Dynamic Characterization of Spot Welds for AHSS

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Project ID: LM025

Overview

Timeline

- Start: Dec, 2006
- End:
  - Phase I: March, 2009
  - Phase II: March, 2013
- Percent complete
  - Phase I: 100%
  - Phase II: 0%

Budget

- Total project funding (Phase I)
  - DOE share: $630K
  - Contractor share: $150K
- Funding received in FY09: $0
- Funding for FY10: $250K (expected in May 2010)

Barriers

- Barriers addressed
  - Efficient optimization of AHSS body structures for light-weighting while meeting crash requirements

Partners

- Interactions/ collaborations
  - University of South Carolina
  - Auto/Steel Partnership Strain Rate Characterization Team
  - GM, Ford, Chrysler, ArcelorMittal Steel, US Steel
- Project lead
  - Oak Ridge National Laboratory

Project Objectives

- Key technical development
  - A spot weld modeling tool capable of incorporating the behavior of spot weld (strength, failure mode, and deformation rate effects) in advanced crashworthiness CAE, for better utilization of materials in light-weighting efforts

- Key objective/deliverable metrics
  - A new, robust spot weld element and implementation procedure that is practical for automotive crash modelers to use
  - An integrated thermal-electrical-mechanical-metallurgical weld process model to predict the microstructure and property distributions in spot welds
  - Companion property database for impact simulation and analysis
  - Focus on resistance spot weld of advanced high-strength steels (AHSS)

Relevance to VT Lightweight Materials Program

- A primary driver for use of AHSS and other high-strength lightweight materials in BIW is the improvement of crash performance while reducing the weight
- Advanced crashworthiness Computer Aided Engineering (CAE) is an essential tool enabling for safety design and optimization, to accelerate the use of new materials
- As welding is extensively used in auto body structures, the dynamic performance of welded structures is an important consideration in crashworthiness CAE
- The spot weld modeling tool from this project addresses a critical need in higher-level optimization of vehicle light-weighting while meeting crash requirement and cost-effectiveness

Technology Gap Analysis*

- Consensus
  - The prediction of spot weld failure in FEM crash analysis is generally unsatisfactory, which greatly impedes the overall accuracy of crash analysis of welded structure components
  - Spot welds in AHSS are of particular concern because these welds are subject to both ductile (button pullout) and interfacial failure

- Gap exists in both the fundamental understanding and the practical capability of predicting the failure of spot welded structures in crash
  - Why do welds in AHSS and other light-weight materials exhibit different failure modes, and fail more often under impact?
  - What are the roles of alloy composition and welding parameters in the change in failure mode?
  - What would it take to have crash model adequately handle the deformation and failure of spot welds under impact?
- Past R&D on AHSS spot welds have been largely under static loading conditions. Experience base for various AHSS under high-strain rate conditions is nonexistent or very limited

* *A/SP Strain Rate Characterization Committee report*

Technology Gap Analysis*

- Impedes the rapid and optimum insertion of AHSS and other lightweight materials in auto body structures.
  - We cannot design components containing AHSS and other lightweight materials, and optimize crash performance using numerical analysis with confidence that weld failures will not occur
  - The weld failures, detected in later stage of new model car development cycle, have frequently resulted in design compromises that can adversely affect weight savings available by using AHSS.
  - Further lightweighting opportunities from optimized use of AHSS and other lightweight materials will not be possible without improved understanding of the phenomena and the development of respective models and CAE tools for crashworthiness analysis.

* A/SP Strain Rate Characterization Committee report

Technical Approach

Input from Project Industry Advisory Committee and OEM
- Weld coupons for testing
- Welding parameters
- Steel composition/process condition

Microstructure/property characterization
- Optical, electron metallography
- Weld nuggets size and geometry
- Microhardness mapping of weld and HAZ
- ABI local stress-strain curves
- Weld quality assessment

Dynamic/static testing
- Strain rates
- Loading modes
- Load-displacement curve
- Energy absorption
- Failure mode

Model validation

Weld process and property model
- Input: welding condition/steel chemistry
- Output: weld nugget/surface indent, microstructure, property and residual stress/strain distribution in weld and HAZ,

3D Solid Weld Coupon Model
- Mapping property & stress/strain states from weld model
- Detailed simulation for local stress/deformation to provide input for failure criteria development

Failure criteria
- Use local stress/strain state around weld region
- Fracture mechanics and damage mechanics based
- Capable of handling different failure modes and mode change due to strain rate and material property changes

Spot Weld Element
- Initial formulation
- Weld property constitutive model
- Incorporation of failure criteria
- SWE model implementation procedure
- Progressive sophistication and improvement (future phases)
- Validation with 3D solid model

Phase I model demonstration
- ORNL RSW tube compression test

Project Milestones

- Phase I Concept Feasibility (Dec 06 – Mar 09) – Completed
  - Initial version of the spot weld element (SWE) and its implementation procedure
  - Companion experimental data set
  - 2 steel grades, multiple weld nugget and quality conditions selected by OEMs
- Decision Gate at End of Phase I – Passed
  - Will SWE model work as expected?
- Phase II Comprehensive R&D – FY2010 - FY2013
  - Complete development of SWE, cover wide range of the AHSS grades, coatings, and spot weld configurations (thickness, 3-T stacks etc) required for advanced crashworthiness CAE implementation
  - Collaborate with OEM modelers to integrate SWE into commercial codes used by OEM
  - Component level demonstration and validation

Progress/Accomplishments:

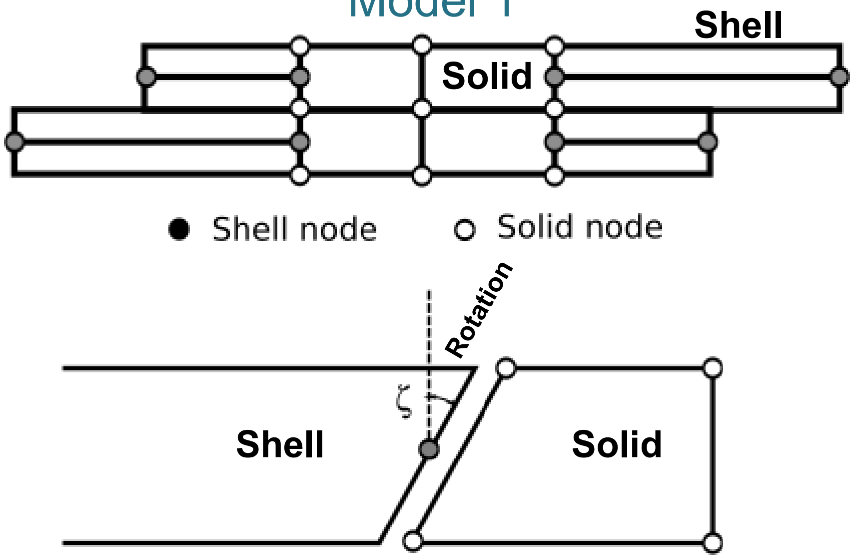
- Successfully completed the concept feasibility development of a new spot weld simulation model for advanced crashworthiness CAE
- Developed an initial version of SWE
  - Capable of handling weld geometry and weld property gradient
  - Capable of predicting different fracture modes and fracture load limit experimentally observed in impact tests
- Developed an initial version of integrated electrical-thermal-mechanical-metallurgical resistance spot weld model
  - Capable of predicting weld geometry, microstructure and microhardness distributions
  - Friendly user input interface for welding parameters, sheet thickness and steel chemistry
- Generated baseline spot weld impact test data on DP780 and DQSK steels
  - Characterization of effects of impact speeds and loading modes;
  - Web-based database for user-friendly interactive data analysis and retrieval.

Accomplishment: Development of SWE

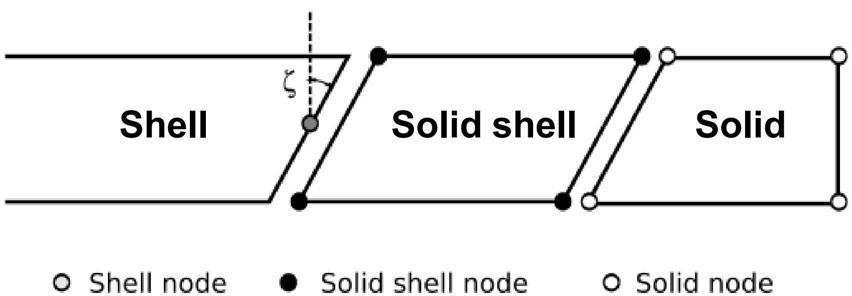
- Create FEM mesh-compatible connection between spot-welded plates
- Take advantage of the fact that the load transfer in a spot weld nugget is mainly accomplished by the material near the nugget boundary
  - Nugget core is relatively stress-free
- Provide weld failure mechanisms typical of high strength materials
- Base failure criteria on intrinsic material properties (stress, strain, fracture toughness), not extrinsic (force, moment, displacement)

Accomplishment: Progression of SWE Formulations

Model 1



Model 2



Model 1: Couple **4-node shell** to solid element

- Shell rotation is coupled to solid nodes through constraint equation
- Requires separate treatment of shell-solid thickness constraint at solid shell-solid connection

Model 2: **8-node shell** to solid element

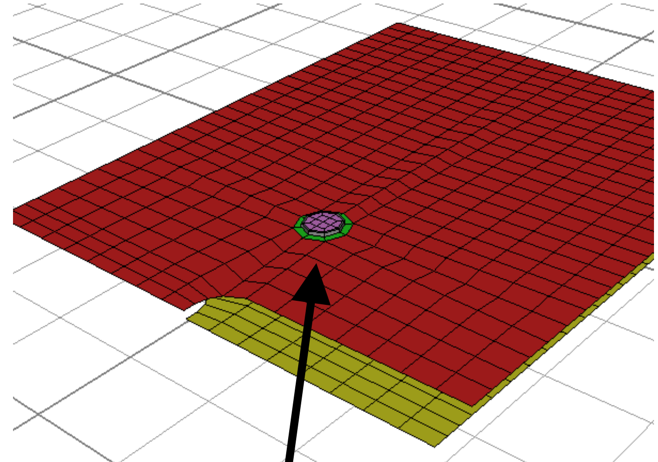
- Provides better accuracy in the HAZ region for:
  - Shear stress at solid shell - solid connection
  - Through thickness stresses in HAZ

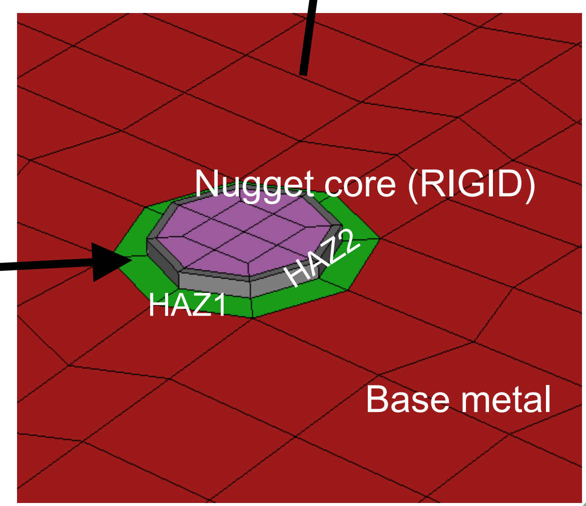
Models (1,2) R: **Rigid nugget center**

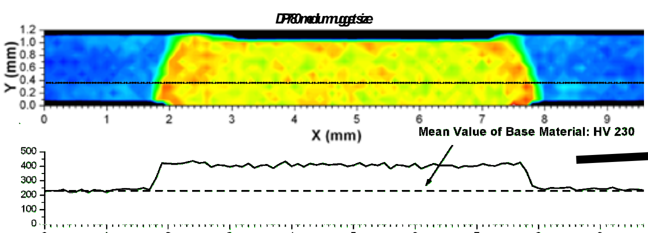
- Faster
- Inner region replaced by rigid body
- Eventually replace by constraints

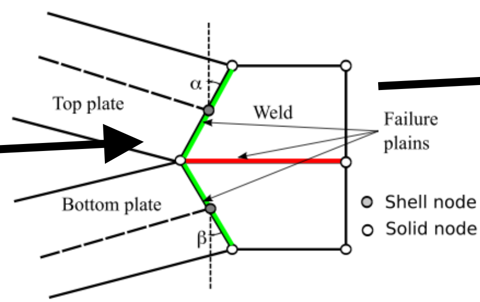
Accomplishment: SWE Formulation (Cont'd)

- Coupling with weld process model
  - Weld properties from weld process simulations
- Weld fracture formulation
  - Different failure modes are triggered by failure criteria at different locations
  - We use simple fracture criterion based on strain energy to break









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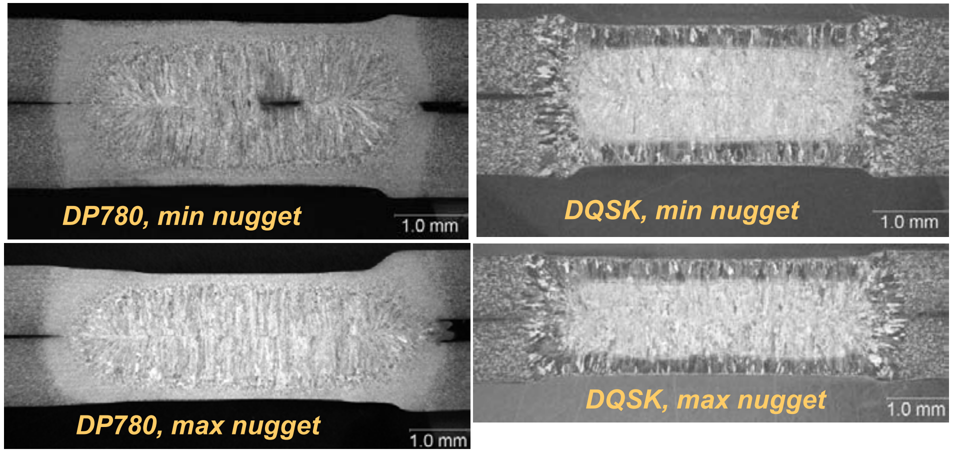
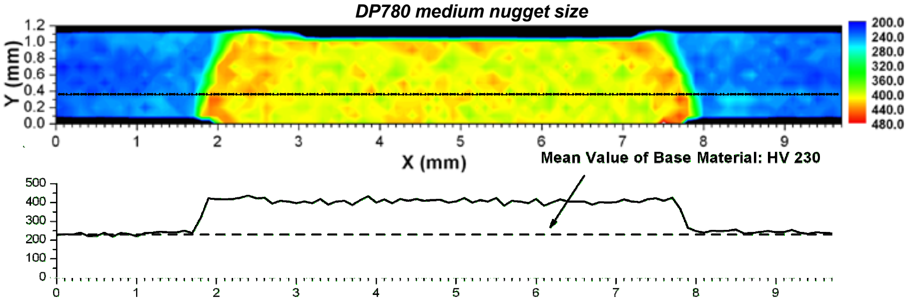
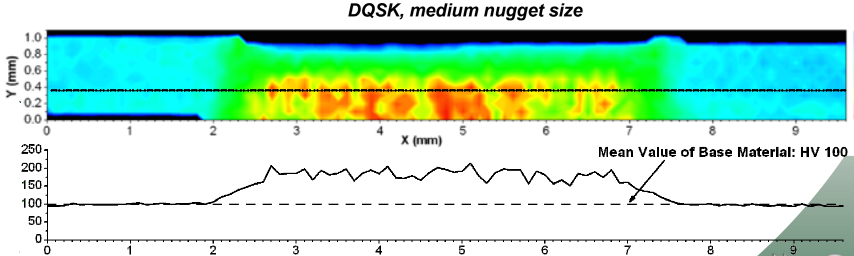
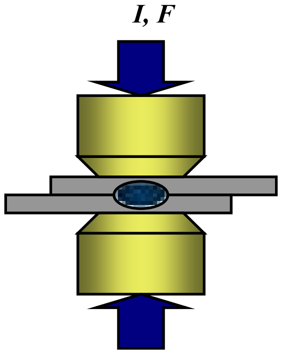
Accomplishment: Weld Microstructure/Property Modeling & Characterization

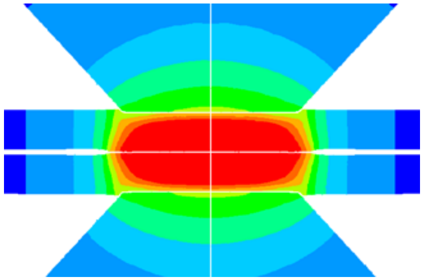
- Weld property gradients are determined and compared among different steels
- Weld size and other geometric attributes including defects are correlated to steel grade and welding conditions
- An incrementally coupled electric-thermal-mechanical-metallurgical model is being developed and under validation



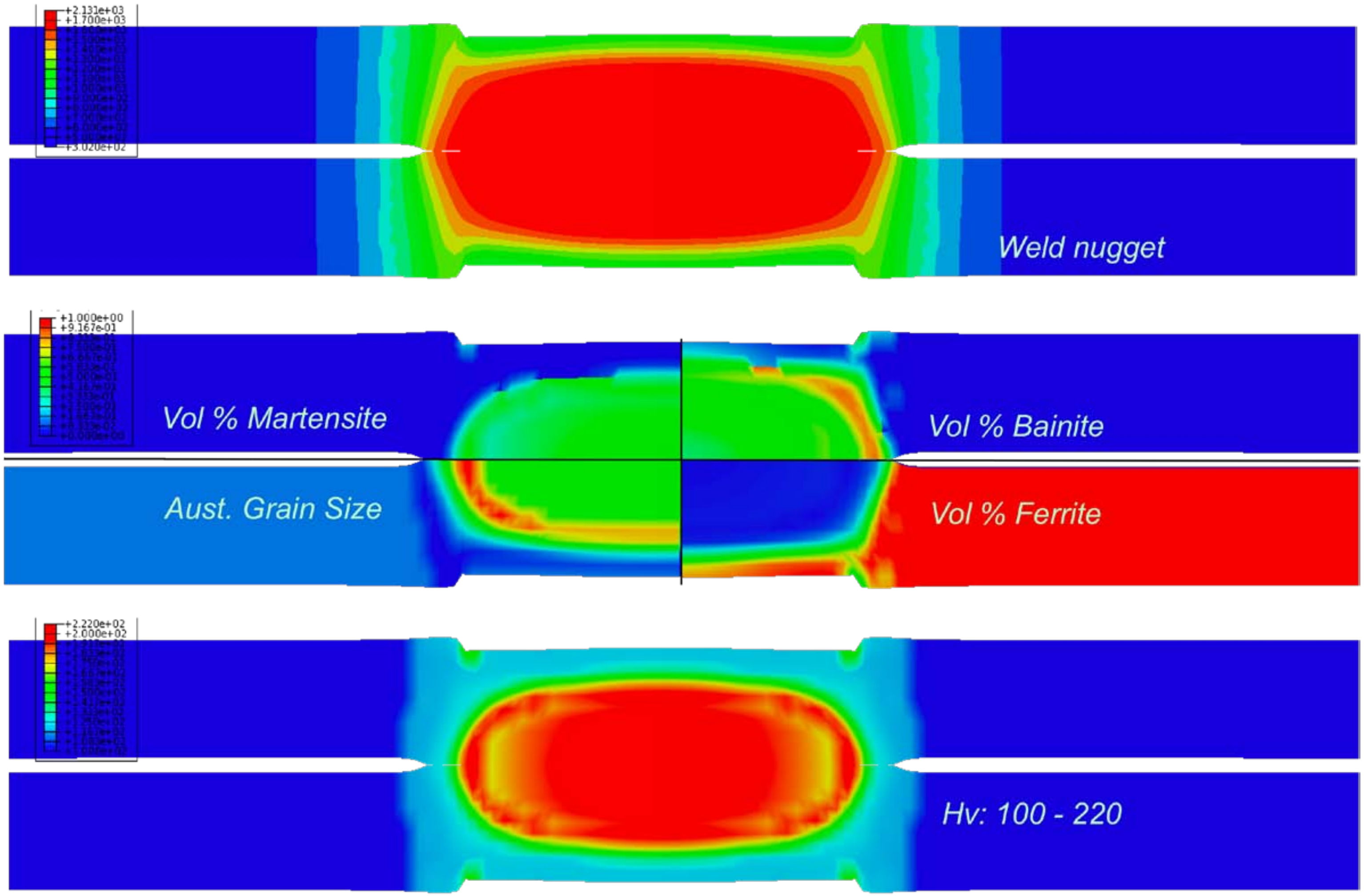




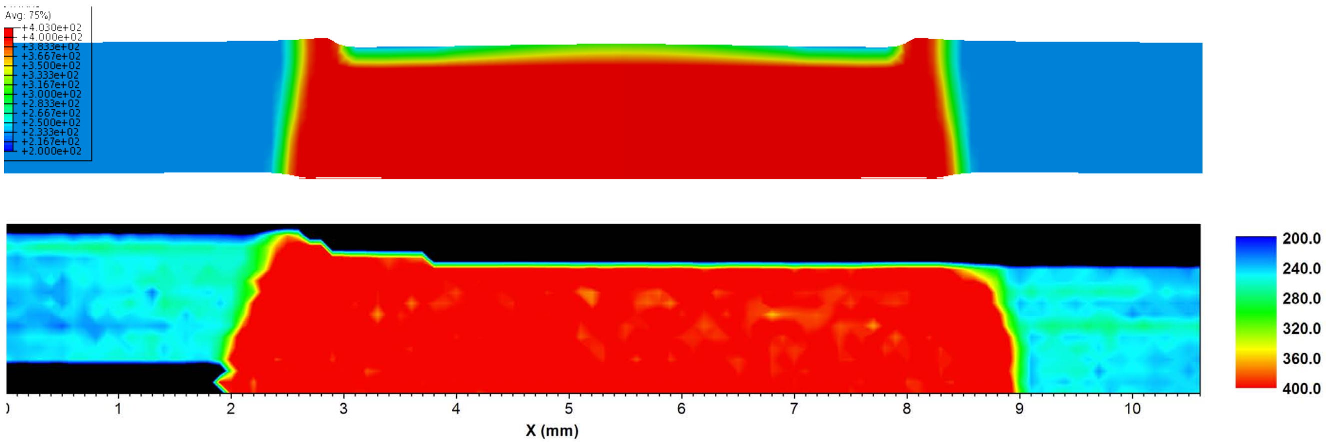




Accomplishment: Prediction of Weld Microstructure and Properties



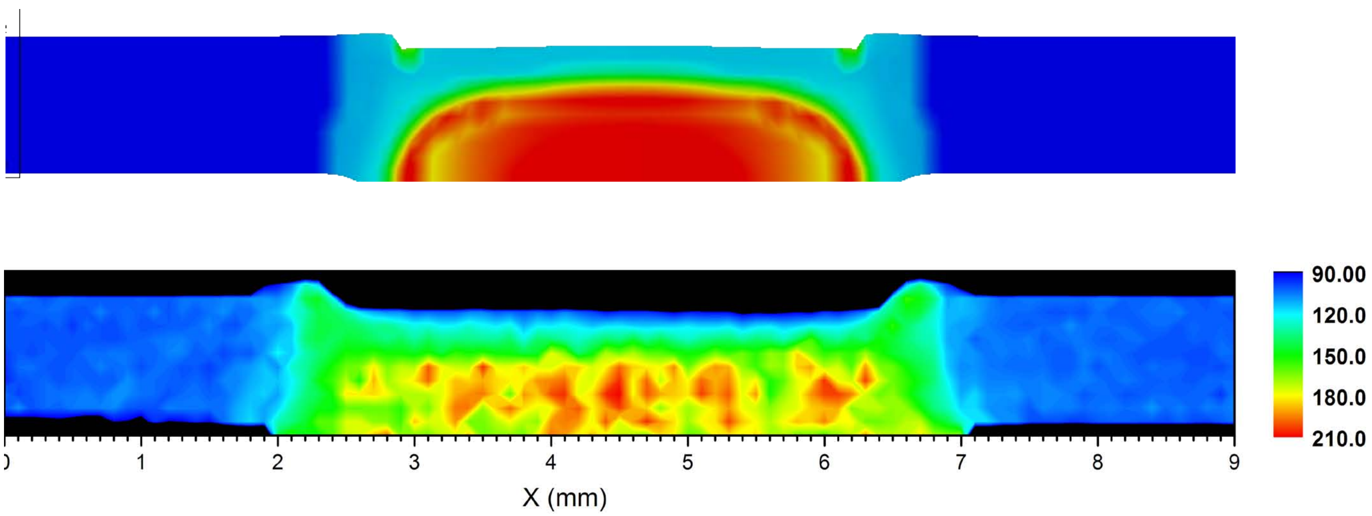
Accomplishments: Comparison of Microhardness Distribution



DP780

Model prediction

Hardness mapping measurement



DQSK

Model prediction

Hardness mapping measurement

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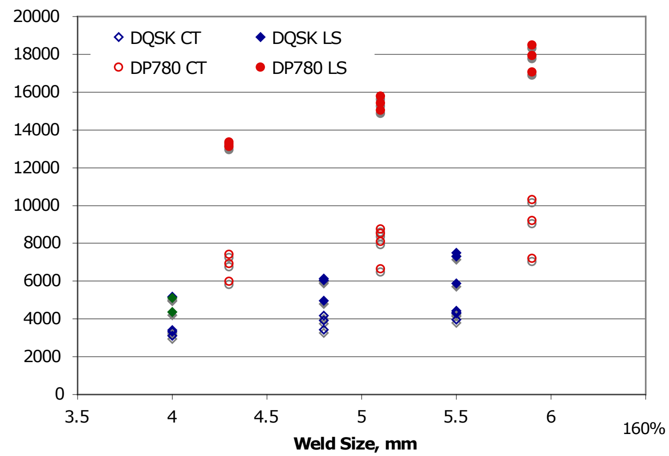
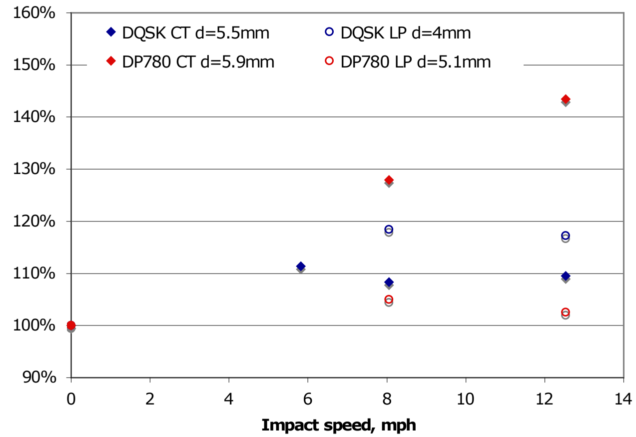
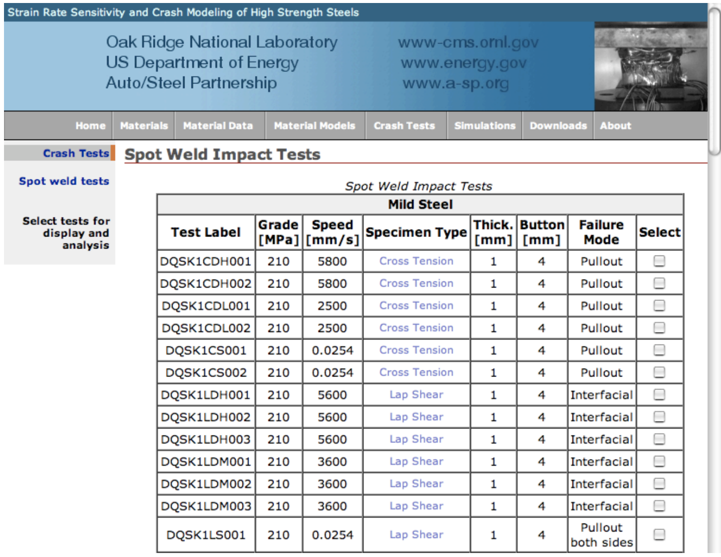
Accomplishment: Dynamic testing

- Two steel grades, three weld nugget sizes, five loading modes, four loading speeds up to 13 mph
- Web-based test data collection and retrieval
- Failure mode and strength correlated to the weld attributes such as weld size and loading rate






Strain Rate Sensitivity and Crash Modeling of High Strength Steels

Oak Ridge National Laboratory www-cms.ornl.gov
US Department of Energy www.energy.gov
Auto/Steel Partnership www.a-sp.org

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Crash Tests

Spot weld tests

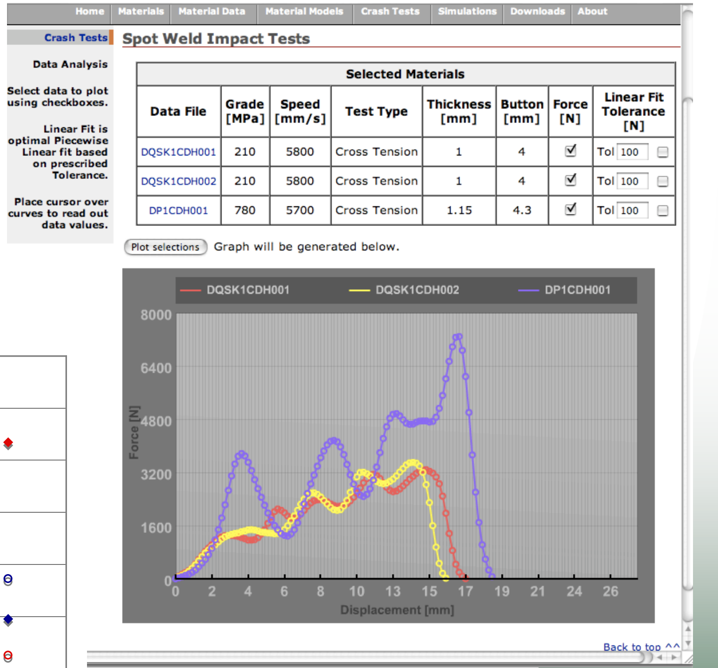
Select tests for display and analysis

Spot Weld Impact Tests

Spot Weld Impact Tests

Mild Steel

Test Label	Grade [MPa]	Speed [mm/s]	Specimen Type	Thick. [mm]	Button [mm]	Failure Mode	Select
DQSK1CDH001	210	5800	Cross Tension	1	4	Pullout	
DQSK1CDH002	210	5800	Cross Tension	1	4	Pullout	
DQSK1CDL001	210	2500	Cross Tension	1	4	Pullout	
DQSK1CDL002	210	2500	Cross Tension	1	4	Pullout	
DQSK1CS001	210	0.0254	Cross Tension	1	4	Pullout	
DQSK1CS002	210	0.0254	Cross Tension	1	4	Pullout	
DQSK1LDH001	210	5600	Lap Shear	1	4	Interfacial	
DQSK1LDH002	210	5600	Lap Shear	1	4	Interfacial	
DQSK1LDH003	210	5600	Lap Shear	1	4	Interfacial	
DQSK1LDM001	210	3600	Lap Shear	1	4	Interfacial	
DQSK1LDM002	210	3600	Lap Shear	1	4	Interfacial	
DQSK1LDM003	210	3600	Lap Shear	1	4	Interfacial	
DQSK1LS001	210	0.0254	Lap Shear	1	4	Pullout both sides	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Crash Tests

Data Analysis

Select data to plot using checkboxes.

Linear Fit is optimal Piecewise Linear fit based on prescribed Tolerance.

Place cursor over curves to read out data values.

Spot Weld Impact Tests

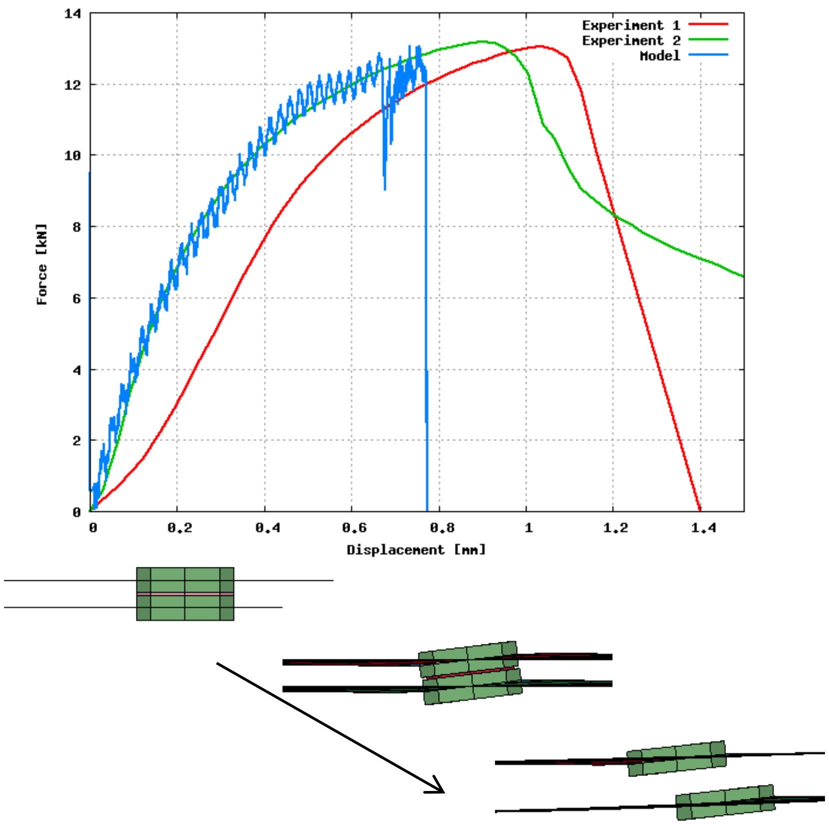
Selected Materials

Data File	Grade [MPa]	Speed [mm/s]	Test Type	Thickness [mm]	Button [mm]	Force [N]	Linear Fit Tolerance [N]
DQSK1CDH001	210	5800	Cross Tension	1	4	☑	Tol 100
DQSK1CDH002	210	5800	Cross Tension	1	4	☑	Tol 100
DP1CDH001	780	5700	Cross Tension	1.15	4.3	☑	Tol 100

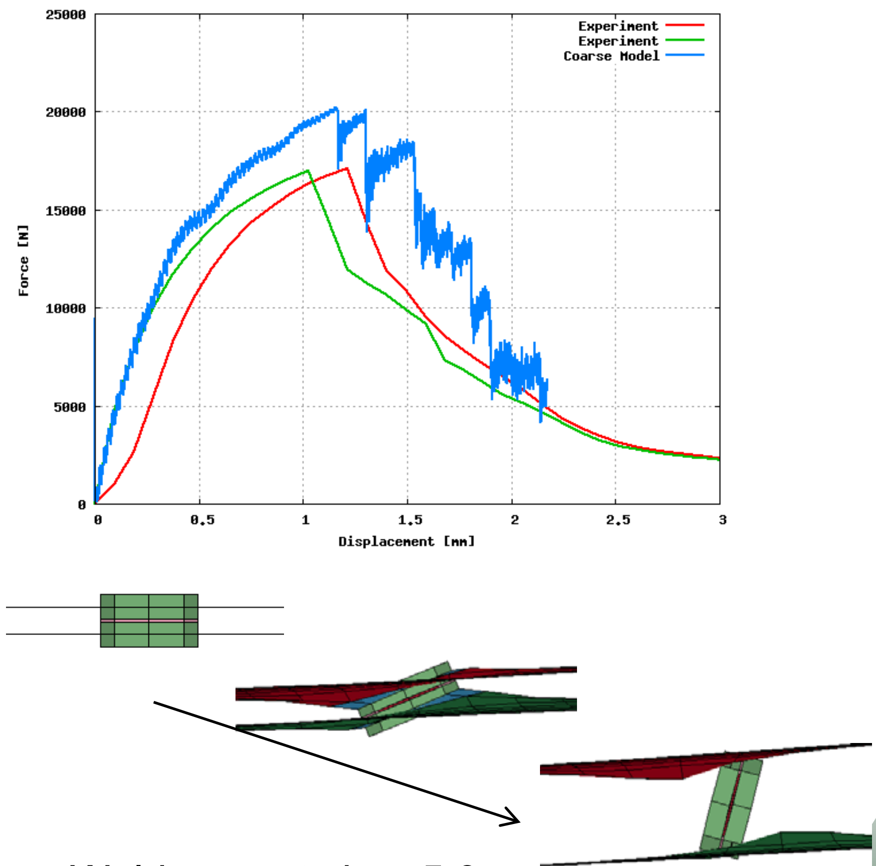
Plot selections Graph will be generated below.

Accomplishments: Simulation of Impact Test

- Our model captures reasonably well the experimentally observed deformation behavior and failure modes

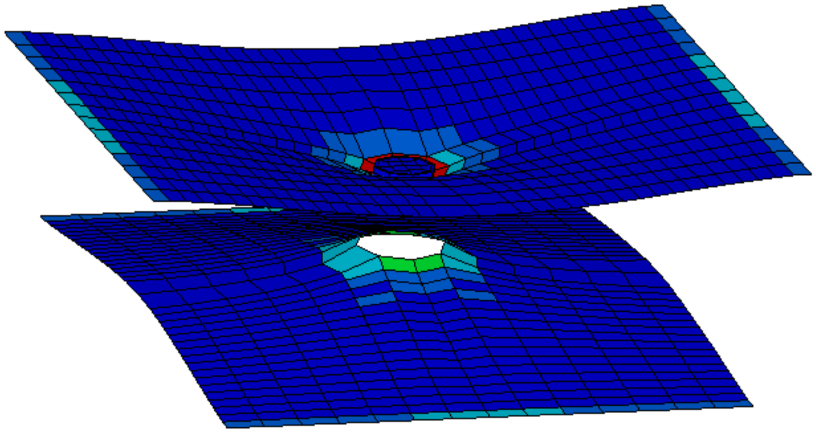


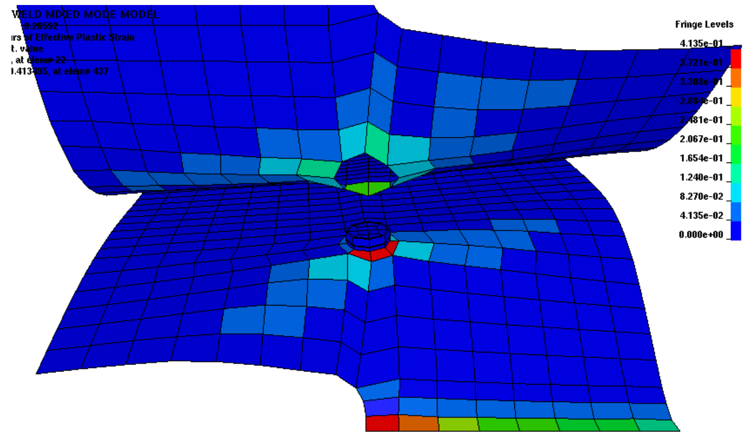
- Weld nugget size: 4.3mm
- Interfacial failure mode



- Weld nugget size: 5.9 mm
- Button pullout failure mode

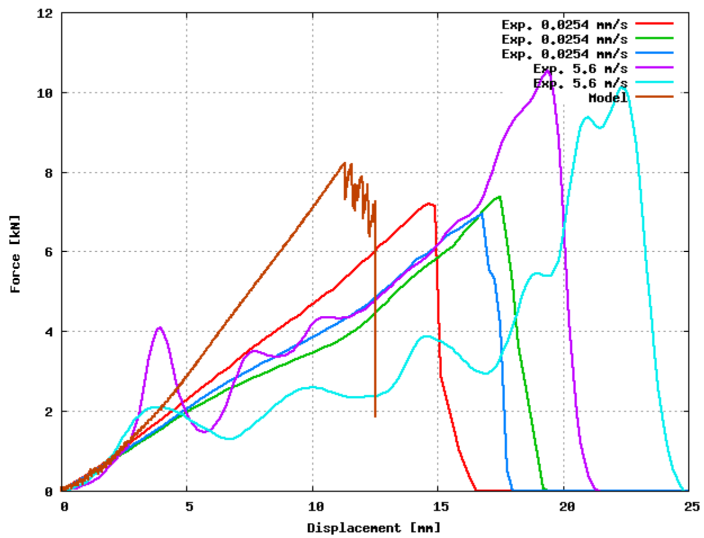
Phase I Accomplishments: Simulation of Impact Tests (Cont'd)

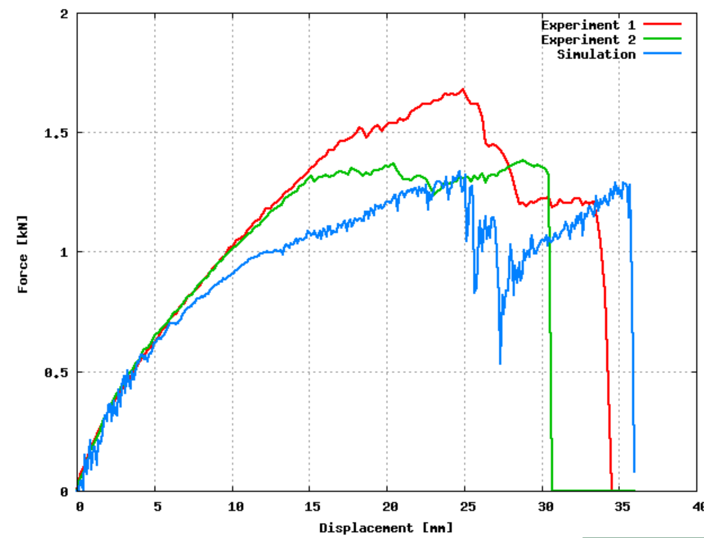




- Cross-tension test. Button pull-out as in experiments

- Mixed loading mode. Button pull-out as in experiments





Summary

- Successfully completed the Phase I concept feasibility development of a new spot weld simulation model for advanced crashworthiness CAE
- Initial version of SWE has been developed
  - Capable of handling weld geometry and property variations in the weld
  - Capable of predicting different fracture modes
  - Computationally robust
  - Has potential for eliminating/reducing extensive tests for new spot weld configurations
- Integrated electrical-thermal-mechanical-metallurgical resistance spot weld model have been developed
  - Capable of predicting weld geometry, microstructure and microhardness distributions in AHSS
  - User inputs are basic welding parameters, sheet thickness and steel chemistry
  - CAE friendly
- Baseline impact test data has been collected
  - Effects of impact speeds and loading modes
  - Web-based data management for interactive data analysis and retrieval

Future Work (Phase II)

- Complete the development of the modeling framework for various AHSS spot weld configurations commonly expected in auto body structures
  - Additional materials, different surface coating conditions, different material combinations, different thickness combinations, edge weld, 3-stacks etc
  - Failure criteria evaluation and development
    - Different failure mode including the effect of HAZ softening
  - Validation on coupon and component tests
- Conduct R&D in close collaboration with OEM modelers
  - Implementation of models in OEM codes
  - Component level demonstration and validation