INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING APPROACH TO DEVELOPMENT OF LIGHTWEIGHT 3GAHSS VEHICLE ASSEMBLY

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United States Automotive Materials Partnership

June 10, 2015

Project ID LM080

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Overview

A/S P Auto/Steel Partnership

Timeline

- Project Start Date: February 1, 2013
- Project End Date: January 31, 2017
- Percent Complete: 42%

Budget

- Total project funding
  - DOE Share: $6,000,00
  - Contractor Share: $2,571,253
- Funding received in FY14 : $1,296,445
- Funding for FY15:
  - DOE share: $1,802,622
  - Contractor share: $772,552

Barriers

A. ***Cost.*** Prohibitively high cost of finished materials is the greatest single barrier to the market viability of advanced lightweight materials for automotive vehicle applications

B. ***Performance.*** Low cost materials needed to **achieve performance** objectives may not exist today

C. ***Predictive modeling tools.*** Predictive tools that **will guide low** cost manufacturing of lightweight automotive structures would reduce the risk of developing new materials.

Participants

Universities/National Labs	Industry
Brown University (BU)	FCA US LLC
Clemson University (CU)	Ford Motor Company (Ford)
Colorado School of Mines (CSM)	General Motors Company (GM)
Michigan State University (MSU)	AK Steel Corporation
Pacific Northwest National Lab (PNNL)	ArcelorMittal
University of Illinois - Urbana Champagne (UIUC)	Nucor Steel Corporation
	U. S. Steel
Consortiums	EDAG, Inc.
Auto/Steel Partnership	Livermore Software Technology Corporation (LSTC)
United States Automotive Materials Partnership	

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Relevance

A/S/P Auto/Steel Partnership

Project Goal:

- To reduce the lead time in developing and applying lightweight third generation advanced high strength steel (3GAHSS) by integrating material models of different length scales into an Integrated Computational Materials Engineering (ICME) model

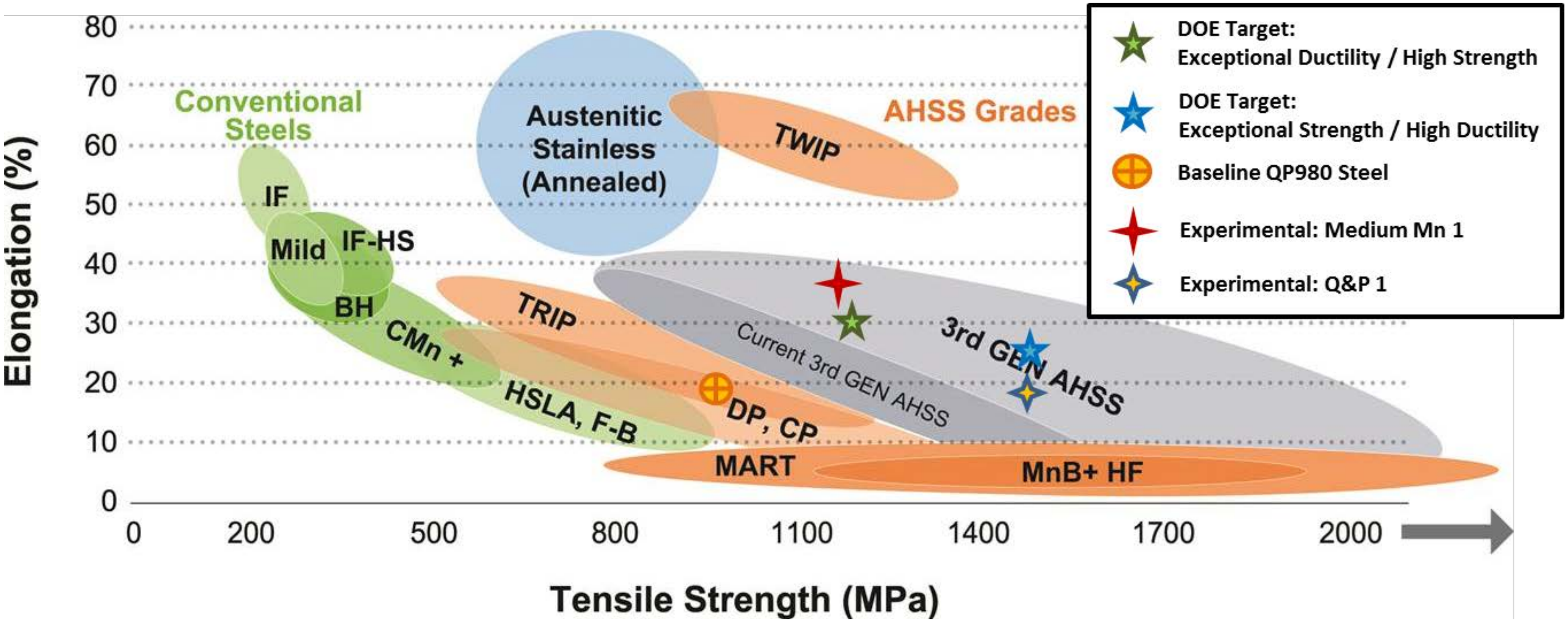
Project Objectives

- Identify, validate (within 15% of experiments) and assemble length scale material models for predicting 3GAHSS constitutive behavior for component forming and performance
- Optimize assembly design using ICME-predicted 3GAHSS model to be **35% lighter** and no more than **$3.18 cost per pound weight saved.**

October 2013 – September 2014 Objectives

- Task 2 “Model Development”: Continue developing material models using experimental results from the QP980 steel as the baseline material
- Produce steel coupons for model validation with mechanical properties within the 3GAHSS ultimate tensile strength (UTS) / elongation space (interim 3GAHSS)
- Task 3 “Forming”: Begin Task 3 (February) and identify forming models to be used to validate the PNNL State Variable Model (SVM) and optimized 3GAHSS component designs
- Task 4 “Assembly”: Outline approach and then assemble the material models.
- Task 5 “Design Optimization”: Define the load cases for the baseline assembly and assess the performance of the baseline side-structure assembly using the defined load cases
- Task 7 “Technical Cost Model”: Complete the baseline technical cost model

Relevance



Elongation (%)
80
70
60
50
40
30
20
10
0
Conventional Steels
IF
Mild
IF-HS
BH
CMn +
HSLA, F-B
Austenitic Stainless (Annealed)
TWIP
AHSS Grades
TRIP
DP, CP
Current 3rd GEN AHSS
3rd GEN AHSS
MART
MnB+ HF
0
200
500
800
1100
1400
1700
2000
Tensile Strength (MPa)
DOE Target: Exceptional Ductility / High Strength
DOE Target: Exceptional Strength / High Ductility
Baseline QP980 Steel
Experimental: Medium Mn 1
Experimental: Q&P 1

Relevance

Predictive Modeling Tools

- Primary deliverable: An ICME model capable of predicting 3GAHSS flow behavior and fracture to:
  - Reduce the time and cost to develop and validate new 3GAHSS alloys
  - Improve the manufacturability of the 3GAHSS automotive components through improved forming simulations
  - Facilitate implementation of 3GAHSS alloys in automotive structures through improved performance modeling
  - Estimate the cost of 3GAHSS components and assemblies

Cost Barrier:

- Will demonstrate the ability to produce 3GAHSS materials at no more than **$3.18 cost per pound weight saved.**

Performance Barrier

- Will demonstrate the viability of 3GAHSS steels to meet vehicle performance requirements while reducing vehicle assembly weight (**35% lighter)**

FY14 Milestones

The project successfully completed two milestones due for the 2014 Fiscal Year.

Milestone #1: 3GAHSS Coupons (Delivered Jan. 31, 2014)

- Outline a plan to manufacture 3GAHSS coupons for model validation.
  - The first iteration of 3GAHSS were made at AK Steel and CANMETMaterials (CMAT) using chemistries provided by CSM for medium manganese and quench and partitioned (Q&P) steels.

Milestone #7:Baseline Assembly Design Defined (Delivered Jan. 31, 2014)

- Characterize the baseline design with respect to performance, materials and mechanical properties.
  - The side structure of a 2008 model year sedan was identified as the baseline assembly.
    - All parts comprising the side structure were identified and characterized in terms of material chemistry, grade and gauge.
    - CAD and FEA models for the side structure and overall body-in-white (BIW) were generated and the load cases defined.

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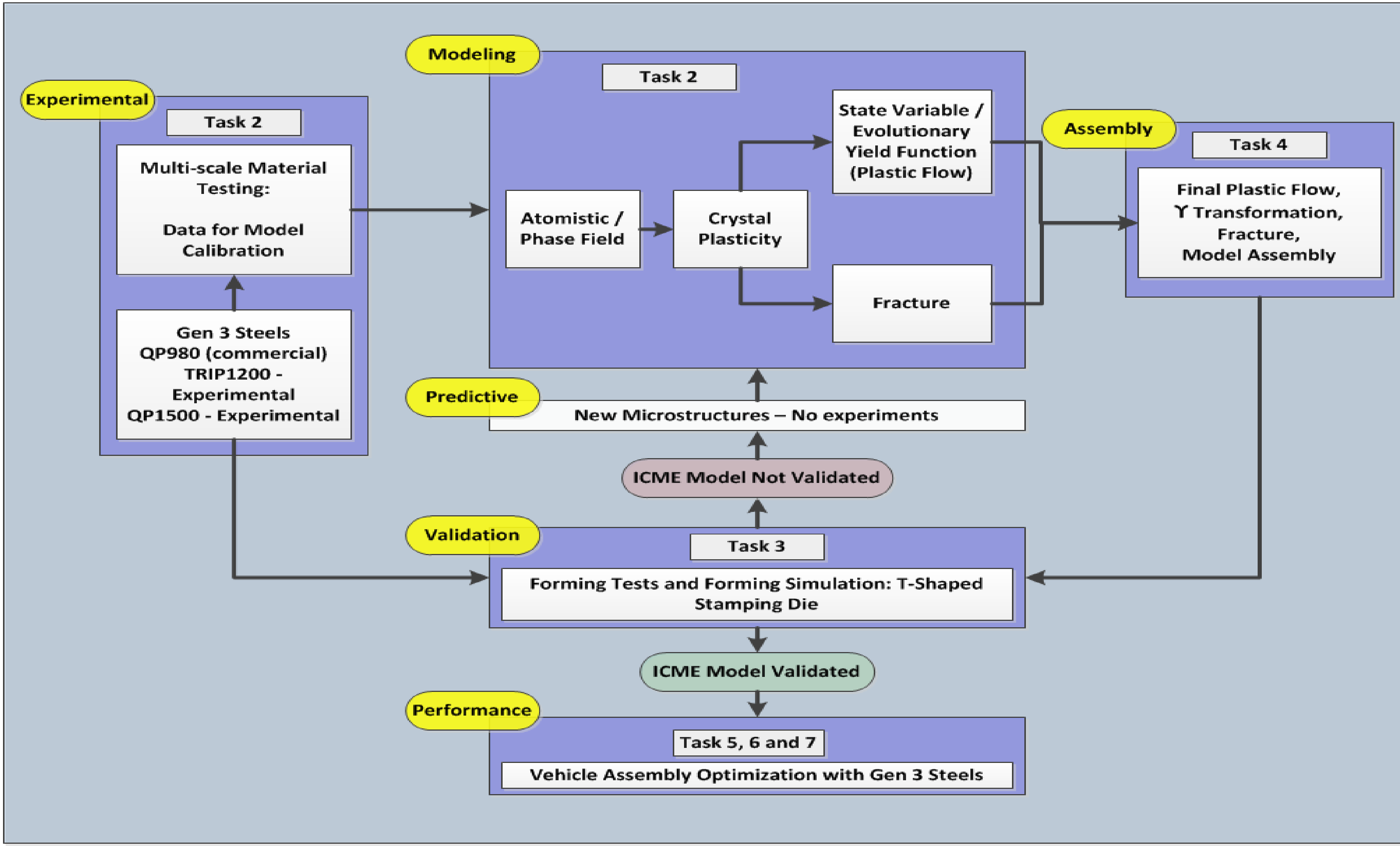
Approach/Strategy

A/S P Auto/Steel Partnership

- An ICME approach specifically aimed at 3GAHSS which will…
  - Further develop existing computational methodologies and tools
  - Enable the development of complete and consistent models both at the component and assembly levels

- A highly collaborative partnership, ***under experienced USAMP consortium and A/SP leadership***, has been created:
  - OEM members: Responsible for system requirements, acceptance criteria and performance targets in the design of 3GAHSS components and automotive assemblies.
  - A/SP steel companies: Responsible for design, manufacture and testing of new 3GAHSS alloys.
  - Universities and national laboratory: Responsible for the development and validation of ICME material models.

Approach/Strategy

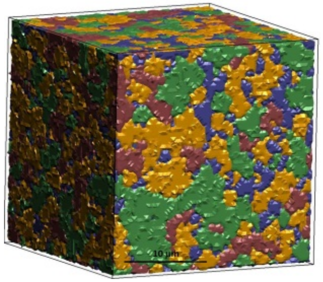


2014 FY Technical Accomplishments and Progress

Task 2: Material Model Development and Validation

- Imported the MSU Crystal Plasticity Model (CPM) and the PNNL solid finite element State Variable Model (SVM) into LS-DYNA as a prelude to model assembly.
- **Developed a three dimensional (3D) representative volume element (RVE) for the baseline QP980 steel**

  The 3D RVEs will enable improved ability to assess anisotropy and microstructural response to strain



- **Used Argonne National Laboratories' (ANL) Synchrotron High Energy X-Ray Diffraction (HEXRD) beam time to measure volume fraction of retained austenite as a function of strain in the baseline QP980 steel.**
  - Existing material models are not currently able to model the transformation of retained austenite as a function of strain, which is an important contributing factor in the strength and ductility of third generation steels.
  - The work at ANL is expected to expand the capability of the AHSS material models to predict the mechanical properties of 3GAHSS.

2014 FY Technical Accomplishments and Progress

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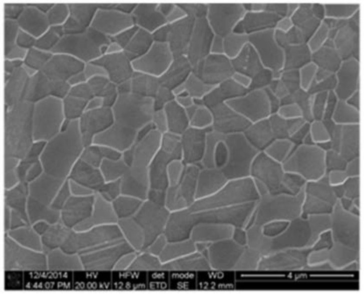
Auto/Steel Partnership

Task 2 – 3GAHSS Coupon Manufacturing

AK Steel Med. Mn 1 Steel

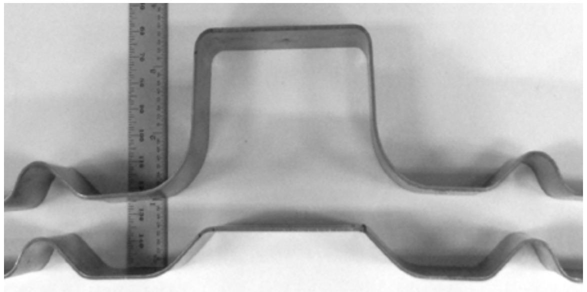


- Hot rolled and cold rolled two 3GAHSS steels at AK Steel using two different processes.
  - **A medium Mn steel achieved the mechanical properties of the high strength, exceptional ductility steel.**
  - A Q&P steel met the tensile strength requirement but did not achieve the ductility requirement for the exceptional strength, high ductility steel.
  - **The mechanical properties of the 3GAHSS coupons are within the 3GAHSS ultimate tensile strength/elongation space and will enable the material models to be effectively calibrated for 3GAHSS**

Mechanical Properties Summary Table	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Tensile Elongation	Uniform Elongation
High Strength, Exceptional Ductility	**≥ 800**	**≥ 1200**	**≥ 30%**	**≥ 20%**
AK Steel Medium Mn 1 Actual Properties (average after surface layer removed)	**750**	**1166**	**37%**	**34%**
Exceptional Strength, High Ductility	**≥ 1200**	**≥ 1500**	**≥ 25%**	**≥ 8%**
AK Steel Q&P 1 Actual Properties	**830**	**1432**	**17%**	

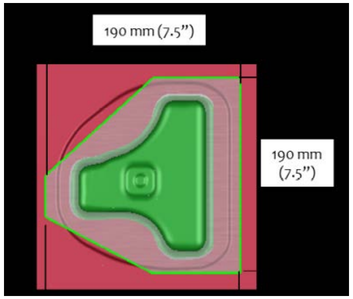
Task 3: Forming Simulation and Validation

- Identified two forming models
  - T-Component
  - U-Channel
- **Designed and built a T-Component Die for forming trials and model validation**
- Defined forming model input criteria from material models



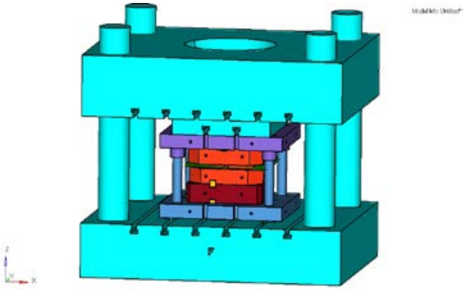
Draw Stretch and Stretch

Bend U-Channel



T-Component Blank

U-Channel Die



T-Component Die

2014 FY Technical Accomplishments and Progress

Task 4 / 6: Assembly and Integration

- Created a framework linking the CPM and SVM and calibrated the assembled material models against the baseline QP980 steel. (**MILESTONE #2**)
- LS-DYNA PNNL State Variable Model
- Multi-level/Multi-stage optimization features in LS-OPT which include:

Task 5:

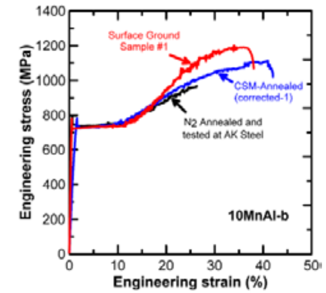
- Identified the loading cases for the baseline side-structure assembly
- Completed the baseline performance assessment for the side-structure assembly using defined load cases

Task 7:

- Completed the baseline technical cost model

Collaboration and Coordination with Other Institutions

- Project participants: (see Slide 2)
  - Five universities
  - One national laboratory
  - Four steel companies
  - Three automotive OEMs
  - Two companies from supporting industries.

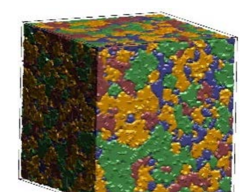


AK Steel Med. Mn 1 Flow Curve (3GAHSS)

- Due to the number of participants, highly leveraged cross-functional task teams have been formed.
  - Examples of integration through collaboration:
    - MSU / BU: 3D RVEs
    - CU / PNNL / GM: HEXRD at ANL
    - A/SP / AK Steel / CSM / PNNL: 3GAHSS coupon creation
    - CU / MSU / PNNL / LSTC: Material model assembly
    - BU / CU / MSU / PNNL: Material model calibration
    - A/SP / GM / EDAG: Side structure baseline performance characterization
    - PNNL / Task 2: Use of PNNL SharePoint website for document storage

CMAT Hot Band Steel


Side-Structure Assembly


3D RVE simulation

Proposed Future Work

For the period October 2014 – September 2015

- **Task 2: Material Model Development and Validation**
  - Complete material model development and calibration with baseline QP980 steel and begin calibration of the models using experimental results from 3GAHSS coupon testing.
  - Cold and hot roll remaining 3GAHSS ingots at CMAT.
  - Identify fracture models and begin process of validating the fracture models
  - Apply digital image correlation to Synchrotron HEXRD to evaluate microstructural response to strain for QP980, medium Mn and Q&P steels.
- **Task 3: Forming Model Development and Validation**
  - Begin baseline QP980 forming trials with the T-Component die and U-Channel die to validate the assembled material models and forming simulations
  - Begin process of aligning and Integrating forming model with material models and design optimization
- **Task 4: Model Assembly**
  - Refine assembled ICME material models with optimization loops using defined input/output parameters for each material length scale model
  - Provide initial 3GAHSS predictions using assembled material models

Proposed Future Work

For the period October 2014 – September 2015

- **Task 5: Design Optimization**
  - Perform a sensitivity analysis to determine which components of the side-structure assembly contribute the most to torsional and bending stiffness.
  - Evaluate the strategic substitution of 3GAHSS and its impact on side-structure assembly and vehicle performance
  - Identify focal components for conversion to 3GAHSS
  - Evaluate the potential of the DOE FOA 3GAHSS to reduce component and assembly weight through improved mechanical properties and gauge optimization

- **Task 6: Integration**
  - Develop ICME framework to integrate material models, forming models and design optimization

- **Task 7: Technical Cost Modeling**
  - No work planned for this period of performance

Summary

- The first year of the project focused mostly on the following:
  - Material testing to develop the baseline constitutive material property information
  - Model development to adapt existing material models for AHSS
  - Identification and characterization of the baseline side-structure assembly
- The second year of the project continued to define baseline conditions but began expanding experimental work into 3GAHSS with the following accomplishments:
  - Assembled and calibrated the material models using the baseline QP980 steel data.
  - Identified a T-Component die and U-Channel die for validating material and forming models
  - Produced hot and cold rolled 3GAHSS coupons
  - Characterized the performance of the baseline side-structure assembly against defined load cases
- The third year of the project will begin the transition toward integration across all tasks with emphasis on the following areas
  - Testing of 3GAHSS to develop constitutive material property information.
  - Initial calibration of the assembled material models using 3GAHSS material property data
  - Use of the Task 3 forming model and forming trials to validate the assembled material models
  - Integration of the material and forming models and alignment of integrated models with design optimization.
  - Generate 3GAHSS predictions using preliminary ICME model

Response to Reviewers' Comments

Q1: Approach to performing the work - the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts.

- A Reviewer asked for the team to clarify Task 4 and make the presentation slides consistent.
- **RESPONSE:** Task 4: Assembly was clarified as requested. Task 4 Assembly is focused on the assembly of material models and not manufacturing joining.

- A reviewer requested a description of the size of 3GAHSS heats made in this project.
- **RESPONSE:** The experimental heats used to develop 3GAHSS process recipes were small (under 5 pounds) but the heats made at AK Steel were approximately 50 pounds and the heats made at CMAT were approximately 450 pounds.

- A reviewer suggested that the approach shown in Slide 10 of the 2014 presentation was too complicated.
- **RESPONSE:** A simplified chart that covers all project tasks has been substituted in this presentation.

Response to Reviewers' Comments

Q2: Technical accomplishments and progress toward overall project and DOE goals – the degree to which progress has been made, measured against performance indicators and demonstrated progress toward DOE goals.

- A reviewer requested an example of how characterization of QP980 could be used in formability modeling.
- **RESPONSE:** The characterization of QP980, in terms of tensile and compression flow curves and forming limit diagrams, will provide constitutive mechanical property information from which material models (crystal plasticity, state variable, and evolutionary yield function) can be developed and validated. The models will include the transformation kinetics of retained austenite transforming to martensite as a function of strain. These multi-level physics models will be used in finite element simulation of manufacturing processes and component response to forming events (i.e. stretch, stretch bending, etc.).

- A reviewer requested an update on progress to prediction uncertainty of the ICME models (goal is 15%) and a risk assessment as to whether the project team will be able to meet that goal.
- **RESPONSE:** PNNL calibrated the state variable model using QP980 experimental data and was able to predict the flow curve of QP980 in good agreement with experimental results. The team expects that similar results will follow with the exceptional strength, high ductility steel which uses a similar quench and partitioning process. No estimate is currently available for the high strength, exceptional ductility material as there are currently no models available that account for austenite transformation during deformation and that account for the competing deformation mechanisms of twinning and transformation induced plasticity.

Response to Reviewers' Comments

Q3: Collaboration and coordination with other institutions.

- The reviewer asked whether foreign participation was considered.
- **RESPONSE:** The emphasis on the project was to maximize domestic participation since the project is funded by the United States Department of Energy. However, CMAT has been contracted to make experimental 3GAHSS coupons using less than 2% of the total project funds.

- A reviewer commented that given the funding executed thus far that there may have been some initial hiccups in operationalizing the planned communication
- **RESPONSE:** There were some delays in finalizing agreements with some of the sub-recipients and vendors that delayed the start of work but did not impact the timing of project milestones.

Response to Reviewers' Comments

Q4: Proposed future research – the degree to which the project has effectively planned its future work in a logical manner by incorporating appropriate decision points, considering barriers to the realization of the proposed technology, and, when sensible, mitigating risk by providing alternate development pathways.

- A reviewer requested clarification on the technical barriers expected in future work, a risk mitigation plan and a slide focusing on technical details.
- **RESPONSE:** Slides 28 and 29 discussing risks were added to the reviewer only section.

- A reviewer requested revisiting the approach.
- **RESPONSE:** The project team continues to revisit the approach in Project Coordination and Integration Team meetings to better clarify the approach at the sub-task level and to insure integration at the task level. The Approach/Strategy section was modified to better show the high-level approach and project organization.

Q5: Does this project support the overall DOE objectives of petroleum displacement? Why or why not?

- No reviewer questions requiring a response.

Q6: Resources: How sufficient are the resources for the project to achieve the stated milestones in a timely fashion?

- No reviewer questions requiring a response.

Technical Back-Up Slides

2014 FY Technical Accomplishments and Progress

Task 2 - Accomplishments by Sub-Recipient (condensed):

- **Brown University (BU)**
  - Using macroscopic testing, high resolution EBSD and TEM together on 201LN stainless steel, BU developed a methodology to extract the deformation-induced transformation characteristics of austenite.

- **Clemson University (CU)**
  - Using a wide array of mechanical testing and microstructural examination approaches, and aided by digital image correlation, CU studied and characterized the behavior of the starting material QP980 (as well as other AHSSs). CU supplied the extracted data to other sub-recipients as needed in support of their modeling efforts.

- **Colorado School of Mines (CSM)**
  - Provided the 3GAHSS process steps for making the medium Mn and Q&P steels at AK Steel and CMAT.
  - Identified process steps that were adversely affecting the mechanical properties of the medium Mn steel and provided recommendations for improvement.

2014 FY Technical Accomplishments and Progress

Task 2 - Accomplishments by Sub-Recipient (condensed):

- **Michigan State University (MSU)**
  - Developed and implemented an austenite to martensite phase transformation model for multi-phase steel (3GAHSS).
  - Developed a 3D RVE for QP980 based on two-point-correlation function.
  - Validated the predictive capability of the CPFEM simulation using experimental uniaxial tension test data.
- **Pacific Northwest National Laboratories**
  - Developed and verified the state variable model (SVM) for QP980.
  - Developed EPSC and crystal plasticity based analyses with in-situ HEXRD test results to characterize individual phase properties in QP980.
  - Co-developed an in-situ DIC/HEXRD method in quantifying austenite transformation kinetics with true strain.
- **University of Illinois (UIUC)**
  - Implemented a 3D phase-field model with elastic strain-energy contributions for predicting martensitic phase transformations in steel;
  - Computed substitutional and interstitial solute size-misfits in ferromagnetic bcc Fe to determine the effect of solutes on lattice parameters and elastic constants

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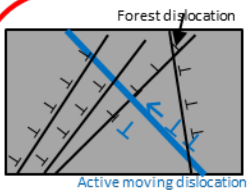
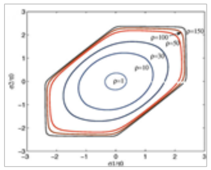
Michigan State University

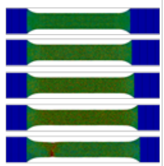
Computational Approach for Modeling 3GAHSS

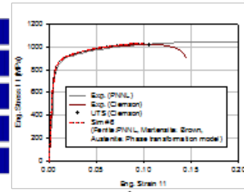
Crystal Plasticity Model



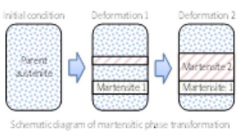


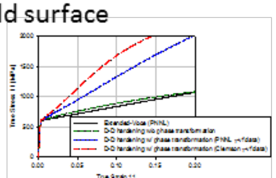
Rate-independent crystal plasticity with smooth yield surface



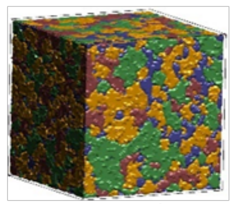


Uniaxial tension simulation



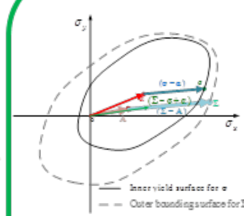


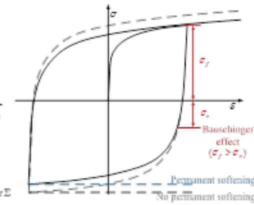
Martensitic phase transformation model



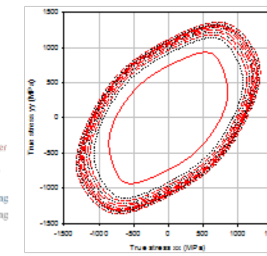
3D RVE simulation

Phenomenological model



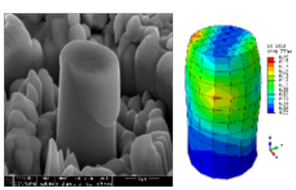


Two-yield surface iso-kine hardening model

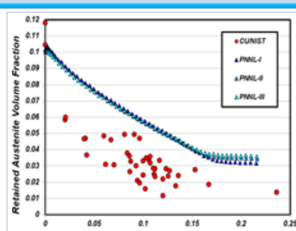


Evolutionary yield function

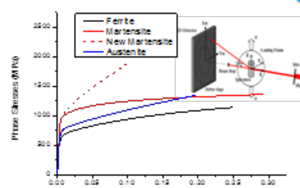
Micro-scale simulations & experiments



Micro-pillar compression (Brown)

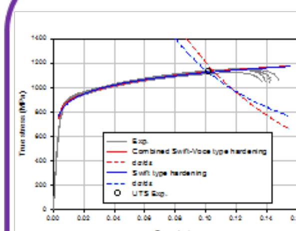


Volume fraction evolution (Clemson Univ. and PNNL)

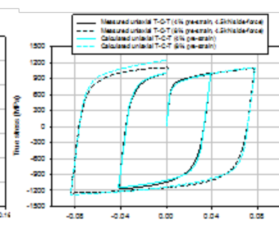


HEXRD and EPSC (PNNL)

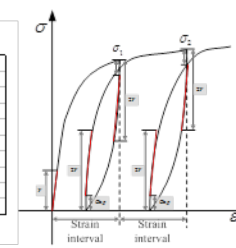
Macro-scale experiments



Uniaxial tension (Clemson Univ.)



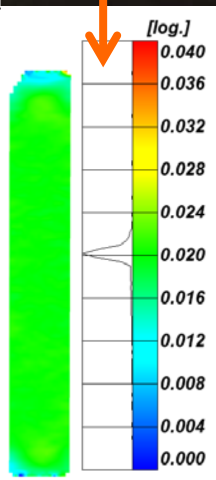
Uniaxial T-C-T and C-T-C (Clemson Univ.)



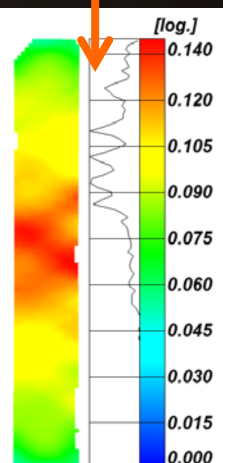
Uniaxial T-U-T (Clemson Univ.)

Clemson University
RAVF Measurements

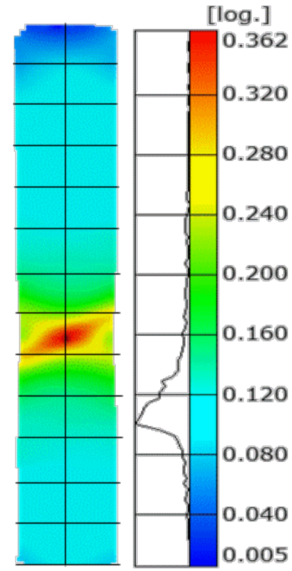
A new approach for accurate RAVF measurements with the aid of DIC

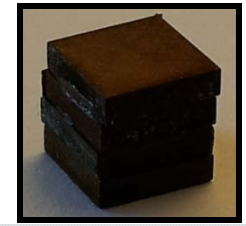


Strain map @ 0.02



Strain map @ 0.1

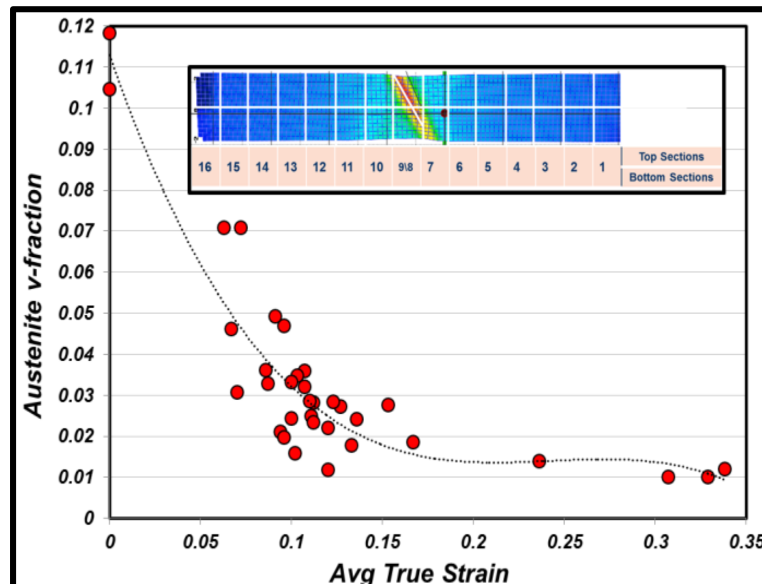




0deg PS0.02-1 (GS-A1 avg Ɛ: 0.02004)								
	T1	T2	T3	T4	T5	T6	T7	T8
Avg Ɛ	0.01979	0.02053	0.02041	0.02069	0.02068	0.02066	0.02029	0.02007
	B1	B2	B3	B4	B5	B6	B7	B8
Avg Ɛ	0.02012	0.02021	0.02042	0.02034	0.02041	0.02019	0.02047	0.02048

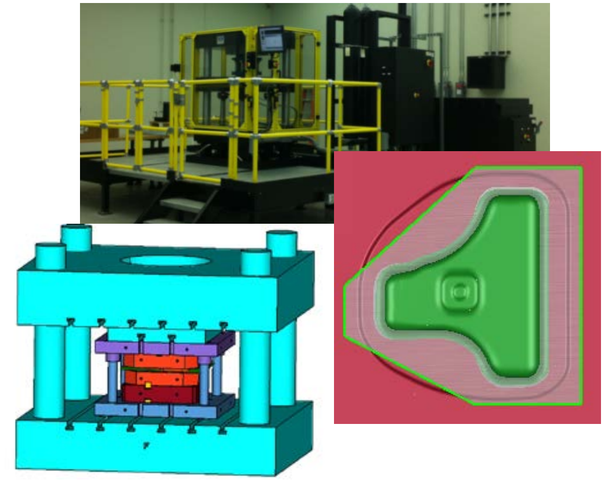
Example of a specimen stack and the corresponding strain measurements

Specimens are prepared based on the localized strains measured using DIC, then RAVF is measured using neutron diffraction at NIST



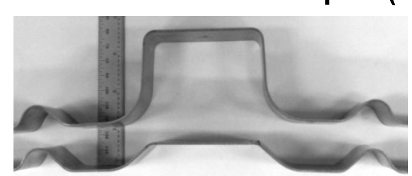
Task 3: Forming – Component-Scale Performance Prediction and Validation

- The Task 3 team selected a U-Channel component and a T-Component models for forming simulation.
  - A U-channel die is available at ArcelorMittal for forming simulation validation.
  - A T-Component Die is being built by A/SP for T-Component forming simulation validation.
- Forming simulations will begin with the QP980 steel and then progress to 3GAHSS.
  - The inputs to the forming simulations include:
    - mechanical properties including compression / tension testing data
    - microstructure based material model: micropillar compression testing, TRIP effect (austenite transformation during forming)
    - forming limit diagrams via digital image correlation and fracture criteria
    - Die geometry and various shape blanks
    - Process variables: binder force, friction
- The validated forming models will be integrated with the length scale material models from Task 2 and the Task 5 Design Optimization



T-Component die and hydraulic press at AK Steel

U-Channel die and part (ArcelorMittal)



Draw stretch sample

Stretch bend sample