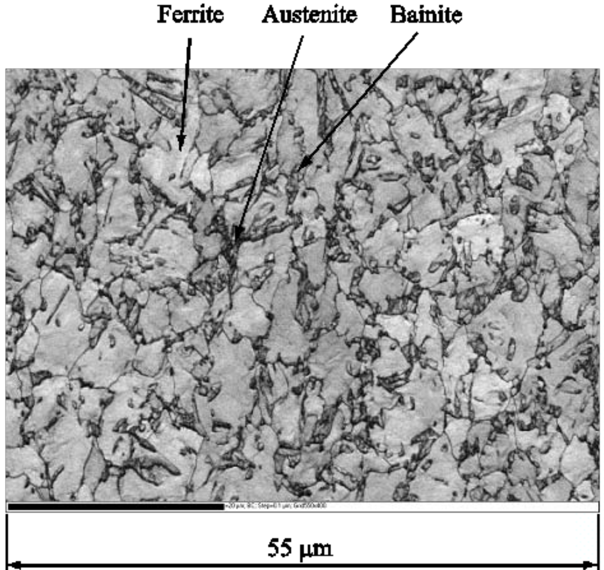
Micrographs for different steel samples near fracture surface
* From EWI's A/SP Shear Fracture Project Update 9-10-2008

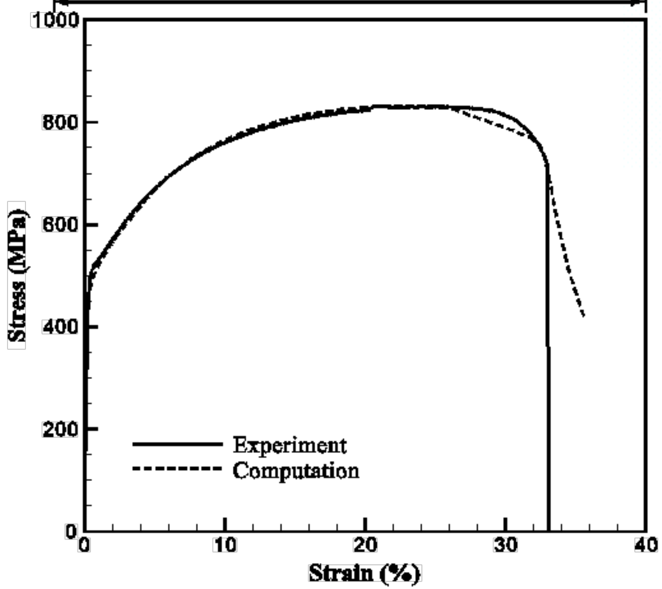


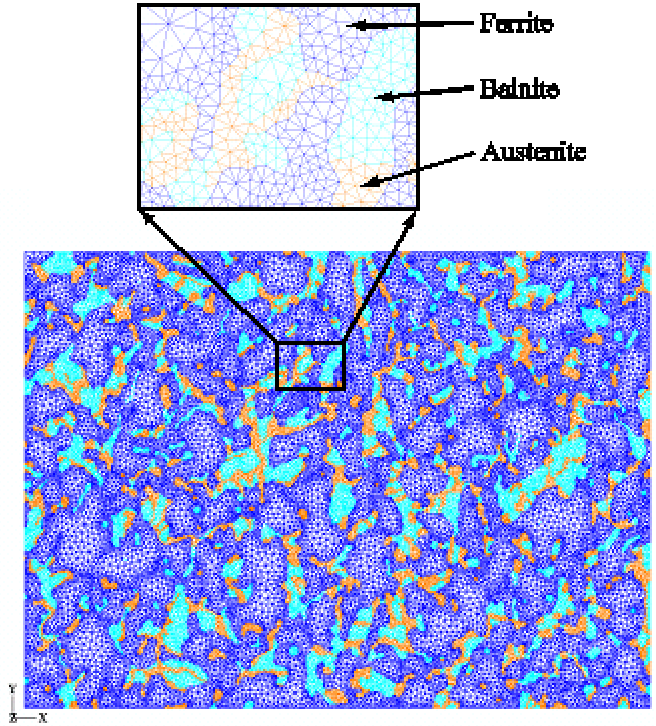


1. For DP600, ductility of ferrite matrix is critical for the overall ductility of the material. Ductile failure is driven by void growth and coalescence in a conventional sense.
2. For DP780 and DP980, microstructure-level inhomogeneous strain distribution during deformation is the key factor influencing ductility of these steels. The driving force for ductile fracture is no longer void growth and coalescence.

Forming and Basic Material Properties Accomplishments -- Modeling of Phase Transformation and Ultimate Ductility of TRIP800 Under Different Loading Conditions



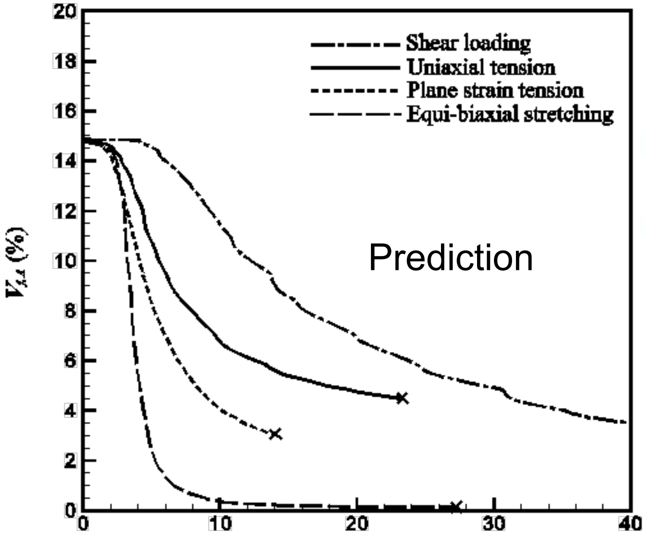


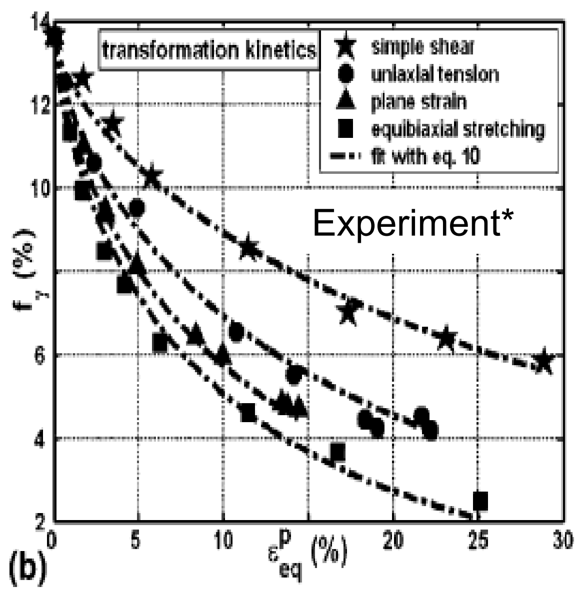


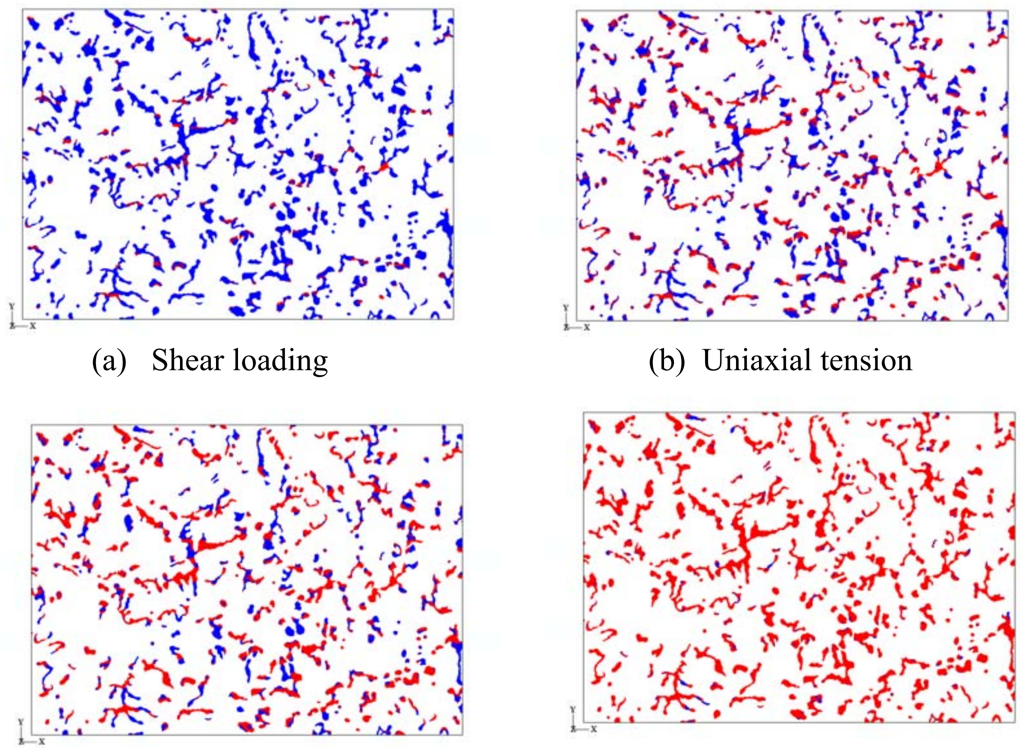
$$\Pi = R\sqrt{3J_2}\left[1 + k\frac{J_3}{J_2^{3/2}}\right] + \frac{\alpha I_1}{3}$$

* Choi, et al., Acta Materialia 2009. doi:10.1016/j.actamat.2009.02.020.

Forming and Basic Material Properties Accomplishments -- Modeling of Phase Transformation and Ultimate Ductility for TRIP800 Under Different Loading Conditions







(a) Shear loading

(b) Uniaxial tension

(c) Plane strain

(d) Equi-biaxial stretching

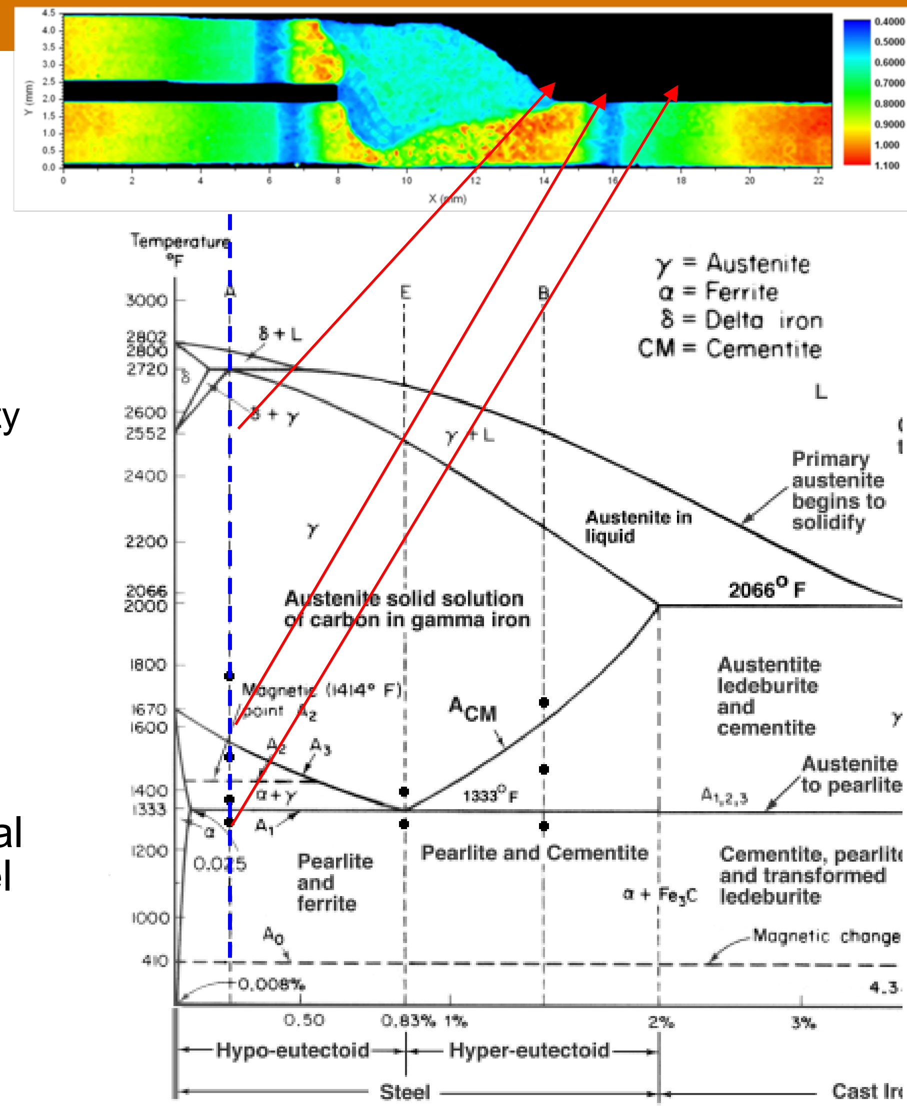
Plotted at 7.7% strain

1. Predicted transformation kinetics and ultimate ductility (indicated by x) under different loading conditions are in qualitatively good agreements with experimental measurements.

* M. Radu et al. / Scripta Materialia 52 (2005) 525–530

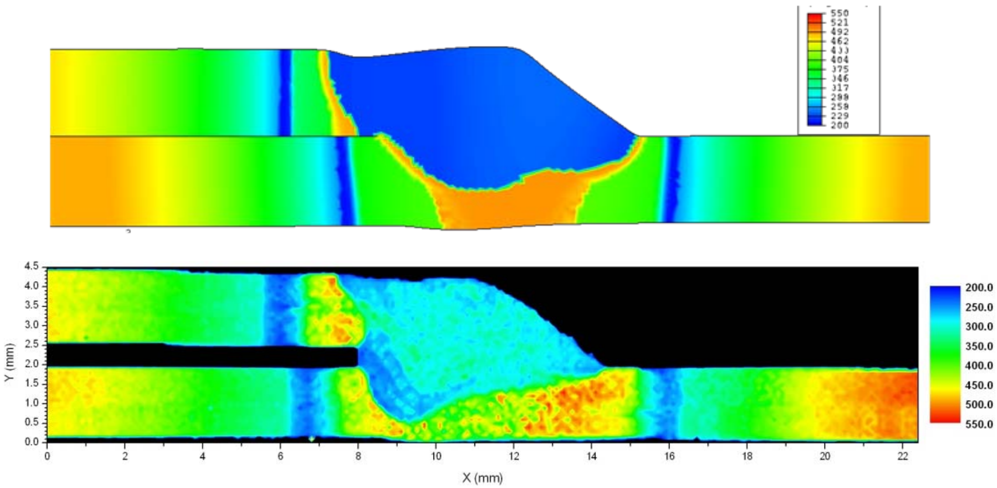
Joining Accomplishment – Fundamental Understanding of HAZ Softening of AHSS

- HAZ softening is primarily related to the intercritical region
- Supercritical region (above T_{A3})
  - Single austenite phase region
  - On-cooling, austenite decomposition to low temperature phases depends on hardenability (composition) of steel and cooling rate
- Intercritical region (between T_{A1} and T_{A3})
  - Co-existence of ferrite and austenite
  - Austenite decomposes
  - Ferrite will remain on cooling
- Below T_{A1}
  - Tempering of martiniste/bainite
- Extent of HAZ soften depending on the initial base metal microstructure & hardness, steel chemistry and welding thermal cycle

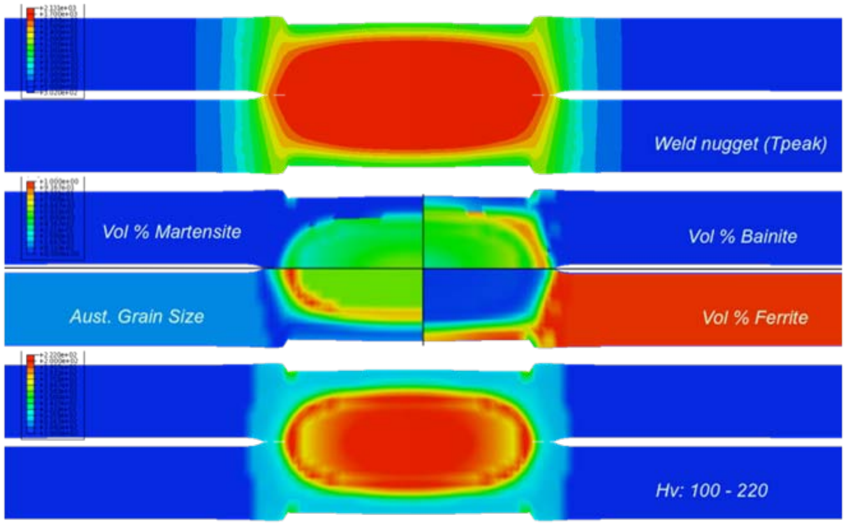


Joining Accomplishment – Developed an integrated thermal-metallurgical-mechanical modeling for AHSS welds

- Capable of predicting HAZ softening and other microstructural changes
- ***Initial version has been licensed and transferred to steel suppliers***
- ***Technology transfer to OEM and other suppliers is under discussion***



Arc weld



Resistance Spot Weld

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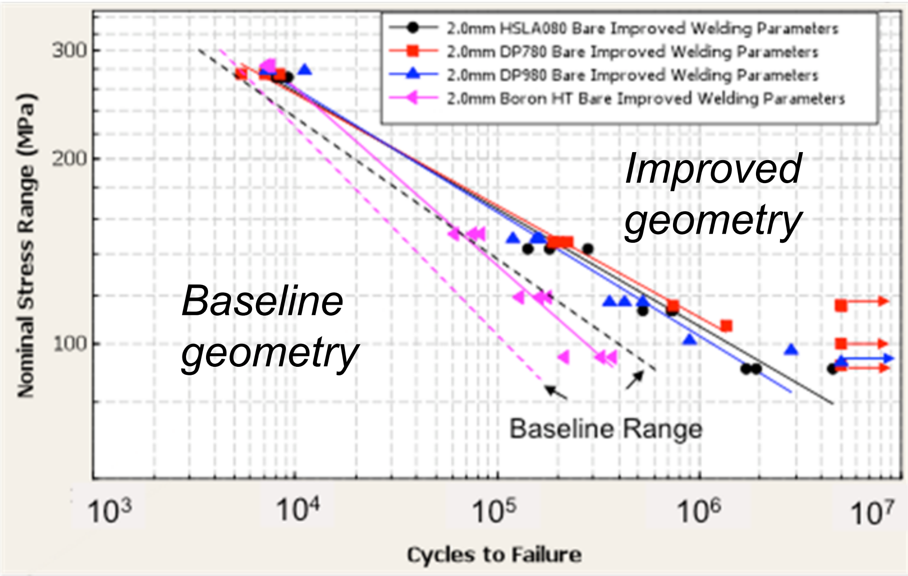
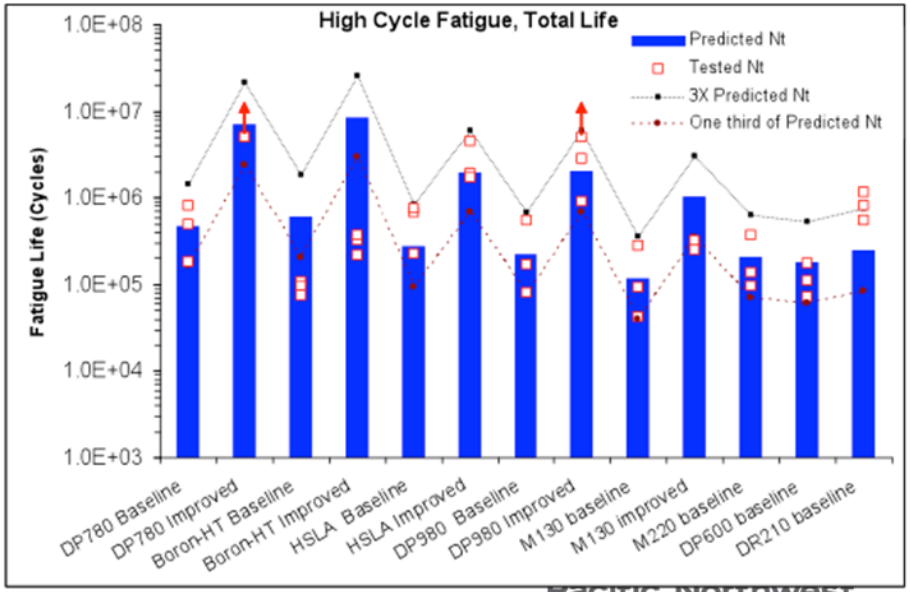
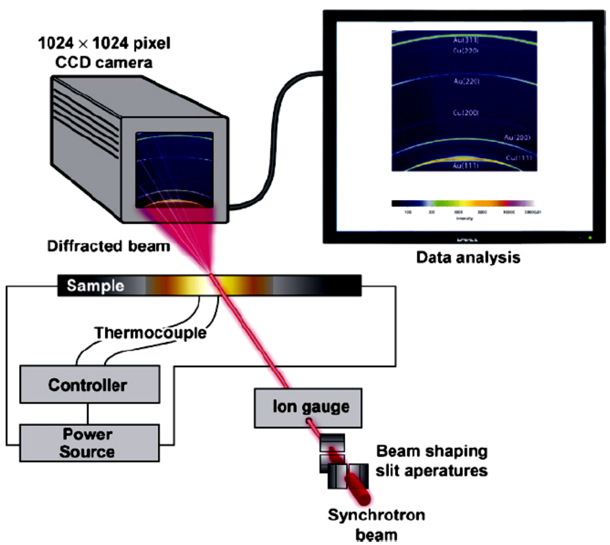
Joining Accomplishment – Improving & Predicting Weld Fatigue Durability

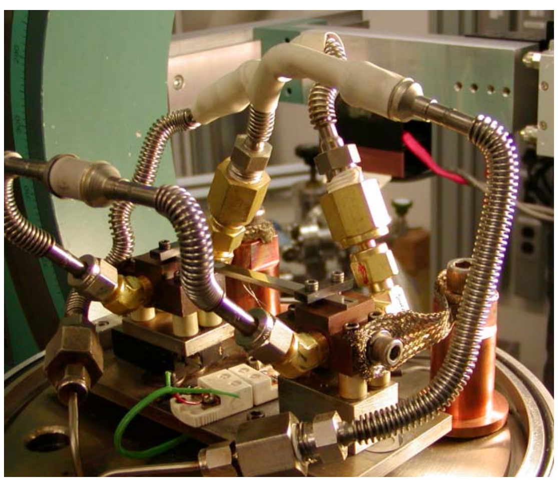
- Achieved significant weld durability (fatigue life) improvement through weld profile control
- Developed weld fatigue life prediction model that explicitly addresses the weld geometry and weld property effects
- They have been further evaluated and tested at OEM on more complex component configurations and loading conditions
- Potential technology transfer to other industry under discussion





Joining Accomplishment – In-Situ Synchrotron Experiments to Quantify the Non-Equilibrium Phase Transformation Process during Welding





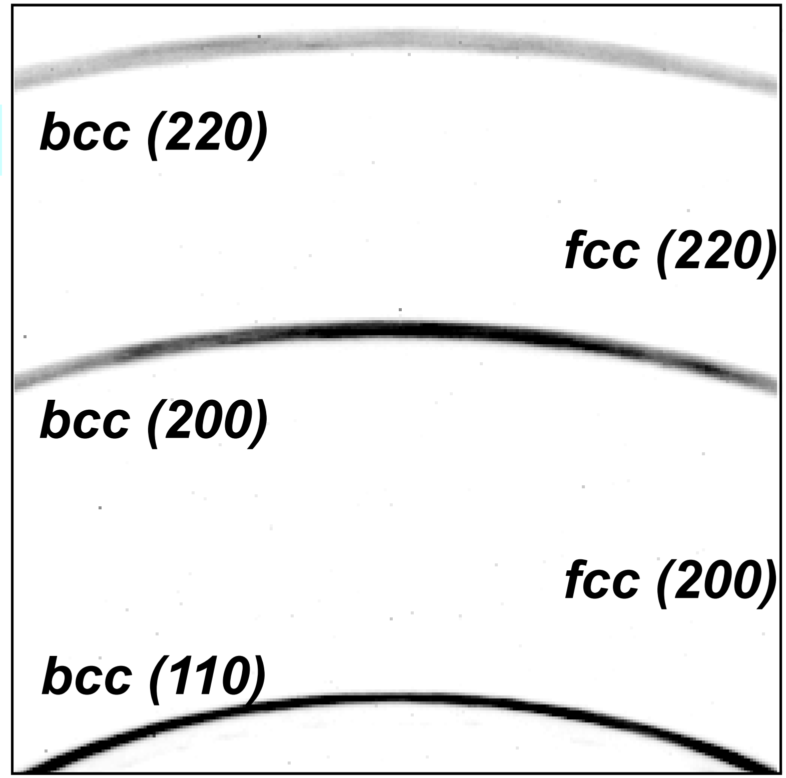
During cooling (~10 ºC/s)

1100 ºC

750 ºC

600 ºC

25 ºC



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Boron steel

Technology Transfer

- Received strong supports from and maintained close interactions with OEM, steel suppliers and A/SP committees
  - A/SP AHSS Stamping Team
  - Joining Technologies Team
  - A/SP Sheet Steel Fatigue Committee
  - A/SP Lightweight Chassis Structure Team
- Research approaches and results have been adopted and further developed/refined by the OEMs and industry consortiums
  - Initial version of integrated weld model licensed and transferred to industry
  - Weld fatigue life improvement technique and predictive model are under further evaluation by industry

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Activities for Next Fiscal Year

- Predictive modeling on forming and welding of 1st generation AHSS:
  - Influence of martensite phase morphology and distribution on stress-strain behaviors and failure modes of DP steels
  - Integrate welding process/microstructure model with mechanical performance model and refine weld fatigue life prediction model
  - Phase transformation kinetics in the intercritical region
  - Provide technical assistance to the development of AHSS Joining Roadmap
- Exploratory studies on TWIP steel and nano precipitate strengthened steels:
  - Investigate effects of steel chemistry on stacking fault energy and develop physically-based phenomenological model for TWIP steels
  - Develop micromechanics model to simulate the strengthening effects of micro-twins
  - Quantify the strengthening effects of nano precipitate in nano steels
- Develop research plan and concrete goals for 3rd generation AHSS:
  - Establish concrete goals for 3rd generation AHSS
  - Integrate the findings of various NSF-funded university programs with national labs' expertise in developing the research plan for the 3rd generation AHSS for lightweighting of automotive structures

Summary

- Potential for petroleum displacement
  - This project provides the knowledge and modeling tools on AHSS subject to forming and welding such that more AHSS can be used to achieve the DOE vehicle lightweighting goals.
- Research approach
  - A complementary experimental and modeling approach has been used to gain fundamental understandings of AHSS under automotive-related thermal mechanical loadings, i.e., forming and welding.
- Technical Accomplishments
  - On target with project objective and timeline
- Technology transfer
  - Continue close interactions with the OEM and A/SP technical committees to exchange research progress and collaborate on other related projects
  - Results are being published in peer reviewed literature, as well as being presented as technical conferences.
- Plans for next year
  - Continue development work in the various technical areas
  - Focus on developing research plan and concrete goals for 3rd generation AHSS