Recent AHSS Developments for Automotive Applications: Processing, Microstructures, and Properties

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Golden, Colorado

***Workshop*: Addressing Key Technology Gaps in Implementing Advanced High-Strength Steels for Automotive Lightweighting**
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***ASPPRC:** *An NSF Industry/University Cooperative Research Center - Est. 1984*
http://aspprc.mines.edu/

Scope of Today's Presentation

- AHSS historical perspective – *very brief*
- Status of recent AHSS developments
- Identify opportunities
  - Enhanced first generation AHSS
  - New Third generation processing routes
- Observations and suggestions

DP Developments – 1970's to ……

- **1960's – 1970's: HSLA steel**
  - **Thermomechancial processing + microalloy additions**

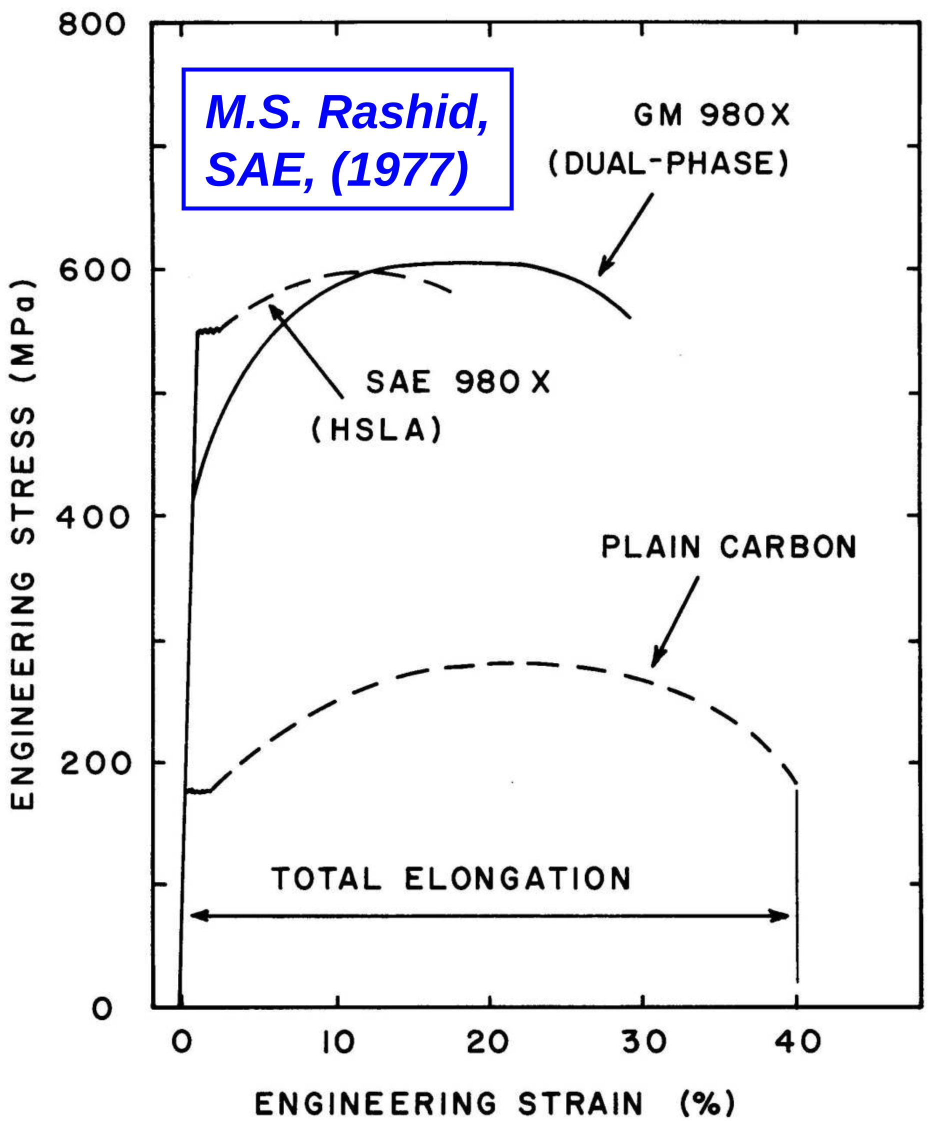
- **1970"s – 1980's: Dual-phase steel**
  - **Fundamentals identified**
  - ***Basis for AHSS developments***

- **1990's --- TRIP (Transformation Induced Plasticity) and other AHSS developments, leading to "3rd Generation AHSS"**

Dual-Phase Steels: "The Early Days"

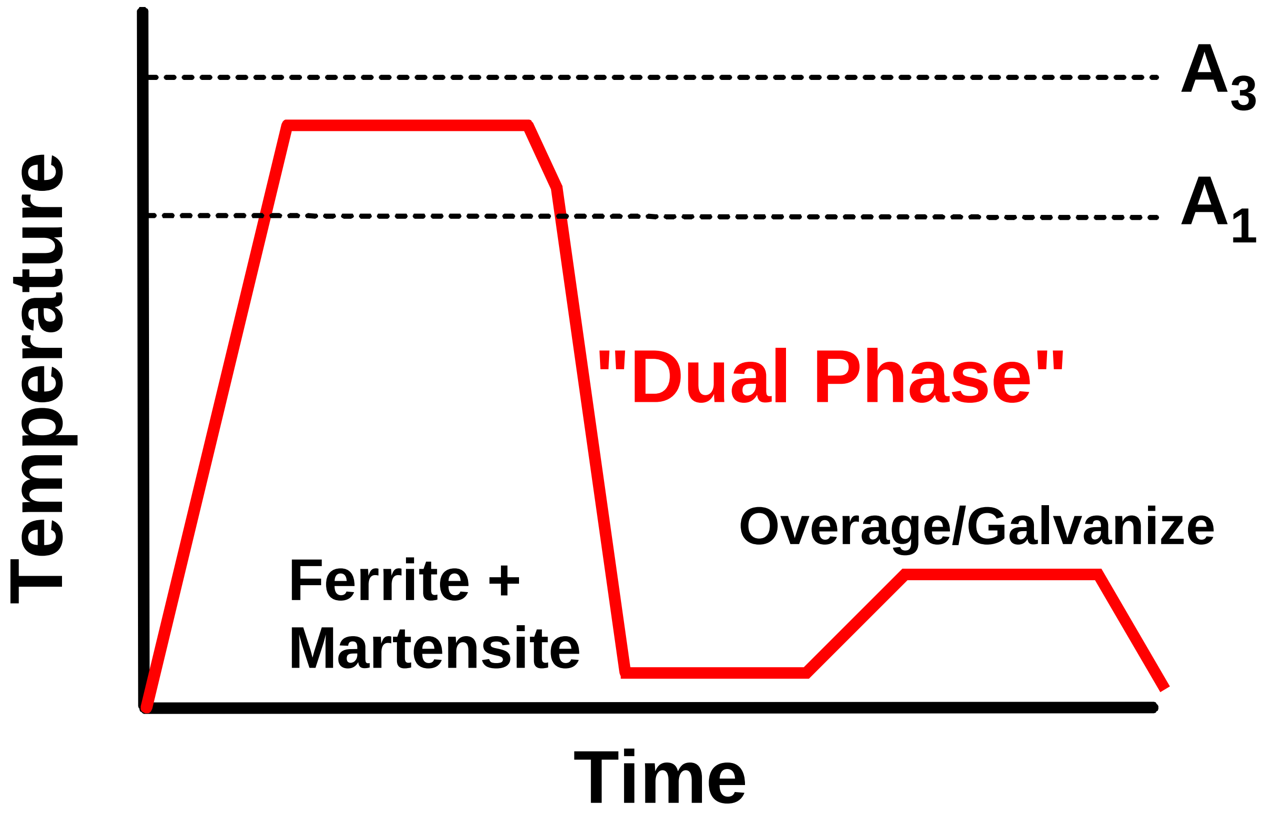
Significant Parallel Research Activities

- **Nippon Steel**
  - **1975:** S. Hayami and T. Furukawa, Microalloying '75
- **GM**
  - **1976:** M.S. Rashid, SAE + others
- **Ford**
  - **1978:** R.G. Davies, Met. Trans. + others



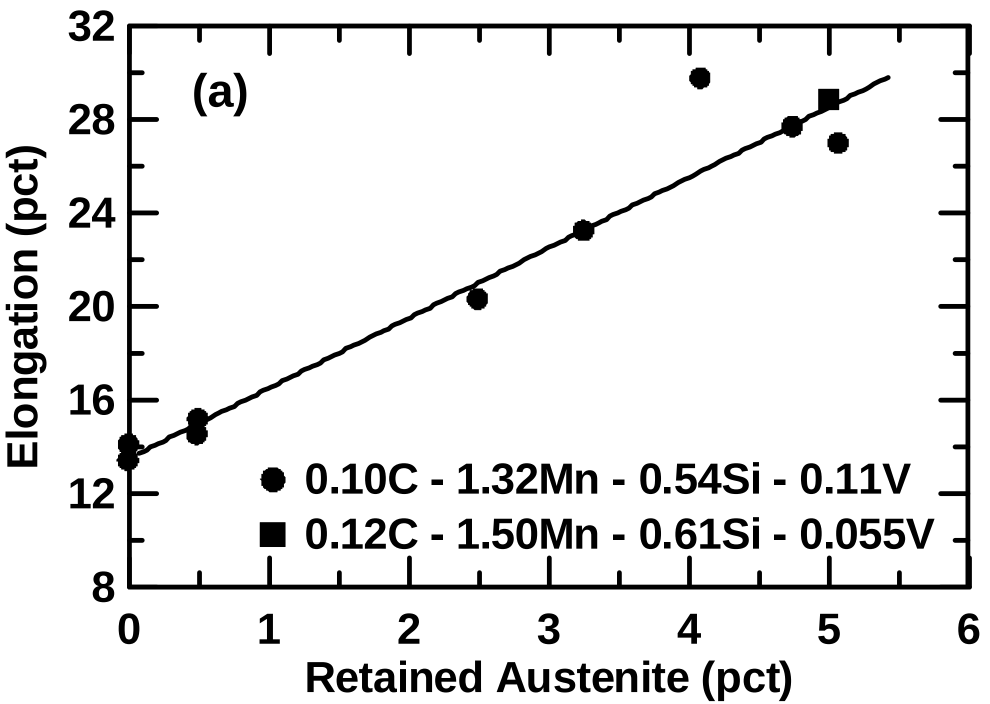
DP Steel Processing

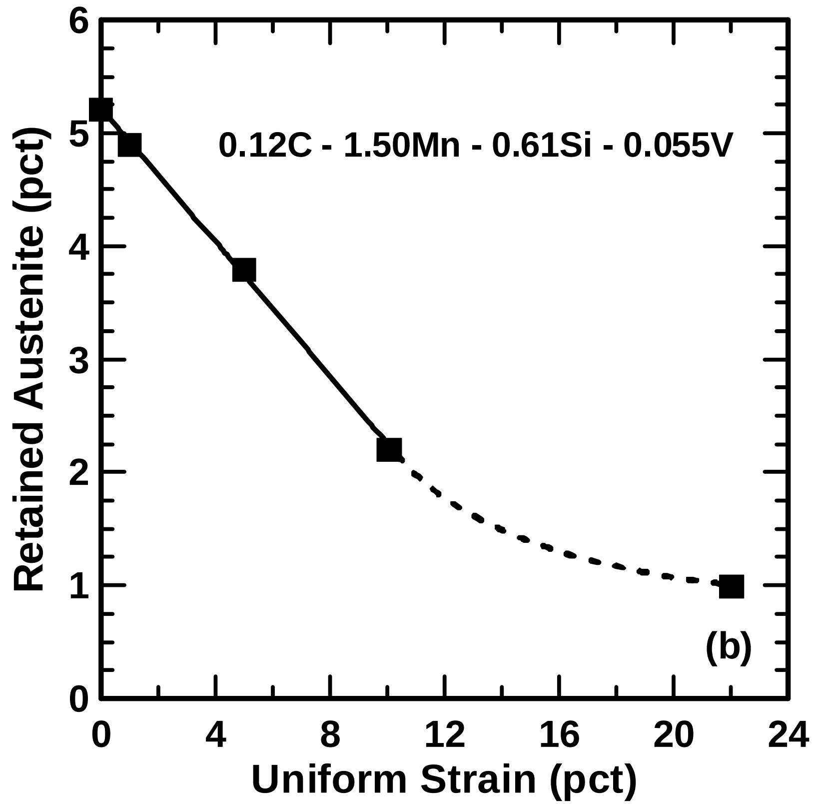
- **Initially conceived based on "simple" processing routes for hot and cold rolled steels**
  - **Microstructures more complex than simply ferrite + martensite and contained retained austenite + ??**



…Lessons Learned from "Early" DP Steels

- Processed as dual-phase steel
- Observed microstructures more complex than ferrite + martensite



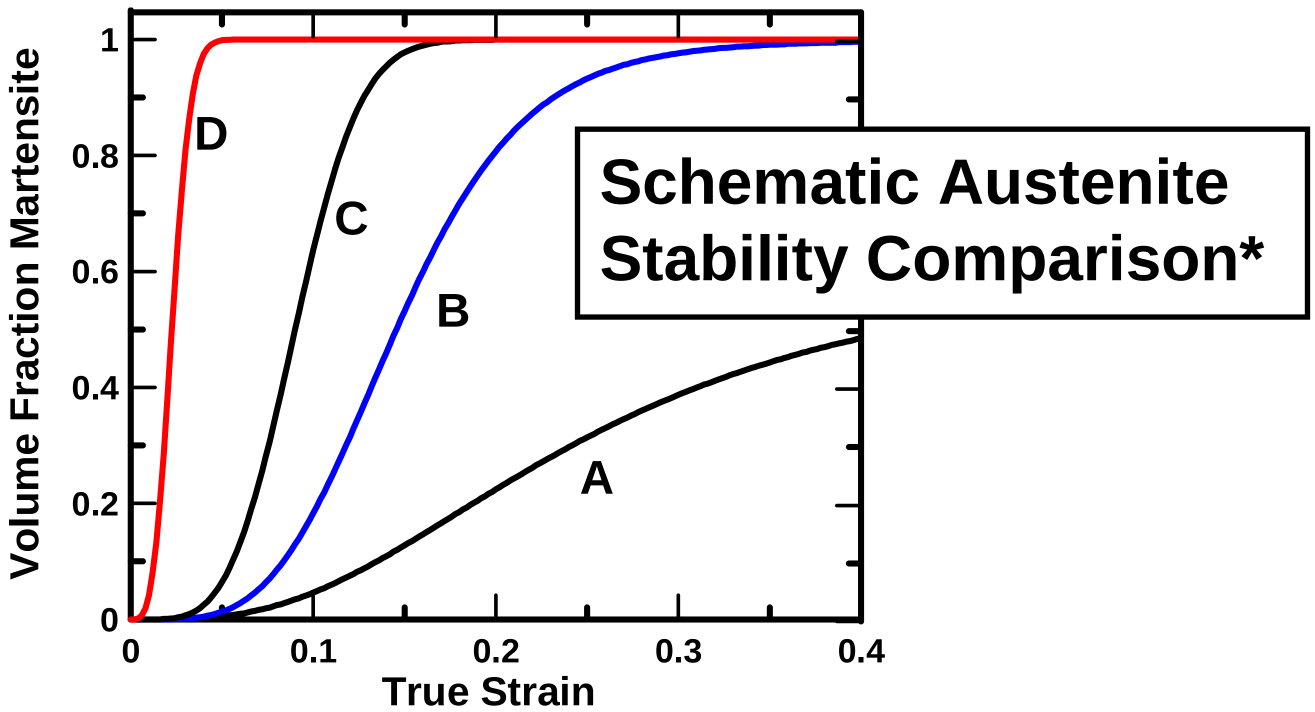


"…the ductility could be further improved by increasing the amount of retained austenite…" A. Marder (1977)

A. Marder, "Factors Affecting the Ductility of Dual-Phase Alloys," TMS, (1979)

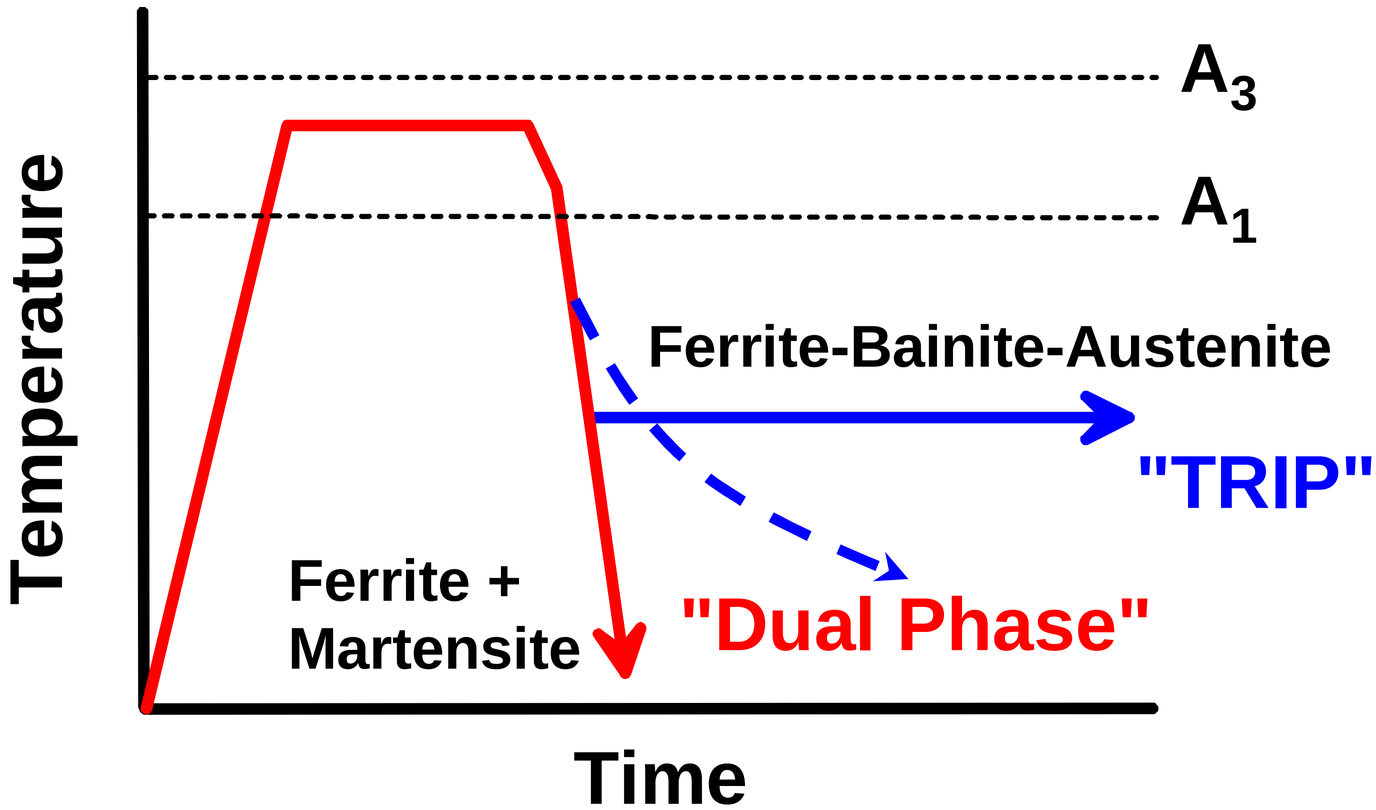
…Lessons Learned from "Early" DP Steels

However, in a different study: "…retained austenite did not have a measureable effect" due in part "to the fact that the first few percent plastic strain eliminated … austenite from the microstructure." ***Eldis, TMS, (1979)***



TRIP Steel Processing – "modified DP"

- **Isothermally transform or control cool**
- **Austenite in high strength matrix (e.g. fine grain ferrite, martensite, bainite, …)**



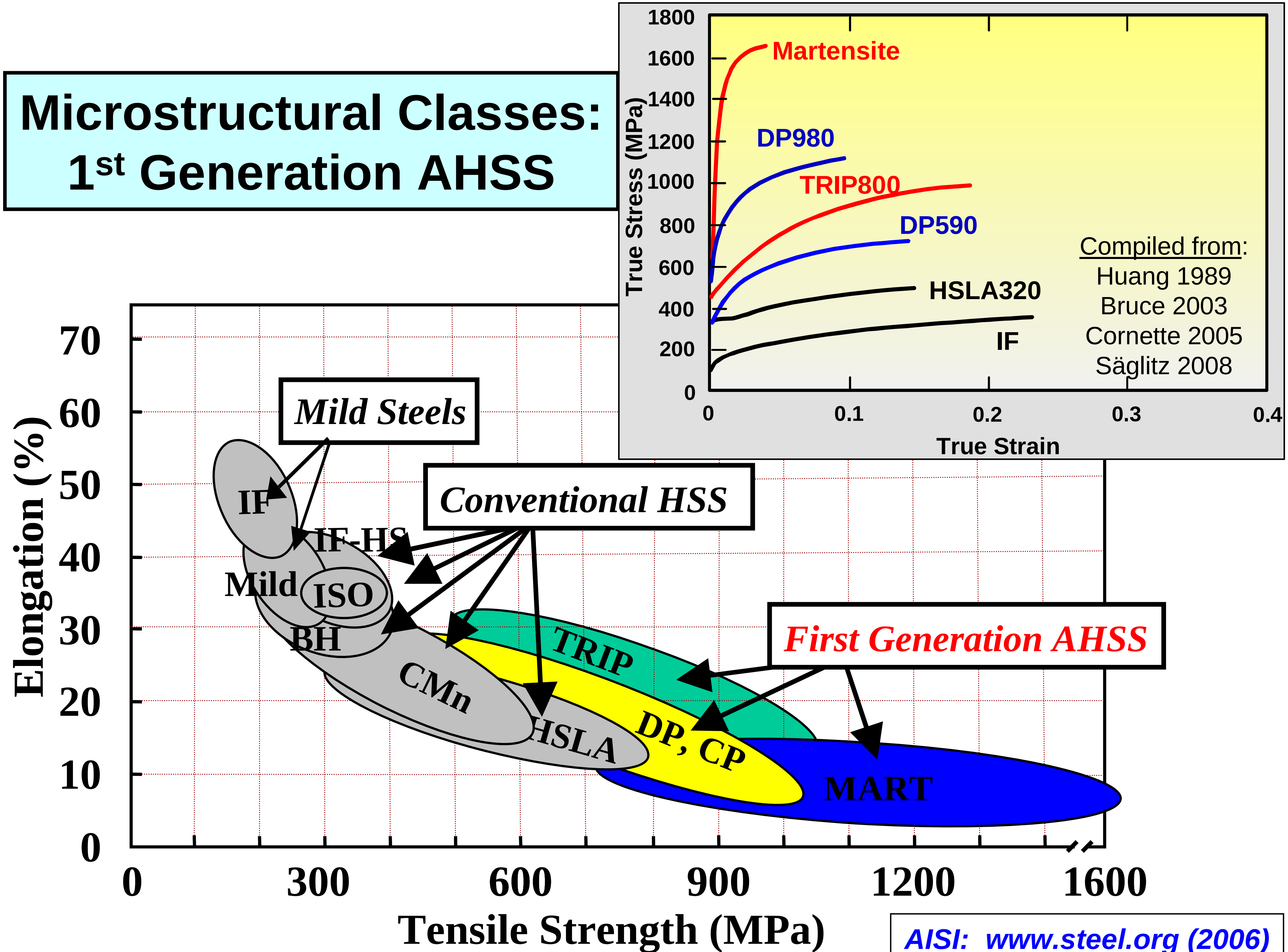
…Lessons Learned from "Early" DP Steels

- Strength = f(MVF, ferrite grain size)

$$\sigma_T = V_f\sigma_f + V_M\sigma_M$$

- Basic TRIP steel requirements identified
  - Control amount of retained austenite at room temperature.
  - Control austenite mechanical stability
- Microstructures are "complex"
- ➡ "First Generation AHSS"

Microstructural Classes: 1st Generation AHSS

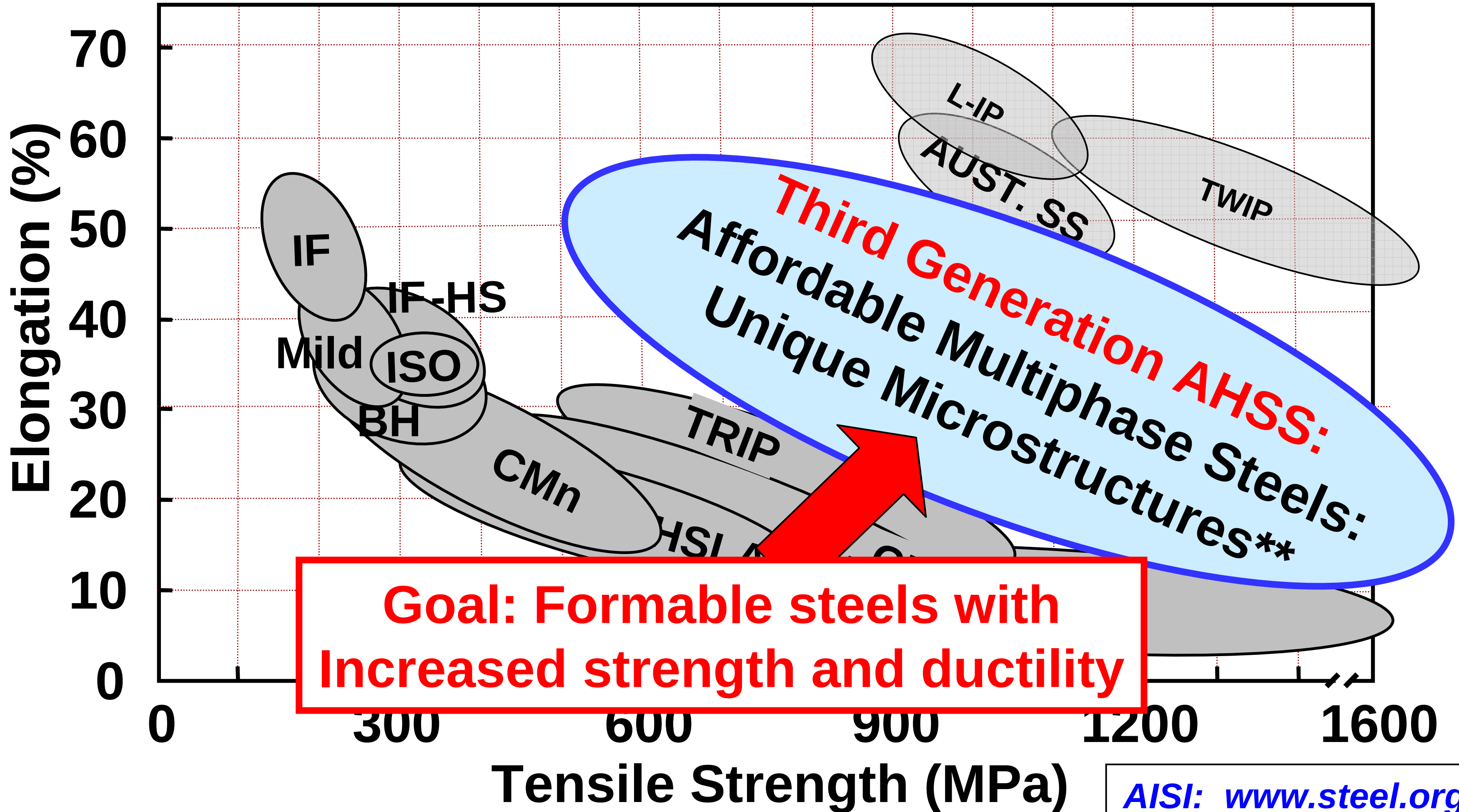


AISI: www.steel.org (2006)

Future Opportunities for AHSS

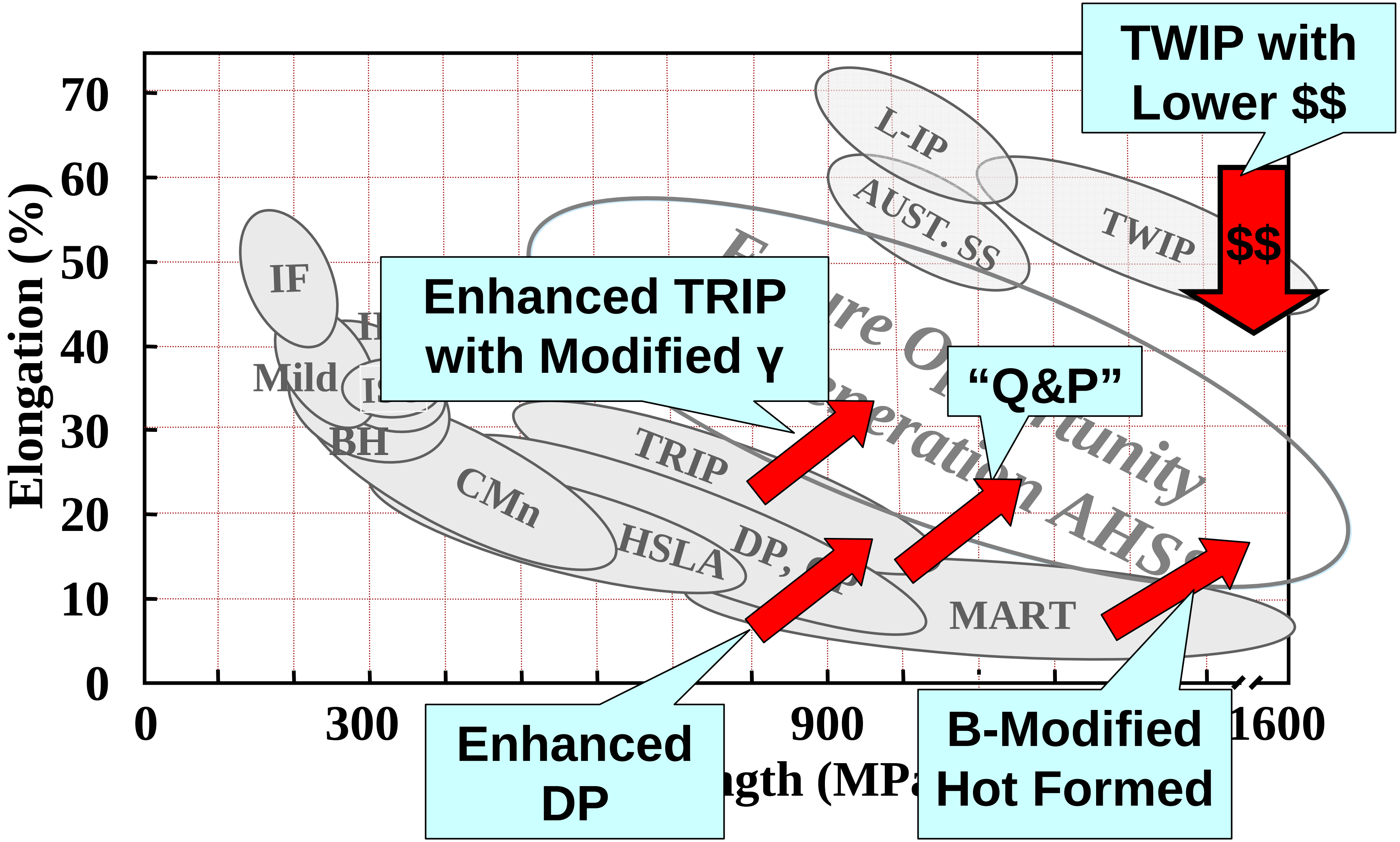
****Predicted to contain:**

- **High strength constituent**
- **Retained austenite with controlled stability**



AISI: www.steel.org (2006)

Processing Opportunities for AHSS



D.K. Matlock and J.G. Speer, "Third Generation of AHSS: Microstructure Design Concepts," Microstructure and Texture in Steels and Other Materials, ed. by A. Haldar, S. Suwas, and D. Bhattacharjee, Springer, London, 2009, pp. 185-205.

Enhanced Dual-Phase Steels

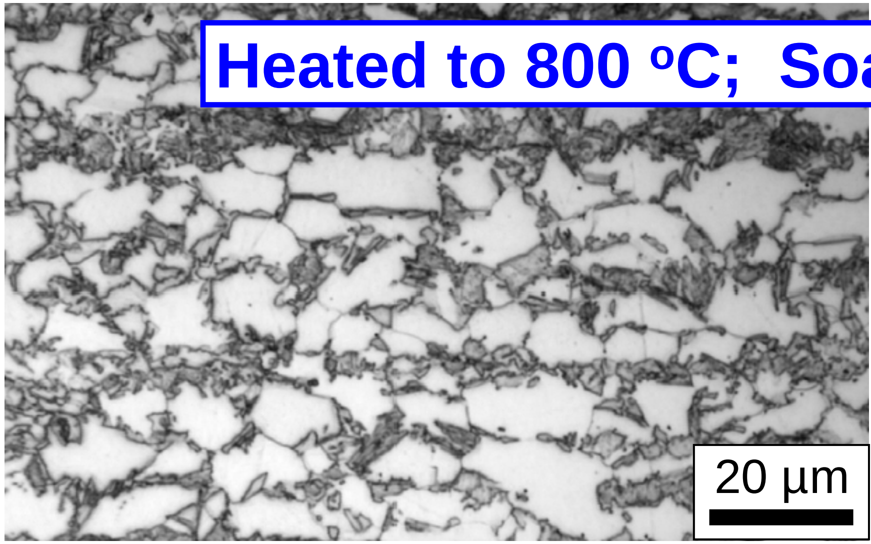
Example approaches:

- Control heating rate
- Thermal cycling to refine grain size
- Alter ferrite strength to control ferrite/martensite strength ratio
- …other….

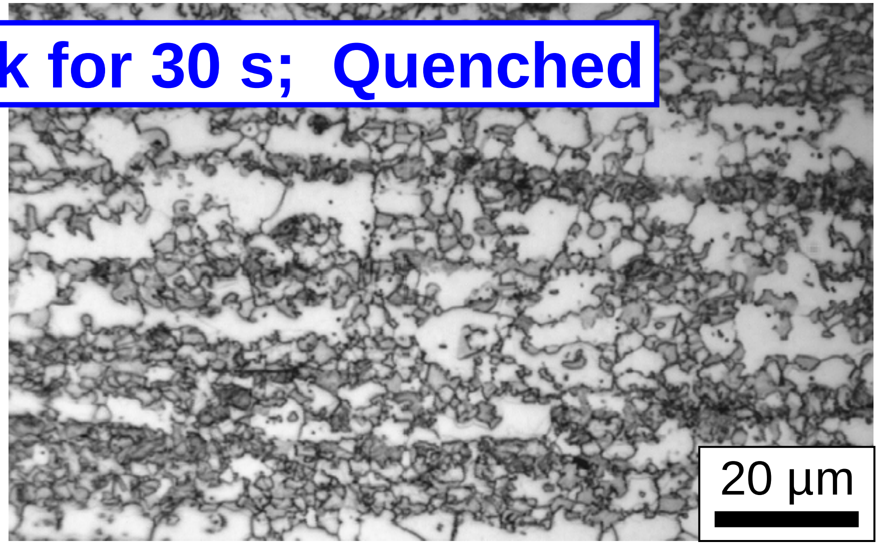
Heating Rate: CMnSiCr DP600 Steel

Heated to 800 ^{o}C; Soak for 30 s; Quenched

Heating Rate = 2 ^{o}C/s

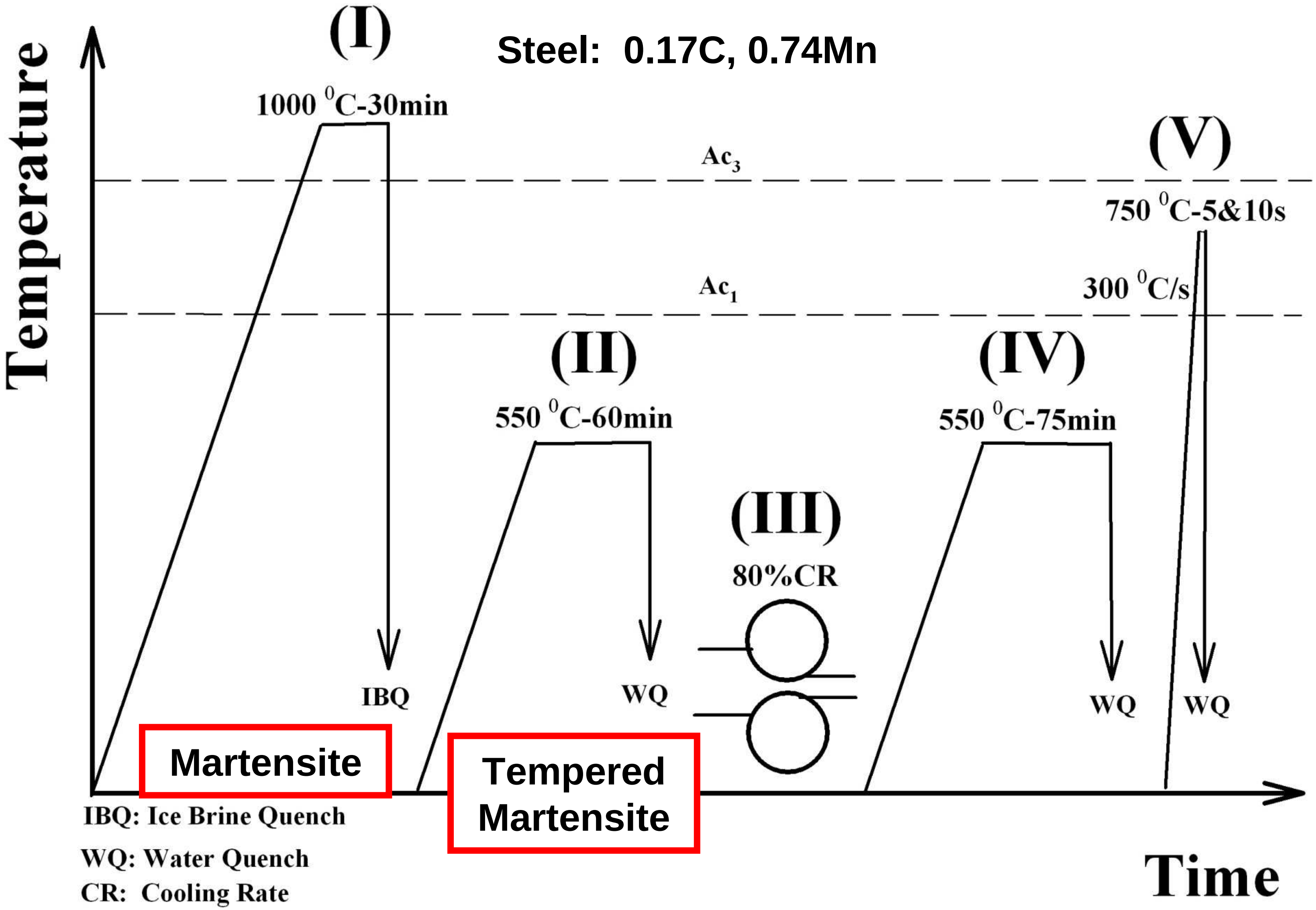


Heating Rate = 200 ^{o}C/s



D. Mumford, G. Fourlaris, A. Smith, and N. Silk, "The Interaction of Recrystallization and Transformation during the Reheating of Multiphase Steels," AISTech, 2008.

Process Control: Ultra-Fine Grain DP Steels



H. Azizi-Alizamini, M. Militzer, W.J. Poole, Proceedings AHSS Conf., AIST Orlando (2008)

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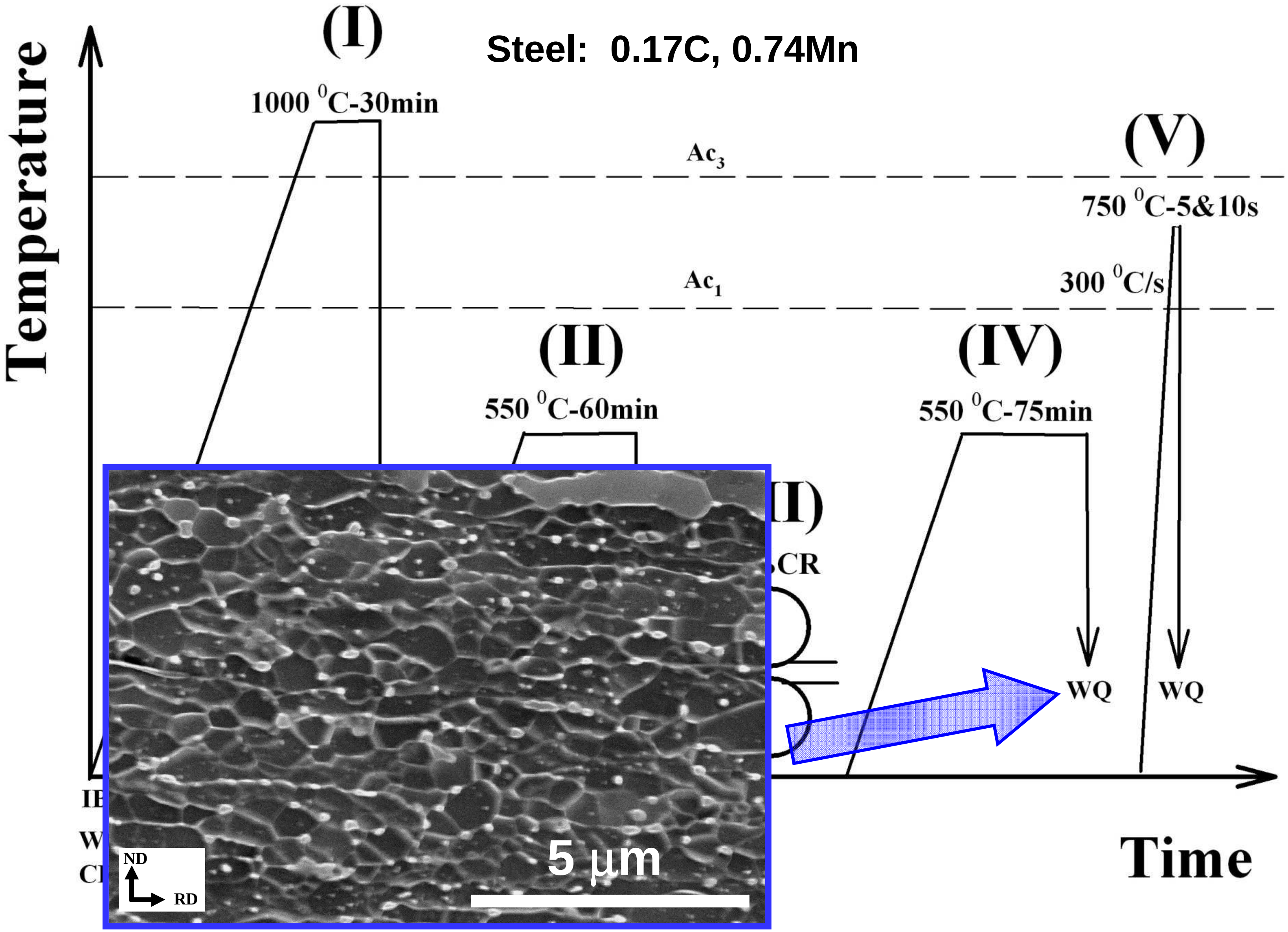

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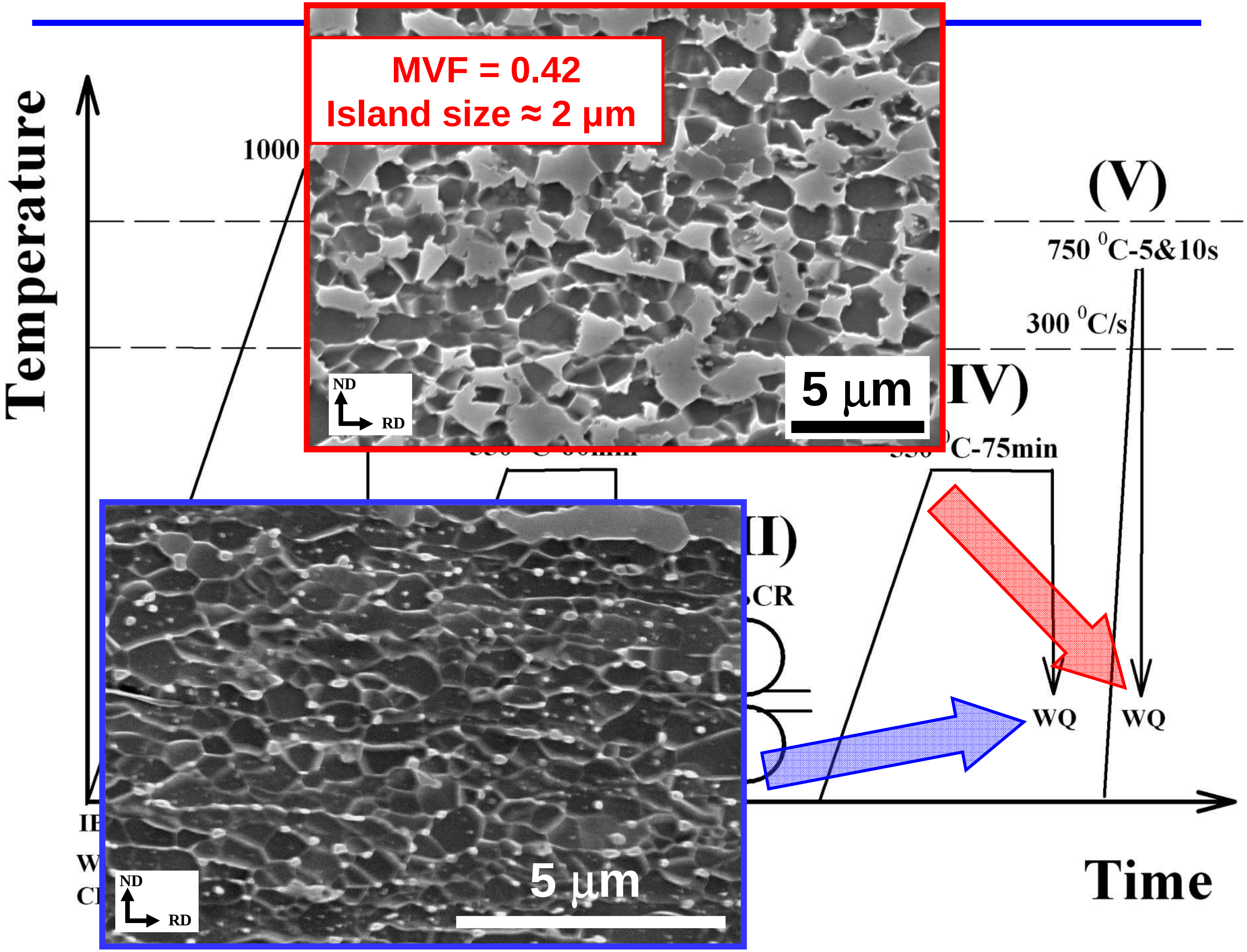

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Advanced DP Steels - Optimization

- **Processing for higher strength & enhanced performance**
  - **High volume fraction of martensite uniformly dispersed as fine particles**
    - **May need to control martensite strength**
  - **Fine grain ferrite**
    - **Modified to control martensite to ferrite strength ratio**
  - **Minimize banding**
- ***However,* Third Generation AHSS *not achievable* by enhanced DP steels!!!**

Multi-phase Modeling to Design "Third Generation AHSS"

(1) Constituent volume fractions
(2) Constituent properties
(3) Austenite Stability

Approaches:

- **Ideal Composite Model**
- **Micromechanical Models**
  - **FEA Based**
  - **…other…**

Application of Composite Model to Identify New Multiphase AHSS Steels (2006)

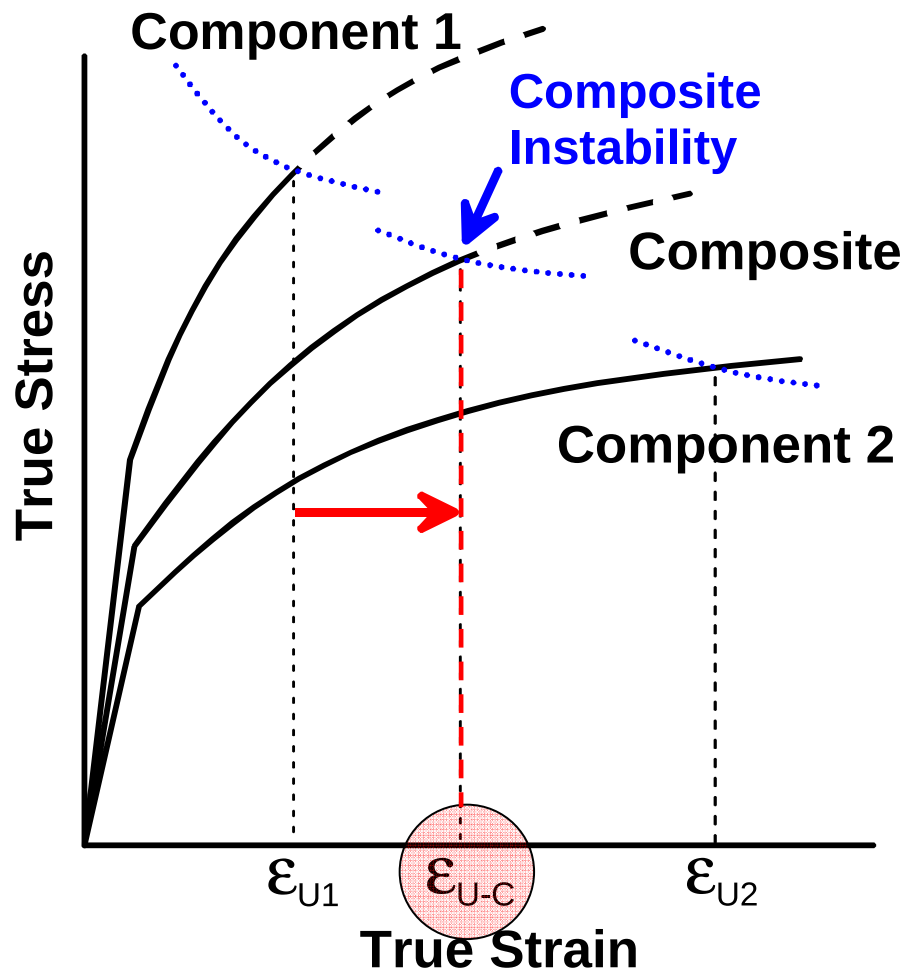
- **Assume each "constituent" described by flow curve:**

$$\sigma = K\varepsilon^{n}\dot{\varepsilon}^{m}$$

- **Apply rule of mixtures for composites *(assumes "Isostrain")***

$$\sigma_T = \sigma_1 V_1 + \sigma_2 V_2 + \ldots$$

- **At Instability** $\frac{d\sigma}{d\varepsilon} = \sigma_U$



REF: "The Tensile Strength and Ductility of Continuous Fibre Composites" S.T. Mileiko, J. Mat. Sci., (1969)

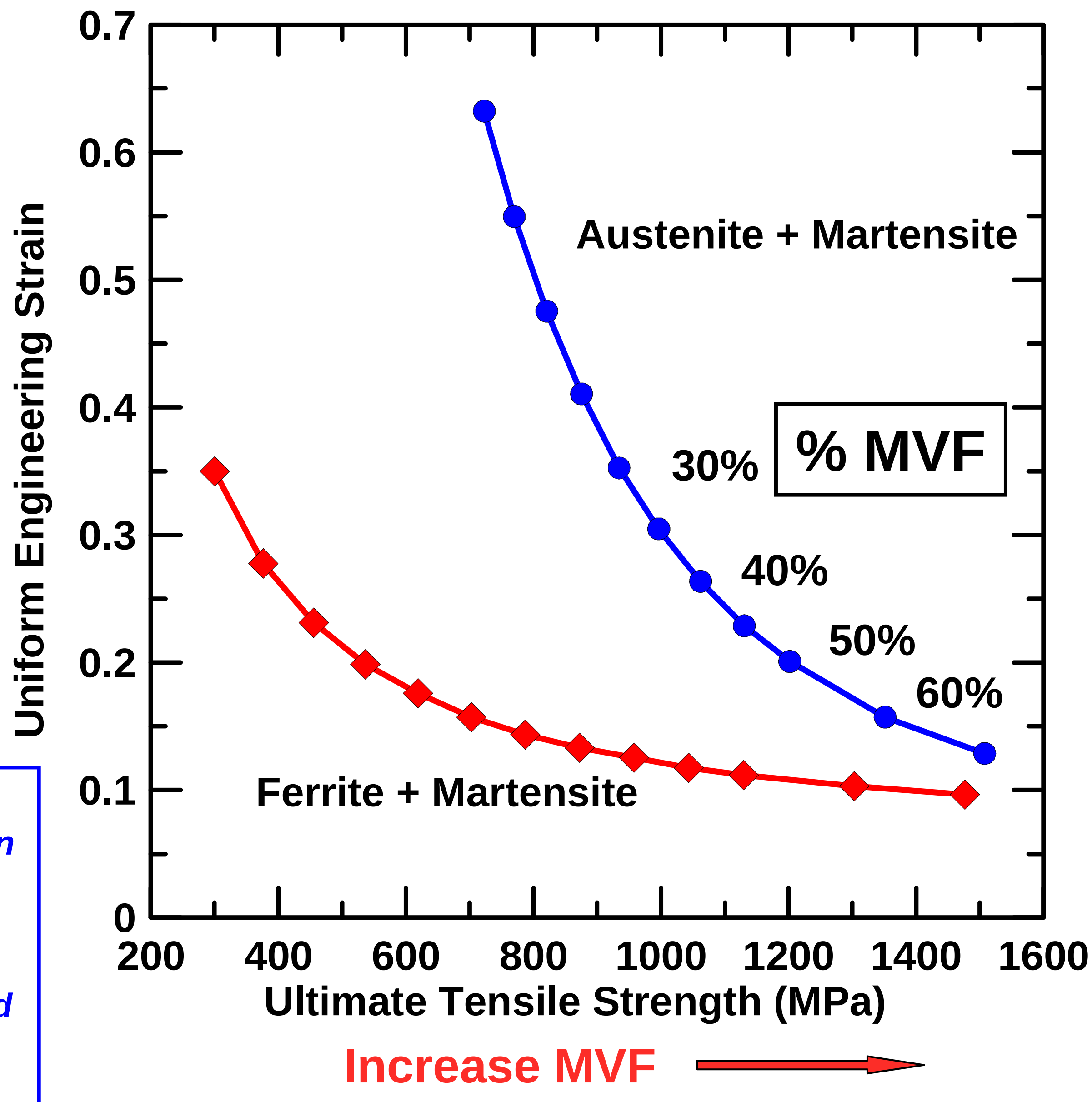
Property Assessment: Stable Austenite (2006)

Constituent properties from the literature

- High Mn Austenite (*assumed* stable)
- Martensite

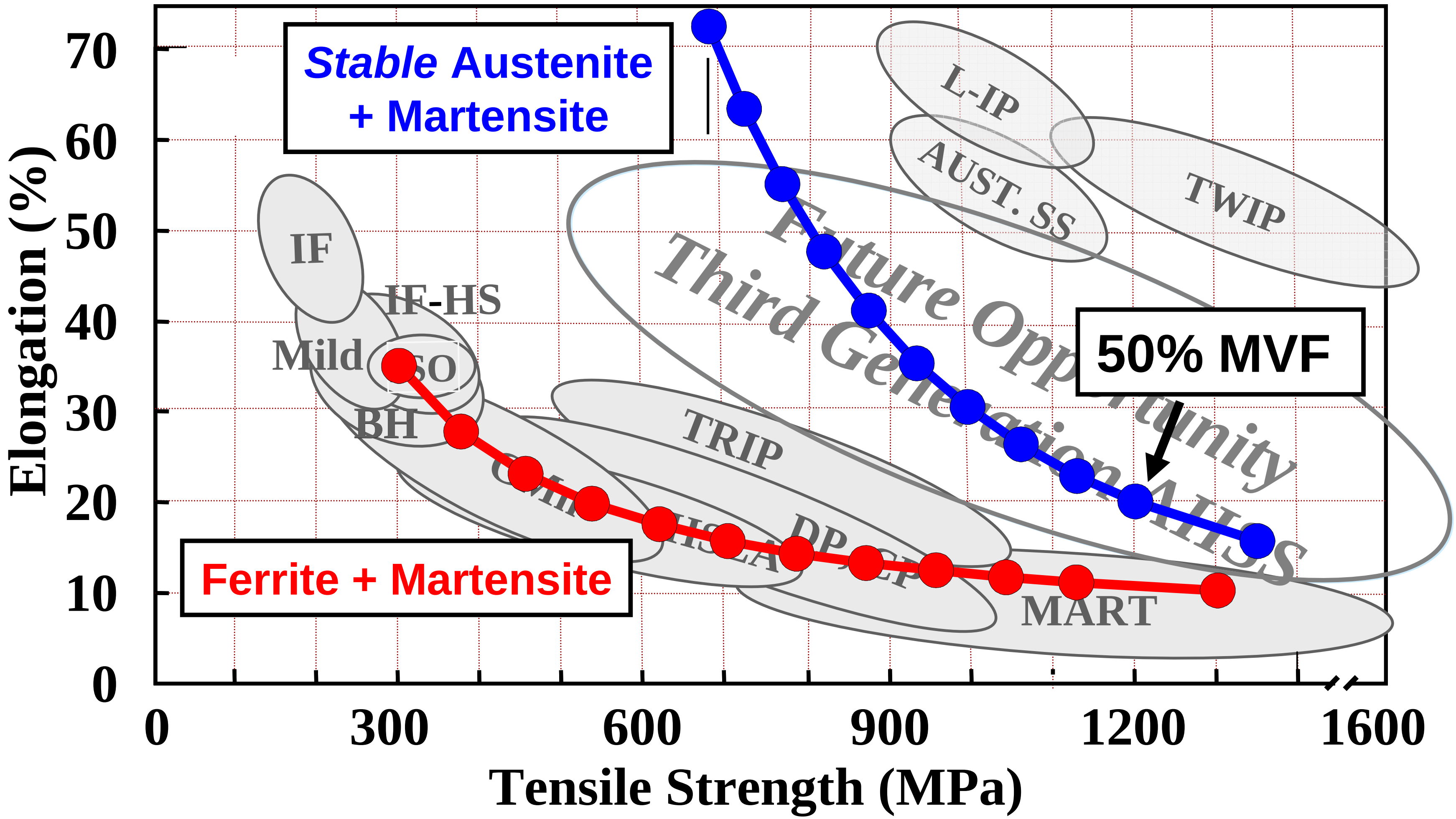
Constituent	UTS (MPa)	Uniform True Strain
Ferrite	300	0.3
Martensite	2000	0.08
Austenite	640	0.6

D.K. Matlock and J.G. Speer, "Design Considerations for the Next Generation of Advanced High Strength Sheet Steels," Proceedings of the 3rd Int. Conf. on Structural Steels, ed. by H.C. Lee, The Korean Institute of Metals and Materials, Seoul, Korea, 2006, pp. 774-781.



Comparison to "3rd Generation" AHSS (2006)

$$e_{Total} = e_U + e_{Post-U}$$



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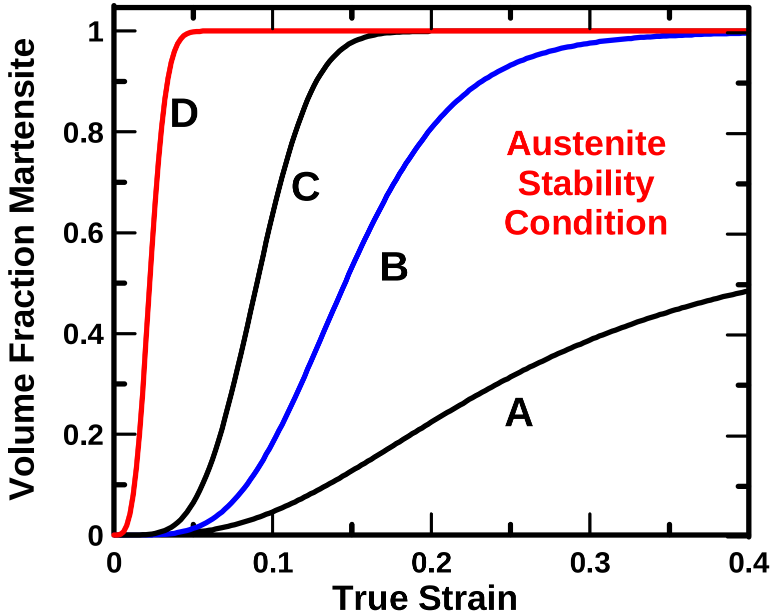
Property Assessment: Metastable Austenite

Initial Microstructure: Ferrite + Austenite
Initial Metastable Austenite = 0 to 85 %



Constituent	UTS (MPa)	Uniform True Strain	Uniform Engineering Stain
Ferrite	300	0.3	0.35
Austenite	640	0.6	0.82
Martensite	2000	0.08	0.08

Calculation Approach

- **Assume austenite stability described by saturation function**
- **Assume function depends on alloying, microstructure, T, etc.**
- **Consider only "static hardening"**
- **Vary initial austenite content in ferrite-austenite composite**

Saturation function reference: e.g. G.B. Olson, in Deformation, Processing, and Structure, ed. by G. Krauss, ASM, Metals Park, OH, 1984, pp. 391-425.

D.K. Matlock and J.G. Speer: [presented at ICASS-2006, Korea, August, 2006 and MATS 2008, Jamshedpur, India, February, 2008]; published as "Third Generation of AHSS: Microstructure Design Concepts," Microstructure and Texture in Steels and Other Materials, ed. by A. Haldar, S. Suwas, and D. Bhattacharjee, Springer, London, 2009, pp. 185-205.

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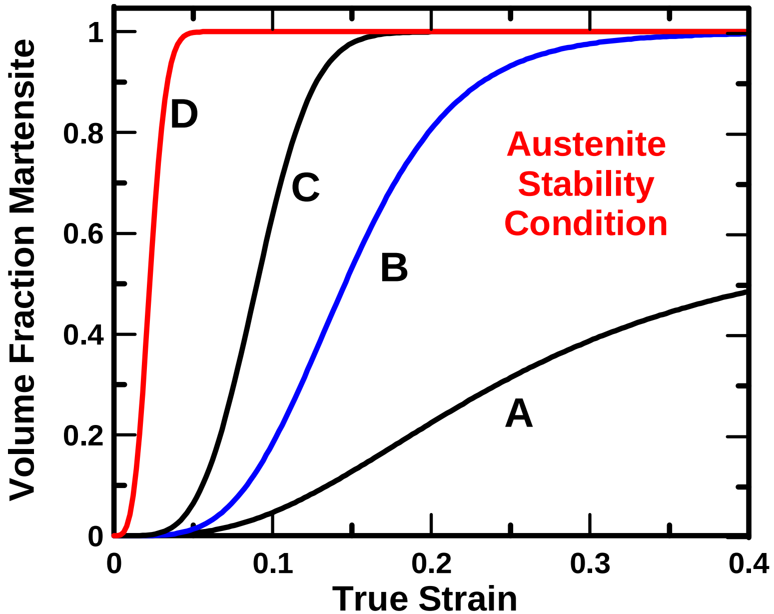

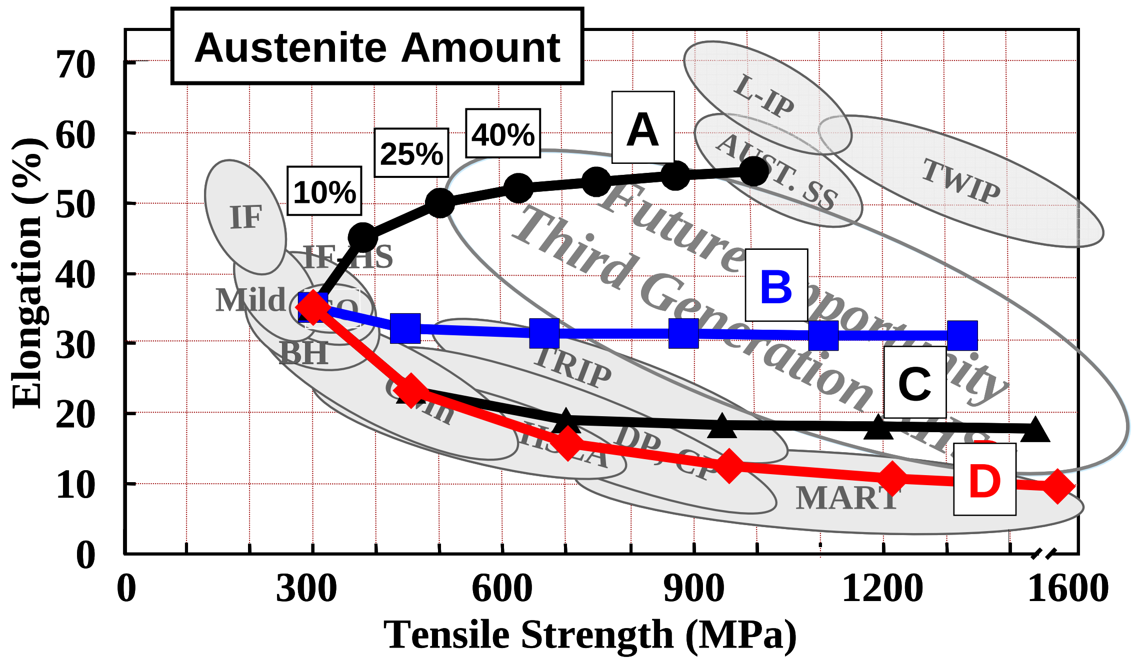

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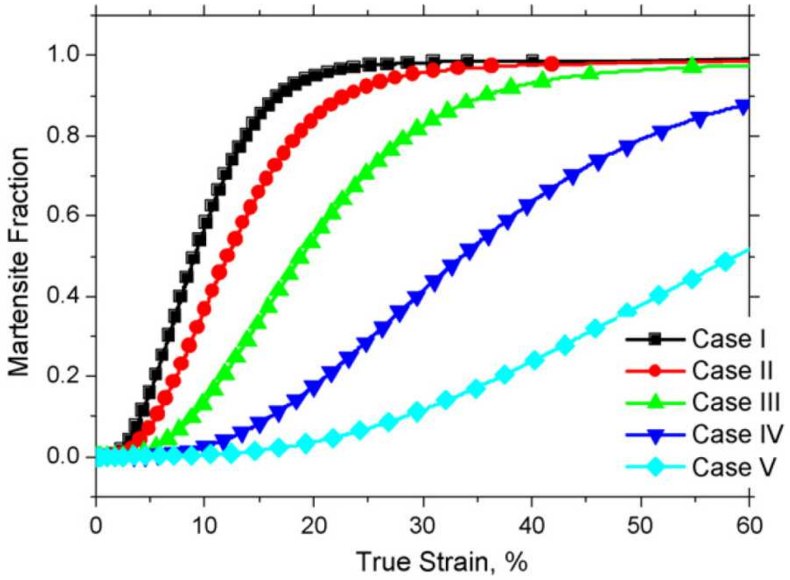
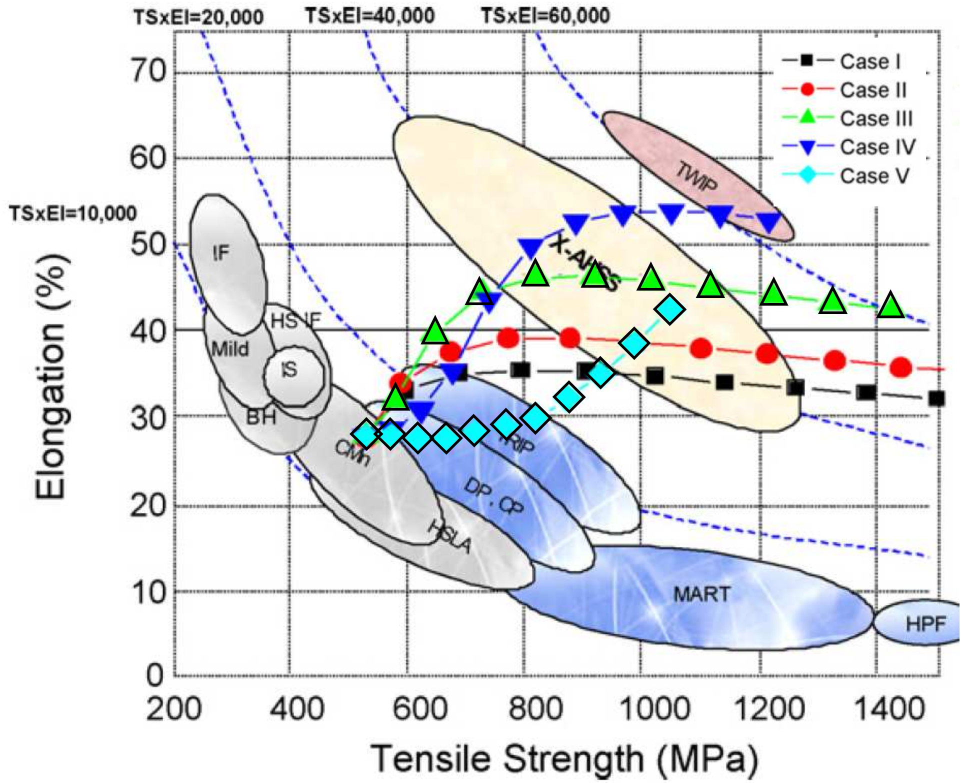
Micromechanical Modeling: Korea (2009)

- **Assumed TRIP, multi-phase steel – varied vol. fractions**
- **Applied a <u>general kinetic model</u> for the mechanically induced transformation of austenite to martensite**

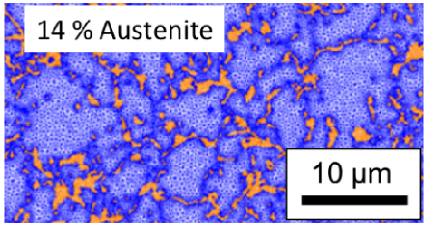


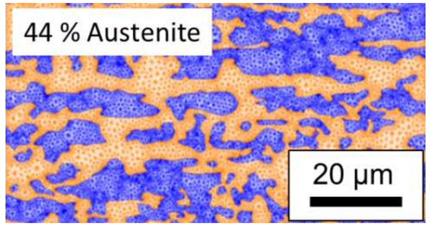


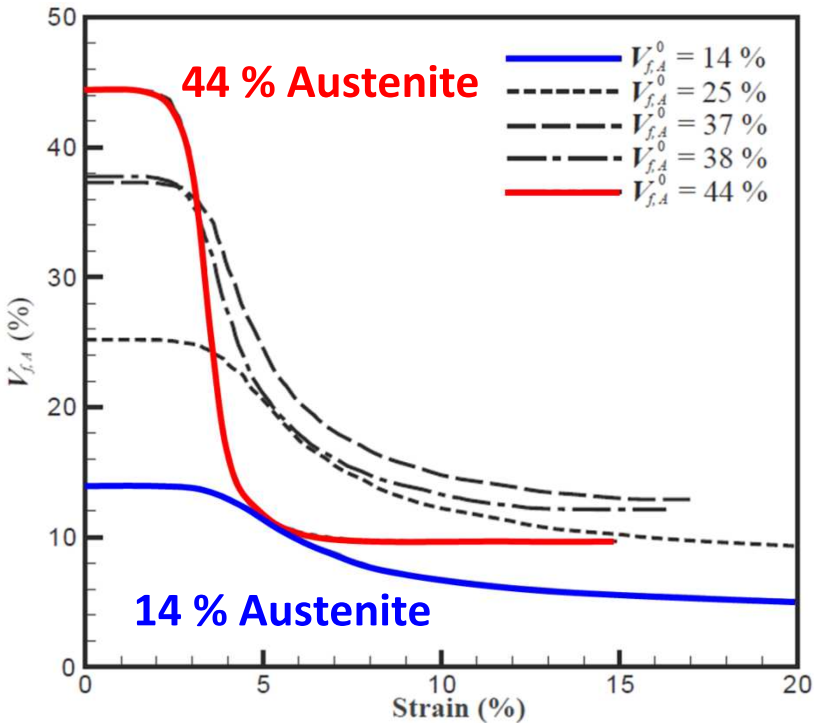
H.N. Han, C.S. Oh, G. Kim, O. Kwon, "Design method for TRIP-aided multiphase steel based on a microstructure-based modeling for transformation-induced plasticity and mechanically induced martensitic transformation," Materials Science and Engineering A, 499 (2009) 462–468.

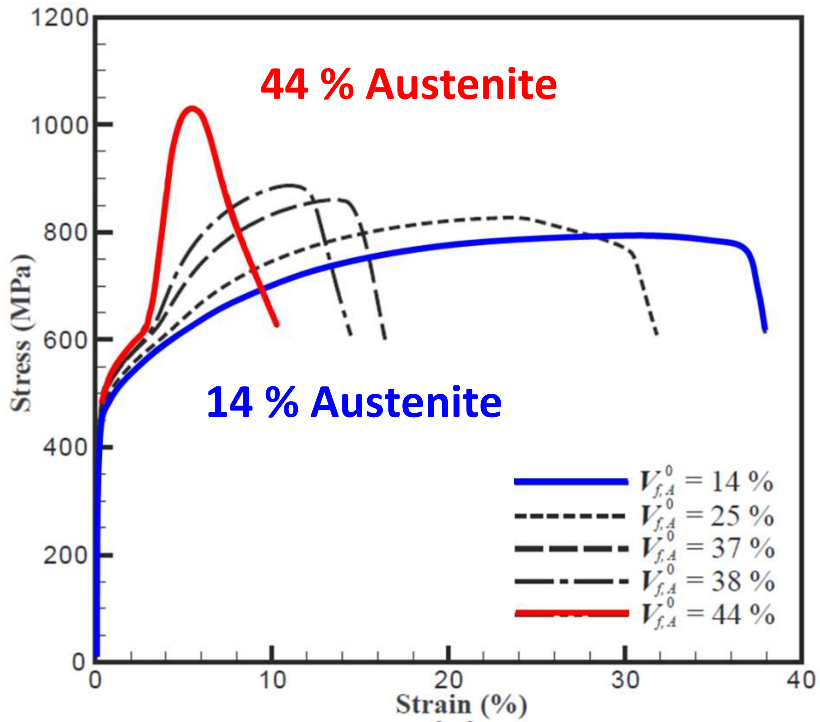
Micromechanical Modeling: PNNL (2010)

- **FEA Model - utilize "Representative Volume Element" (RVE) to describe TRIP Steel microstructure**
- **RVE based on actual microstructures**









K.S. Choi, A. Soulami, W.N. Liu, X. Sun. M.A. Khaleel, "Influence of various material design parameters on deformation behaviors of TRIP steels," Computational Materials Science 50 (2010) 720–730.

Summary of Model Predictions

- **"Big-Picture" predictions independent of modeling approach**
- **New (e.g."3rd Generation") AHSS will require:**
  - **High strength constituents**

    e.g. Martensite, fine grained ferrite, bainite…
  - **Austenite with controlled stability**
    - **e.g. transformation to martensite**
- **Additional Predictions: Steels with improved resistance to localized fracture obtained by**
  - **Refined microstructures**
  - **Minimized property gradients**

Advances in Steel Processing

New 3rd Generation AHSS

Processing Examples

(1) "Enhanced" TRIP Steels with high austenite volume fractions

(2) Q&P Steels produced by Advanced Processing = f (T, t)

Mn-Modified TRIP Steels

Design Approach:

- **Add alloying elements**
  - **Mn or N or C or …. to stabilize austenite**
- **Increase ferrite strength**
  - **Decrease Ferrite Grain Size by TMCP (Thermomechanical processing)**
- **Increase austenite volume fraction > 20%**
  - **Fine and uniformly distributed**

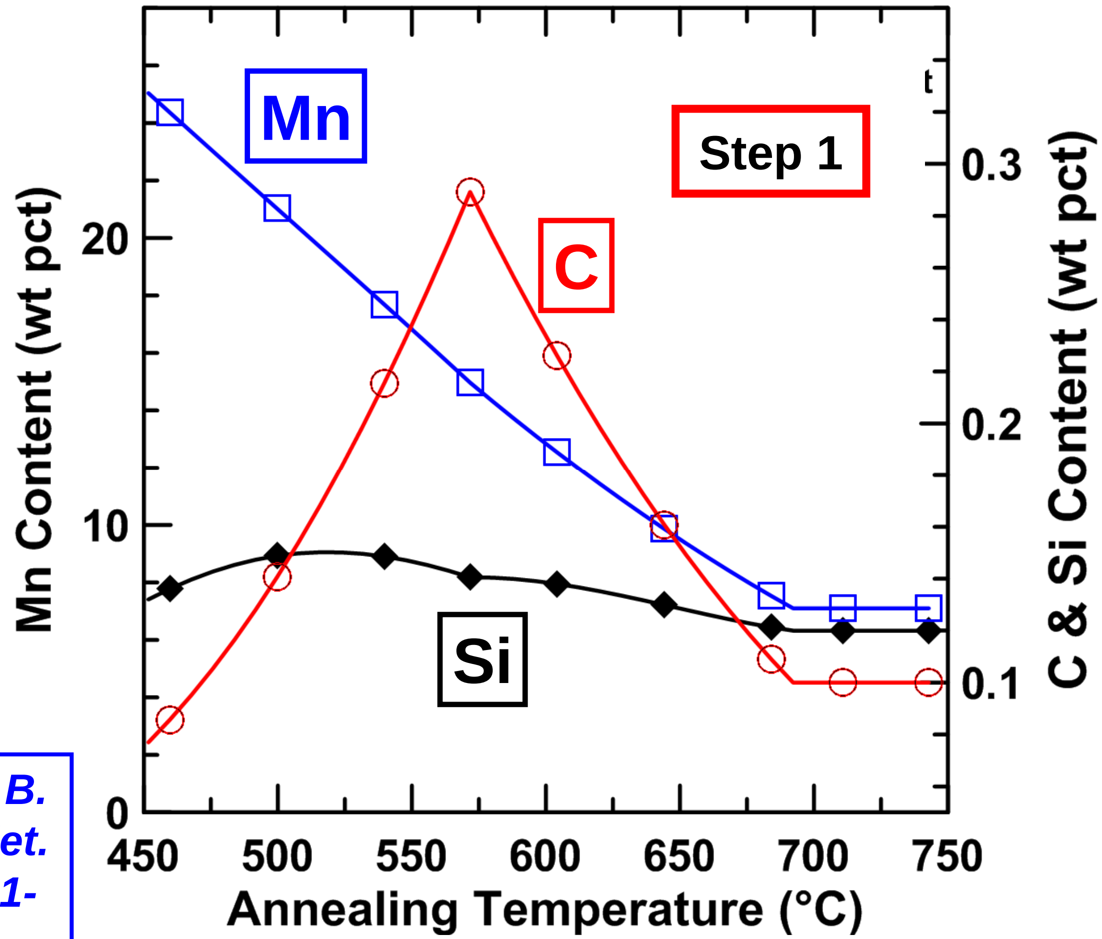
•***Acknowledge: NSF, CMMI Grant # 0729114***

P. J. Gibbs, E. De Moor, M. J. Merwin, B. Clausen, J. G. Speer, D. K. Matlock, "Austenite Stability Effects on Tensile Behavior of Manganese Enriched Austenite TRIP Steel," Met. and Mat. Trans., vol. 42, (2011), pp. 3691-3702.

Experimental Approach

- **Material – 7.1 Mn**
- **Partition Mn:**
  long-time intercritical heat treatments
- **Predict heat treatments**
  - **Use ThermoCalc: TCFE2 Data (1999)**
  - **Austenite composition**
  - **Austenite fraction**

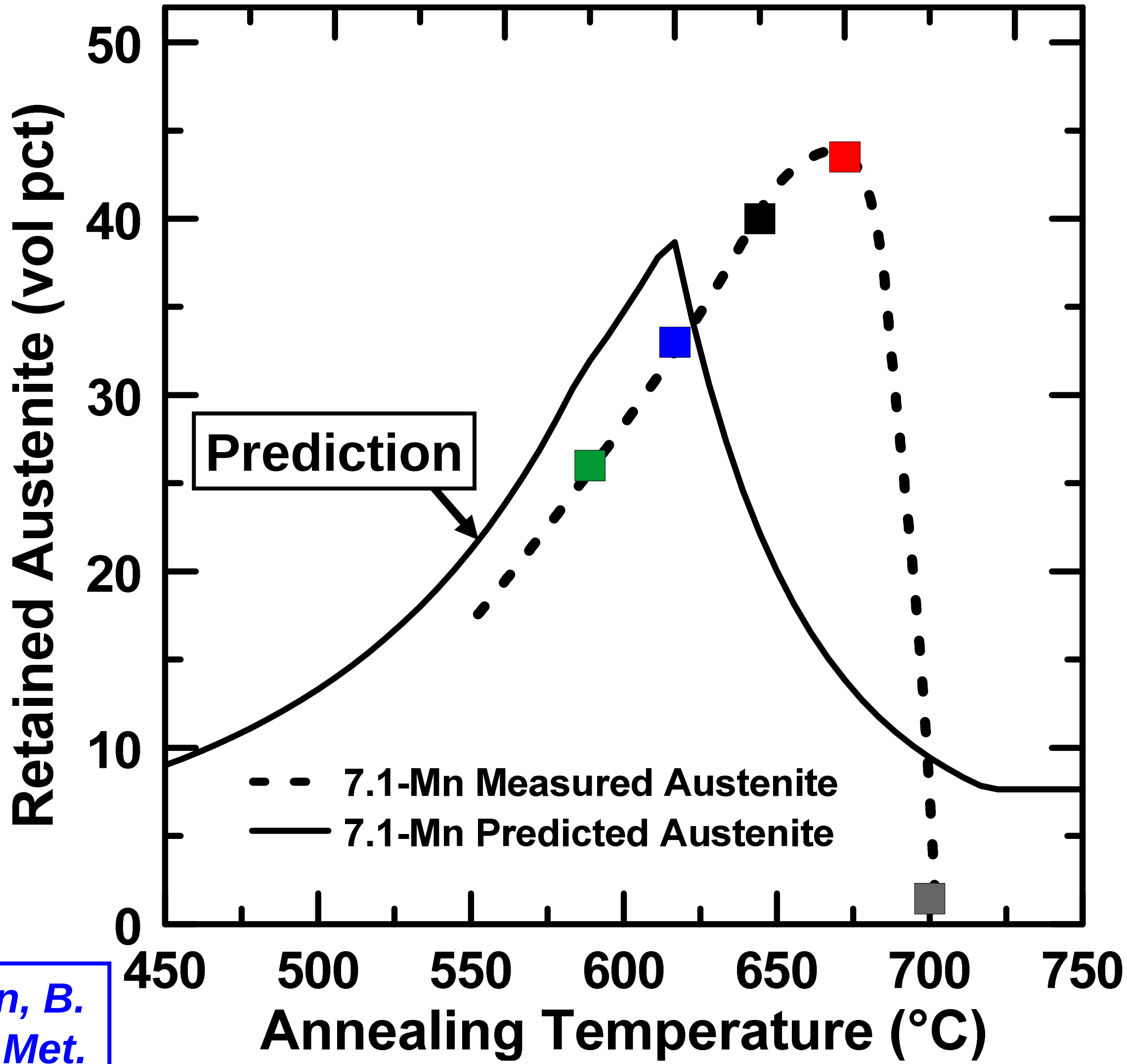
wt pct	C	Mn	Si
	0.099	7.09	0.13



P. J. Gibbs, E. De Moor, M. J. Merwin, B. Clausen, J. G. Speer, D. K. Matlock, Met. and Mat. Trans., vol. 42 (2011) pp. 3691-3702.

Microstructure

- **Heat treat for 1 week**
  - **575 to 675 °C**
- **Retained austenite measured by <u>neutron diffraction</u> *(Lujan Center at the Los Alamos National Laboratory)***



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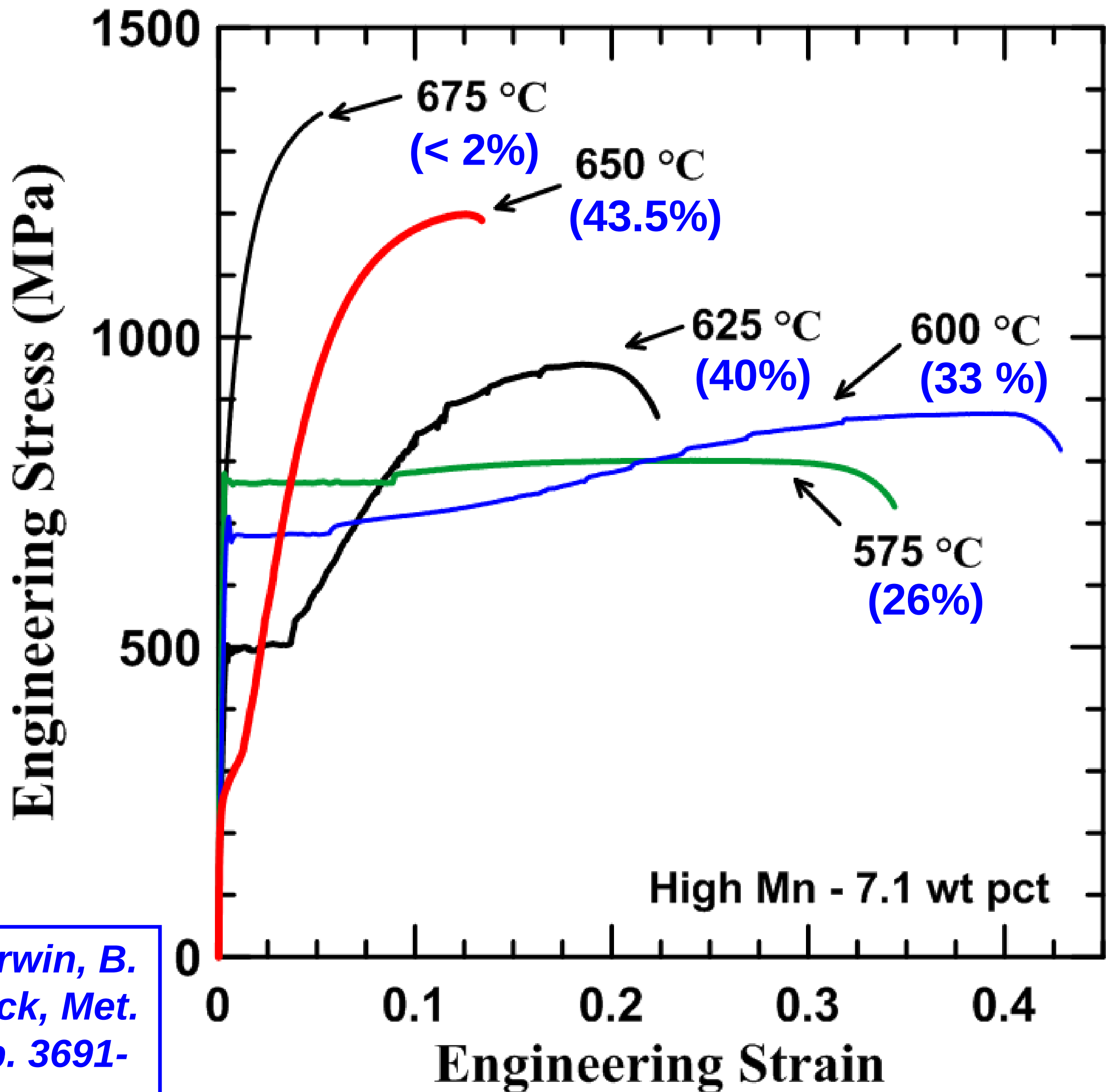
Tensile Properties – Room Temperature

- Constant engineering strain rate
- ASTM E-8 sub-sized samples
  - 32 mm reduced section
- Initial austenite contents in (%)



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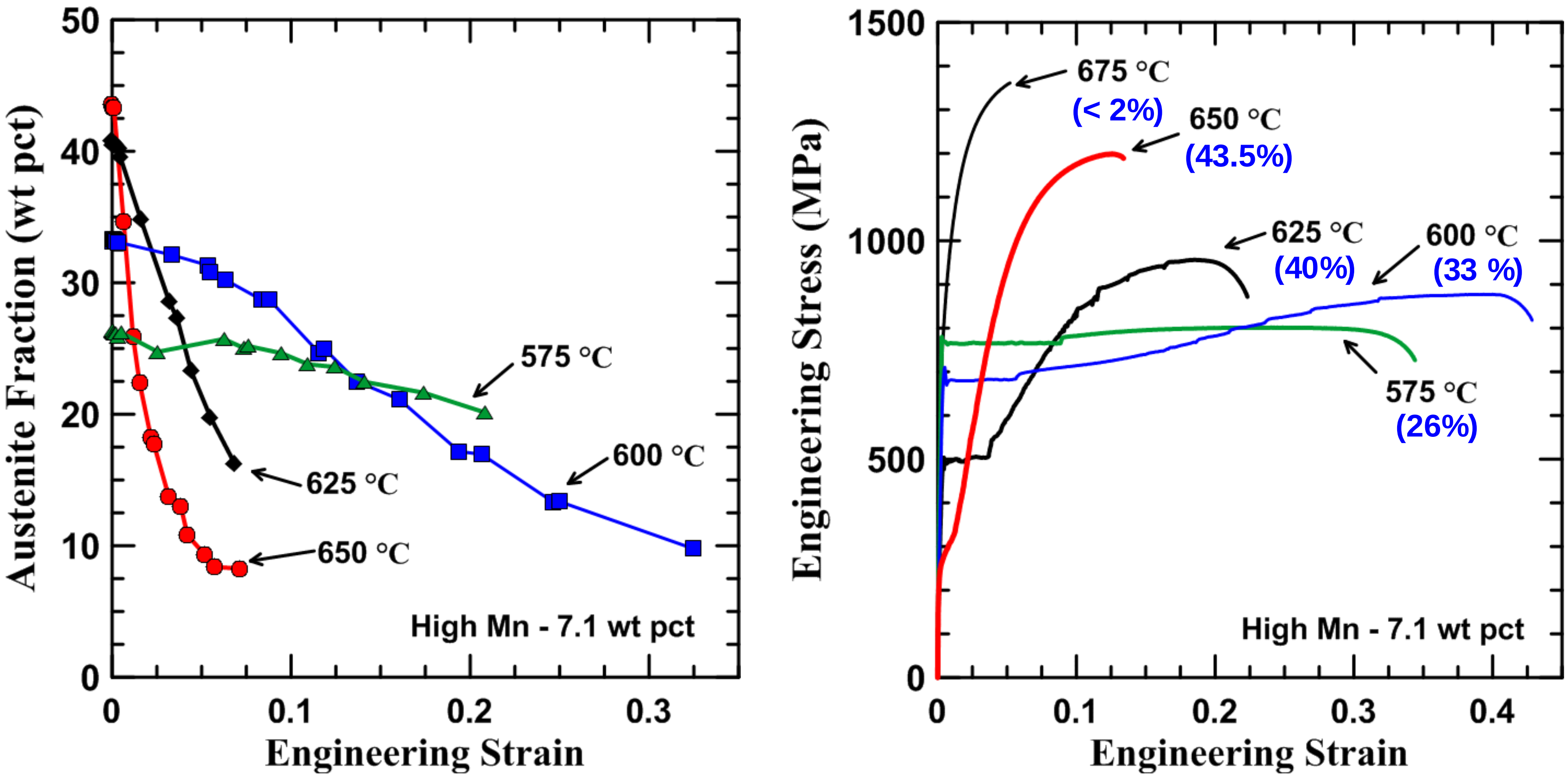
Strain-dependent Austenite Transformation



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Ferrite-Austenite: Mn-Modified TRIP Steels

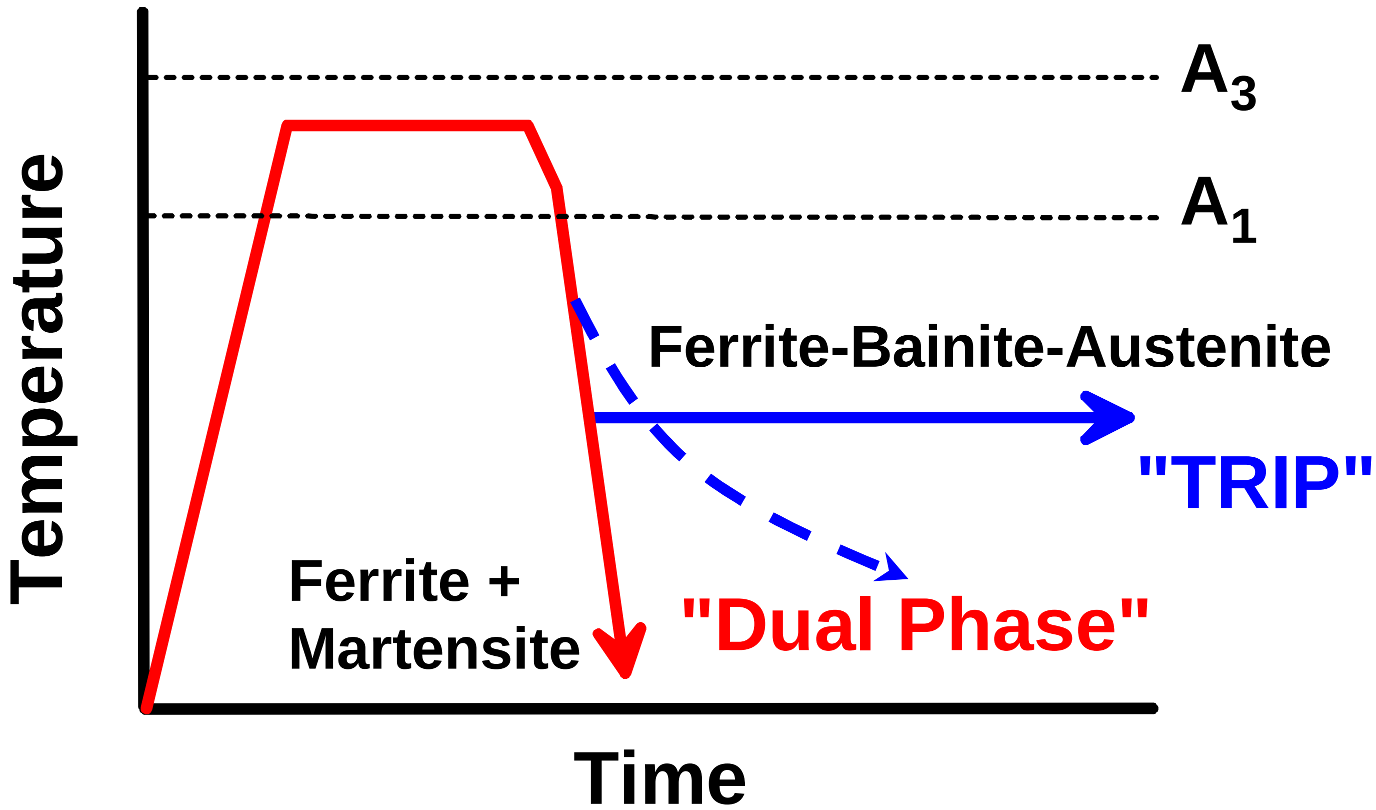
- **Intercritical annealing:**
  - **Enhances Mn partitioning**
  - **Increases austenite stability**
- **Cost efficient ways to enhance partitioning need to be identified**
- ***….Research is ongoing……..***

- ***Acknowledge: NSF, CMMI Grant # 0729114***

Quenching and Partitioning
“Q&P”

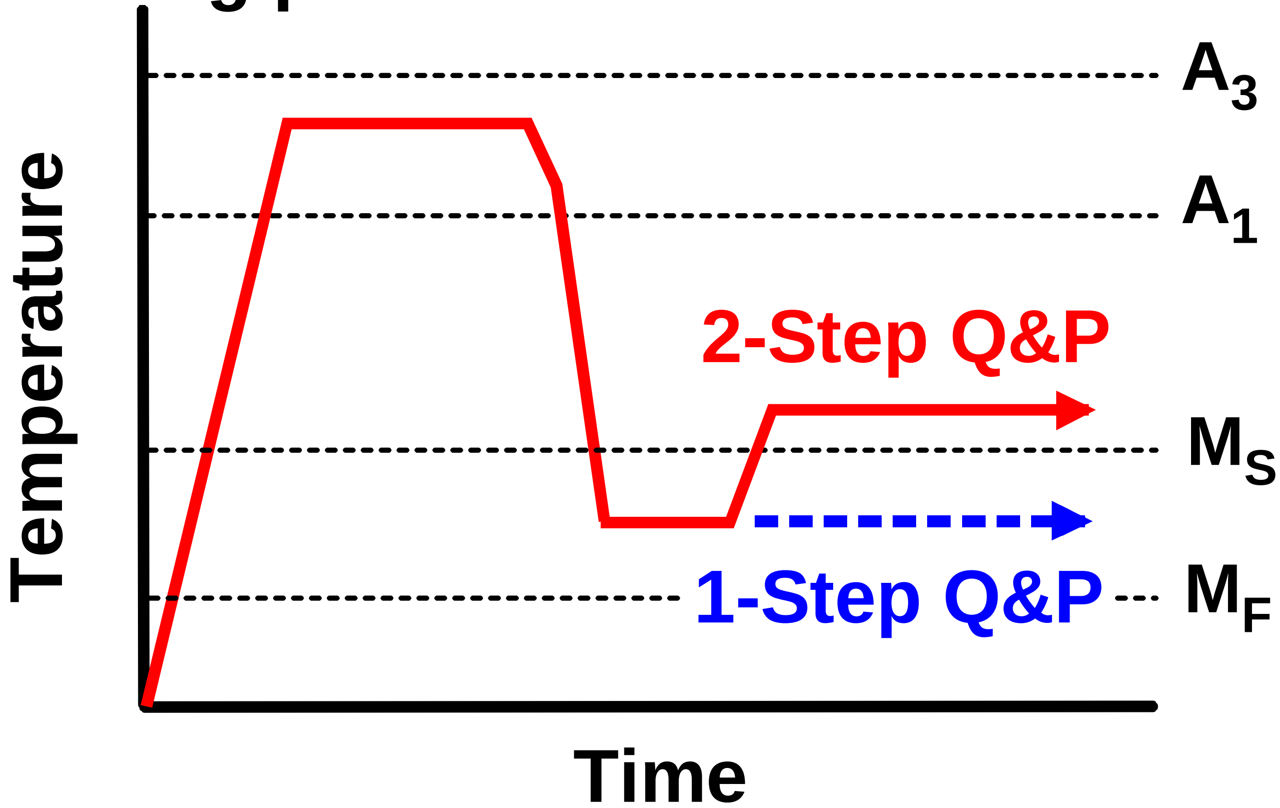
TRIP Steel Processing

- Isothermally transform or control cool
- Austenite in high strength matrix (e.g. fine grain ferrite, martensite, bainite, …)



Interrupted Cooling: The "Q&P" Process

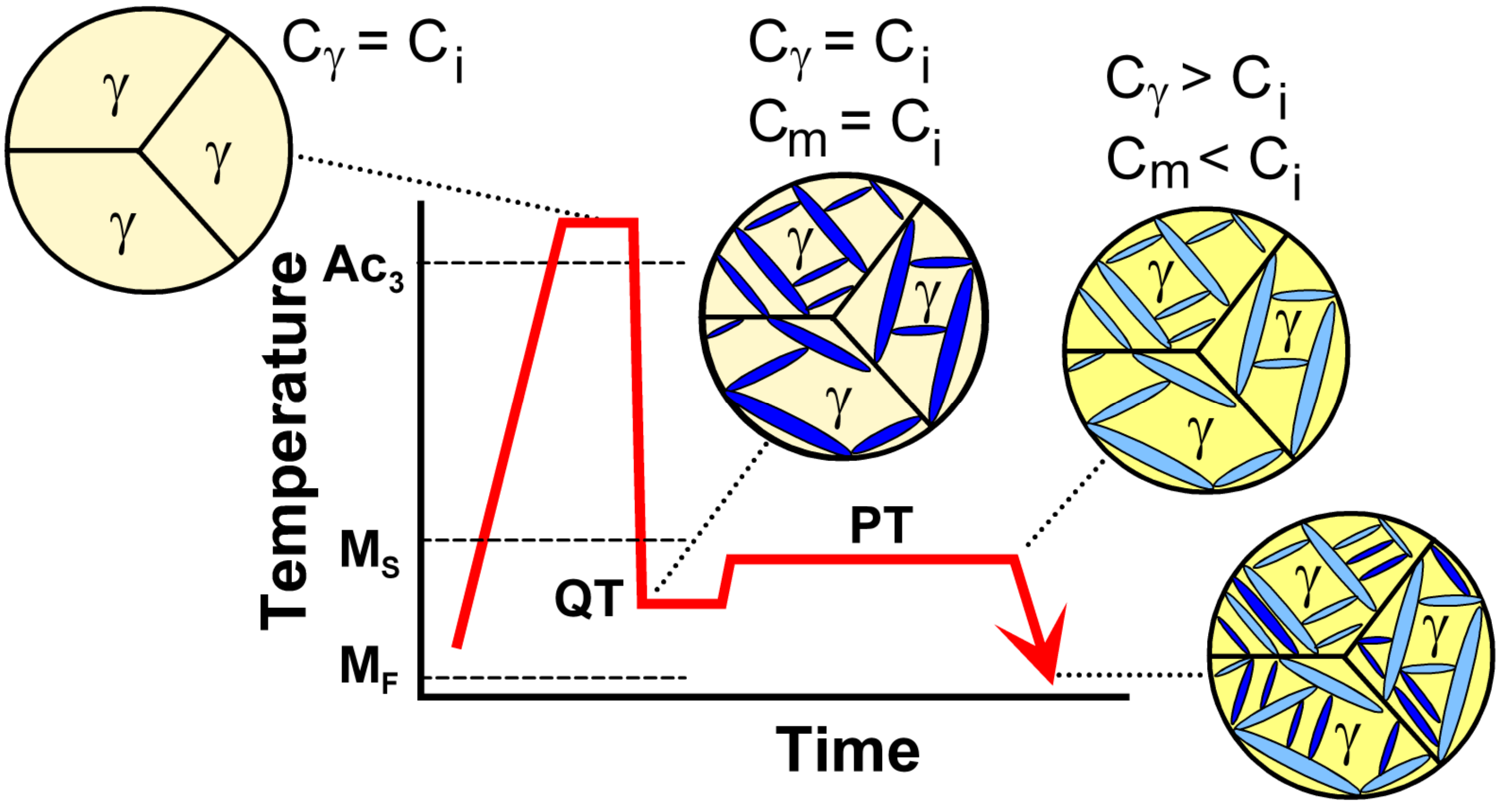
- **Novel method to produce high strength material with significant amounts of retained austenite**
- **Processing path to 3rd Generation AHSS**



J.G. Speer, et al. ASPPRC, Colorado School of Mines, (2003 - 2011)

Quenching and Partitioning (Q&P)

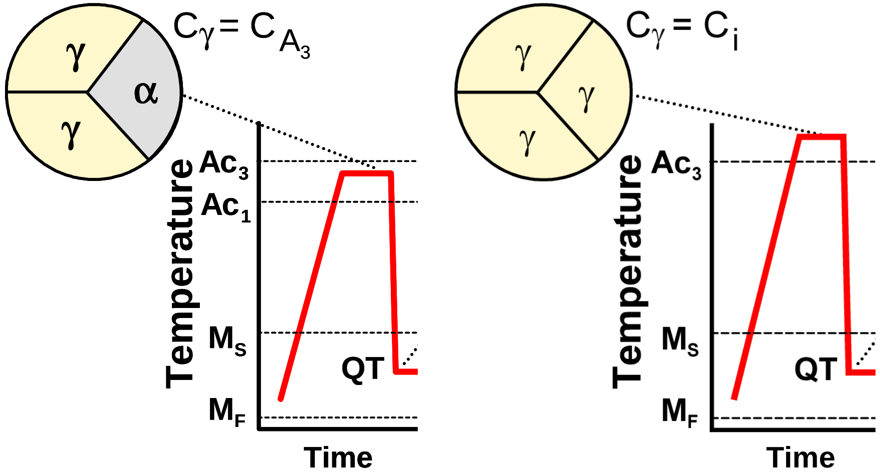
- Fundamentally new approach developed by Prof. John G. Speer at ASPPRC/CSM with automotive collaborators
- **Designed to produce enhanced AHSS with retained austenite in controlled martensite/ferrite matrix**



J.G. Speer, D.K. Matlock, B.C. De Cooman, and J.G. Schroth, "Carbon Partitioning Into Austenite after Martensite Transformation," *Acta Materialia*, vol. 51, 2003, pp. 2611-2622.

Q&P: Unique Designed Microstructures

(1) Annealing temperature controls amount of initial ferrite



(2) Quench temperature (QT): controls amount of initial martensite

(3) Alloying controls carbide stability

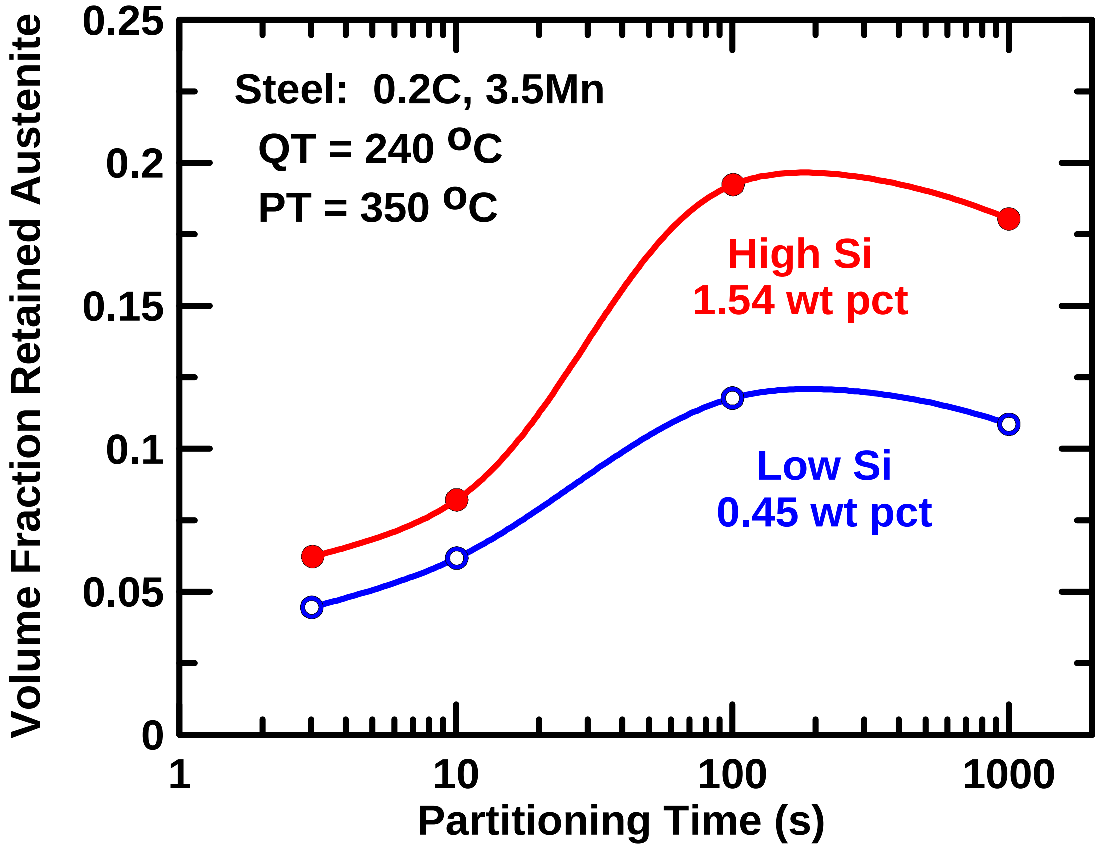
(4) Partitioning temperature and time: control austenite stability

(5) Result: unique combinations of martensite + austenite + ferrite + ..other..

J.G. Speer, D.K. Matlock, B.C. De Cooman, and J.G. Schroth, “Carbon Partitioning Into Austenite after Martensite Transformation,” *Acta Materialia*, vol. 51, 2003, pp. 2611-2622.

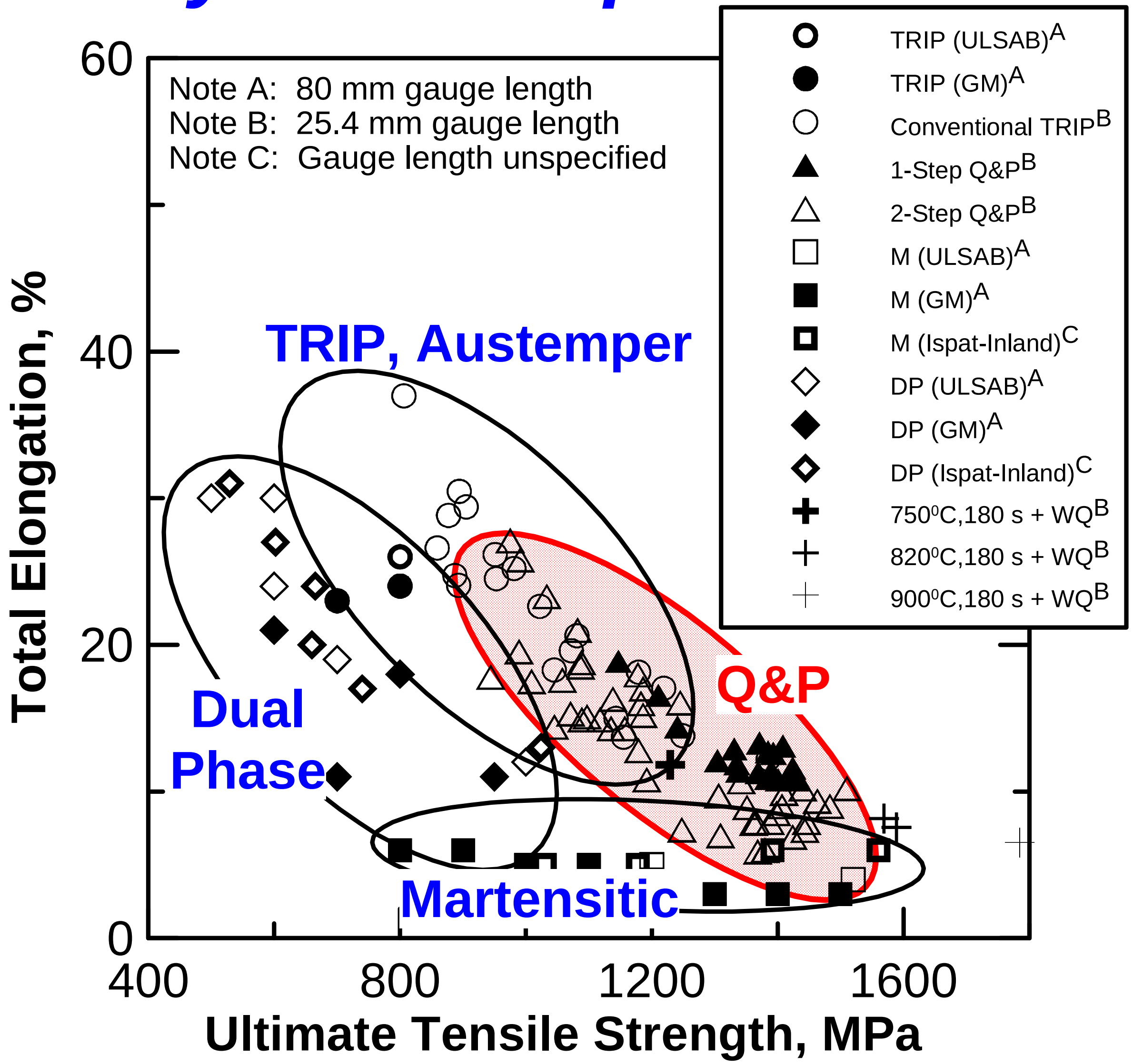
“Q&P” Alloying and Processing

- **Alloying: e.g. Mn Si Al C Mo**
- **… to control critical temperatures: M_s M_f …..**
- **… to suppress cementite formation**



M.J. Santofimia, et al., “Experimental Investigation of Q&P on Two Low-Carbon Steels with Different Silicon Contents,” Proc. Int. Conf. on New Developments in AHSS, ed. by J.G. Speer, B. Nelson, and R. Pradhan, AIST, Warrendale, PA, 2008.

Properties of Q&P
Summary and Comparison with AHSS



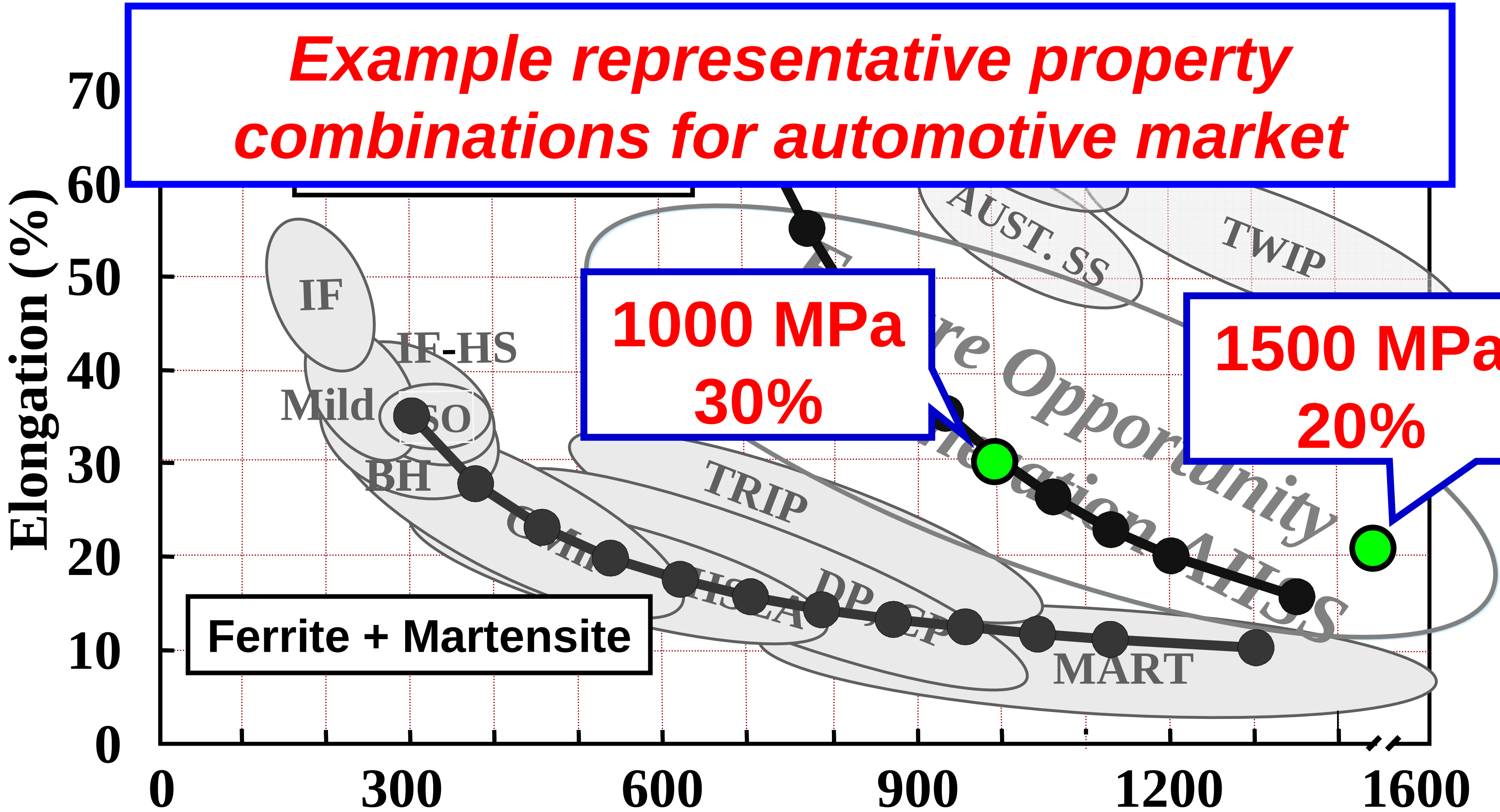
A.M. Streicher, J.G. Speer, D.K. Matlock, and B.C. De Cooman, *Int. Conf. on AHSS for Automotive Applications Proc.*, ed. by J.G. Speer, AIST, Warrendale, PA, 2004, pp. 51-62.

International Interest in the “Q&P” Process

- **Initially conceived, 2003**
- **Ongoing R&D at:**
    - **Universities**
        - **21 in 13 countries**
    - **Research Institutes**
        - **13 in 7 countries**
    - **Companies**
        - **14 in 10 countries**

Current Status of AHSS Developments

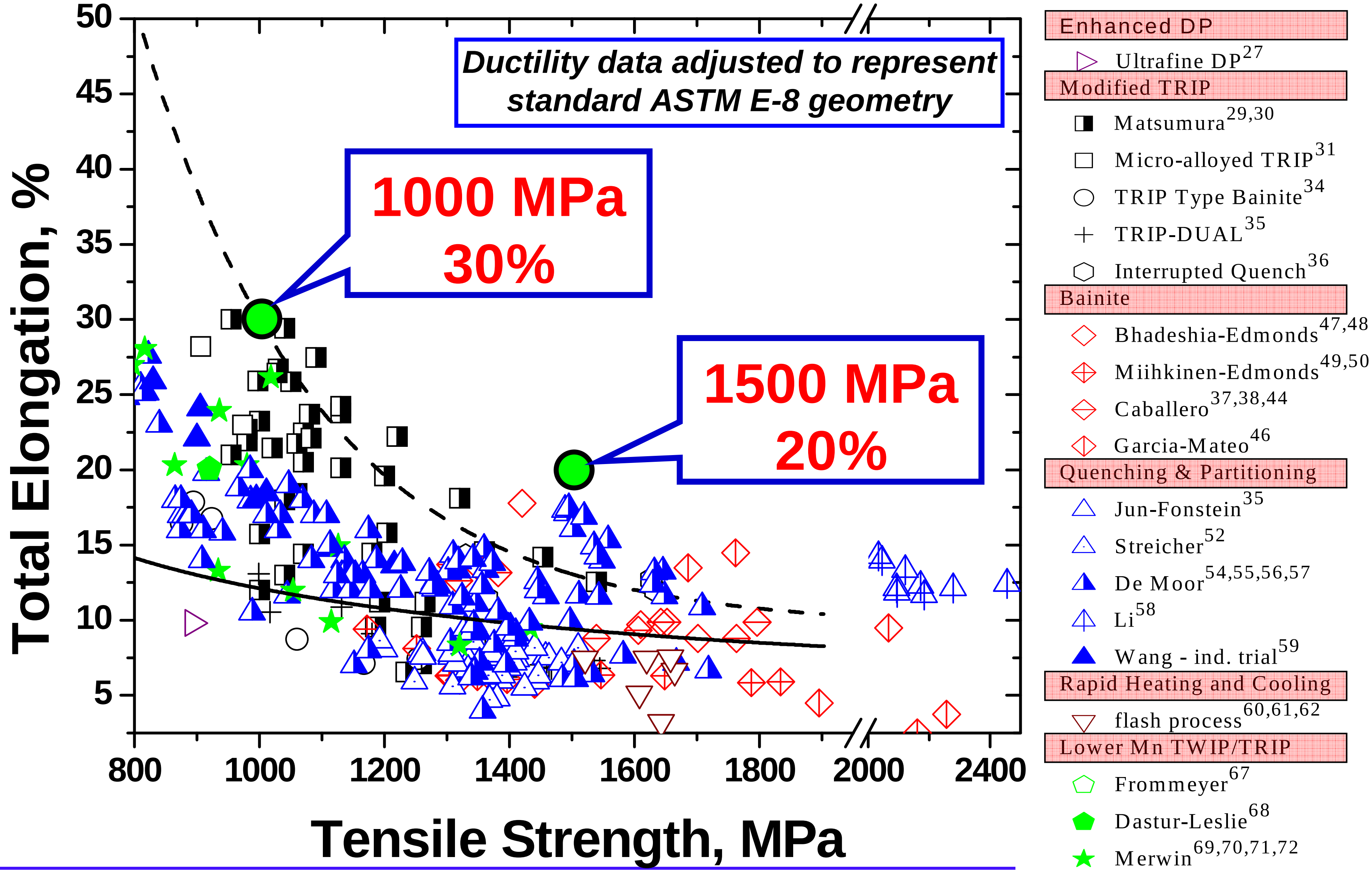
AHSS Property Targets



AISI: www.steel.org (2006)

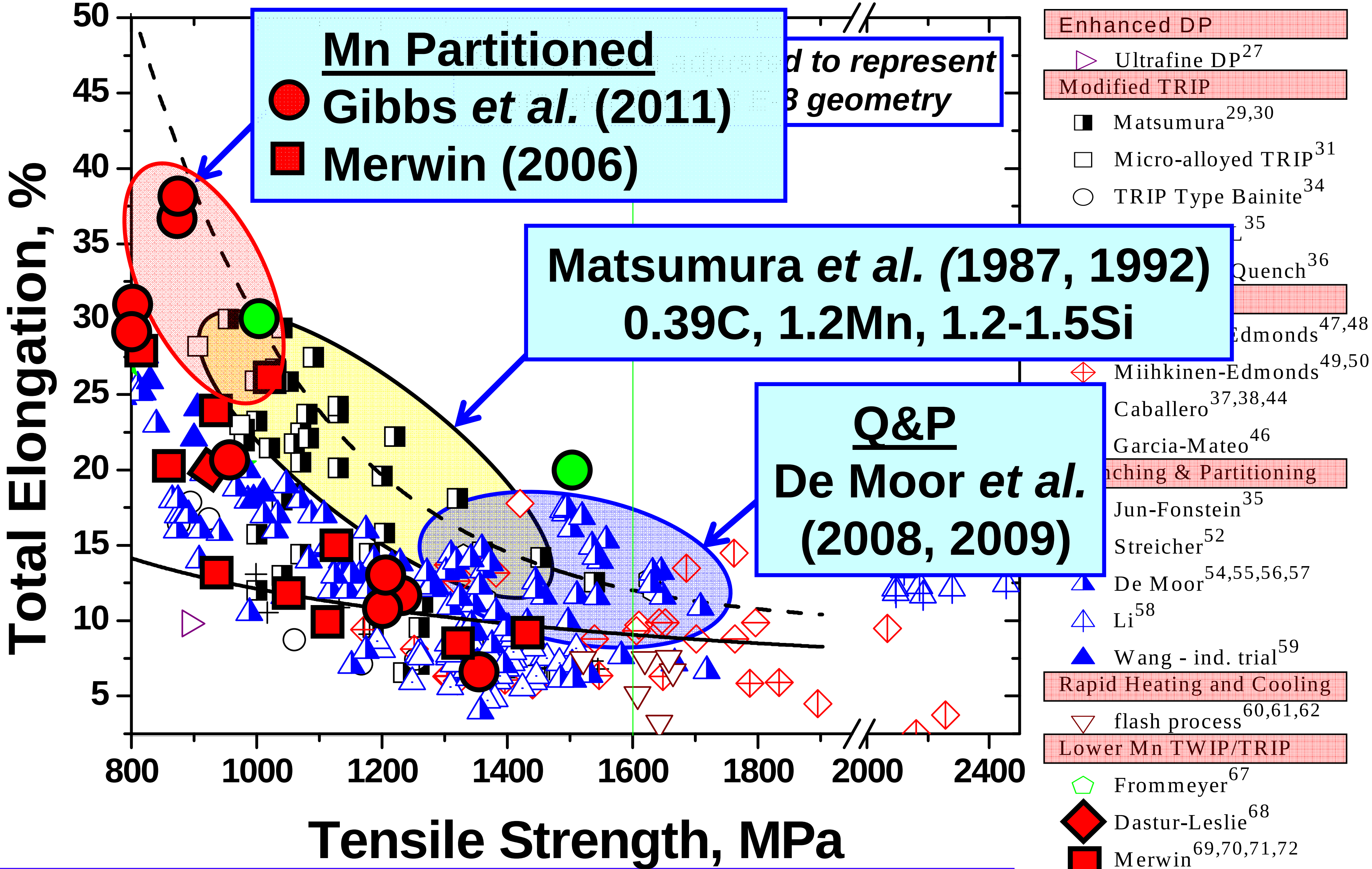
D.K. Matlock and J.G. Speer, "Design Considerations for the Next Generation of Advanced High Strength Sheet Steels," Proceedings of the 3rd Int. Conf. on Structural Steels, ed. by H.C. Lee, The Korean Institute of Metals and Materials, Seoul, Korea, 2006, pp. 774-781.

AHSS Development Status



De Moor, Gibbs, Speer, Matlock, and Schroth, "Strategies for Third-Generation Advanced High-Strength Steel Development", AIST Transactions, Iron & Steel Tech. Nov. 2010.

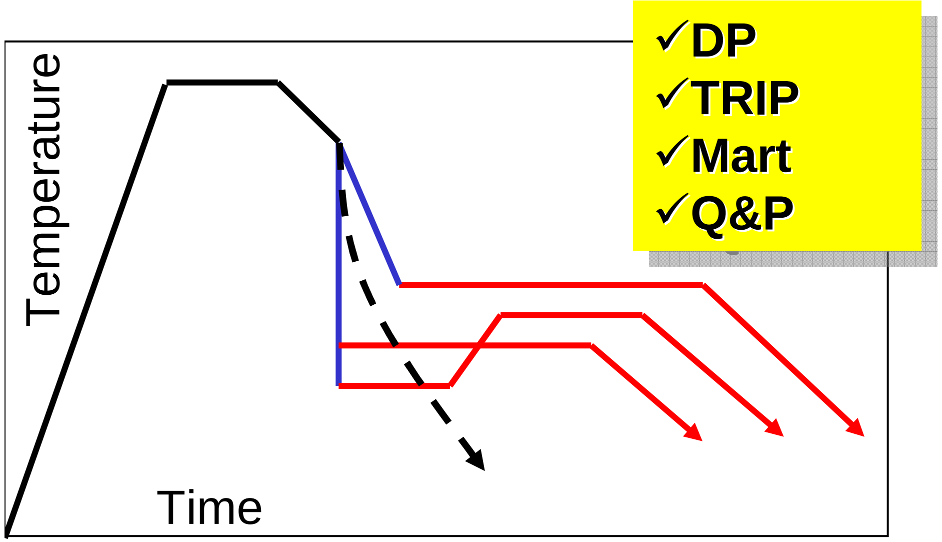
AHSS Development Status



De Moor, Gibbs, Speer, Matlock, and Schroth, "Strategies for Third-Generation Advanced High-Strength Steel Development", AIST Transactions, Iron & Steel Tech. Nov. 2010.

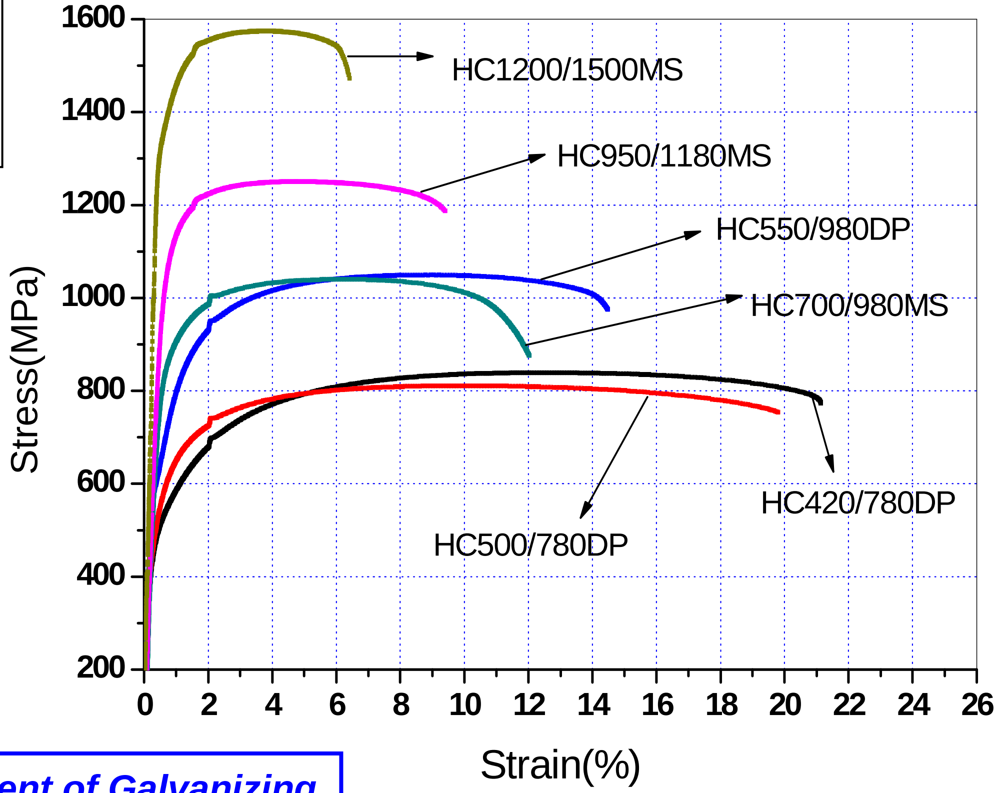
Flexible Processing Lines and the Production of New AHSS

Baosteel's Special Flexible HSS Line



- **Opened March 2009**
- **Multi-purpose processing**
  - **CR and GI**
- **Flexible heating/cooling**

Cooling medium	Max Cooling ratio
5%H2+95%N2	40℃/s
75%H2+25%N2	140℃/s
water	2000℃/s

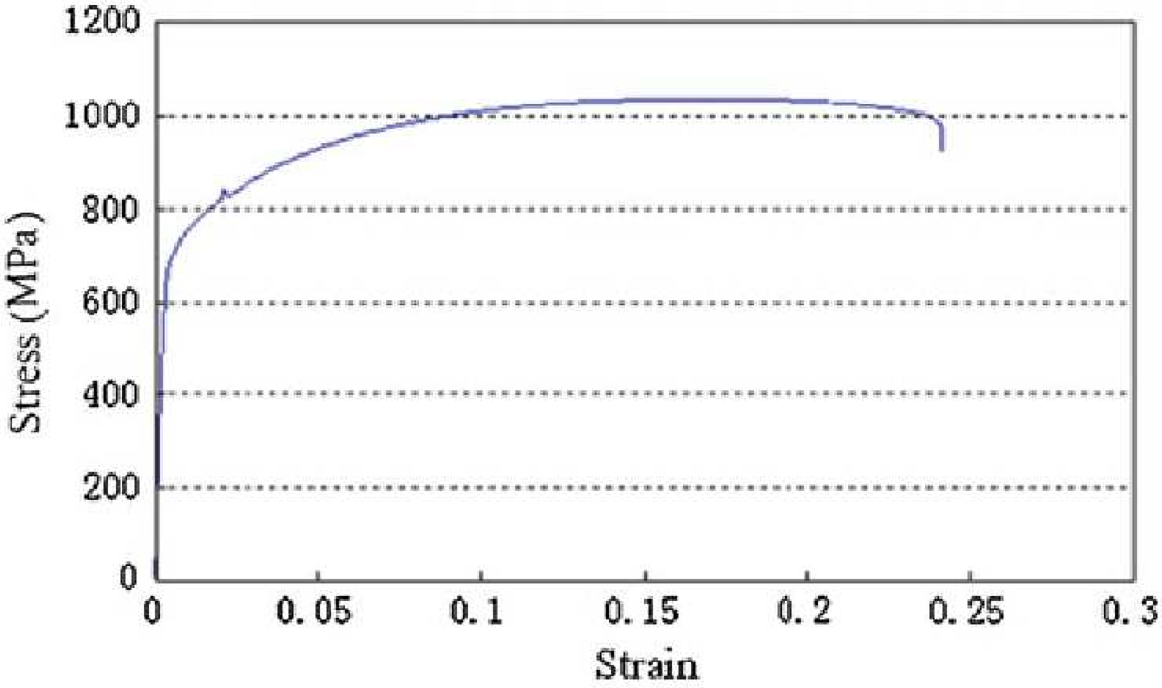


L. Wang, X. Jin, and H. Qian, "Recent Development of Galvanizing Sheet Steels in Baosteel," Proceedings Galvatech 2011.

Baosteel: Q&P from New Line

Q&P1000:

Composition (wt pct)
0.2C, 1.5 Si, 1.8 Mn



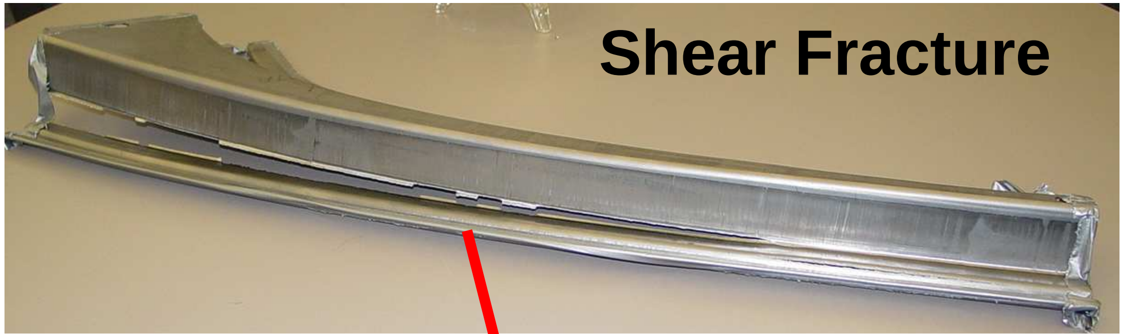
B pillar Trial

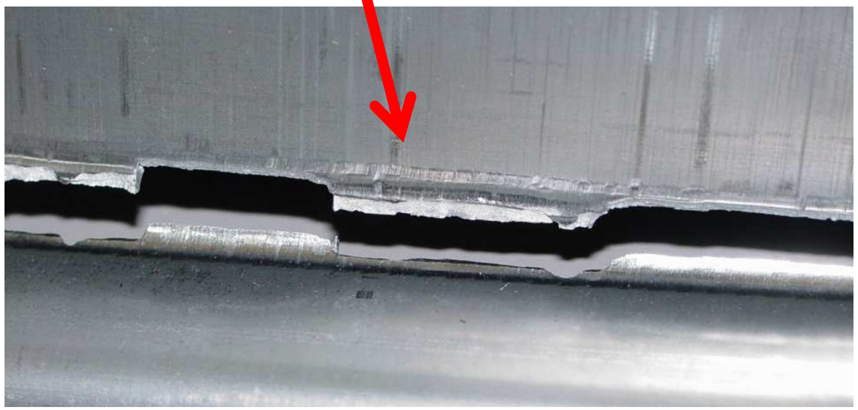
Li Wang and Weijun Feng, "Development and Application of Q&P Sheet Steels," Advanced Steels, Y. Weng et al. (eds), Springer-Verlag, Berlin, (2011) .

Formability Limited by Fracture

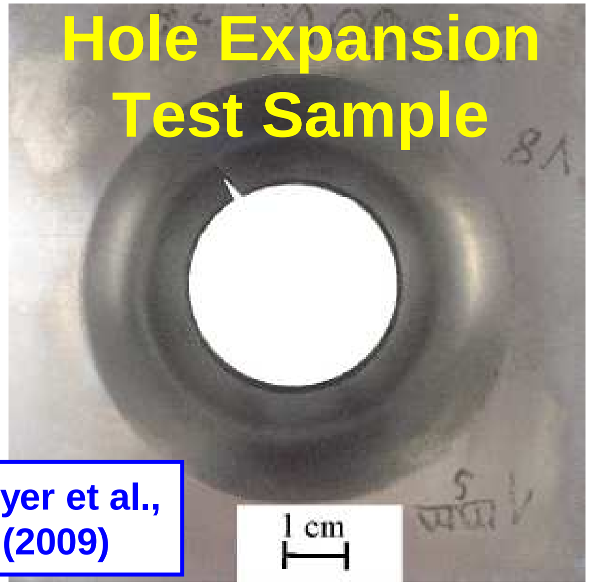
Tensile Properties… NOT the Whole Story…

Formability Limited by Fracture





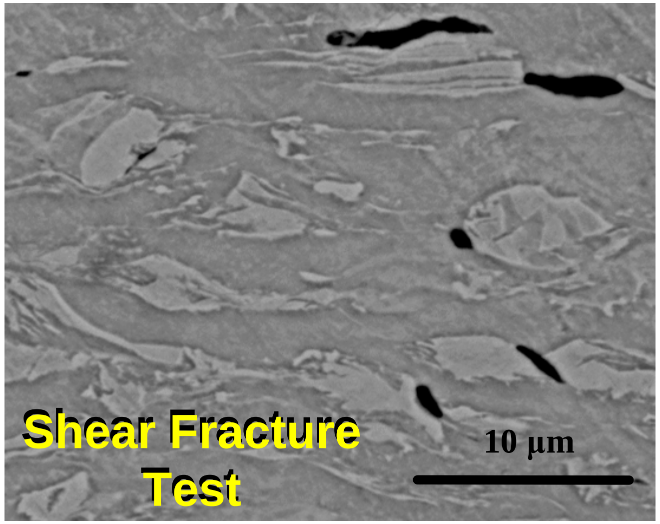
Images Courtesy of Jim Fekete, GM (2006)



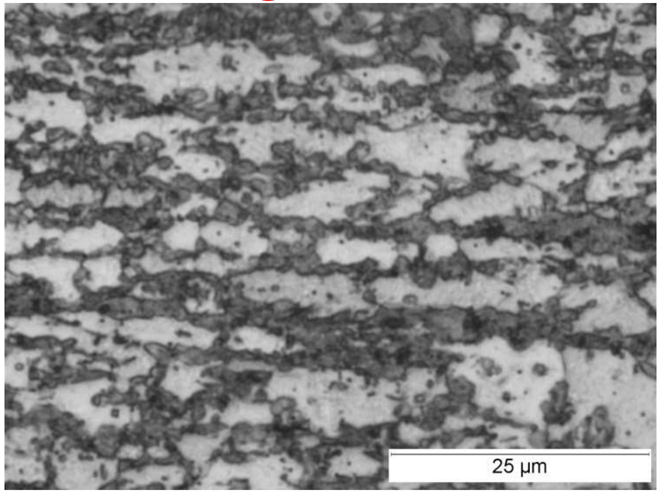
Dünckelmeyer et al., Slovika (2009)

Tensile Properties… NOT the Whole Story…

Void Nucleation: DP 740 MPa

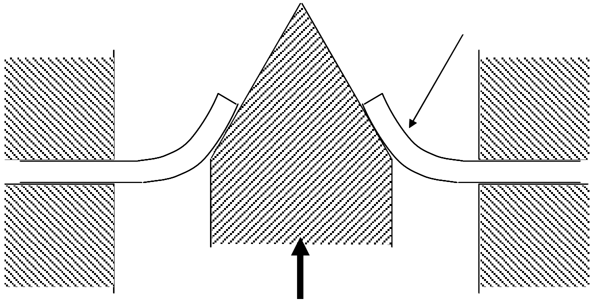


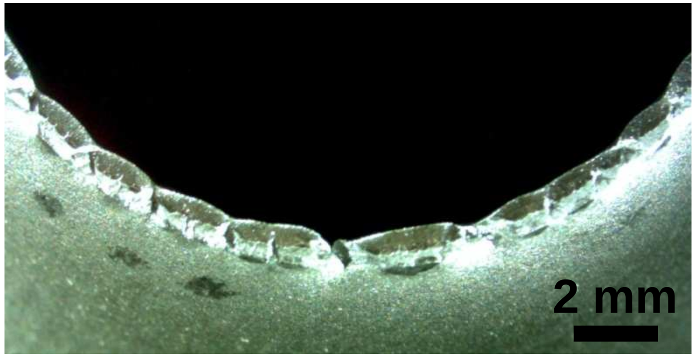
Banding: DP980



A. Hudgins, et al. ASPPRC 2010

Hole Expansion



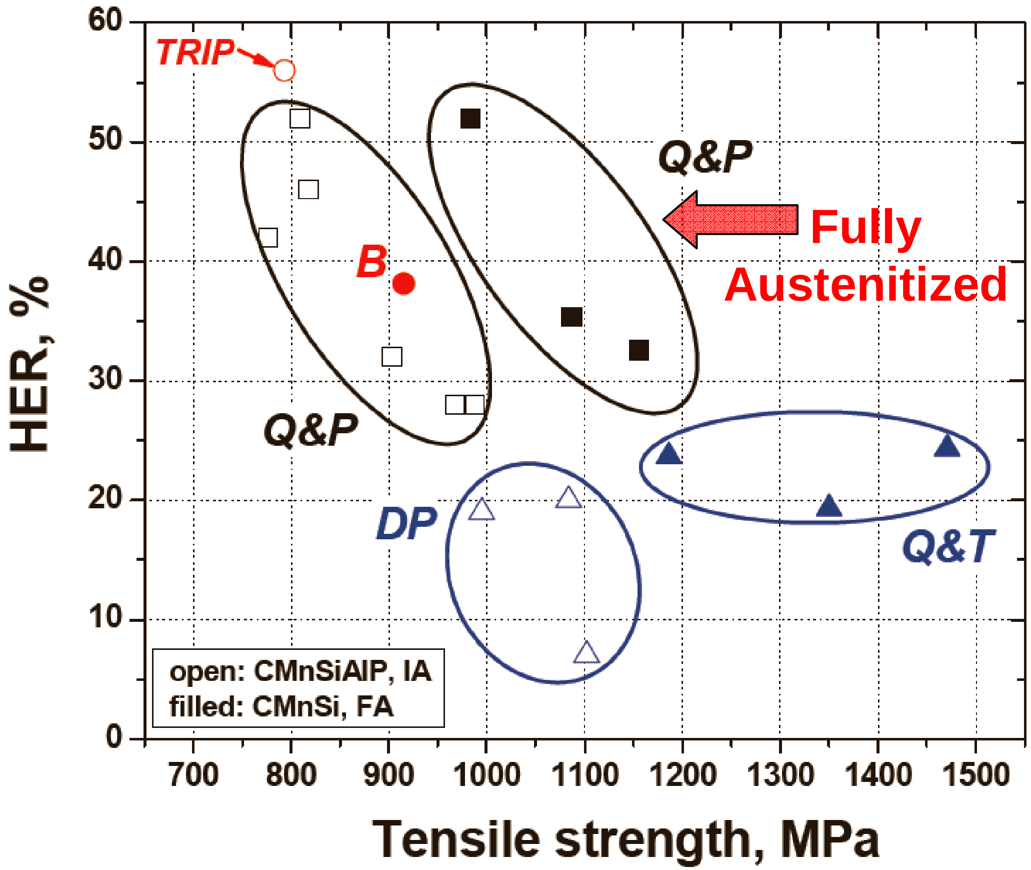


Steel (780 MPa)	Tensile Elong.	Stretch-flangeability (HER)
DP	19 %	60 %
TRIP	30 %	40 %

Lee et al. ASPPRC/Posco 2005
after Cho, Pusan Nat. U., 200

Hole Expansion Tests: Summary

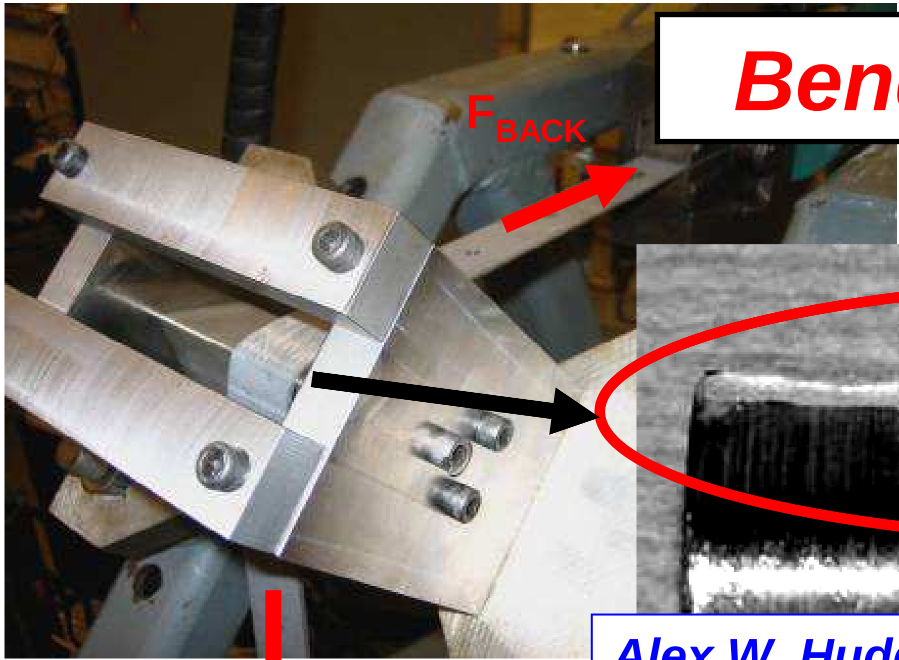
- **Hole Expansion Ratio (HER) = f(microstructure)**
- **Improved microstructural homogeneity = higher HER**



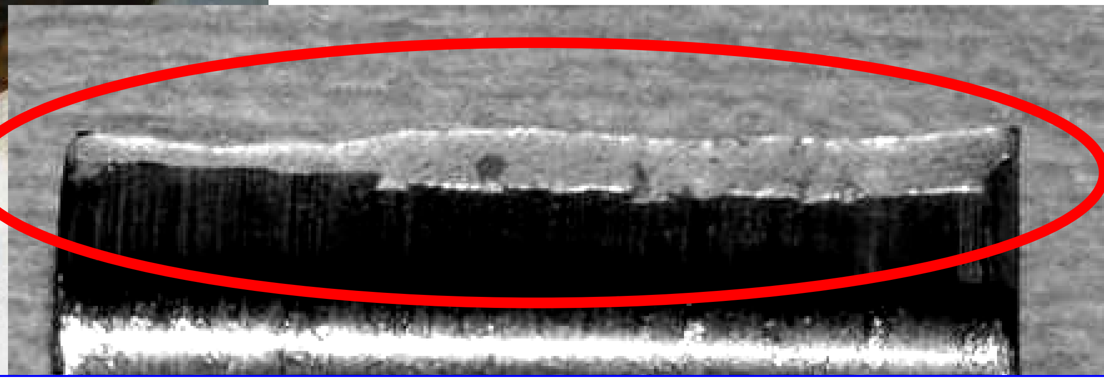
E. De Moor, C. Föjer, J. Penning and J.G. Speer, *Proc. of IIDDRG 2009 Conference*, ed. by B.S. Levy, D.K. Matlock and C.J. Van Tyne, Colorado School of Mines, Golden, CO, 2009, pp.413-424.

Microstructural Effects on AHSS Fracture

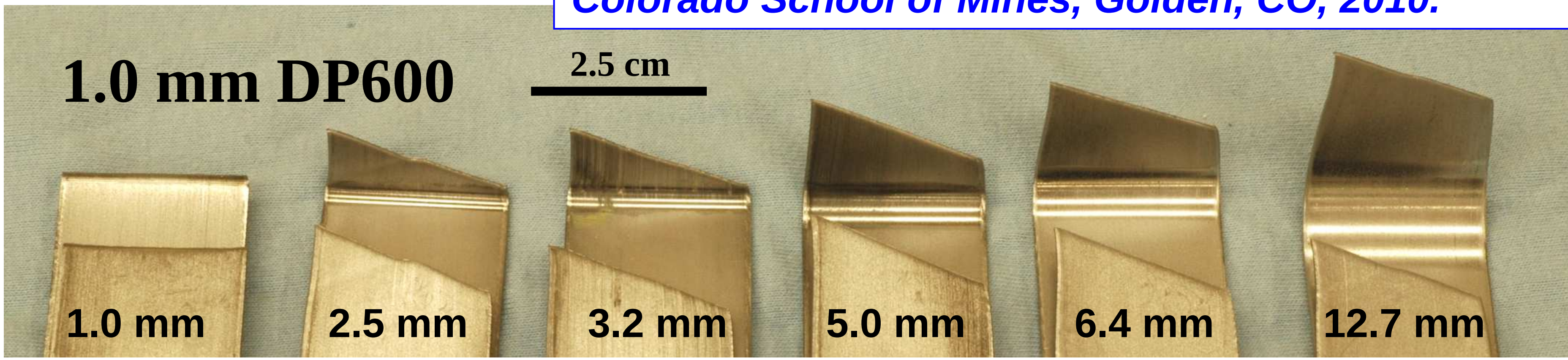
Bending Under Tension



V_{Pull}, F_{Front}



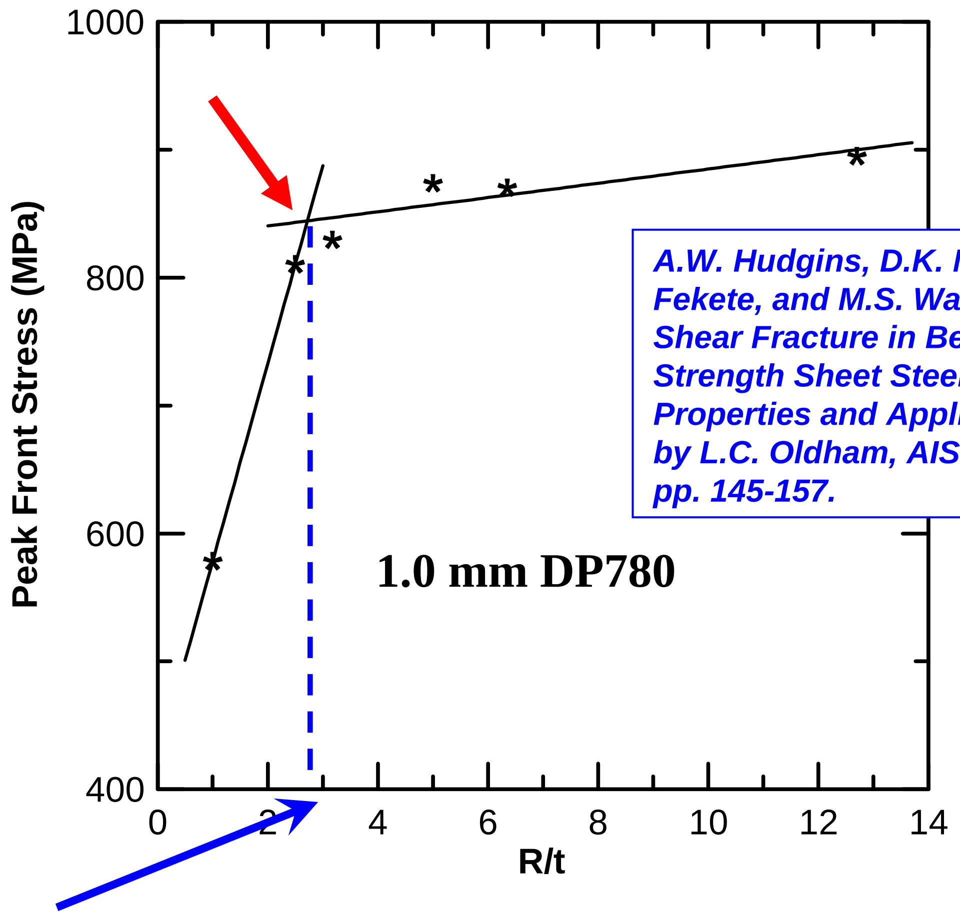
Alex W. Hudgins, "Shear Failures in Bending of Advanced High Strength Steels," PhD Thesis, Colorado School of Mines, Golden, CO, 2010.



Increase Radius →

Commercial Steel Matrix

Bending Under Tension Data



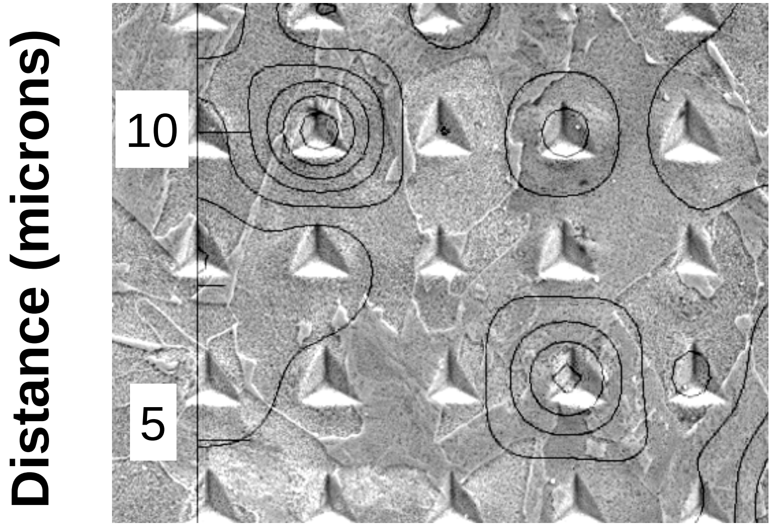
A.W. Hudgins, D.K. Matlock, J.G. Speer, J.R. Fekete, and M.S. Walp, "The Susceptibility to Shear Fracture in Bending of Advanced High Strength Sheet Steels," Proceedings of Steel Properties and Applications Conference, edited by L.C. Oldham, AIST, Warrendale, PA, 2007, pp. 145-157.

$(R/t)_{crit}$ = measure of formability

↓ $(R/t)_{crit}$ = ↑ formability (i.e. susceptibility to shear↓)

Application of Nanoindentation Techniques

- **0.1C-1.0Mn-0.3Si DP**
- **Vary intercritical T**
- **Vary MVF and martensite hardness**
- **Determine “hardness ratio”**
- **Result: $R/t_{critical}$ decreases with a decrease in the martensite to ferrite hardness ratio**



A.W. Hudgins, D.K. Matlock, J.G. Speer, J.R. Fekete, and M.S. Walp, “The Susceptibility to Shear Fracture in Bending of Advanced High Strength Sheet Steels,” Proceedings of Steel Properties and Applications Conference, edited by L.C. Oldham, AIST, Warrendale, PA, 2007, pp. 145-157.

Summary: Shear Fracture Susceptibility

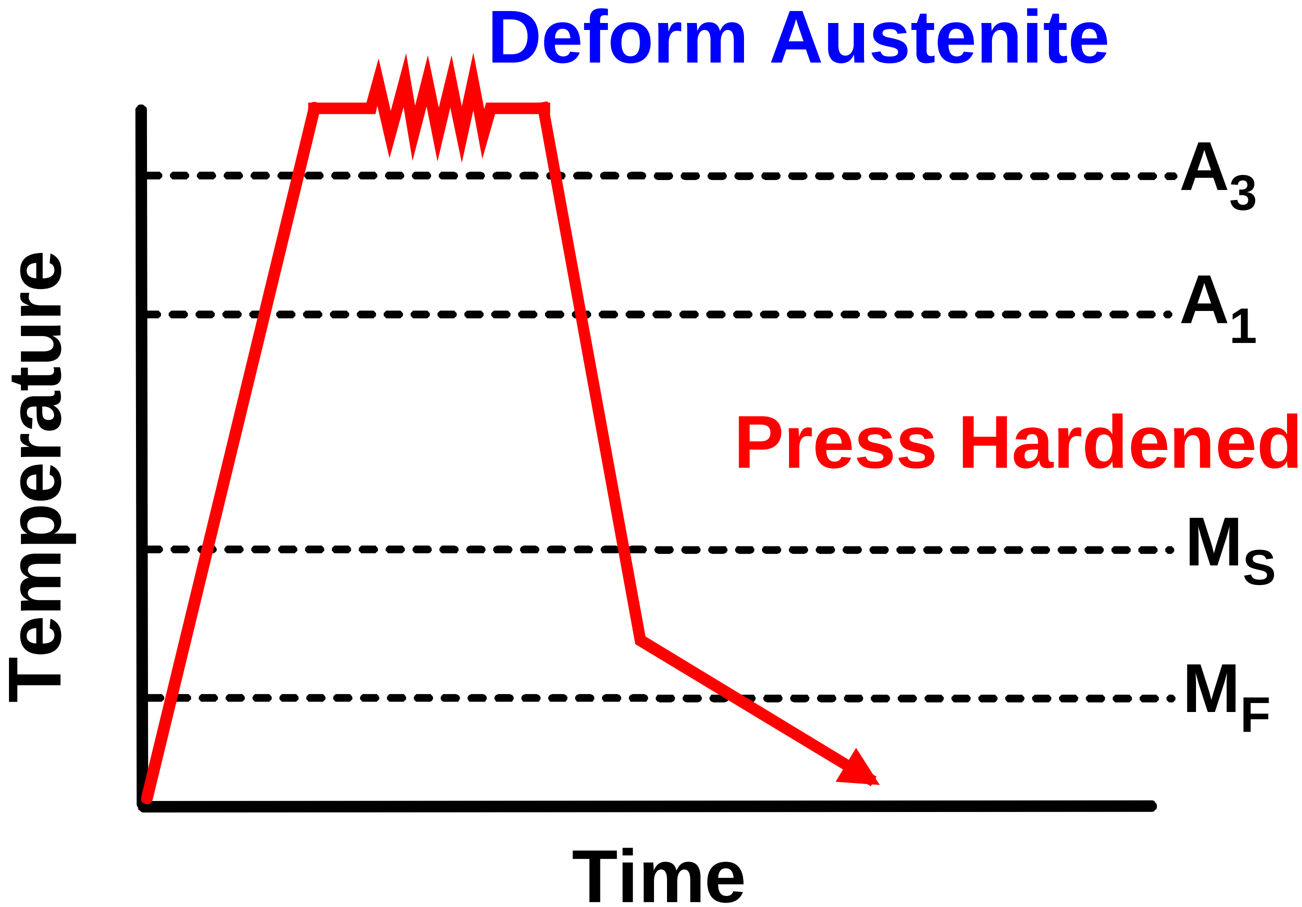
- **Formability (as measured by R/t) increased with a decrease in hardness ratio between martensite and ferrite.**
- **Other variables evaluated**
  - **Martensite morphology (limited effect)**
  - **Banding (effect orientation dependent)**

A.W. Hudgins, D.K. Matlock, J.G. Speer, J.R. Fekete, and M.S. Walp, "The Susceptibility to Shear Fracture in Bending of Advanced High Strength Sheet Steels," Proceedings of Steel Properties and Applications Conference, edited by L.C. Oldham, AIST, Warrendale, PA, 2007, pp. 145-157.

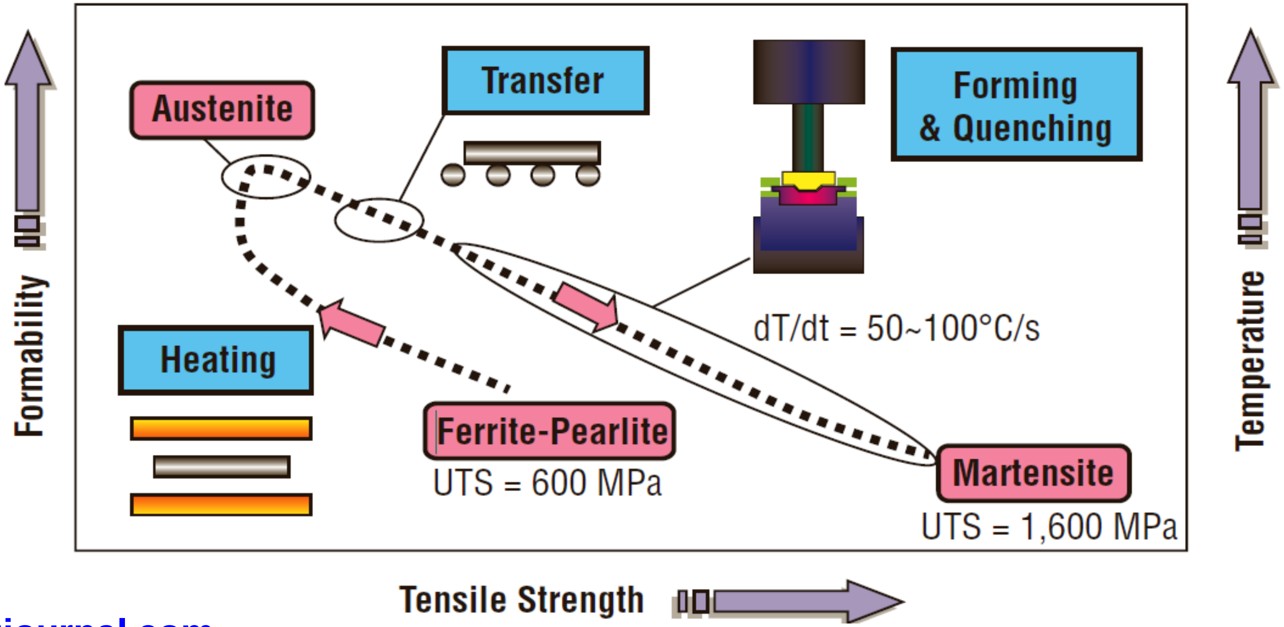
Alternate Processing Routes: Press Hardening

Press Hardened Steels (PHS)

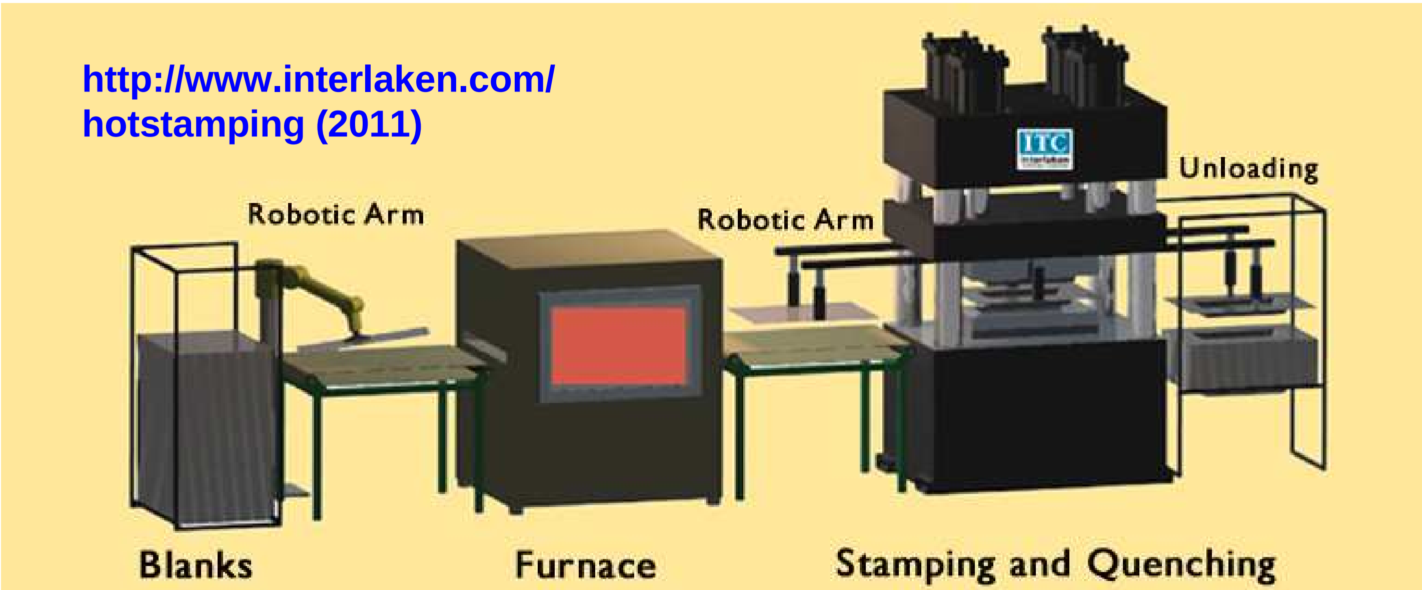
- Production of high strength (1500 MPa) parts
- Martensitic microstructures; boron alloys



Press Hardened Steels (PHS)



T. Altan, 2007
www.stampingjournal.com

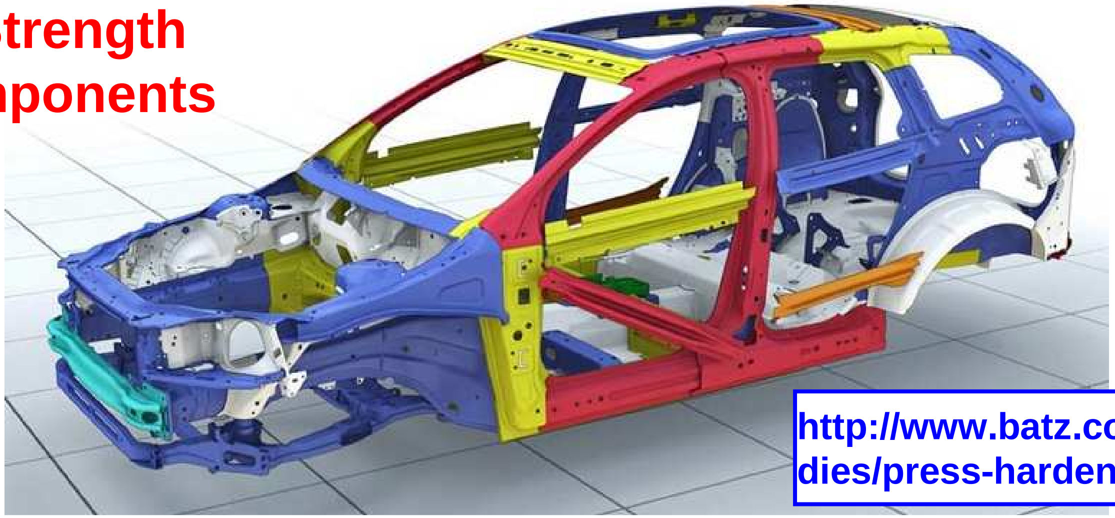


Press Hardened Steels (PHS)

Heated Blank

Blank in Die

PHS for High Strength Structural Components



http://www.batz.com/stamping-dies/press-hardening.php (2011)

Press Hardening

- **Enhanced press hardening steels still maturing**
- **Cost (e.g. heating, etc) and surface finish continue to be issues for consideration**
- **Steel developments leading to alternate processing routes for similar strength parts are of significant interest**
  - **e.g. Q&P, bainitic, …**
  - **Cold or warm forming**

AHSS Closing Comments

- **Approaches to potentially produce Third Generation AHSS have been identified**
- **Need optimized production routes to control:**
  - **Constituent volume fractions, size, distribution**
  - **Constituent mechanical properties**
  - **Austenite stability**
  - **…other**
- **Possibility for national research processing facility???**

AHSS Closing Comments

- **AHSS: Additional Important Points**
  - **Welding and Joining**
  - **Formability – Springback**
  - **Surface Finish**
  - **Coating**
  - **Hydrogen effects**
  - **……..**
  - **TWIP steels???**
    - **Significant government funding in Germany and Korea**

AHSS Closing Comments

- **AHSS developments need to optimize time to implementation!!!**
  - **…DP Steels, 35 years +….**
    - **"*Most Important*" AHSS**
  - **…TRIP Steels, >20 years**
  - **…Q&P ≈ 7+ years**
  - **………**
- **…*The Competition Continues*…**

AHSS -- “Beyond Automotive”

- **Multiple inquires received at ASPPRC - Examples:**
  - **Lightweight military vehicles**
    - **DOD/DOE workshop Detroit, July 2011**
  - **Blast resistant surfacing – US Army**
  - **Metal storage cabinets (shipping costs!)**
  - **Personal hand tools**
  - **….others…..**

The support of the Advanced Steel Processing and Products Research Center corporate partners, listed below, is gratefully acknowledged.

Steel Producers
AK Steel
ArcelorMittal Steel
Baosteel
Essar Steel Algoma Inc.
Evraz Inc., N.A.
Gerdau
Nucor Steel Co.
POSCO
SABIC
Severstal NA Inc.
SSAB Enterprises, LLC
Tata Steel Europe
The Timken Co.
United States Steel
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Caterpillar Inc.
Deere & Co.

Automotive Manufactures
Chrysler Group LLC
General Motors Co.
Toyota

Suppliers
Bekaert
Johnson Controls
Tube Investments of India

Other
East Metals N. Amer. (Vanadium)
Los Alamos National Lab
Precision Cast Parts Corp.
Reference Metals (Niobium)

http://aspprc.mines.edu/