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# 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
- 45% 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

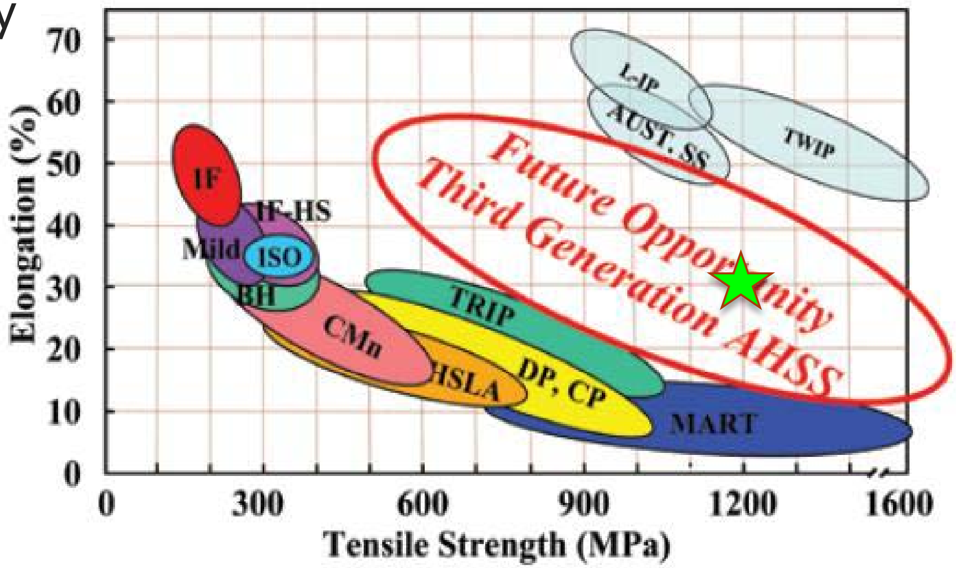
## Partners

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

# Project Objectives and Technical Approaches



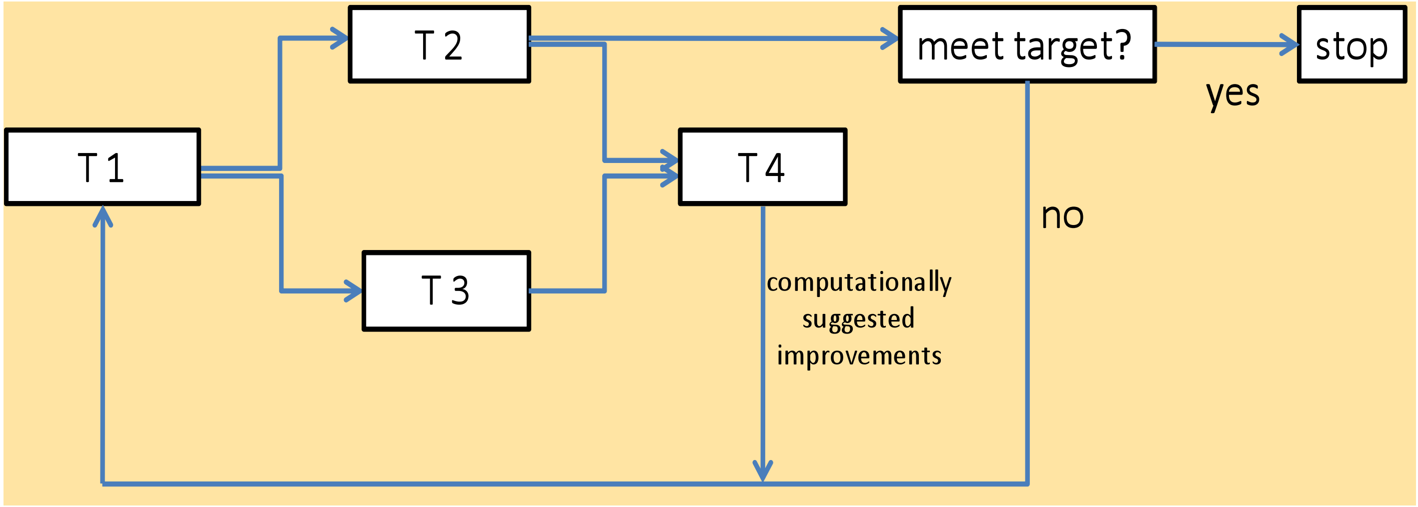
- As the application of 2nd Gen. AHSS may be limited due to its economic considerations, 3rd Gen. AHSS concepts are being pursued vigorously to identify lower alloy steels which achieve ultra-high strength properties with good formability.
- The purpose of this project is to *improve overall understandings* 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 *1200MPa UTS and 30% ductility* are the property goal along with a consideration of cost targets of this class of materials.



# Technical Approaches



- 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, on-going).

- Candidate 3rd Generation AHSS material systems with 1200MPa UTS and 30% ultimate elongation (Sept. 2014, on-going).

# ASPPRC Accomplishments–
# Produced Model Steels by Q&P Process

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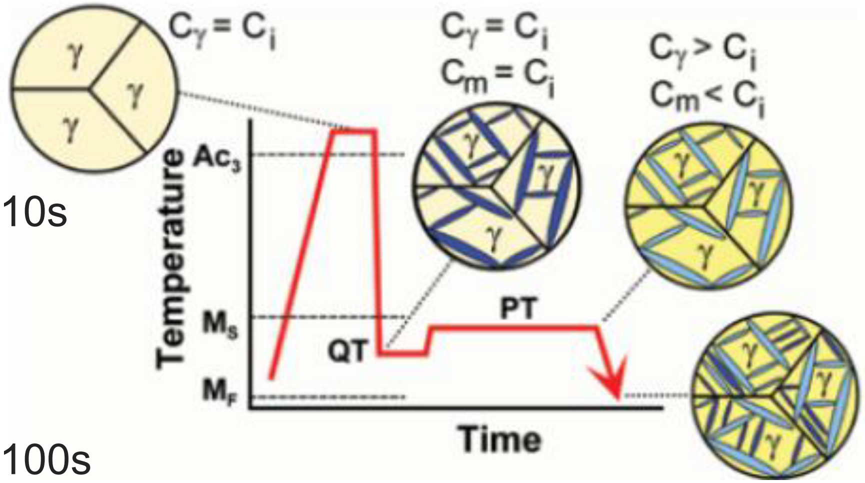
**1. 0.3C-3Mn-1.6Si**

**FA**

RHT: 820°C-120s, QT: 180°C-10s, PT: 400°C-100s




**2. 0.2C-3Mn-1.6Si**

**FA**

RHT: 840°C-120s, QT: 250°C-10s, PT: 400°C-10s

**3. 0.2C-3Mn-1.6Si**

**FA**

RHT: 840°C-120s, QT: 250°C-10s, PT: 400°C-100s

**4. 0.2C-3Mn-1.6Si**

**IA**

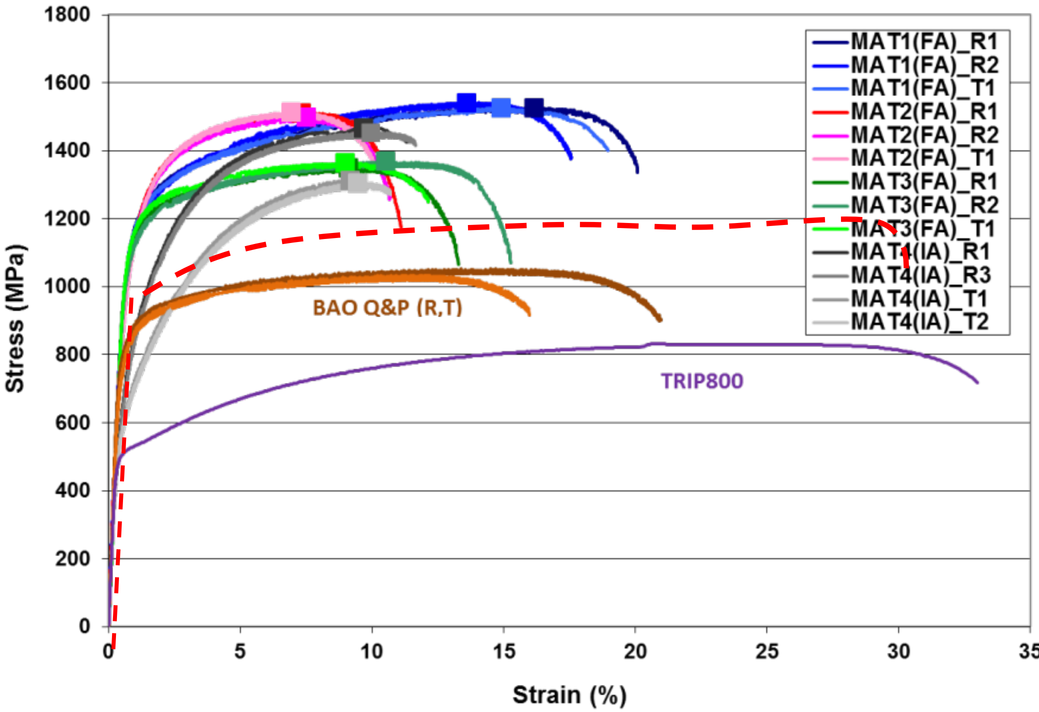
RHT: 725°C-120s, QT: 185°C-10s, PT: 450°C-10s

*RHT: Reheating Temperature/Time, FA: Fully Austenized, IA : Intercritically Annealed, QT : Quenching Temperature/Time, PT: Partitioning Temperature/Time, UTS : Ultimate Tensile Strength, TE : Total Elongation, R : Rolling direction, T: Transverse direction

# Characterization of Tensile Properties for the Four Model Steels



Comparison of tensile curves




Comparison of tensile failure modes

# Characterization of Tensile Properties for the Four Model Steels

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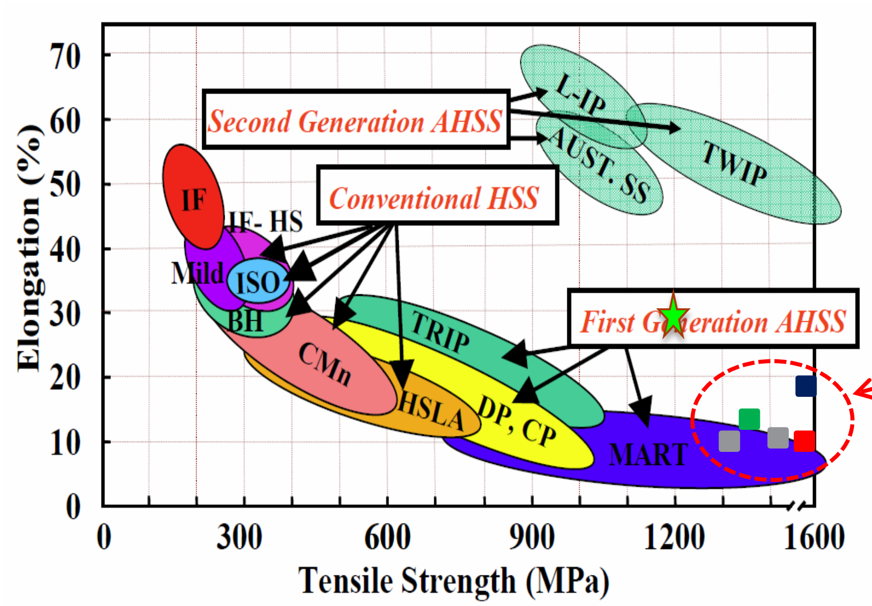
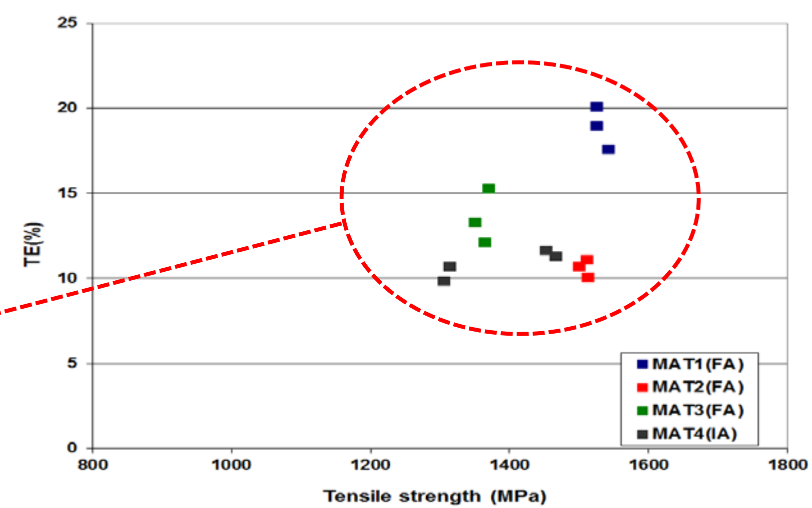
| Heat # | UTS (Mpa) | Ductility (%) |
|---|---|---|
| 1 | 1531 | 19 |
| 2 | 1508 | 11 |
| 3 | 1361 | 14 |
| 4 | 1460 | 12 |

- Target: *1200MPa UTS and 30% ductility*
- Overshooting strength
- Undershooting ductility
- Need to improve ductility without too much sacrifice on strength
- Need to quantify how much to change phase properties



# Factors Influencing Strength and Ductility of TRIP-based Multi-Phase Steels



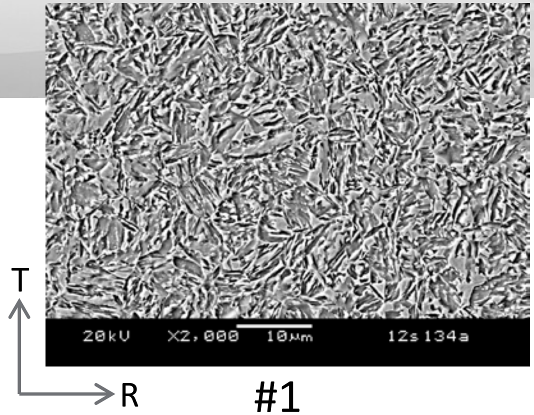
- Retained austenite volume fraction
- Retained austenite stability
- Grain size
- Secondary phase morphology
- Phase strength disparity

- Need to establish the quantitative relationship between steel chemistry and processing parameters to stress vs. strain curves through the critical link -- ***microstructure***

Sun et al, *Mat. Sci. Eng. A,* 2009.
Choi, et al., *Acta Mater.*, 2009.
Choi, et al., *Comp. Mat. Sci.*, 2011.

# Material 1



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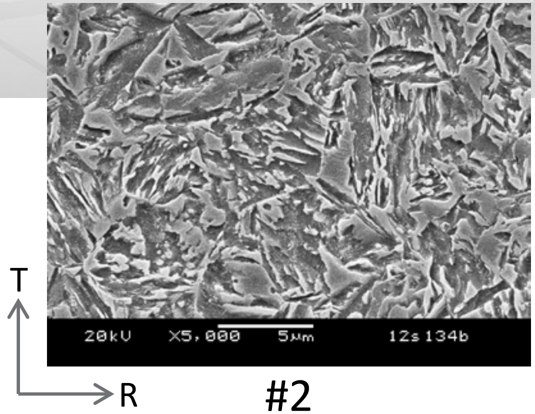


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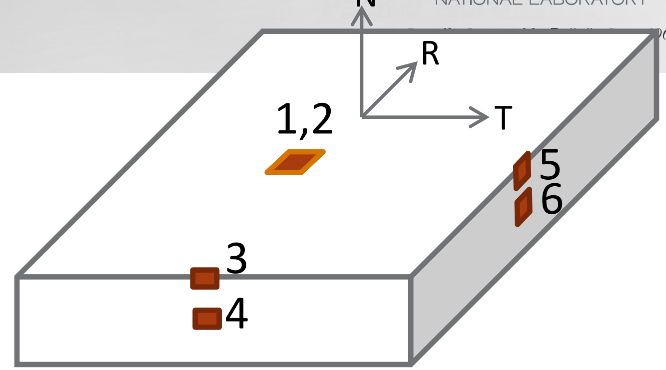


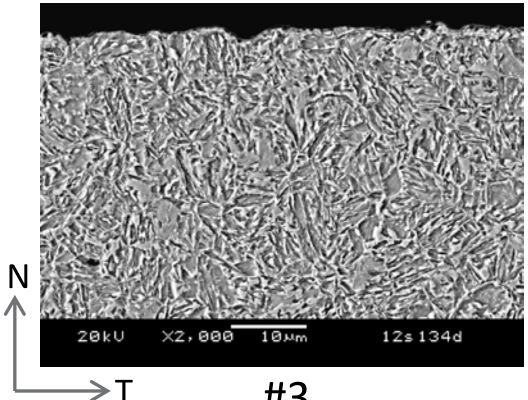


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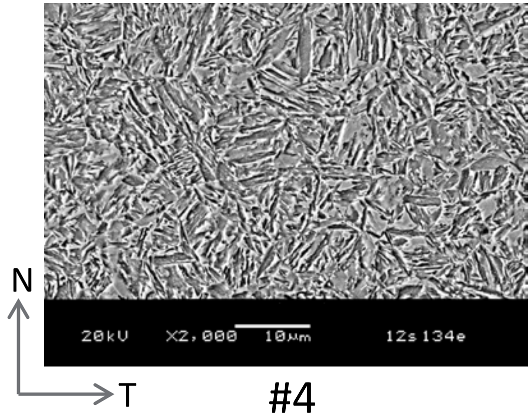
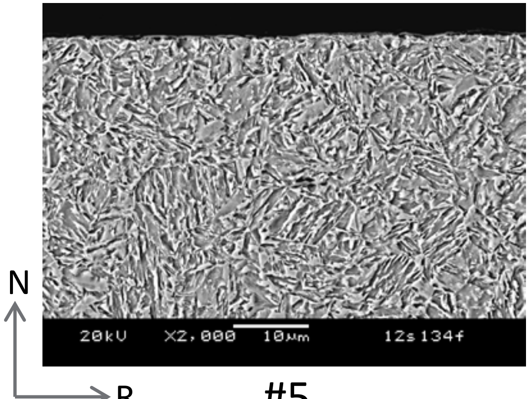



#4

- Complex microstructure with very fine-sized grains
- Isotropic with no directionality observed

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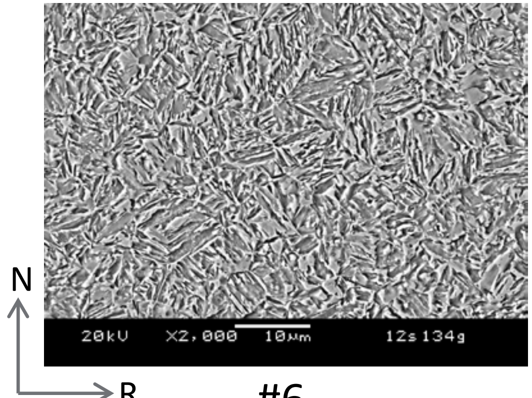


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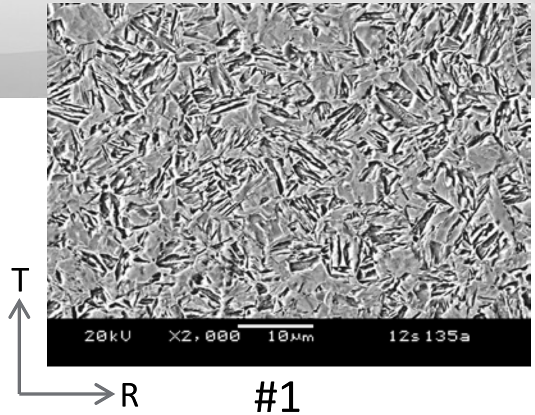
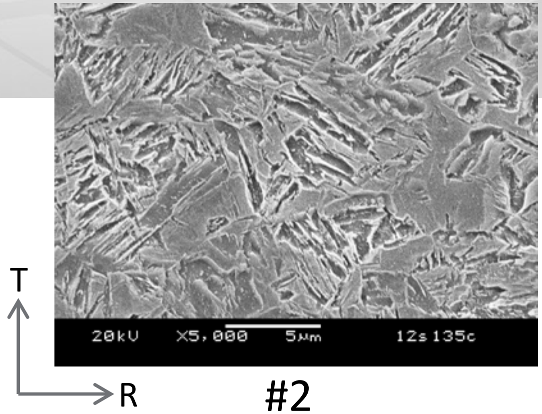
# Material 2



#1



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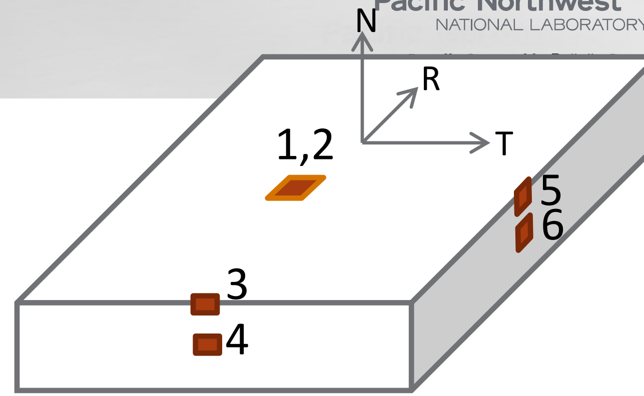


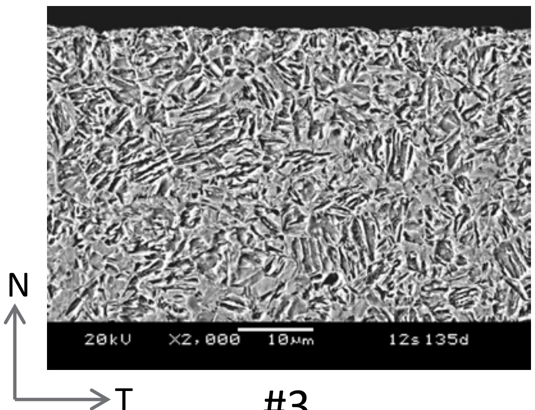

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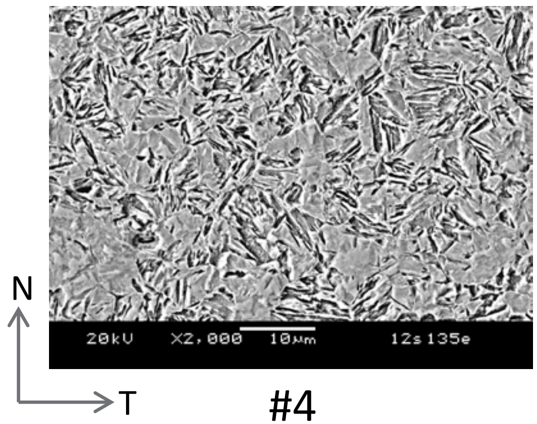

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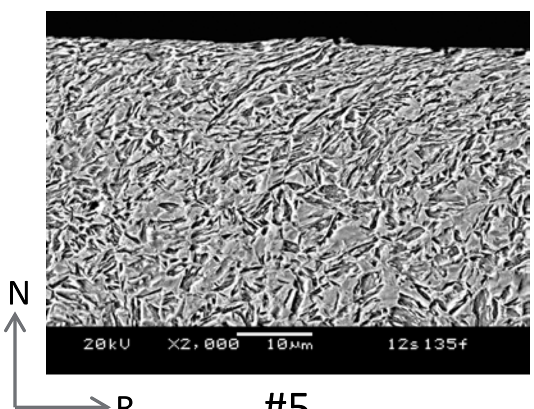

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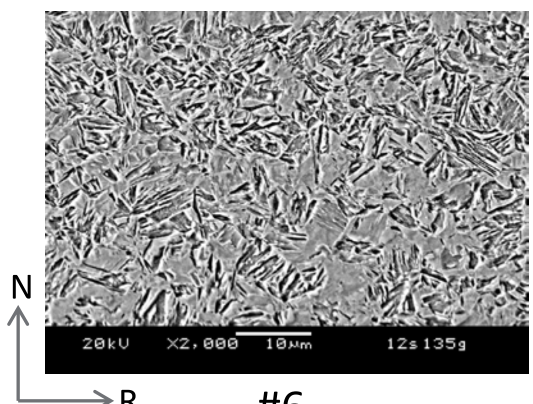

#6

-Complex microstructure with fine-sized grains
-Large-size grains are also observed
-No directionality is observed

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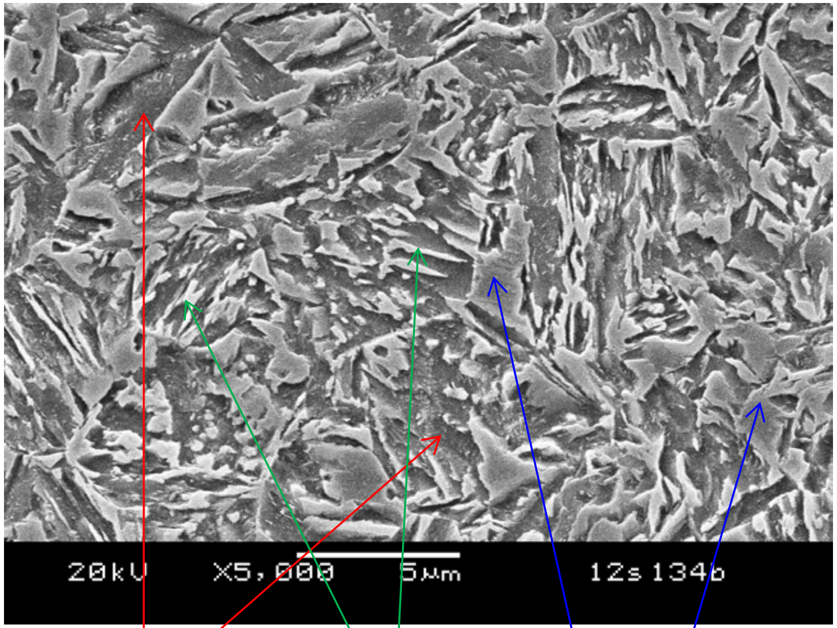
# Comparison of Microstructure Features



## MAT1




Tempered martensite or bainite

Very thin flakes : Austenite

Relatively large flakes : Austenite, untempered martensite or mixture of the two phases

T

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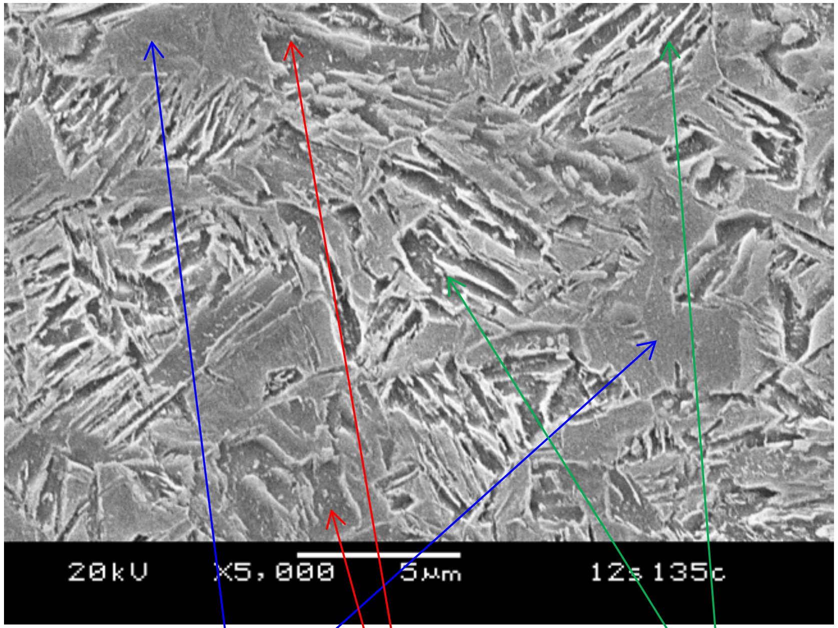
## MAT2



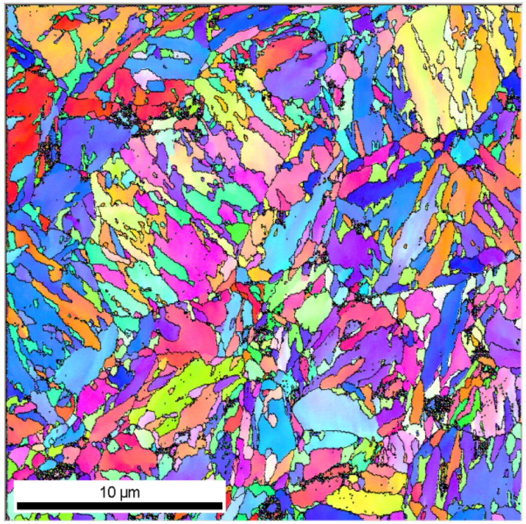

Chunk area : Untempered marrtensite

Thin/thick flakes : Austenite films

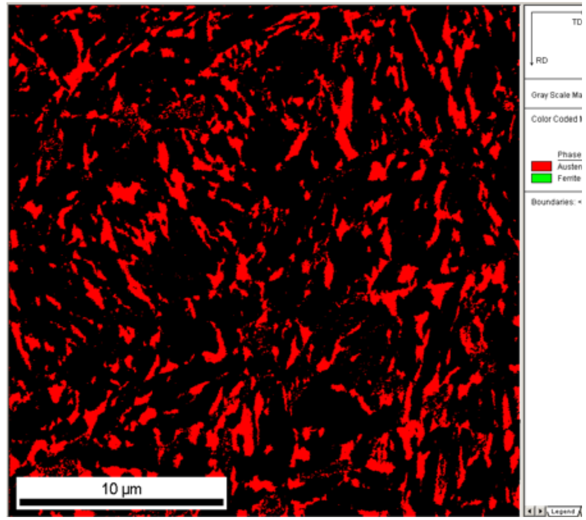
Tempered martensite or bainite

# EBSD Results (Mat1, Mat2)

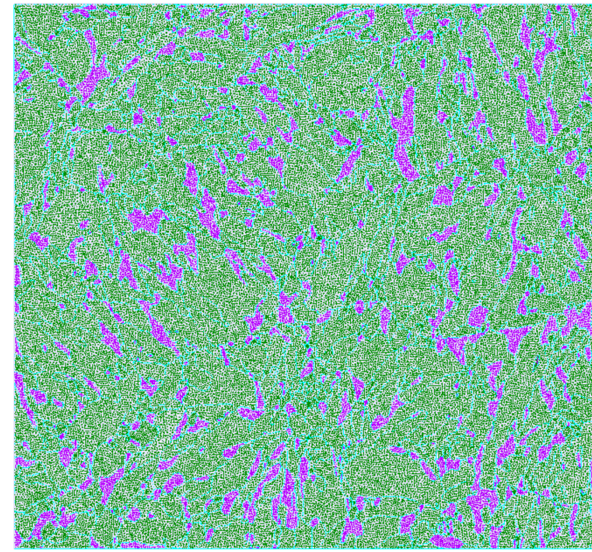


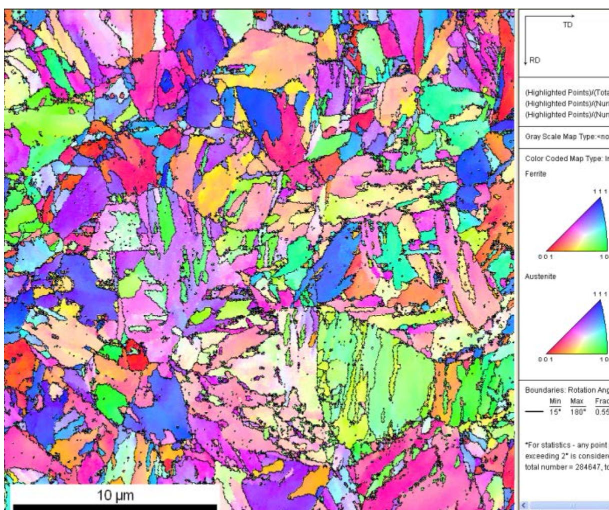



Mat 1

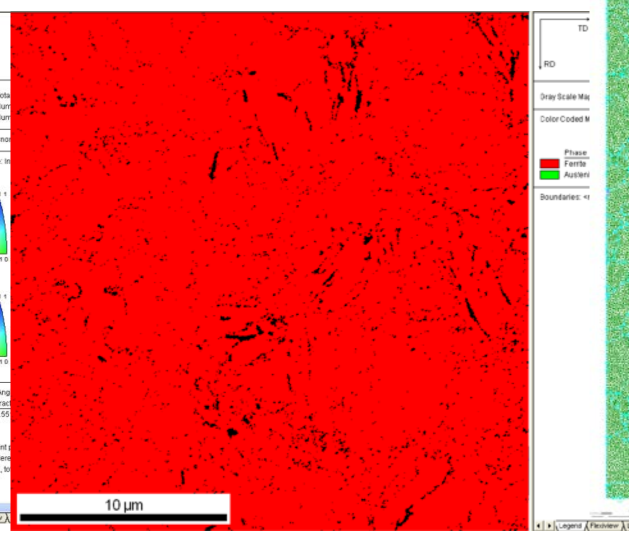



Austenite 21.4%

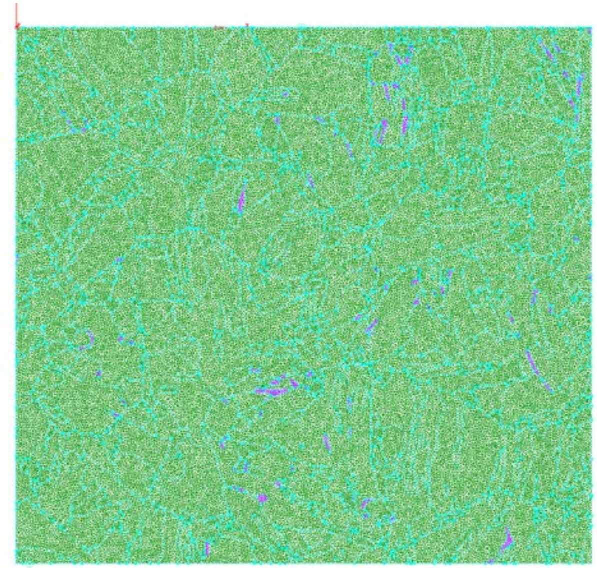





Mat 2




Austenite 2.9%



FE models

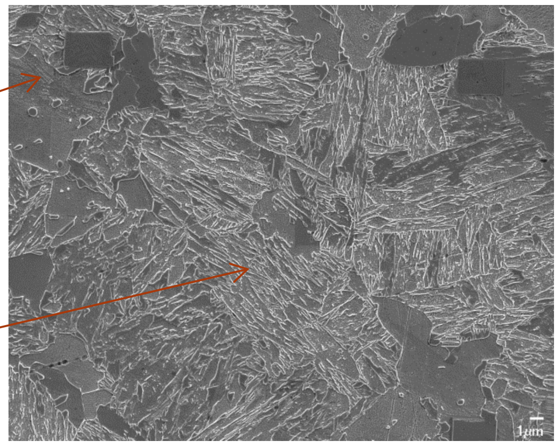
# Determination of Individual Phase Mechanical Properties



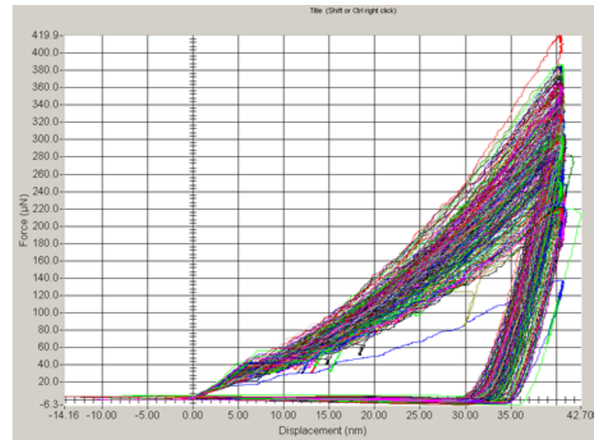
Nano-indentation results for Bao Q&P steel

ferrite

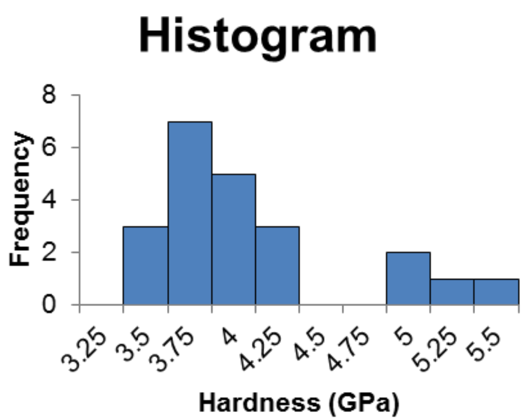
Bainite
(small grain region)



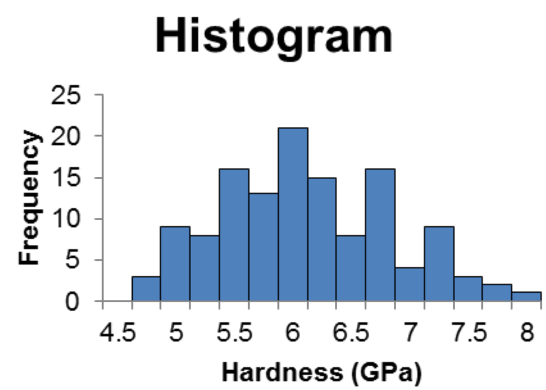

Microstructure of a Q&P steel




Load-displacement curves




Average hardness of ferrite : 3.96 GPa

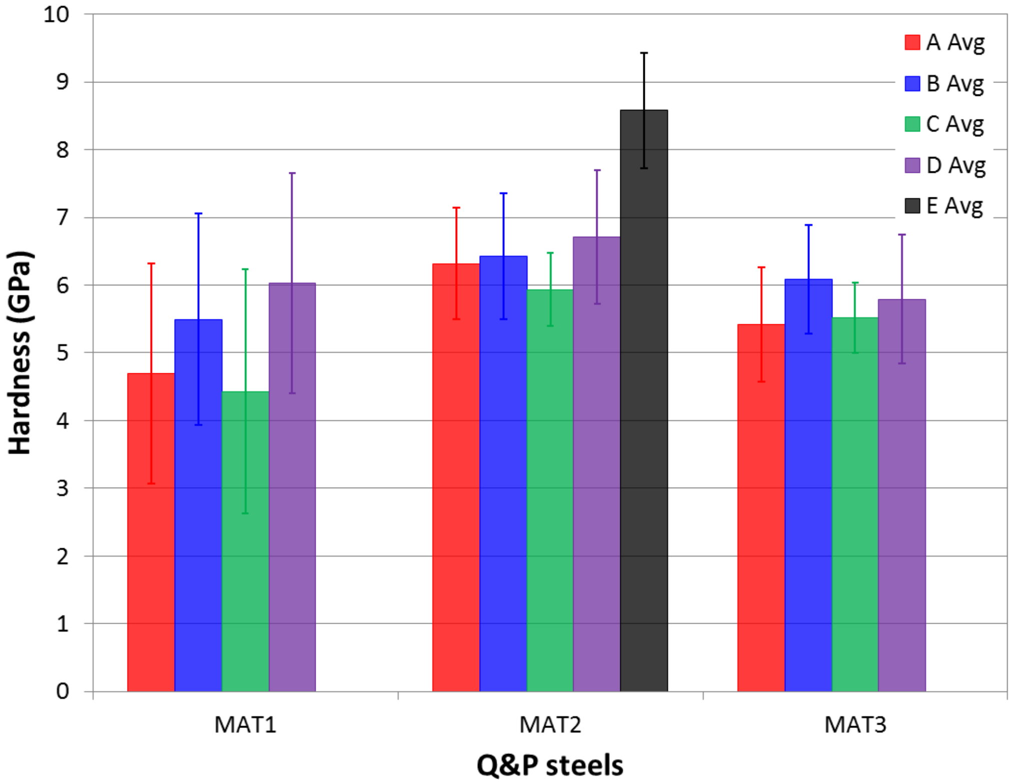


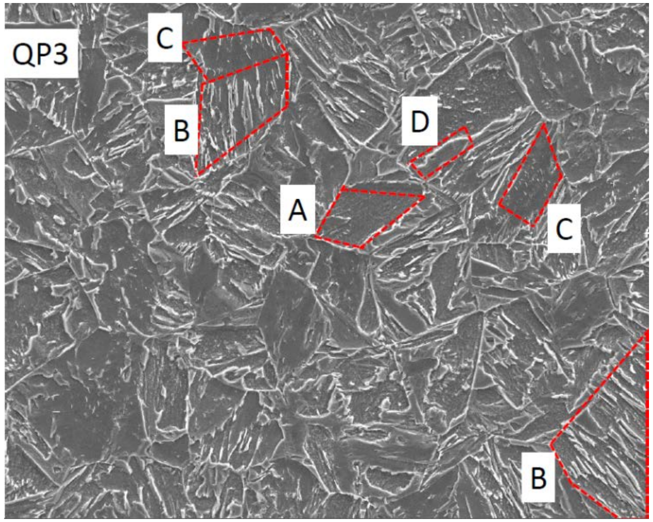

Average hardness of bainite : 5.99 GPa

# Nano-Hardness Measured for MAT1, MAT2, and MAT3



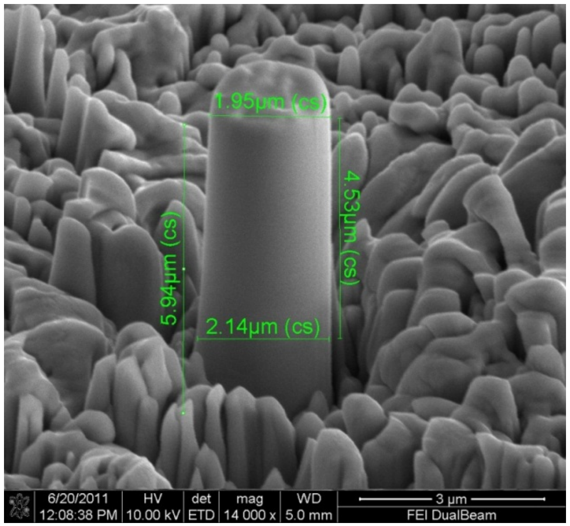
- Hardness #  measured close to the grain boundary are not counted.
- Hardness # are different among materials ($H_{MAT2} > H_{MAT3} > H_{MAT1}$)
- MAT1 shows larger variation in hardness than other materials.

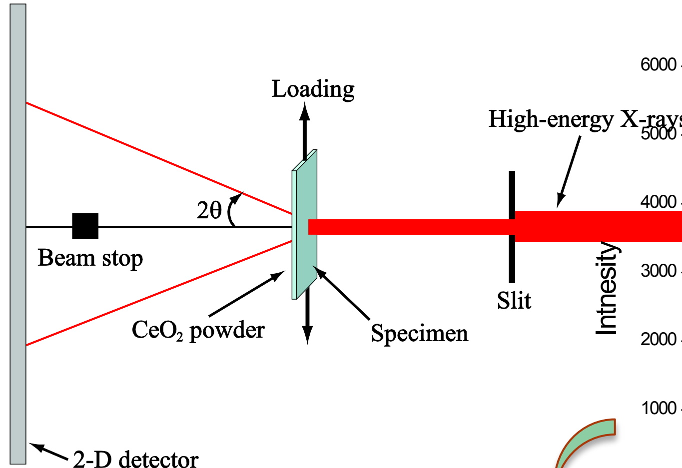


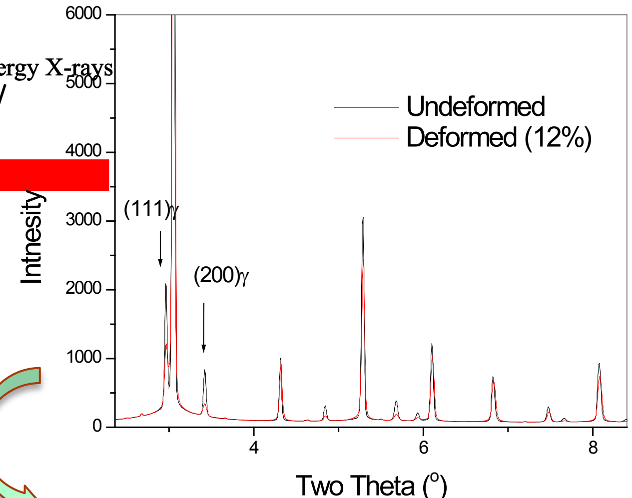



# Other Possible Methods for Strength Characterizations of Different Phases

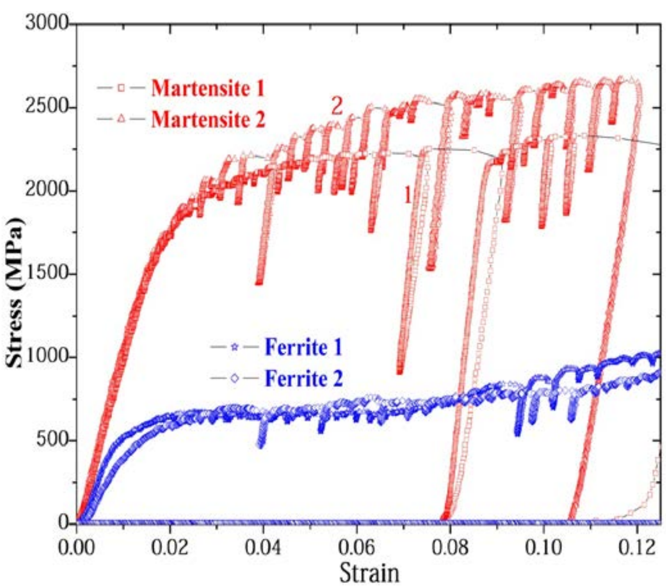




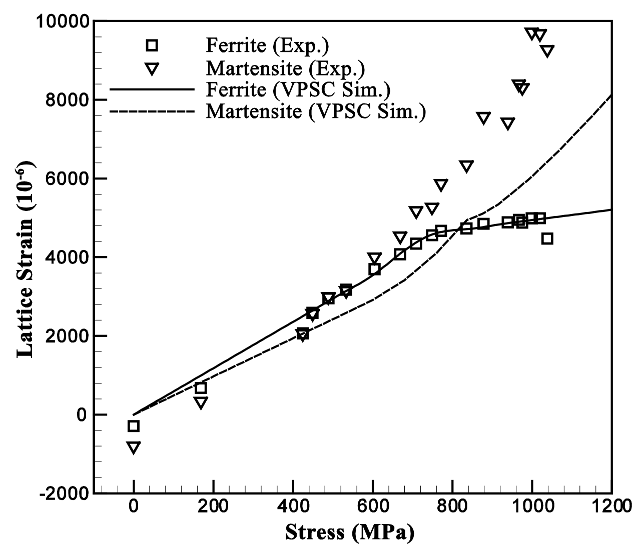




Results for DP steels from Brown U




- Discrete grain-based measurement:
  - Direct grain level measurement
  - Expensive process
- Volume-based measurement:
  - Indirect
  - Ensemble measured
  - In-situ testing possible
  - APS beamtime obtained in April



# Technical Accomplishments- Estimation of Phase Properties and Preliminary Simulation Results

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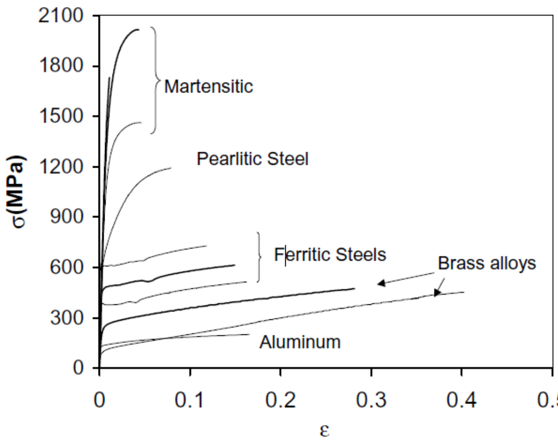
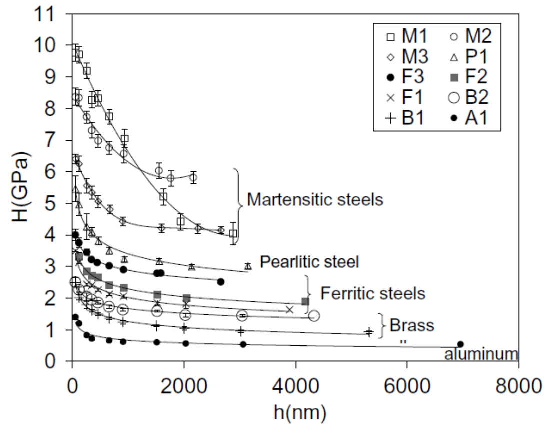
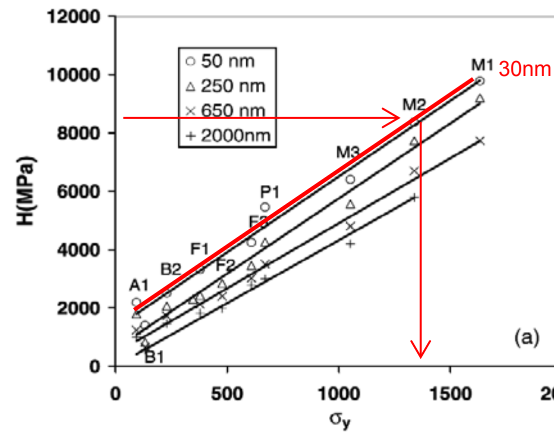
- Further tuning of FE models and phase properties are needed to obtain similar S-E curves to those of experiments. (i.e., adjustment of volume fractions/strengths of the constituents, variation of hardness…)
- Computational material design will then be performed to improve the material performance.



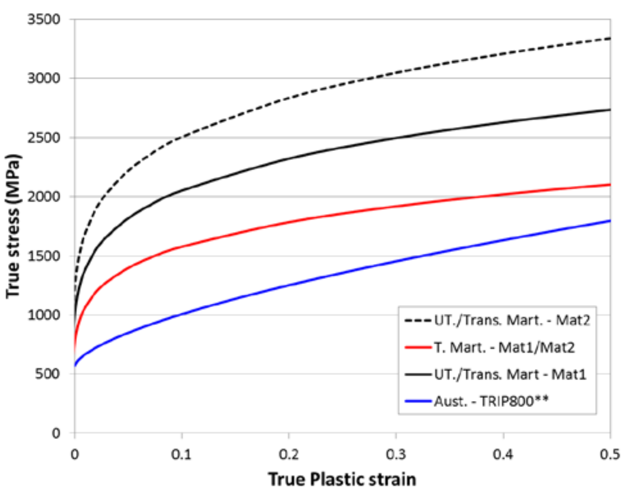

S-E curves for different materials*



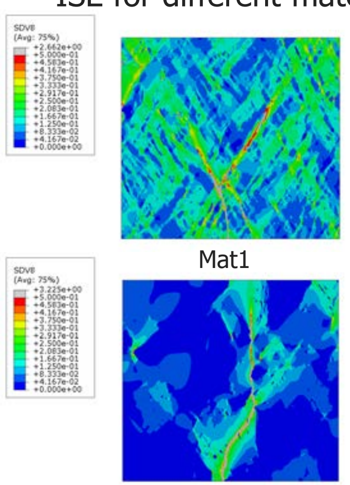

ISE for different materials*



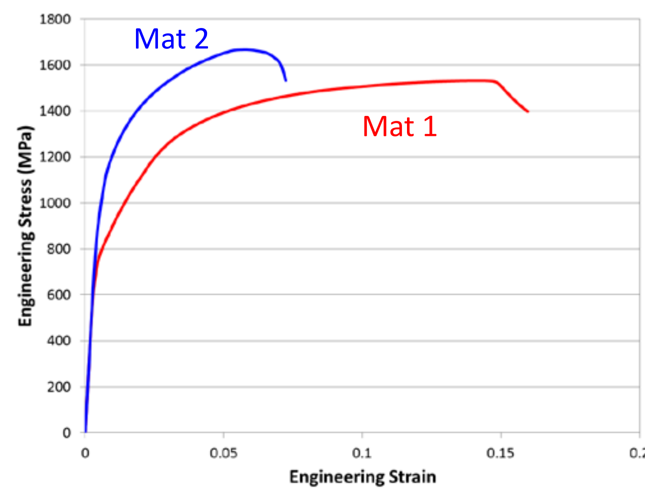

H vs. YS depending on indentation depth*




Estimated constituents' properties




Failure modes




Predicted S-E curves



*Rodriguez and Gutierrez (2003) Mater. Sci. Eng. A361, pp.377-384. **Choi et al. (2009) Acta Mater. 57, pp.2592-2604.

# Summary

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- Developed initial alloy composition and processing parameters for model steel
- Produced lab heats of 4 model steels
- Performed mechanical property characterizations and microstructure characterizations for model steels
- Performed EBSD analyses on model steels to determine the volume fractions of retained austenite and other phases
- Performed nano-indentation tests on all four model steels to determine the hardness distributions of different phases
- Developed multi-phase finite element models for Mat 1 and Mat2
- Performed preliminary microstructure-based finite element analyses for property predictions on Mat 1 and Mat 2

# Collaborations

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- Advanced Steel Processing and Products Research Center (Industry)
  - Provided initial alloy design and developed processing parameters
  - Produced experimental heats of four model steels
- Colorado School of Mines (Academic)
  - Performed nano-indentation tests for hardness measurements
  - Performed EBSD tests for phase identification

# Future Work



- Continue the modeling work on three cases:
  - Mat 1 and Mat 2:
    - Quantify effects of RA volume fraction and phase properties
  - Mat 1 and Mat 3:
    - Quantify effects of carbon content
  - Mat 2 and Mat 3
    - Quantify effects of partitioning time
  - Perform computational materials design for property improvements:
    - Provide microstructure-level guidance for next iteration
- Perform localized formability test with materials produced:
  - Sample from heat treated plates too small for CSM's stretch-bending test setup
  - Explore hole expansion test for localized formability with USS or POSTECH
- Produce next heat with modeling input – start 2nd iteration