Development of 3rd Generation Advanced High Strength Steels (AHSS) with an Integrated Experimental and Simulation Approach

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Project ID#: LM082

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Overview

▶ Timeline
- Start: Oct. 2010
- End: Sep. 2014
- 85% Complete

▶ Budget
- DOE - $1,200K
  - FY11 - $400k
  - FY12 - $400k
  - FY13 - $300k
  - FY14 - $100k
- Industries (in-kind) - $300K
 - ASPPRC - $100k/YR FY11 – FY13

▶ Barriers
- Further vehicle weight reduction requires 3rd GEN AHSS with excellent strength, ductility and low cost
- Lack of quantitative understanding on the relationship between processing routes and material properties
- Lack of understanding on the fundamental relationships between AHSS microstructural features and the global and local deformation mechanisms

▶ Partners
- Advanced Steel Processing and Products Research Center
- Colorado School of Mines

Project Objectives and Technical Approaches

- As the application of 2nd GEN AHSS may be limited due to its economic considerations, 3rd GEN AHSS concepts are being pursued vigorously to identify lower alloy steels which achieve ultra-high strength properties with good formability.

- The purpose of this project is to *improve overall understandings* on the material parameters which control the mechanical properties of new AHSS products in order to accelerate the development of the 3rd GEN AHSS.

- Steels with *good strength (1200MPa UTS) and excellent ductility (30%)* are the property goal along with a consideration of cost targets of this class of materials.
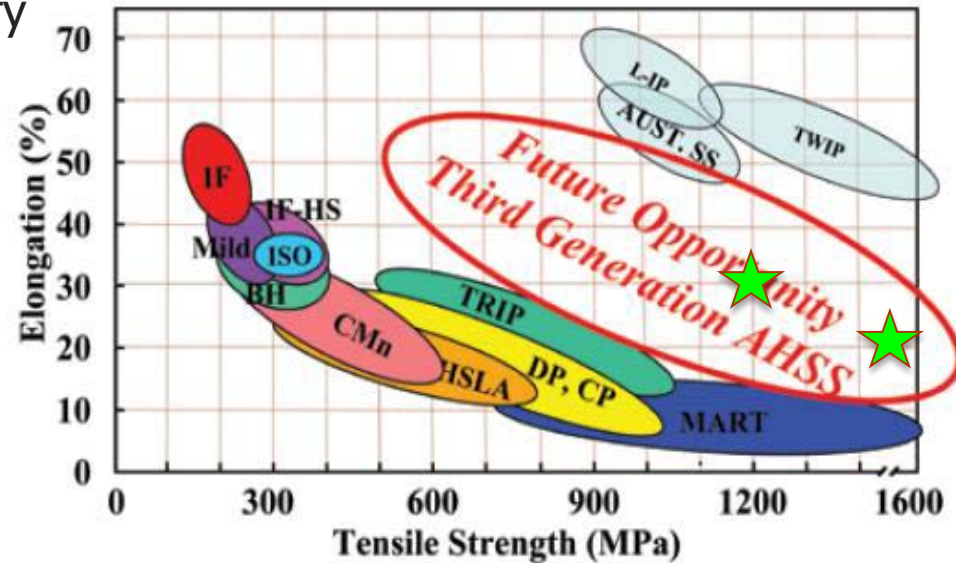
- Develop alloy compositions and processing parameters for model steel
- Perform macro- and micro-scale property characterizations of model steels generated
- Determine transformation kinetics and mechanical properties of each phase
- Perform microstructure-based finite element analyses for property prediction and property improvements

Deliverables
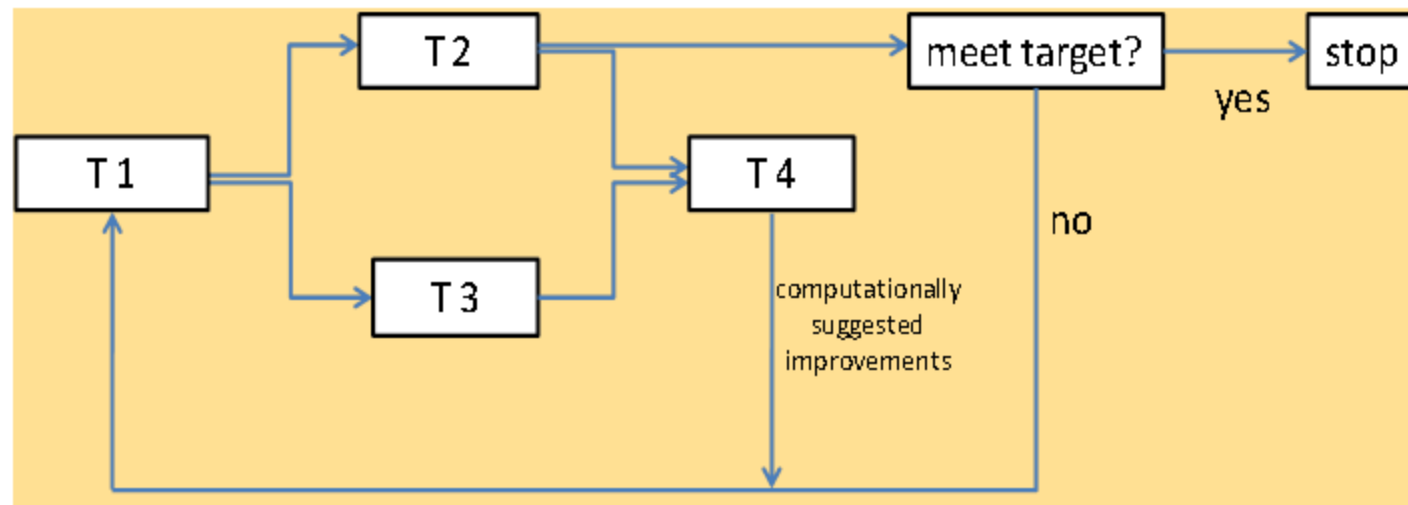
► A validated integrated experimental and simulation framework for the development of multi-phase 3rd Generation AHSS (Sept. 2014).

► Candidate 3rd Generation AHSS material systems with *good strength (1200MPa UTS) and excellent ductility (30%)* (Sept. 2014).

Mat	Chemistry	Annealing (°C/s)	Quenching (°C/s)	Partitioning (°C/s)
QP1(Mat1)	0.3C-3Mn-1.6Si	820/120	180/10	400/100
QP2(Mat2)	0.2C-3Mn-1.6Si	840/120	250/10	400/10
QP3(Mat3)	0.2C-3Mn-1.6Si	840/120	250/10	400/100
QP4(Mat4)	0.2C-3Mn-1.6Si	725/120	185/10	450/10

1st Heat Q&P steels

S-E curves of 1st Heat Q&P steels

Example of SEM (QP3)

FE model (QP1)

Aust.(19%)+UT. Mart.(18%) +T. Mart
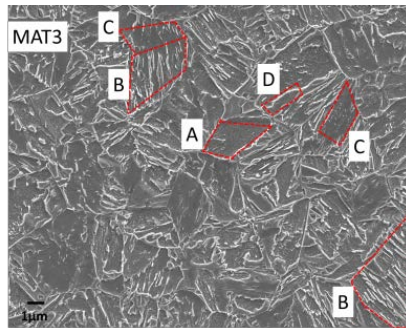
Est. Input Properties from hardness
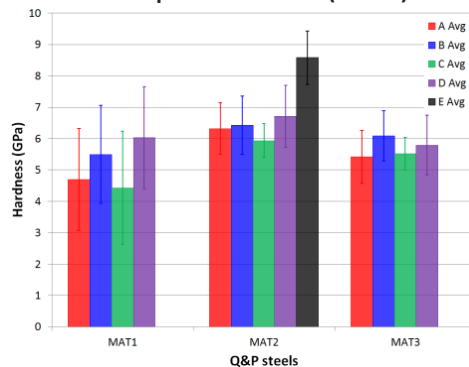
Hardness from nanoindentation

FE model (QP2)

Aust.(1%) +UT. Mart. (65%) +T. Mart.

Predicted S-E curves

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- ▶ Materials: QP1(Mat1), QP2(Mat2), QP3(Mat3)
- ▶ Calculated austenite volume fractions and lattice strains along LD from in-situ tensile HEXRD test.
- ▶ Developed Elastic Plastic Self-Consistent (EPSC) model to determine the constituent phase properties
- ▶ Limitations: Phase transformation and bainite, not considered
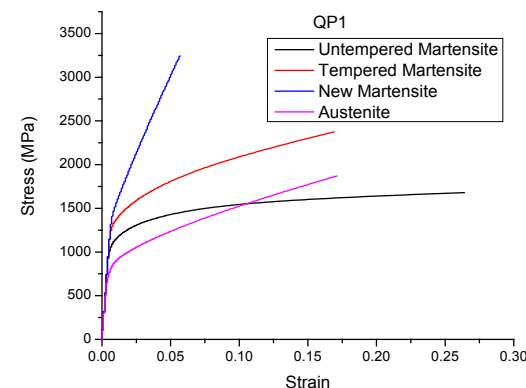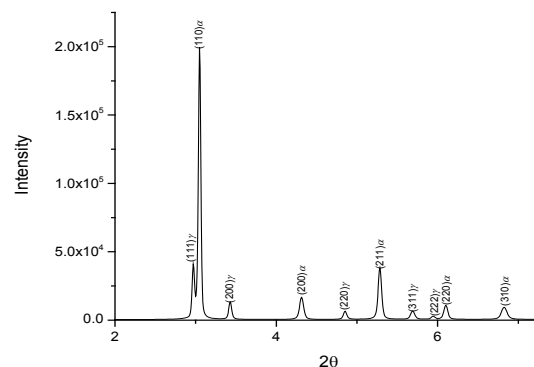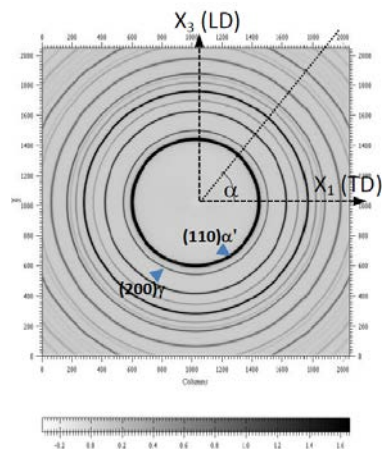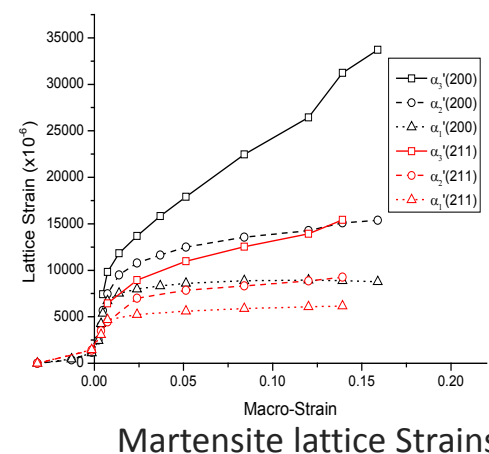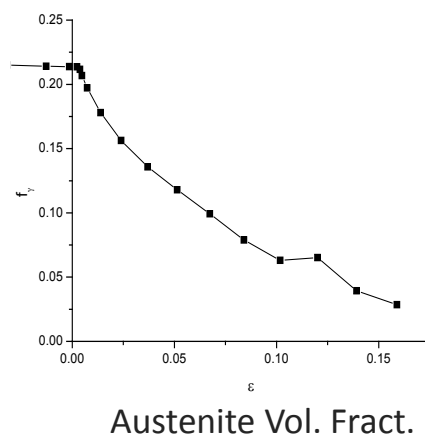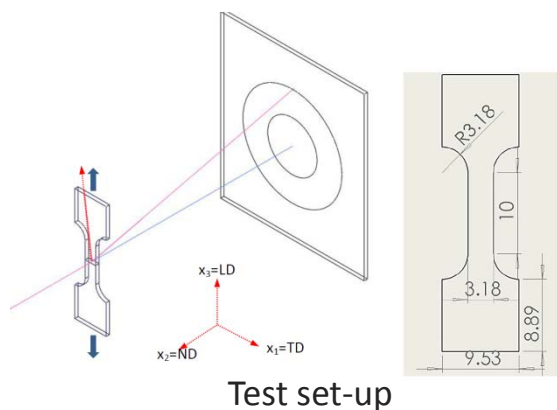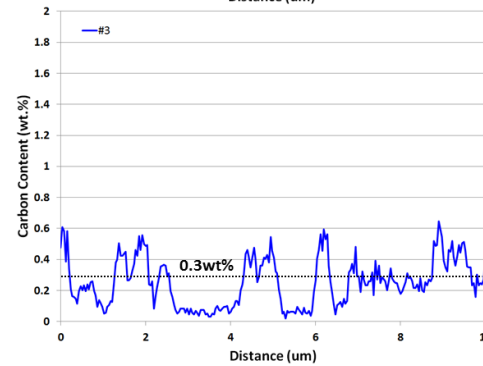

Test set-up

Austenite Vol. Fract.

Martensite lattice Strains

Recorded Diffraction Rings

Intensity-2θ profile integrated from the rings

Phase Stress-Strain Curves (QP1)

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Hu et al., Journal Paper in preparation.
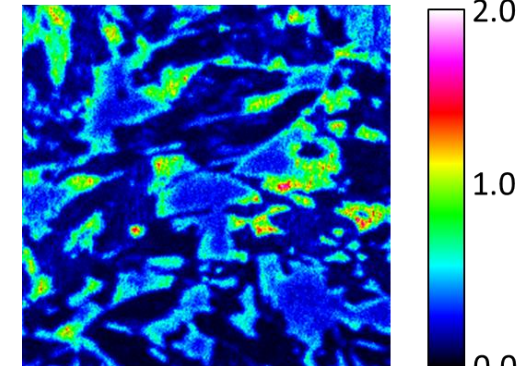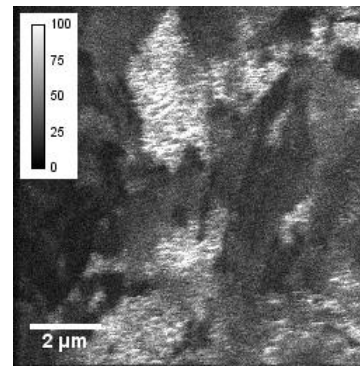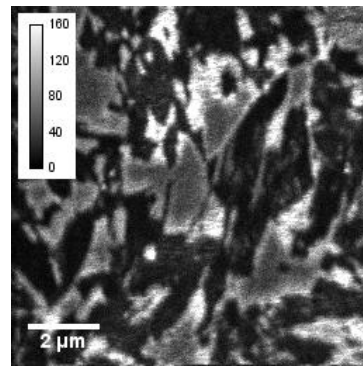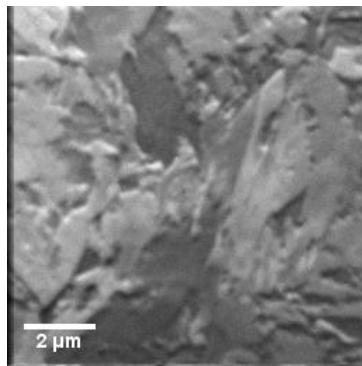
Nano-SIMS results (SEM, C counts, Si Counts)

C concentration in wt%
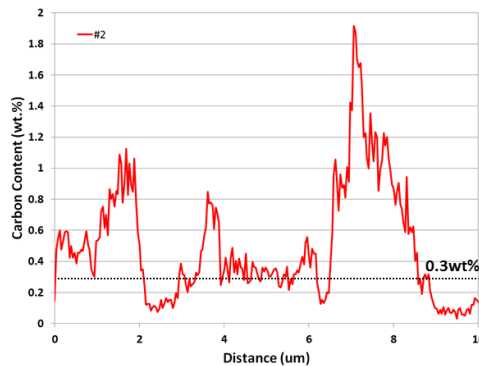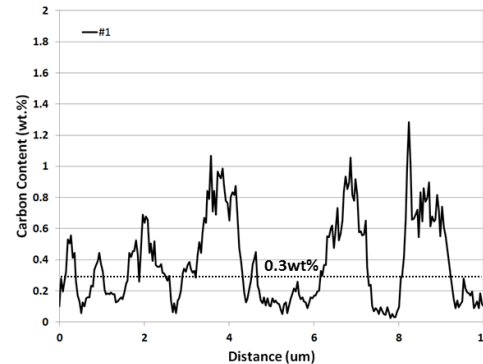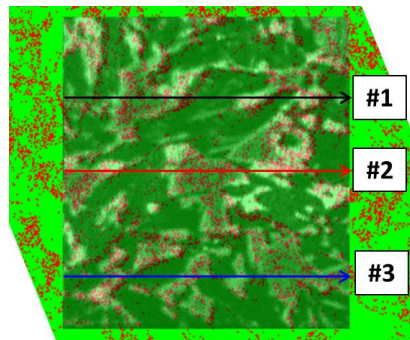
Overlay of C count on EBSD/Line scans of C distributions

▶ Microstructure-based FE model was upgraded so that variable stability within Aust. grains can be considered.

Variable stability within Aust. grains

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Choi et al., Journal Paper in preparation.
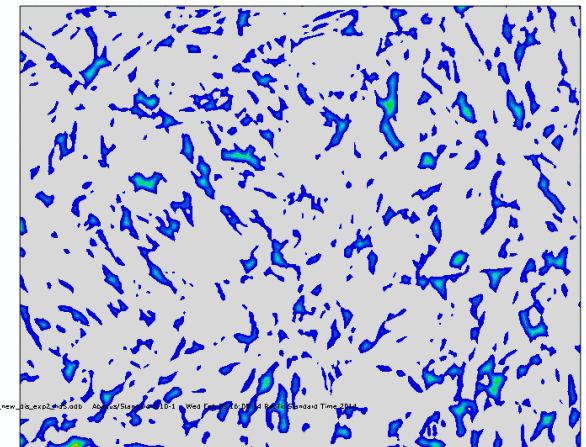
PNNL, CSM Technical Accomplishments - Microstructure-based FE Modeling (1)

▶ EBSD phase map and SEM were used to group the grains with the same phase properties.

▶ In the simulations, the same phases are assumed to have the same properties based on the preliminary S-E curves from HEXRD.

QP1
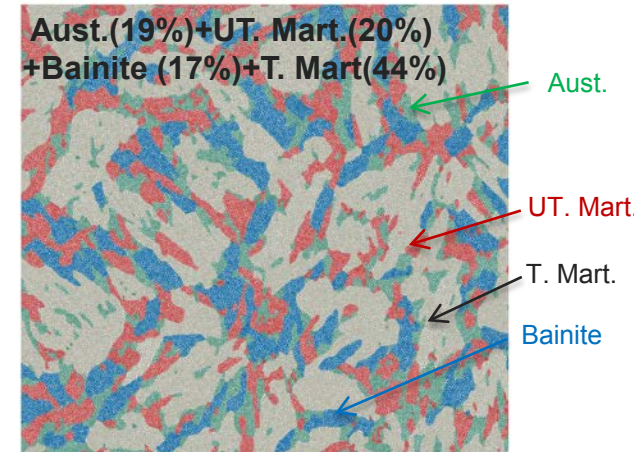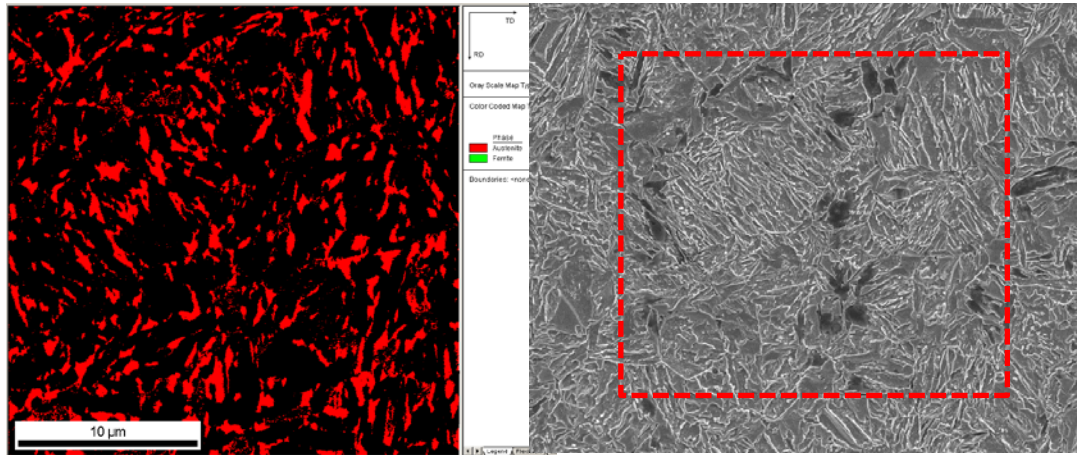
QP3
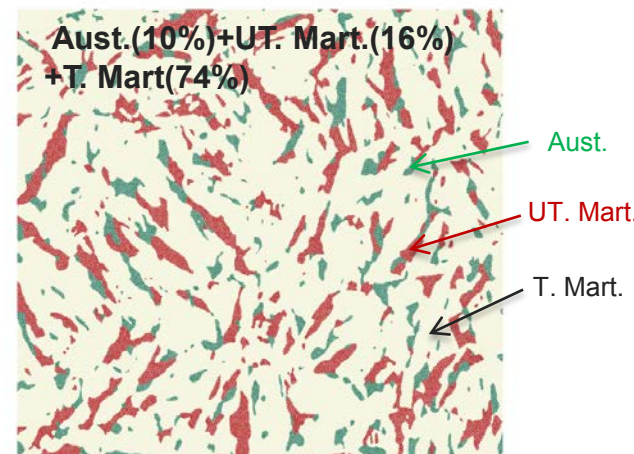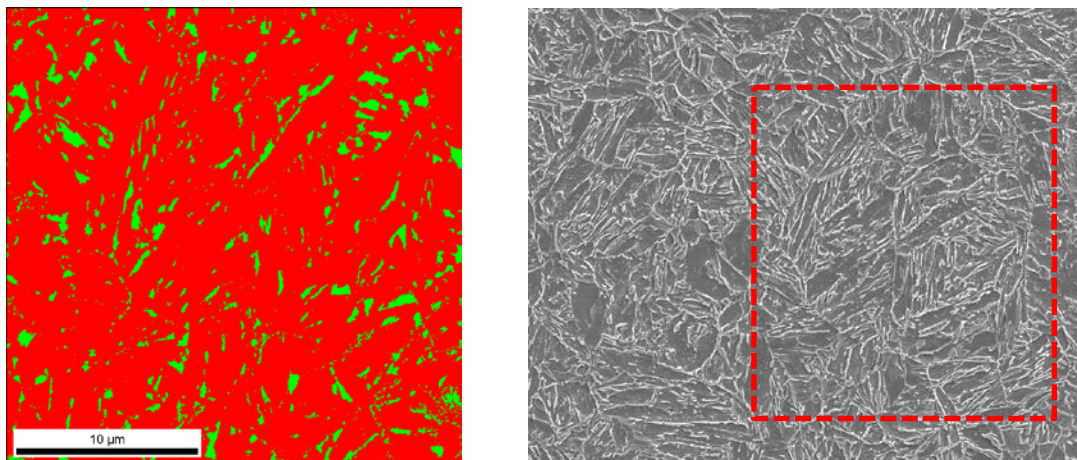
Austenite phase map

SEM of the same region

Model

▶ Transformation yield function for martensitic transformation*

Π is compared with Πc which may be related to the austenite stability

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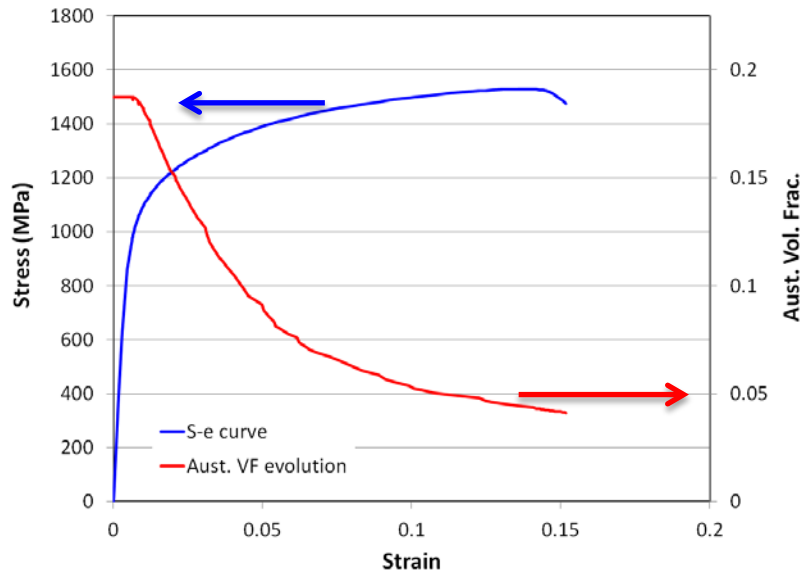
Martensitic transformation
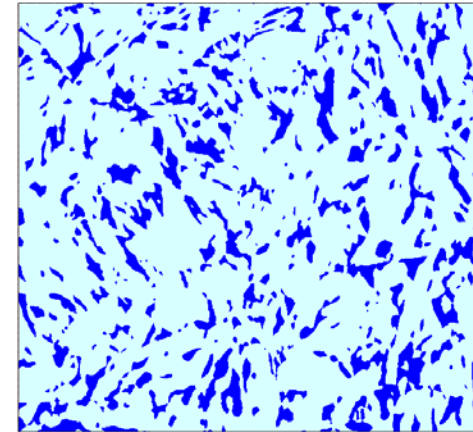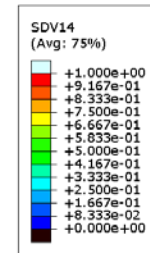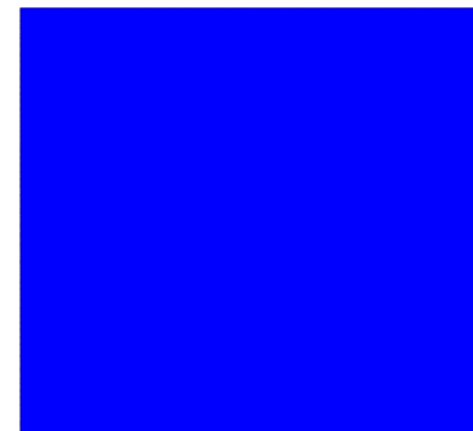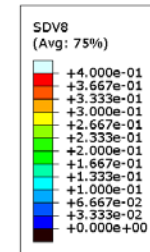
Model response

PEEQ distribution

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* Choi et al., Acta Mat. 57(8),2592-2604,2009.
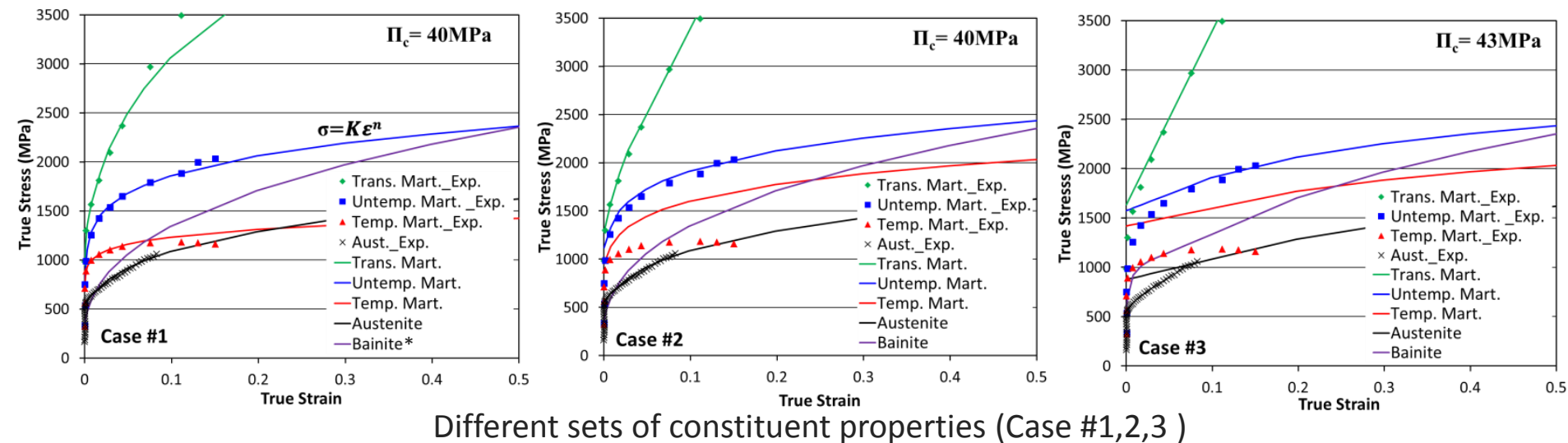
Different sets of constituent properties (Case #1,2,3)

▶ The fitting was started with the preliminary S-E from HEXRD.

▶ The constituent properties were determined by adjusting the initial S-E and fitting the model response to the experiment.
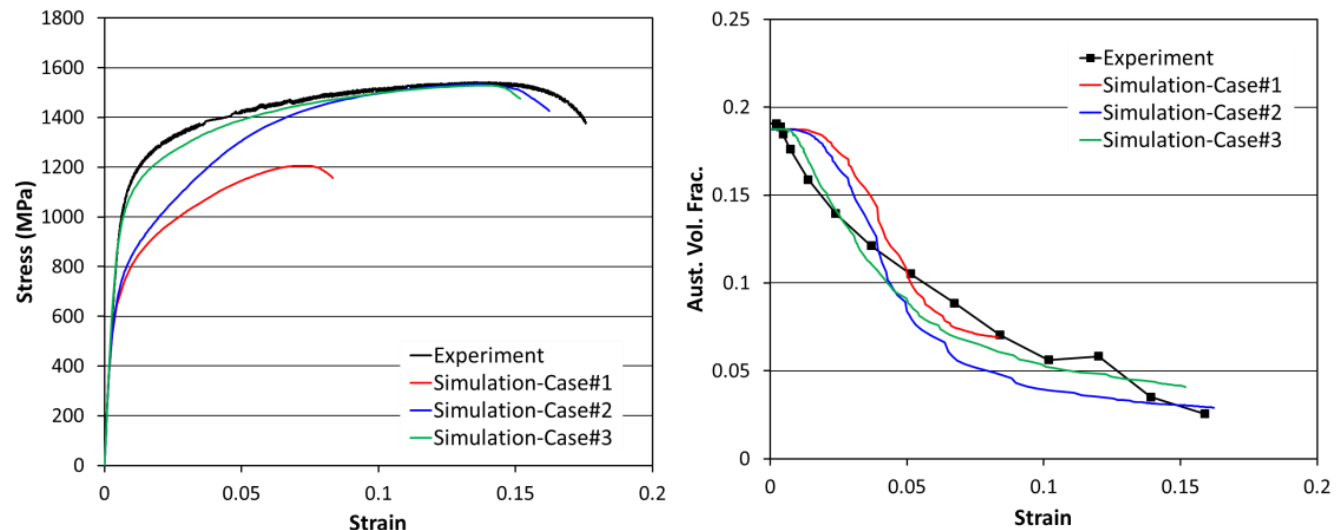
Effects of different constituent properties on S-E and austenite transformation

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* Choi et al., Acta Mat. 57(8),2592-2604,2009.

Choi et al., SAE paper #2014-01-0812, 2014.

▶ Holloman type S-E relation was used for the constituent properties.

▶ Separate effects of each parameter were examined by varying K (±12%), n (±20%), etc.

▶ Strength difference between Temp. Mart. and Untemp. Mart.

▶ Hardening exponents of Temp. Mart. and Untemp. Mart.

▶ Austenite strength   Austenite Stability

▶ New Mart. Strength

▶ Bainite volume fraction
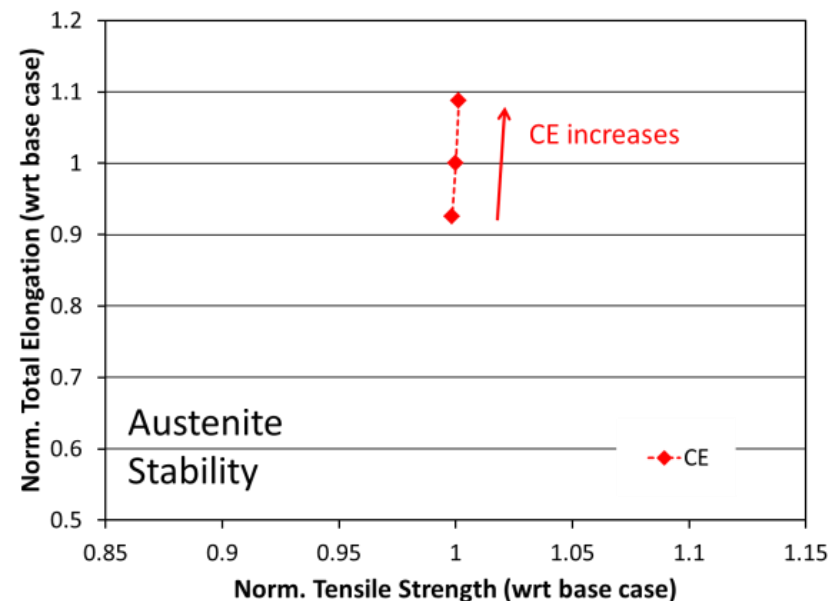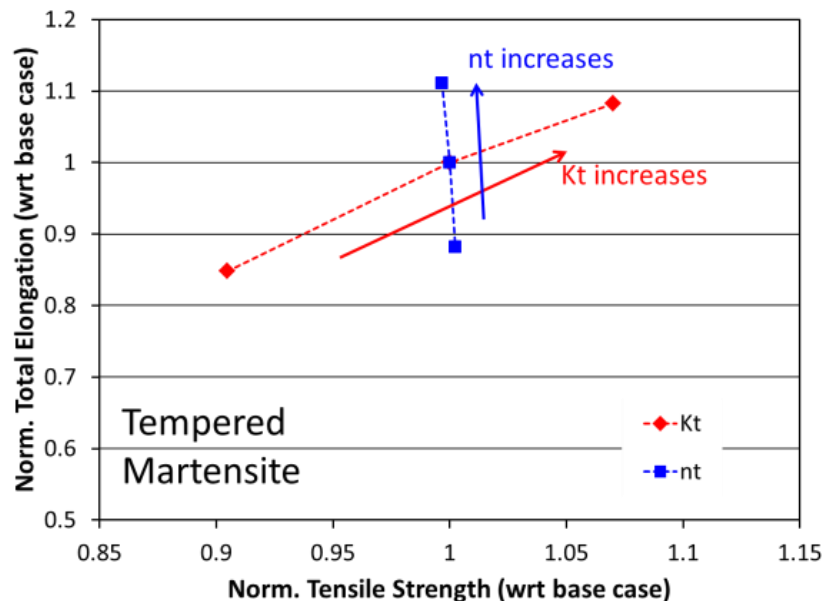
Examples of material parameter effect

$$\sigma = K\varepsilon^n$$
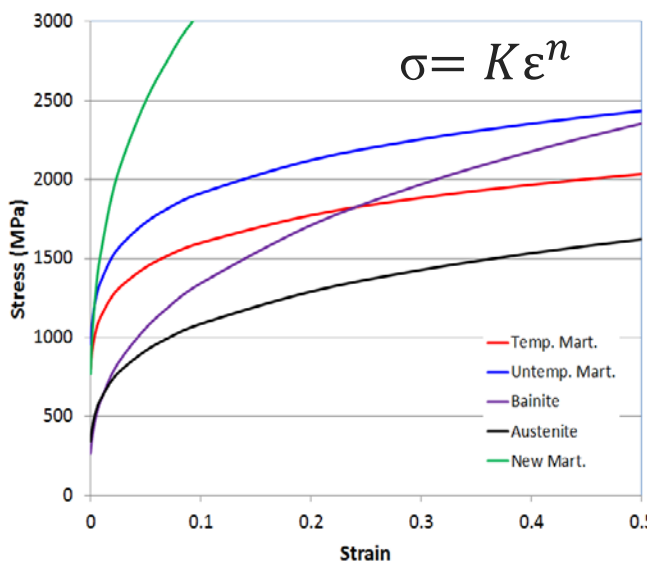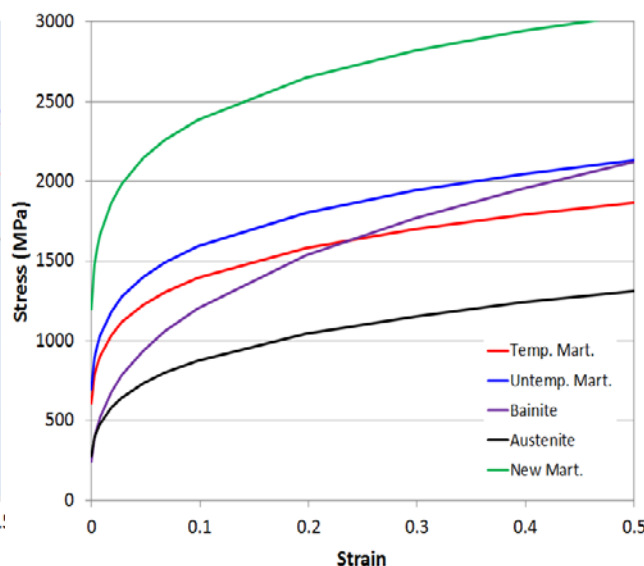
Original Input S-E

Modified Input S-E
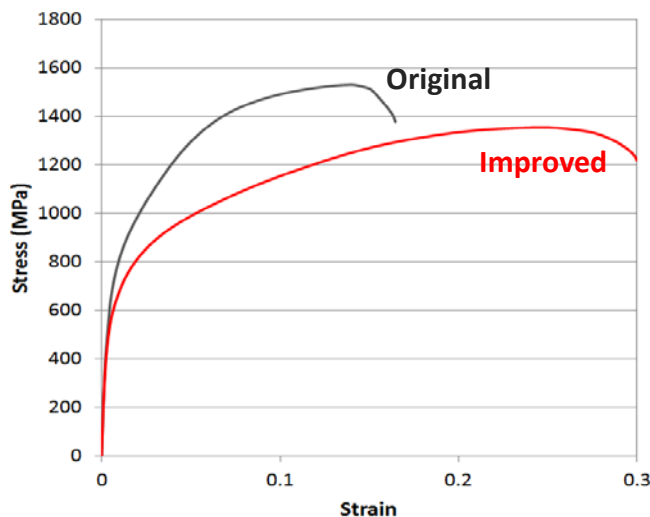
S-E Curves
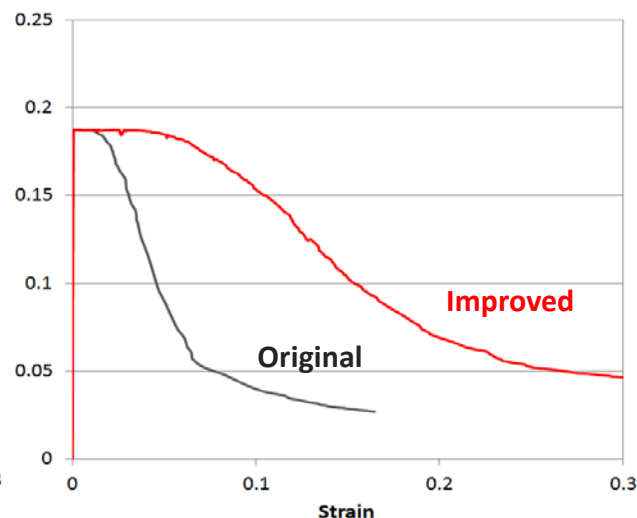
Aust. Transformation

▶ Material parameters were adjusted one after another by some amounts such that each adjusted parameter leads to some ductility improvement.

	Original Input	Modified Input
New Mart.	$6097\varepsilon^{0.3}$	$3379\varepsilon^{0.15}$
Untemp. Mart.	$2701\varepsilon^{0.15}$	$2413\varepsilon^{0.18}$
Temp. Mart	$2257\varepsilon^{0.15}$	$2113\varepsilon^{0.18}$
Bainite	$3000\varepsilon^{0.35}$	$2700\varepsilon^{0.35}$
Aust.	$1928\varepsilon^{0.25}$	$1562\varepsilon^{0.25}$
Aust. CE	40	45

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Choi et al., SAE paper #2014-01-0812, 2014.

CSM Technical Accomplishment
- Production of 2nd and 3rd Heat Q&P Steels

- 2nd Heat samples (QP5~8) were produced using QP1 chemistry (0.3C-3Mn-1.6Si)
  → QP5,8 showed increased UTS (>1550MPa) and TE (~21%)
- 3rd Heat samples (QP9~11) were produced based on QP8 heat-treating parameters
  → QP9,10 showed the ductility similar to that of QP8

Mat (0.3C 3Mn 1.6Si)	RHT (°C/s)	QT (°C/s)	PT (°C/s)	RA VF (%) (EBSD)	RA C content (wt %)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
QP1	820/120	180/10	400/100	21.4	1.13	1100	1526	16.16	20.09
						1045	1542	13.59	17.57
						1100	1526	14.92	18.95
QP8	820/120	160/10	400/100	14.6	1.28	1142	1598	14.56	21.80
QP9	820/120	160/10	400/100 (150°C/10hr Temp.)	20.4	1.20	1225	1542	16.46	21.57
						1260	1540	11.86	17.35
QP10	820/120	160/10	400/300	21.1	1.28	1250	1518	13.65	20.79
						1270	1520	12.85	19.73

- ① Decreased QT : more fraction of martensite → Strength increase and more carbon available for increasing austenite stability
- ② Tempering : strength decrease, possibly with ductility increase
- ③ Longer Partitioning : austenite carbon content increase and the overall strength level decrease

QP1

QP8

QP9
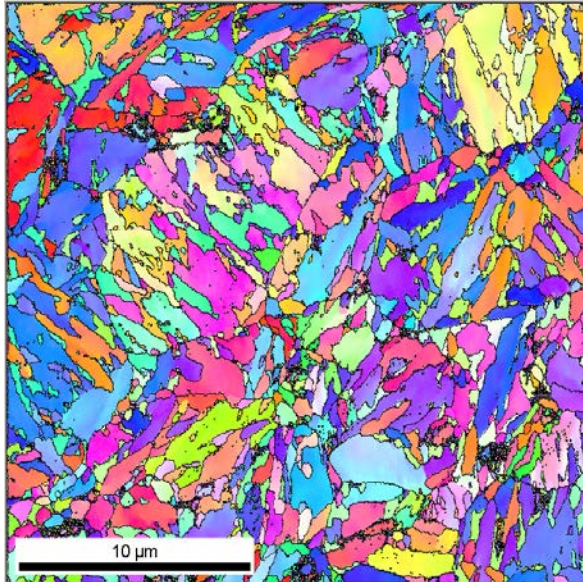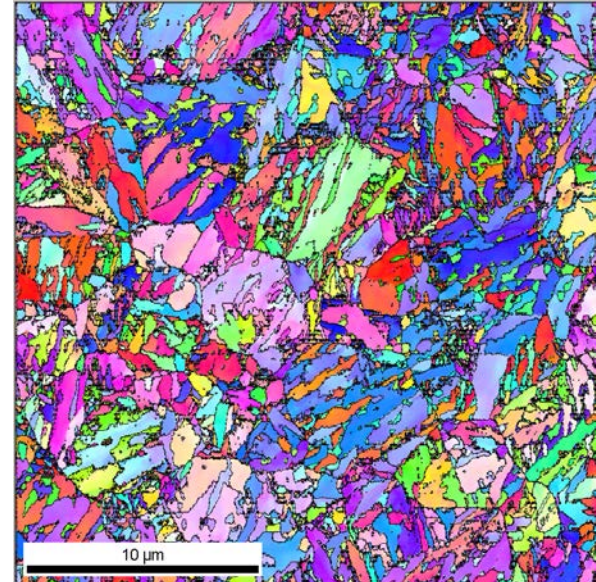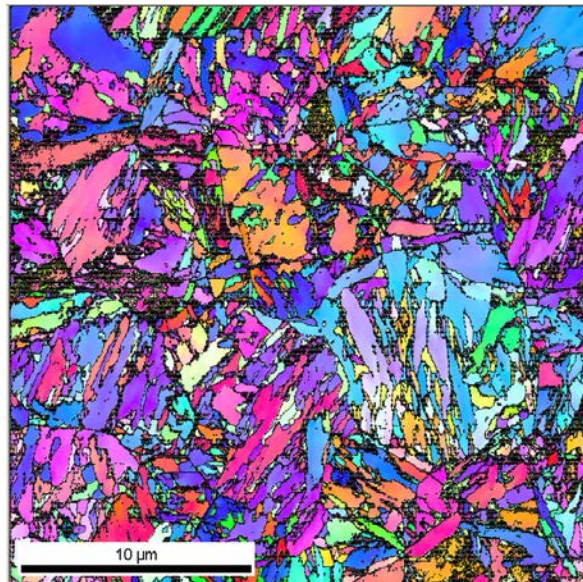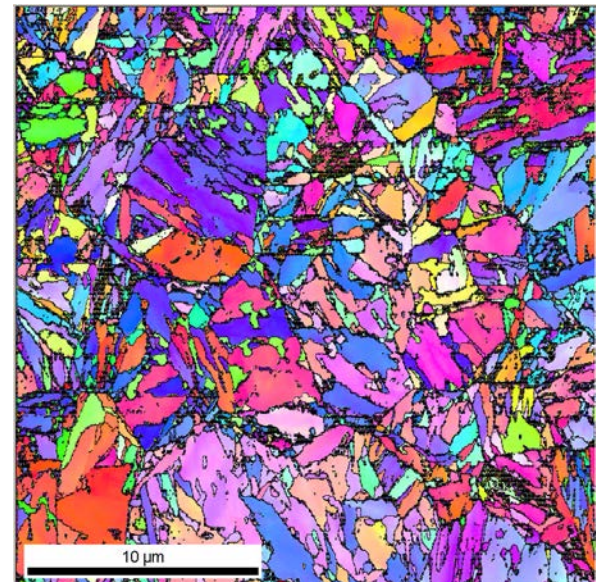
QP10

QP1
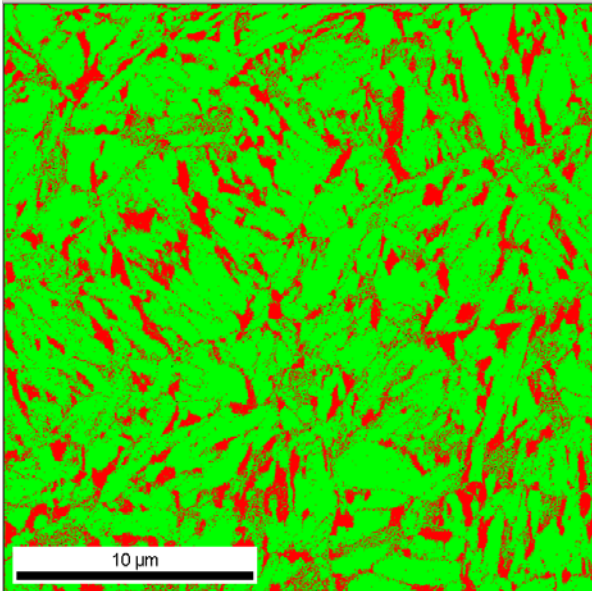
Aust. VF
21.4%

QP8

Aust. VF
14.6%
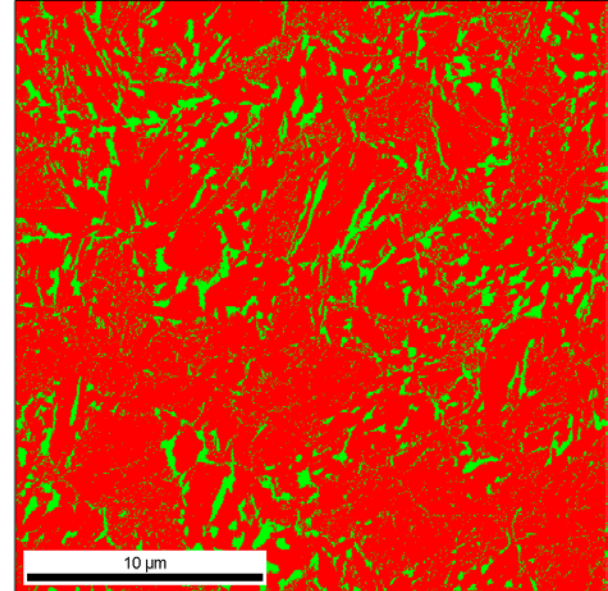
QP9

Aust. VF
20.4%
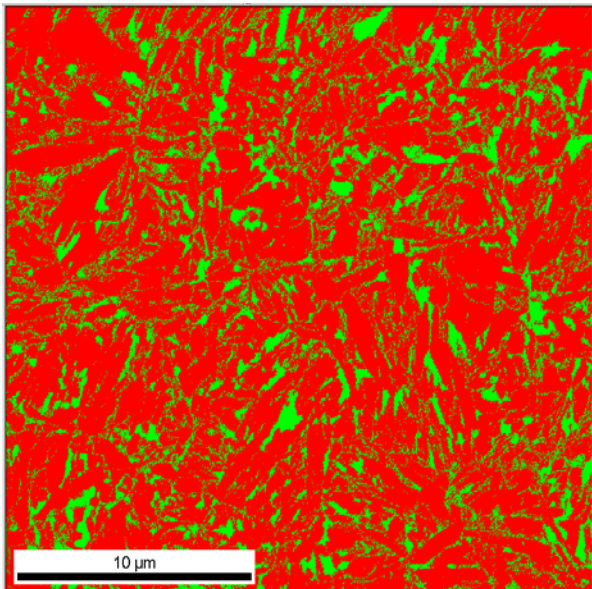
QP10

Aust. VF
21.1%
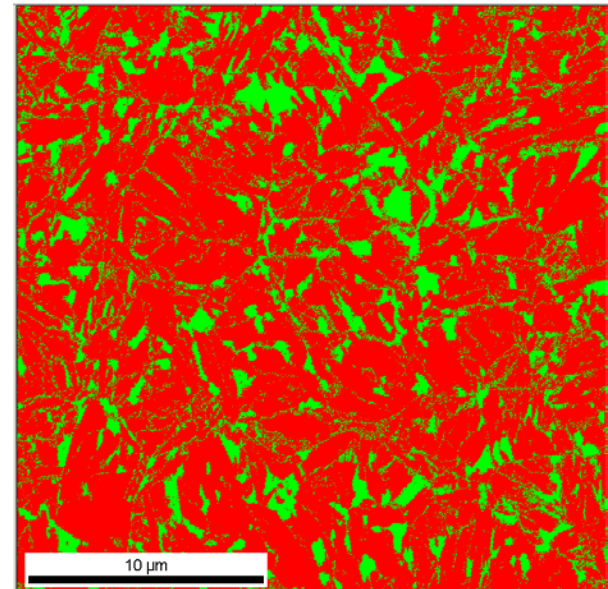
▶ Properties achieved in both the 2nd and the 3rd Heat of 0.3C-3Mn-1.6Si steel meet the alternative 3rd GEN AHSS requirement of excellent strength (>1500MPa) with good ductility (>20%)
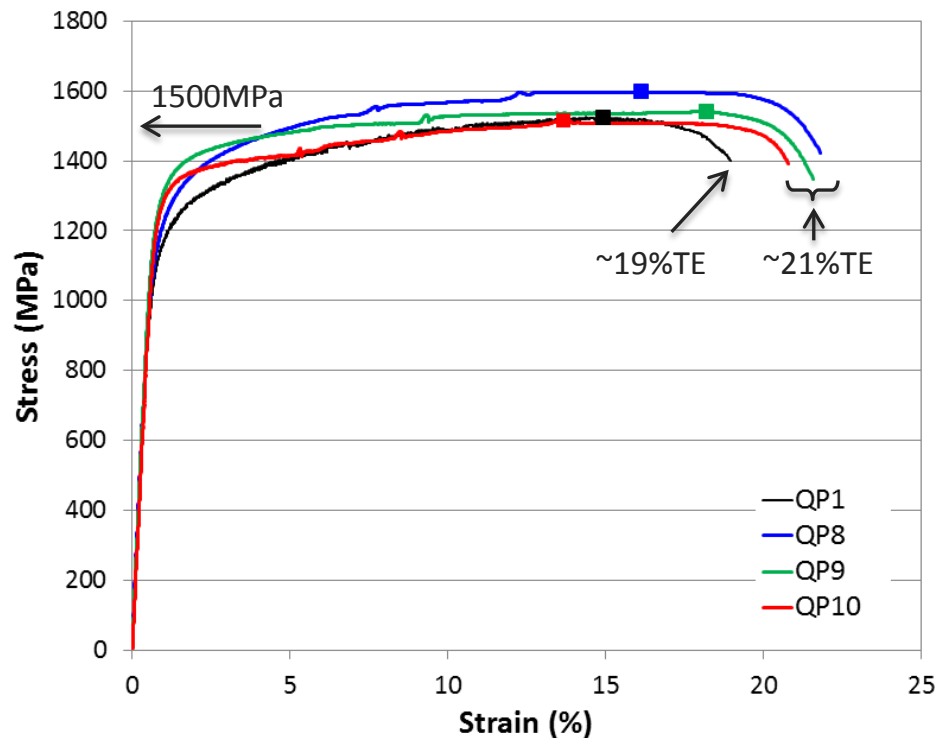
S-E curves of 3 heats of Q&P steels

▶ Limitation of thermo-mechanical processing: ~21% seems to be the max. level of TE that could be achieved with the chemistry of 0.3C-3Mn-1.6Si.

▶ Other alloying elements may need to be introduced to achieve the phase property requirements for further bulk property improvements.

Response to Reviewers' Comments

▶ Approach

- ■ Reviewer 3: The reviewer stated the method of micro-pillars compression testing is likely no good for grains of nano dimension.

- ■ Reviewer 4: This reviewer opined that the nanoindentation of nanoscale individual embedded phases is worthless. The reviewer then asked what the project team uses as the modulus, and what is below giving a composite response.

Response: We agree with these concerns. In FY14, we have started cross comparing phase properties measured by different measurement techniques and found general correlation between nanohardness and HEXRD data.

▶ Accomplishments

- ■ Reviewer 2:This reviewer indicated the presentation could have been clearer; four new compositions are made (heat 1 to 4) and two commercial steels are used (Bao Q&P / DP). A good labeling would be beneficial; the four experimental steels are labeled as Mat 1 / Mat 2 as well as Q&P steels.The reviewer also pointed out that the focus is on developing specific microstructures, but inquired about what would happen if further processing changes these phases. The ICME approach should address this issue as well.

Response: We agree with these comments and are making linkages with the ICME project.

- ■ Reviewer 3:The reviewer observed that questionable data is being compared to with limited success. The reviewer said that the method of micro-pillars compression testing is likely no good for grains of nano dimension.

Response: We agree that micro-pillars compression test may not be valid for nano grains. See response above.

- ■ At this stage for just two materials the reviewer would expect the project to be further along. Additionally, the reviewer indicated that the project team has not gotten through their composition-characterization-modeling cycle even one time (but claim the project is 45% complete). This reviewer stated that the project was to add quantitative understanding, but the results seem more qualitative. As mentioned above, the modeling shows a high sensitivity to phase fraction of Austenite, which is known to be hard to accurately measure, suggesting the model may never work for the intended purpose.

Response: The project has made great progress in FY14 and we now have produced three heats and 10 materials, with 3 meeting excellent strength and good ductility.

Collaborations

- ▶ Advanced Steel Processing and Products Research Center (Industry)
  - ■ Provided initial alloy design and materials
  - ■ Developed processing parameters for all 3 heats
  - ■ Produced 3 experimental heats of model steels
- ▶ Colorado School of Mines (Academic)
  - ■ Performed nano-indentation tests for hardness measurements
  - ■ Performed EBSD tests for phase identification
- ▶ PNNL (National Laboratory)
  - ■ Performed all tensile tests
  - ■ Performed in-situ HEXRD tests
  - ■ Performed nano-SIMS test
  - ■ Performed microstructure-based analyses for performance enhancements

Future Work

▶ Finish local formability assessments and characterizations at CSM with hole expansion test

▶ Correlate nano indentation results with HEXRD and compare with similar measurements on single phase steel measurements reported in the literature

▶ Correlate the observations from virtual material design process with nano-indentation results of 2nd and 3rd Heat steels

▶ Disseminate project findings to broader community through journal publications

  ■ 3-page short paper on QP1-10 by CSM
  ■ Nano-SIMS based C distribution measurements
  ■ In-situ HEXRD test for constituent property estimation
  ■ Virtual materials design process for improved properties