"Laboratory-based Research and Education Programs to Support the Steel Industry"

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Colorado School of Mines
Golden, Colorado

https://aspprc.mines.edu/

Institute for Roll Design
Durant, Oklahoma
October 17, 2019

***An NSF Industry/University Cooperative Research Center - Est. 1984**

Presentation Overview

- *Overview of Industry/University Cooperative Research at the Colorado School of Mines*
- ***Introduction to simulation techniques and a novel thermomechanical processing laboratory – Gleeble 3500***
- *Thermomechanical processing (TMP) simulation of deformation behavior and microstructural development in a commercial bar mill*
- ***Selected examples of laboratory hot rolling experiments***

Advanced Steel Processing and Products Research Center (ASPPRC)

Advanced Steel
Processing and Products
Research Center

Established 1984

Concentrate on research at the interface between producers and users of steel

https://aspprc.mines.edu/

ASPPRC Participants: September 2019

Steel Producers

AK Steel
Algoma
ArcelorMittal Steel
Baosteel
Evraz Inc., N.A.
Gerdau
Hyundai Steel
Kobe Steel
Nucor Steel Co.
POSCO
SSAB Enterprises, LLC
Tata Steel Europe
Ternium
TimkenSteel
TKS
United States Steel
voestalpine Stahl GmbH

Heavy Equipment Mfg.

Caterpillar Inc.
Deere & Co.

Automotive Manufactures

Fiat Chrysler Automobiles
General Motors Co.
Honda R&D Americas

Suppliers

Nexteer Automotive
Gestamp (Autotech Engineering R&D USA)

Other

Blount International
Chevron Energy
CBMM
AMG Vanadium
Climax Molybdenum
Los Alamos National Lab
Precision Castparts Corp.

Overview: ASPPRC

- **History**

  Established October 1, 1984

  In the 36th year of operation

  National Science Foundation I/UCR Center

  One of over 50 NSF I/UCR Centers

  Now Self Sufficient –

  Corporate Funded with 31 Sponsors

  Initially North American – Now Global

- **ASPPRC Operations**

  Consortium – annual fees

  Sponsors define research agenda

  Research staff:

  Graduate students, post-docs, research faculty, visiting scientists, CSM academic faculty

Overview: ASPPRC Research

- **Research programs in three areas (2019)**
  - **Bar and Forging Steels (36 %)**
  - **Plate and Hot Rolled Steels (28 %)**
  - **Sheet and Coated Steels (36 %)**

- **Research Focus - Physical Metallurgy**
  - **Steel development**
    - **Microstructure**
    - **Heat treatment**
    - **Thermomechanical processing**
  - **Mechanical Metallurgy**
    - **Deformation**
    - **Fatigue**
    - **Fracture**
    - **Forming and forging**

Objectives

- **Perform Research of Direct Benefit to Producers and Users of Steel**
- **Educate Graduate Students by Research Involvement**
- **Develop International Forum for Steel Producers, Users, Government, and Academia**
- **Enhancement of Undergraduate Education / Maintain Faculty with Interest in Ferrous Metallurgy**

ASPPRC Sponsor Locations - 1990

ASPPRC Sponsor Locations - 2019

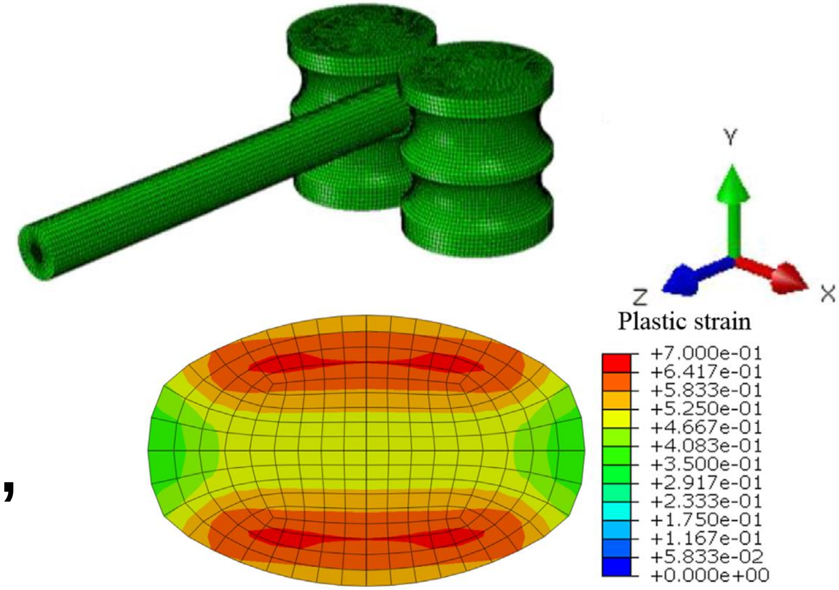
Many international facilities of corporate participants not shown

Background: Simulation of Hot Rolling and Thermomechanical Processing (TMP)

Simulation Methodologies

- **Theoretical modeling**
  - **Finite element modeling of deformation**
  - **Inputs: Shape, deformation rate, stress-strain behavior critical temperatures, etc.**
  - **Outputs: strain distribution, temperature gradients …**

X. Wang, *et al.*, "Modeling and Simulation of Dynamic Recrystallization Behavior in Alloyed Steel 15V38 during Hot Rolling," *Steel Res. Int.* 2019.



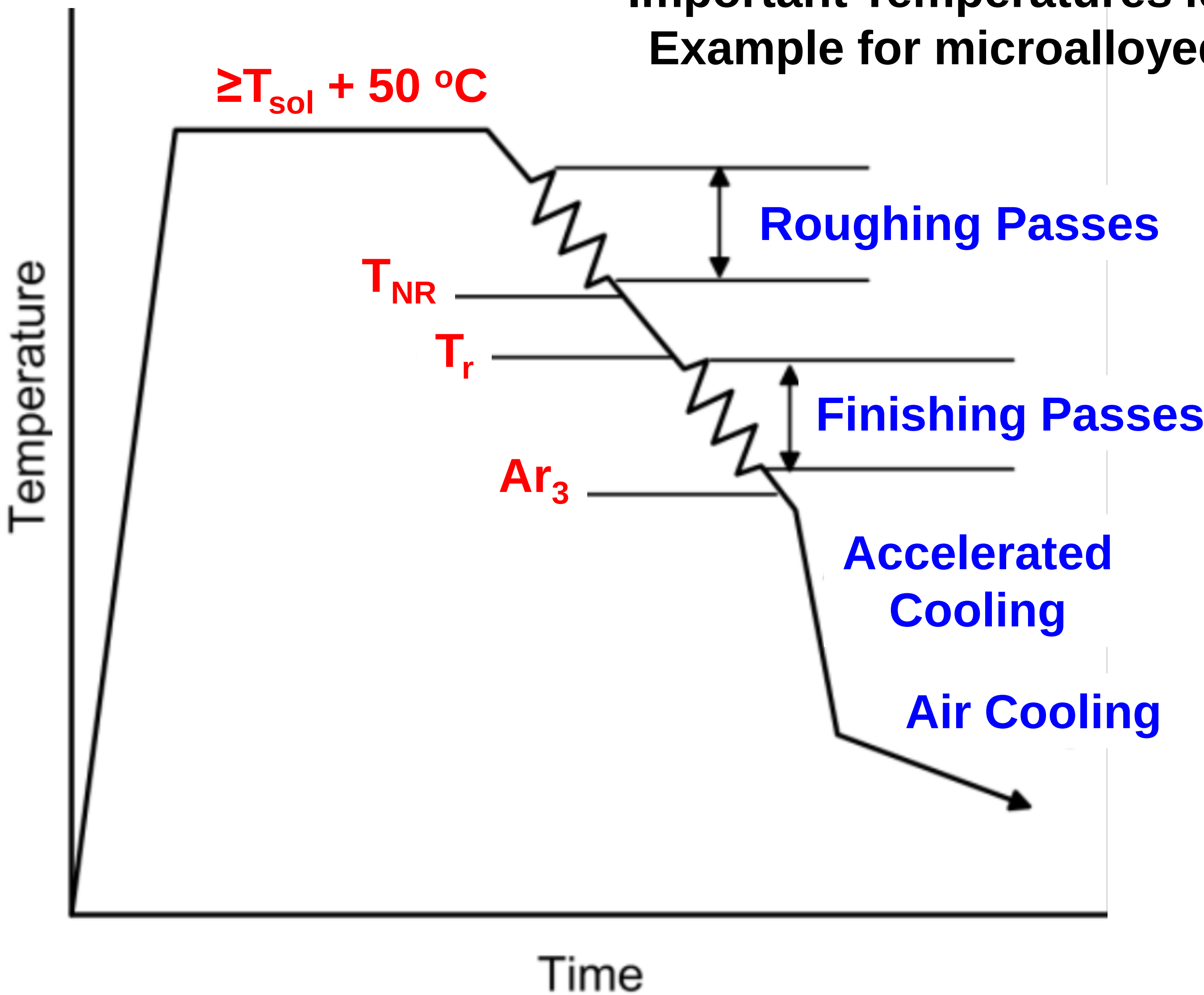
Plastic strain distribution

- **Physical simulation**
  - ***"…the exact reproduction of the thermal and mechanical processes in the laboratory that a material is subjected to during the manufacturing process or end use…"*****
  - **Outputs: stress-strain behavior = f(T, strain rate, …), microstructures, properties….**

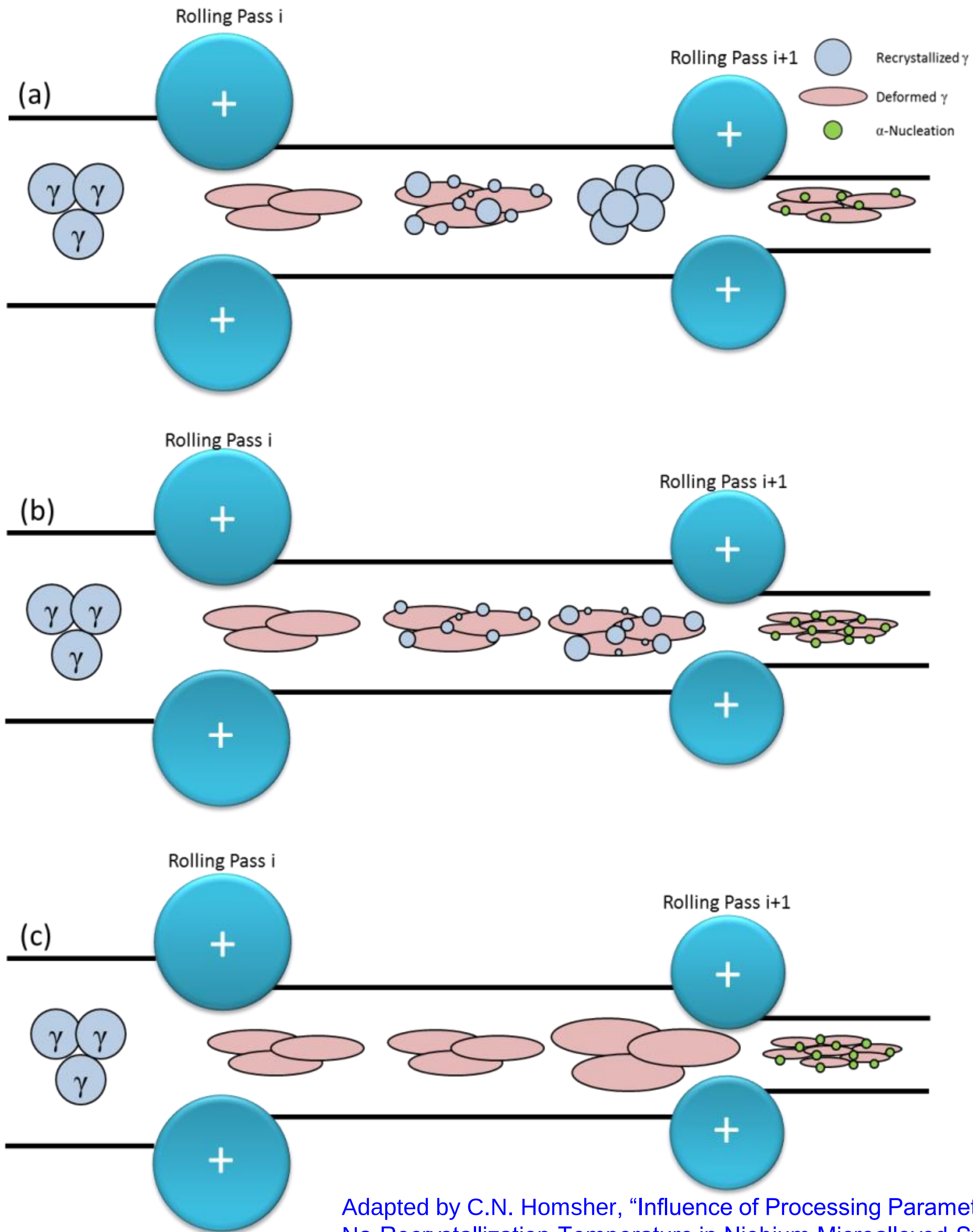
**https://www.gleeble.com/ Accessed Oct. 2019

Example Rolling Schedule

Important Temperatures identified
Example for microalloyed steels



C.N. Homsher, "Influence of Processing Parameters and Alloying Additions on the Mechanically Determined No-Recrystallization Temperature in Niobium Microalloyed Steels," PhD Thesis, Colorado School of Mines, 2016.



(a) above T_{NR} where complete static recrystallization takes place between passes

(b) between T_{NR} and T_r where partial static recrystallization takes place between passes

(c) below T_r where no static recrystallization can occur between passes

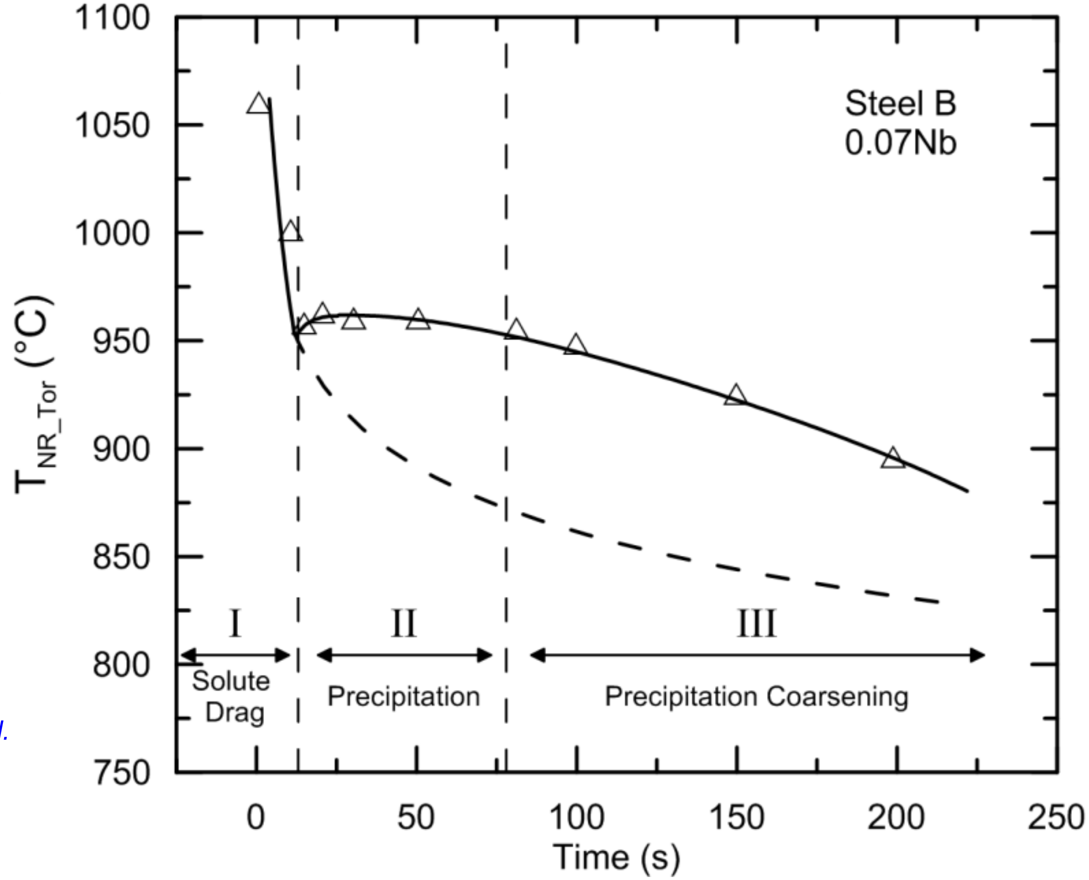
Adapted by C.N. Homsher, "Influence of Processing Parameters and Alloying Additions on the Mechanically Determined No-Recrystallization Temperature in Niobium Microalloyed Steels," PhD Thesis, Colorado School of Mines, 2016.

Factors which control T_{NR}

- **Alloy content**
- **Austenite microstructure**
  - **Precipitates**
  - **Residual cold work**
  - **…**
- **Process variables**
  - **Strain**
  - **Strain rate**
  - **Interpass time**
  - **…**

D. Q. Bai *et al.*, "Effect of deformation parameters on the no-recrystallization temperature in Nb-bearing steels," *Metall. Trans.A*, 1993.

Example:
T_{NR} increase with interpass time (t_{ip}) and its relationship to precipitation in a 0.07Nb-steel.



C.N. Homsher, "Influence of Processing Parameters and Alloying Additions on the Mechanically Determined No-Recrystallization Temperature in Niobium Microalloyed Steels," PhD Thesis, Colorado School of Mines, 2016.

Introduction to a Novel Thermomechanical Processing Laboratory - Gleeble 3500*

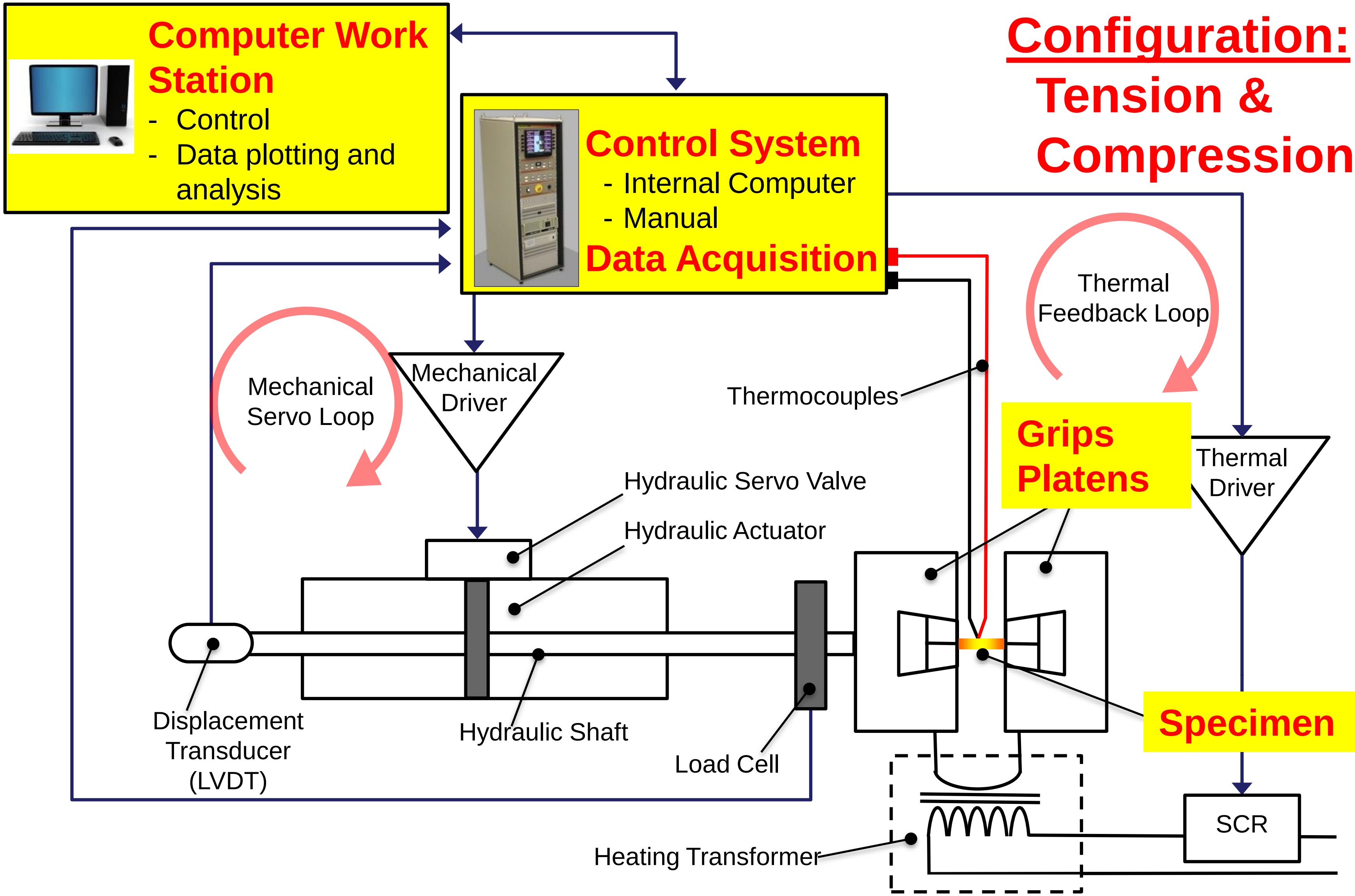
*A Product of Dynamic Systems Inc.
Poestenkill, NY 12140 USA
https://www.gleeble.com/

Physical Simulation Laboratory

- **Gleeble 3500 at the Colorado School of Mines**
  - **Temperature = function of time**
  - **Force or displacement = function of time**
  - **Tension, compression, torsion**

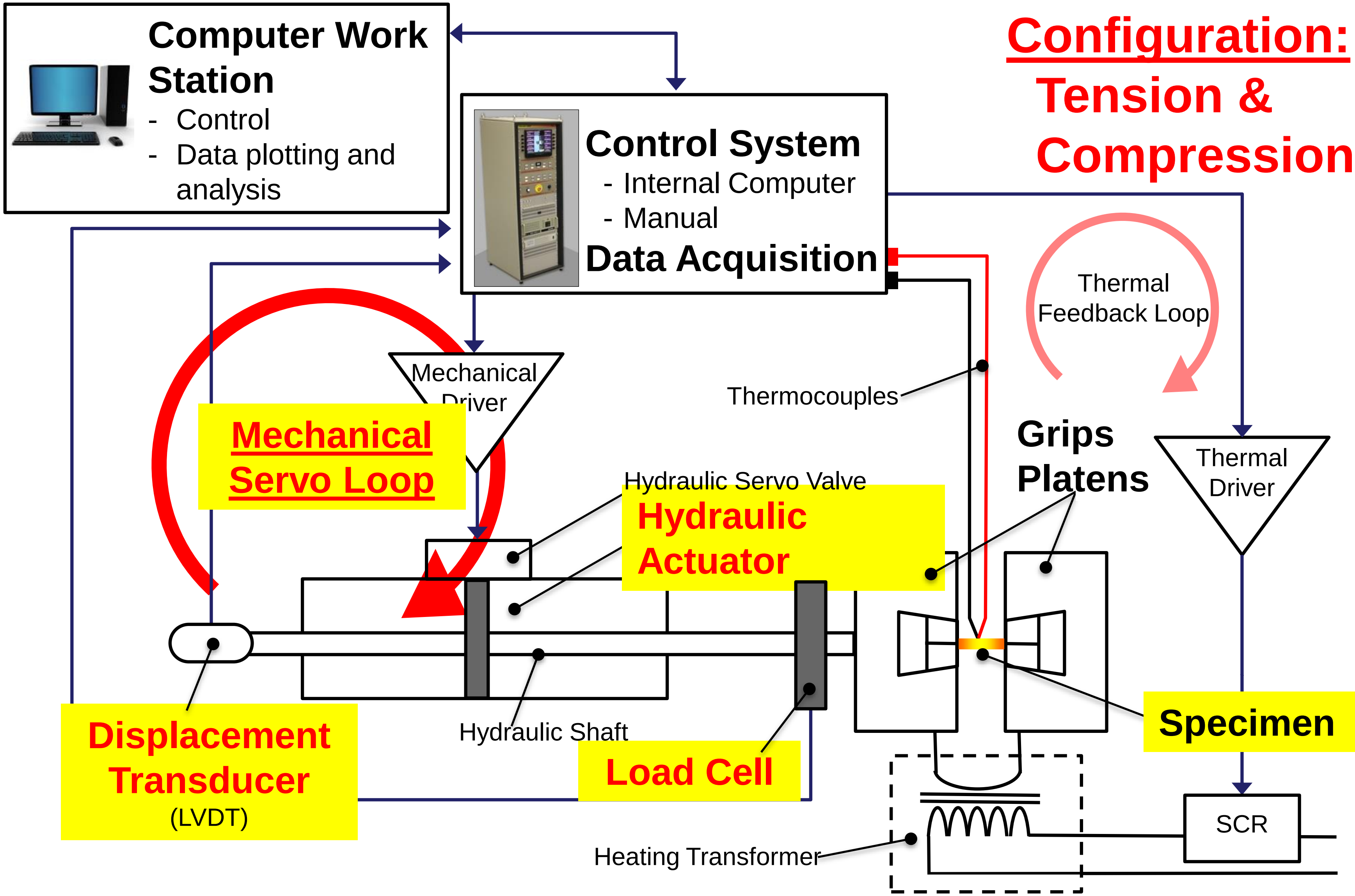
Gleeble 3500 located in Room 173 in Hill Hall at the Colorado School of Mines

Schematic of the Gleeble Control System



Adapted from slide courtesy of Todd Bonesteel, VP, Dynamic Systems Inc.(September 2019)

Schematic of the Gleeble Control System



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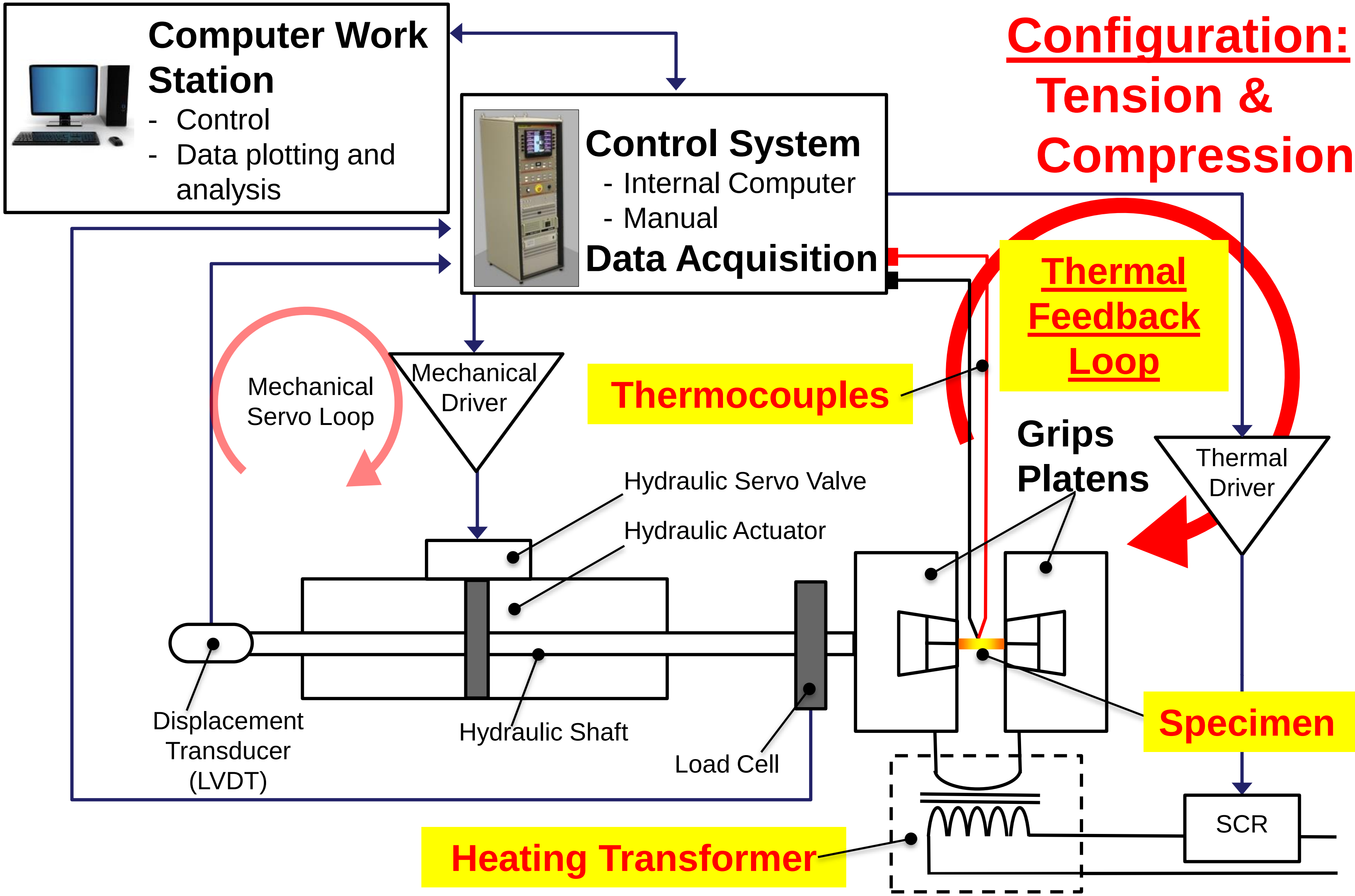
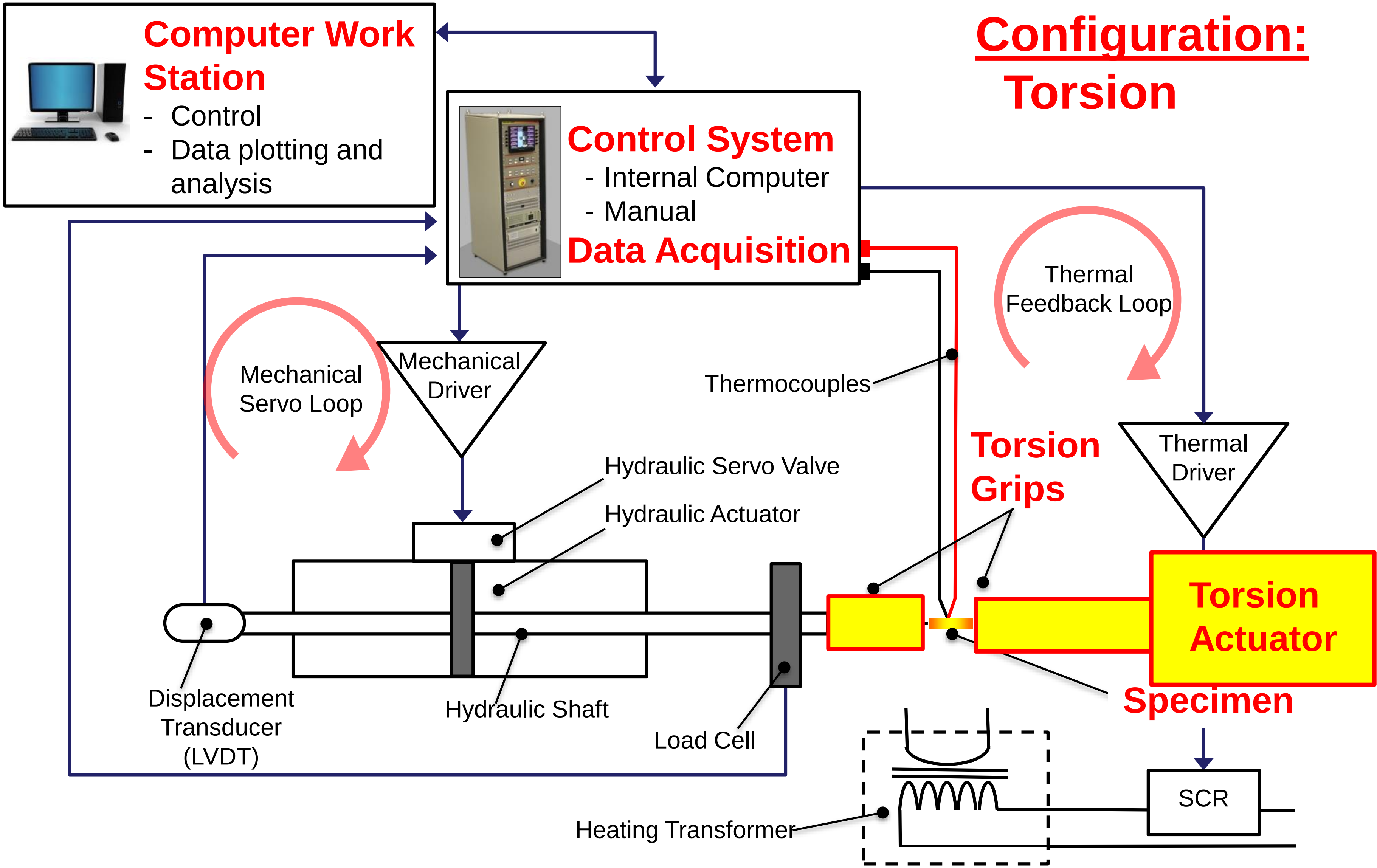
Schematic of the Gleeble Control System



Adapted from slide courtesy of Todd Bonesteel, VP, Dynamic Systems Inc.(September 2019)

Schematic of the Gleeble Control System



Adapted from slide courtesy of Todd Bonesteel, VP, Dynamic Systems Inc.(September 2019)

Torsion Conversion

Replace Tension/Compression Module with Hot Torsion System

Gleeble 3500 located in Room 173 in Hill Hall
at the Colorado School of Mines

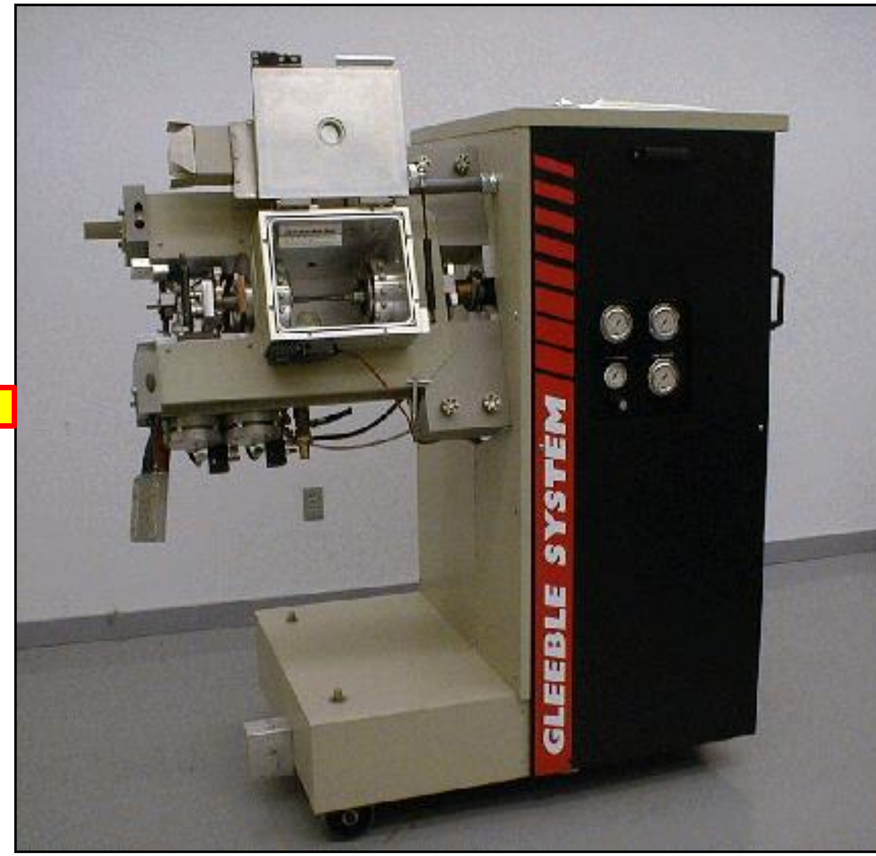


Image of torsion system courtesy of Todd Bonesteel, VP,
Dynamic Systems Inc.(September 2019)

Example Process Simulation Capabilities

- **Continuous casting**
- **Hot Deformation**
  - **Rolling**
  - **Forging**
  - **Extrusion**
  - **Thermomechanical processing**
- **Welding and Joining**
  - **Weld HAZ cycles**
  - **Upset butt welding**
  - **Diffusion bonding**
- **Heat Treating**
  - **Continuous strip annealing**
  - **Heat treating**
  - **Quenching**
  - **Time-Temperature-Transformation Diagrams**

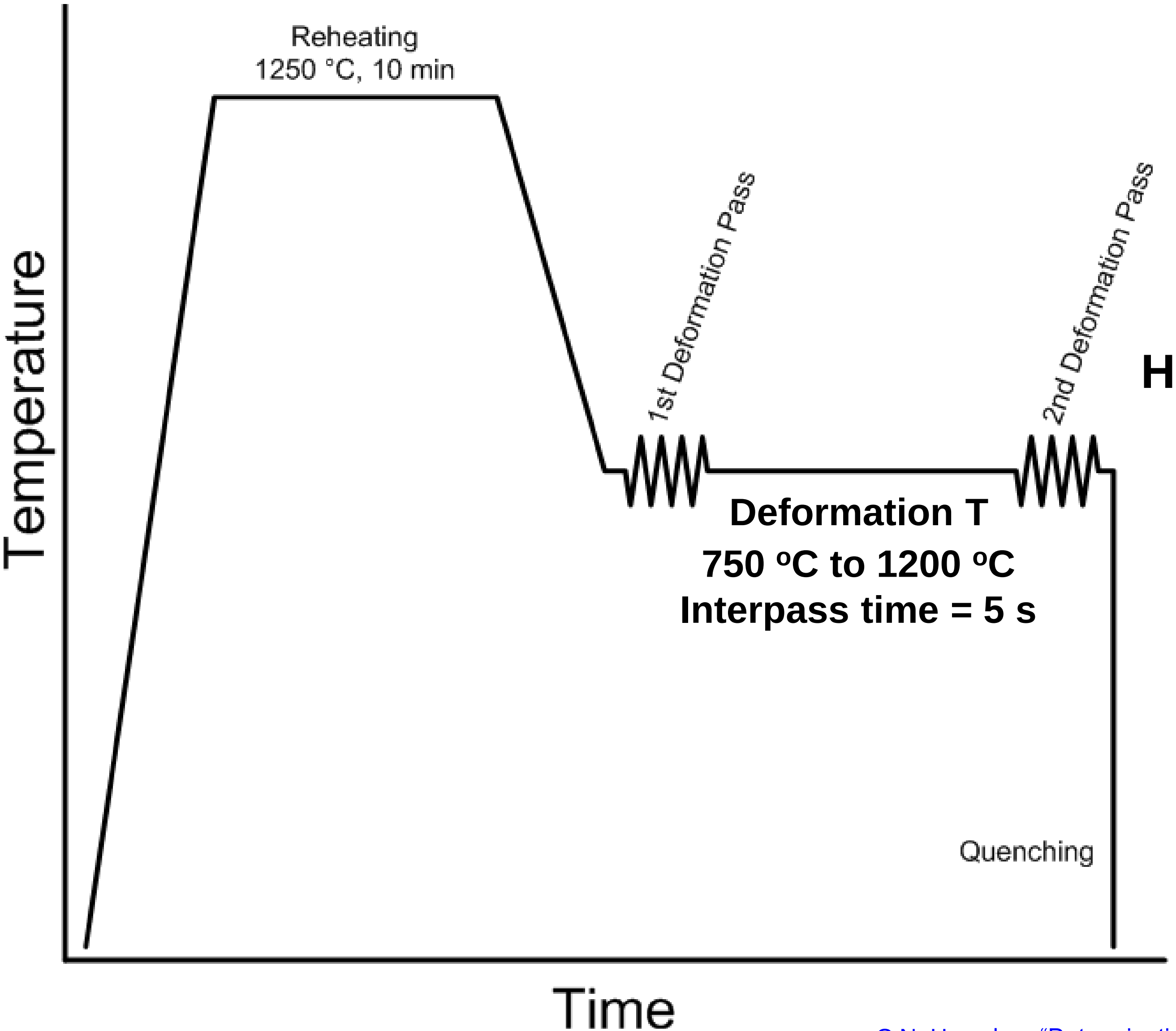
https://www.gleeble.com/ (accessed October 2019)

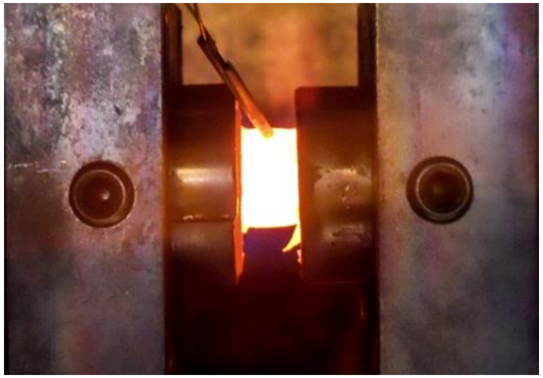
Gleeble 3500 Applications

Simulation of Thermomechanical Processing (TMP)

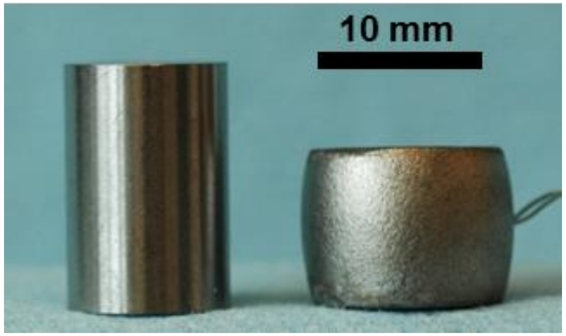
Deformation Behavior and Microstructural Development in a Commercial Bar Mill

T_{NR} with Double-Hit Compression Test





Hot compression 10 mm diameter sample.

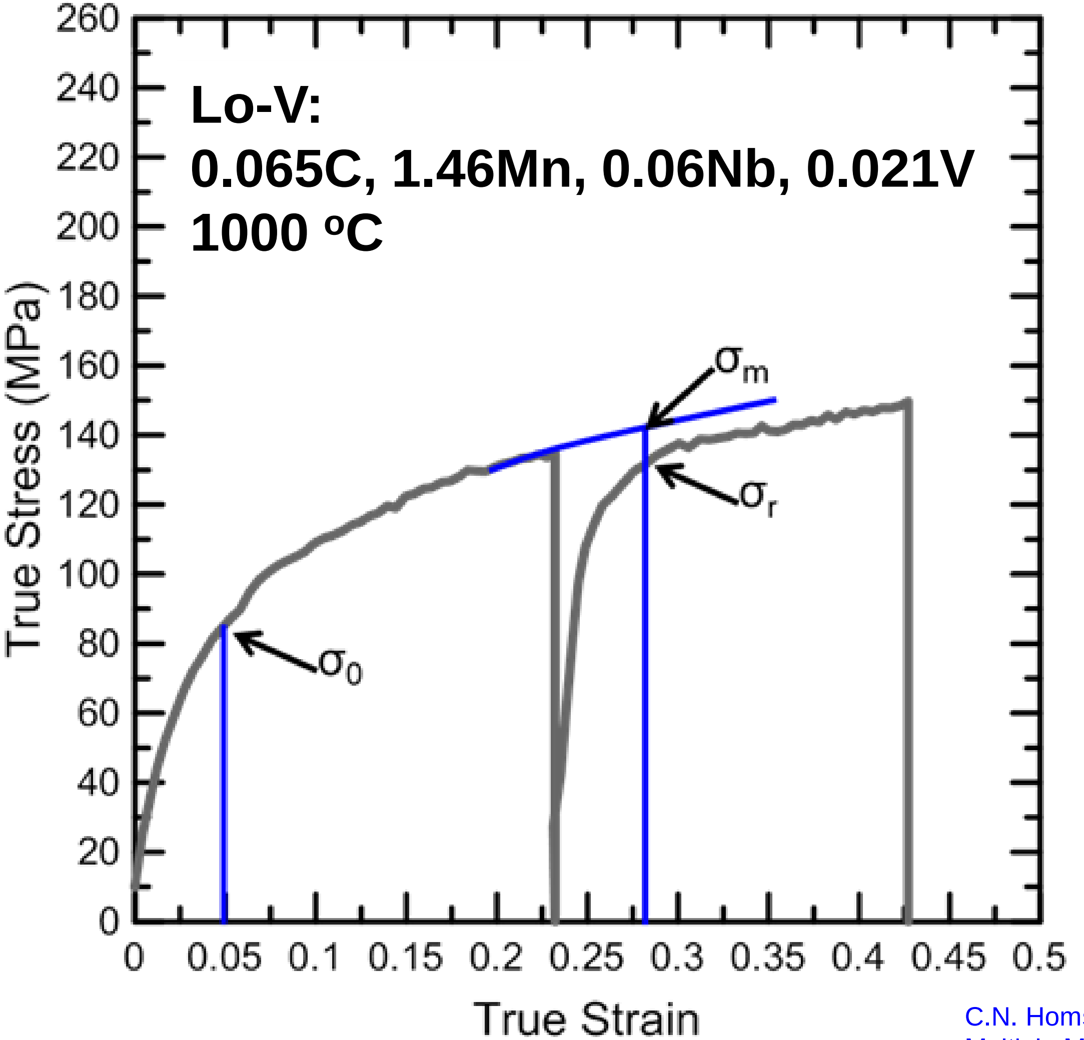


Total target strain of - 0.4

C.N. Homsher, "Determination of Non-Recrystallization Temperature (TNR) of Multiple Microalloyed Steels," MS Thesis, Colorado School of Mines, 2012.

T_{NR} with Double-Hit Compression Test

ASPPRC study: **Assess effects of microalloying elements on TNR in a nominally 0.06 to 0.07 C steel**



FS = fractional softening (a measure interpass recrystallization)

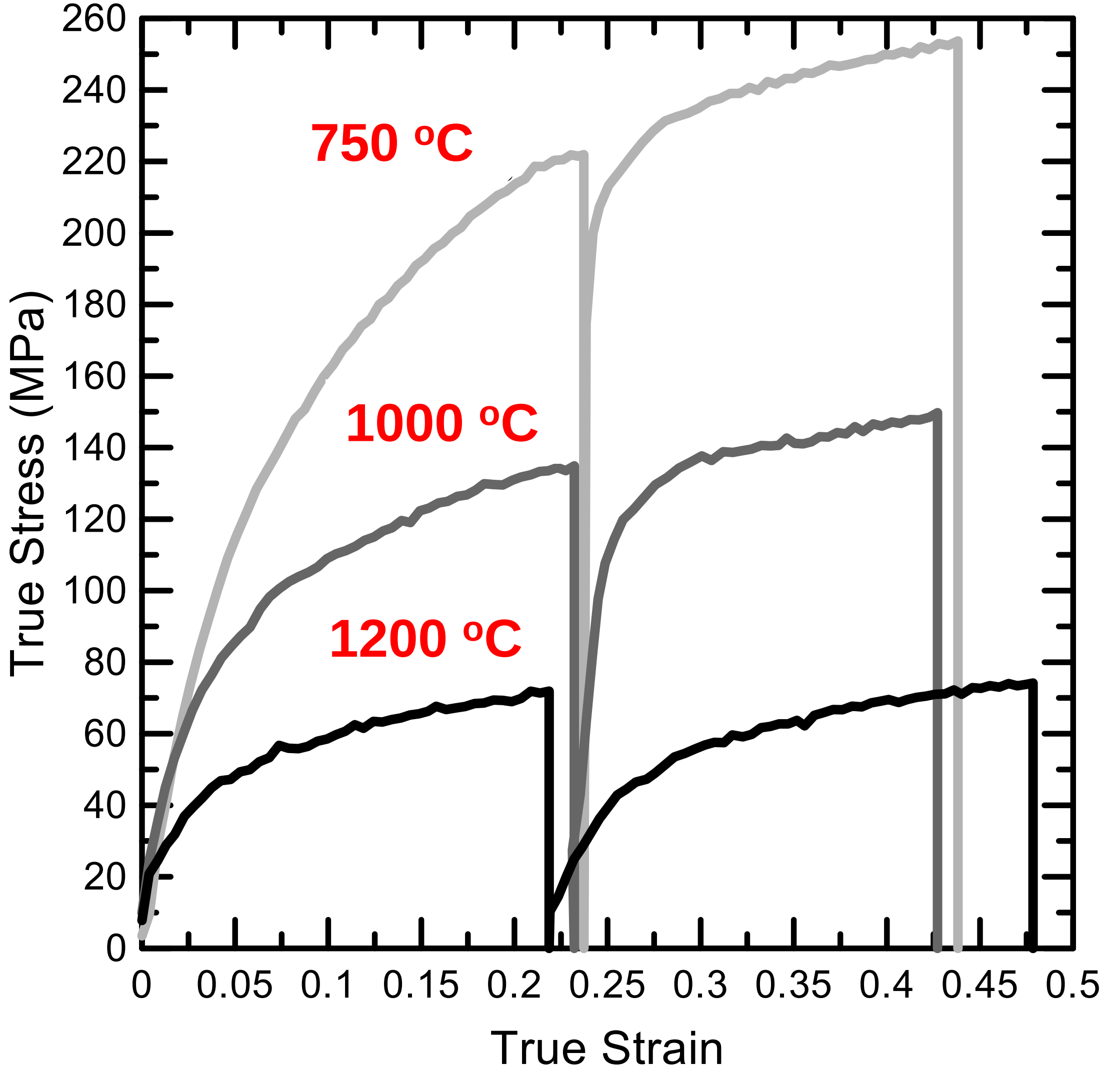
$$FS = \frac{\sigma_m - \sigma_r}{\sigma_m - \sigma_0}$$

Stress values defined based on 0.05 true strain increments

C.N. Homsher, "Determination of Non-Recrystallization Temperature (TNR) of Multiple Microalloyed Steels," MS Thesis, Colorado School of Mines, 2012.

T_{NR} with Double-Hit Compression Test

Lo-V: 0.065C, 1.46Mn, 0.06Nb, 0.021V



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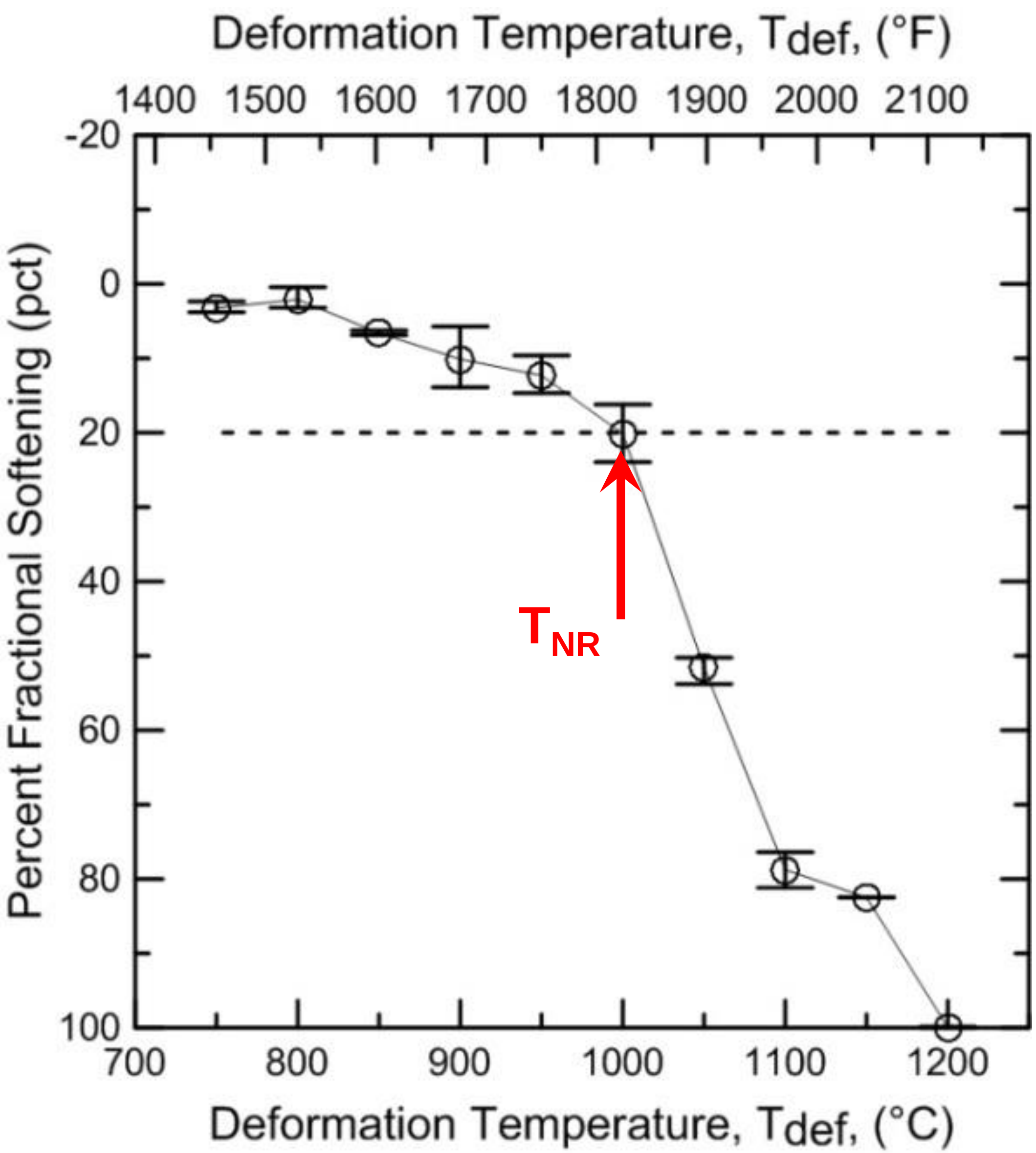
T_{NR} with Double-Hit Compression Test



Lo-V:
0.065C, 1.46Mn, 0.06Nb, 0.021V

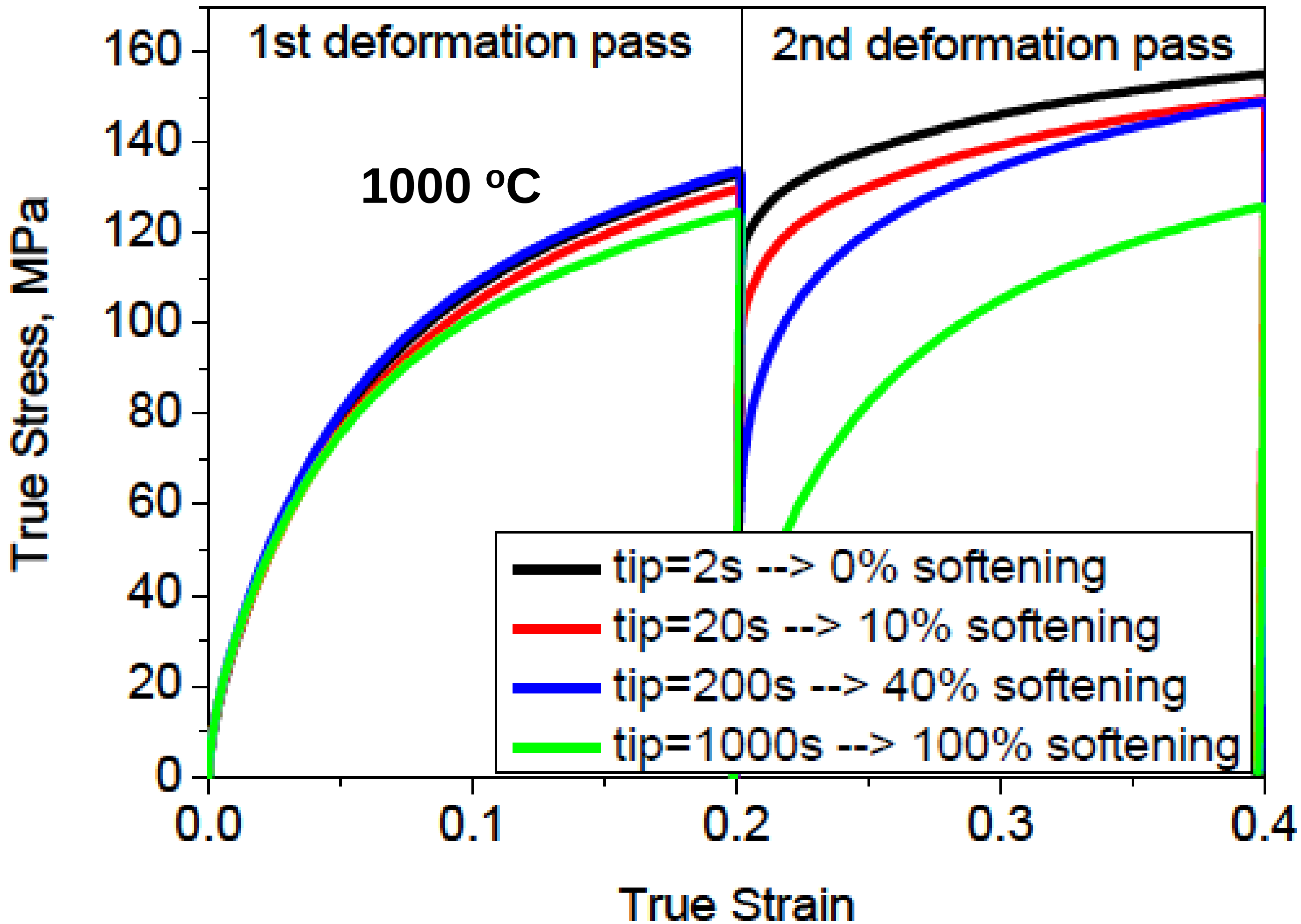
T_{NR} defined as value which corresponds to 20 % FS.

Note: Multiple definitions in literature

C.N. Homsher, "Determination of Non-Recrystallization Temperature (TNR) of Multiple Microalloyed Steels," MS Thesis, Colorado School of Mines, 2012.

T_{NR} with Double-Hit Compression Test

Effect of Interpass time – Nb Microalloyed Steel

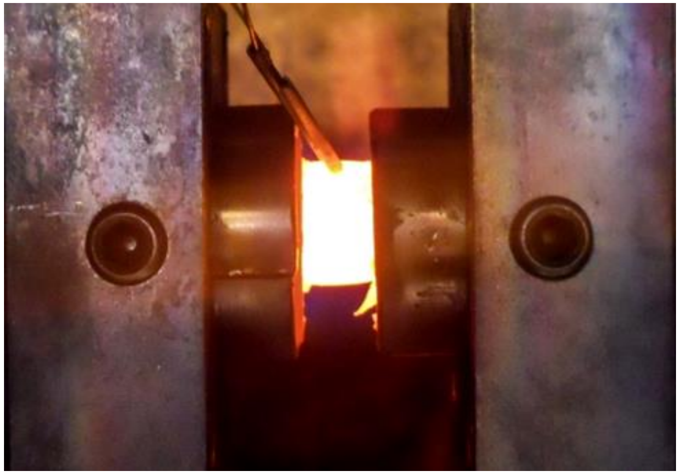


S. Vervynckt, "Control of the non-recrystallisation temperature in high strength low alloy (HSLA) steels: Recrystallisation-precipitation interaction in model Nb-steels," in *Austenite Processing Symposium (Internal company presentation)*, 2008, p. 29.

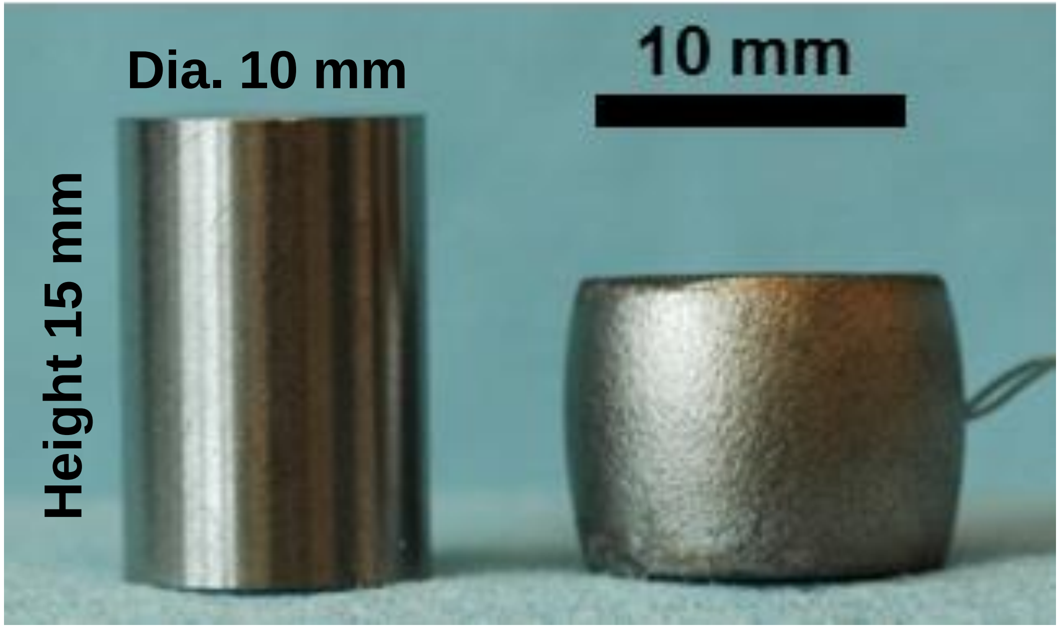
In C.N. Homsher, "Influence of Processing Parameters and Alloying Additions on the Mechanically Determined No-Recrystallization Temperature in Niobium Microalloyed Steels," PhD Thesis, Colorado School of Mines, 2016.

Limitations of Compression Test

Maximum strain obtainable in compression test is limited & much less that strain experienced in multi-stand rolling operation



Hot compression of 10 mm diameter sample.

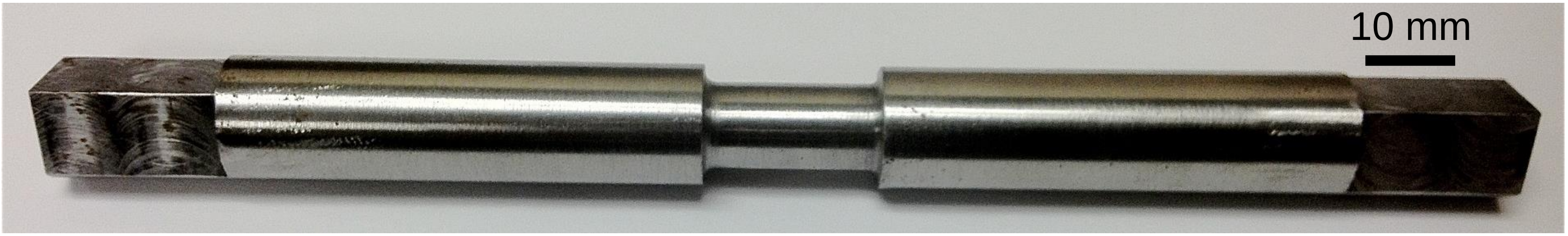


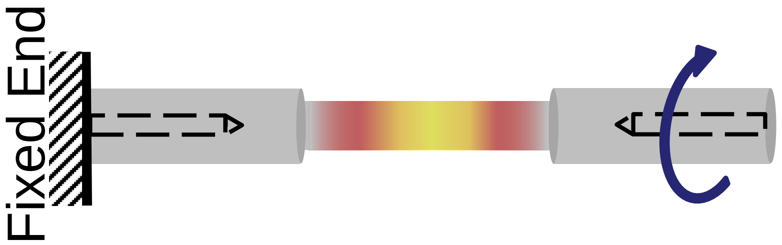
Compressed to true strain of -0.4

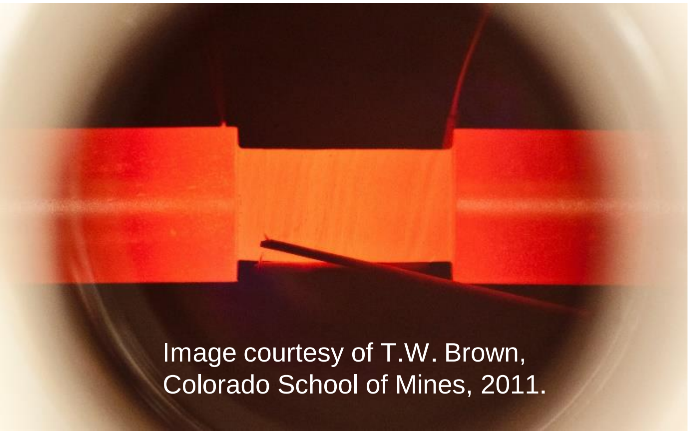
C.N. Homsher, "Determination of Non-Recrystallization Temperature (TNR) of Multiple Microalloyed Steels," MS Thesis, Colorado School of Mines, 2012.

Torsion to Simulate Multi-Stand Rolling

- Multi-stand bar rolling
  - Reduction in cross-section > 90%
  - Total true strain > 2
- Torsion testing with Gleeble 3500
  - Measure torque v. angle of twist
  - Convert to stress-strain data



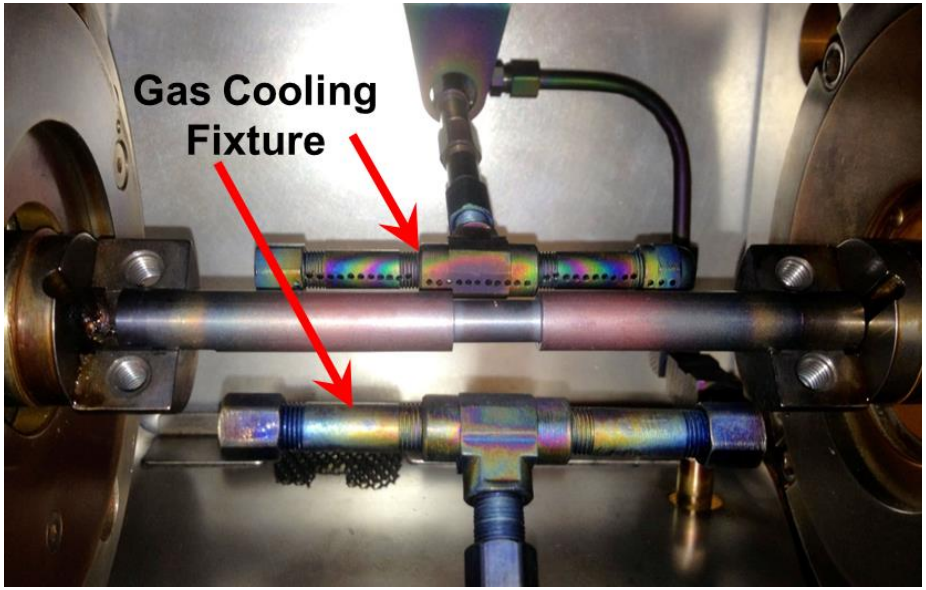


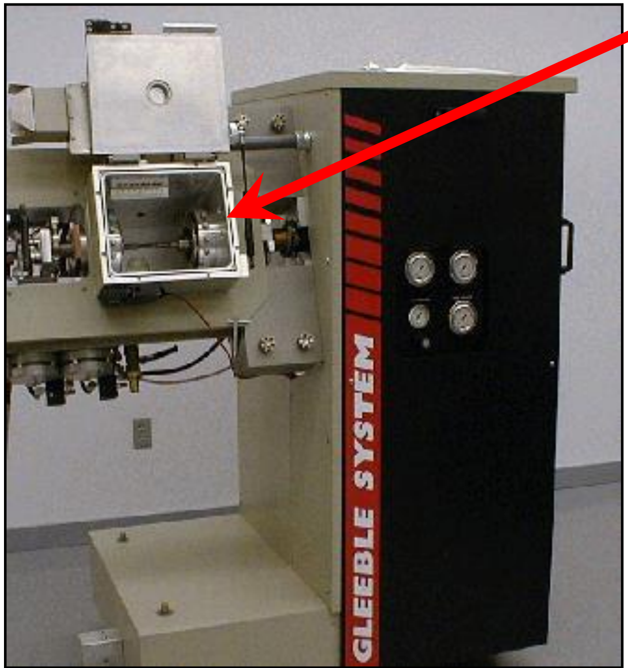


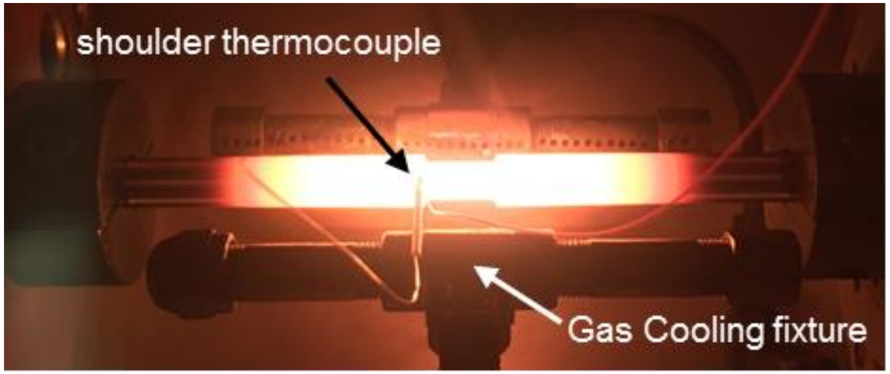
B.M. Whitley, "Thermomechanical Processing of Microalloyed Bar Steels for Induction Hardened Components," PhD Thesis, Colorado School of Mines, 2017.

Torsion Set-Up in Gleeble

Ginny Judge and Blake Whitley spot welding thermocouple to sample

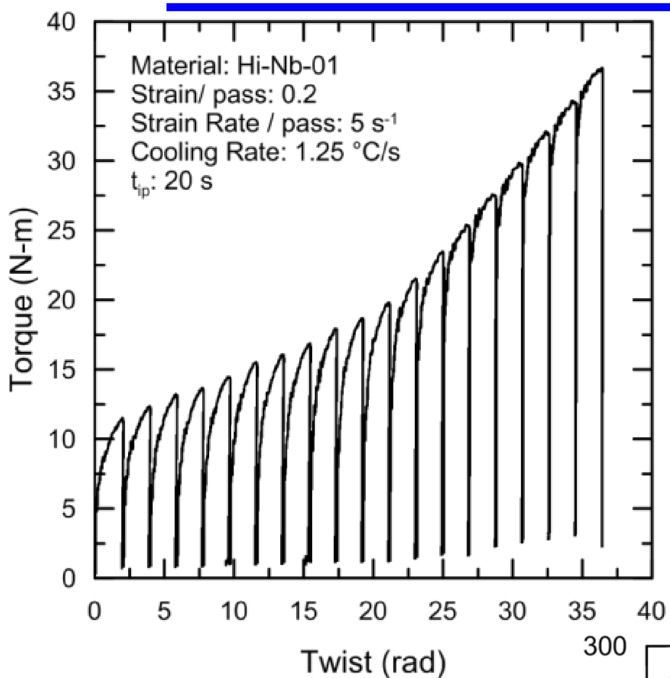






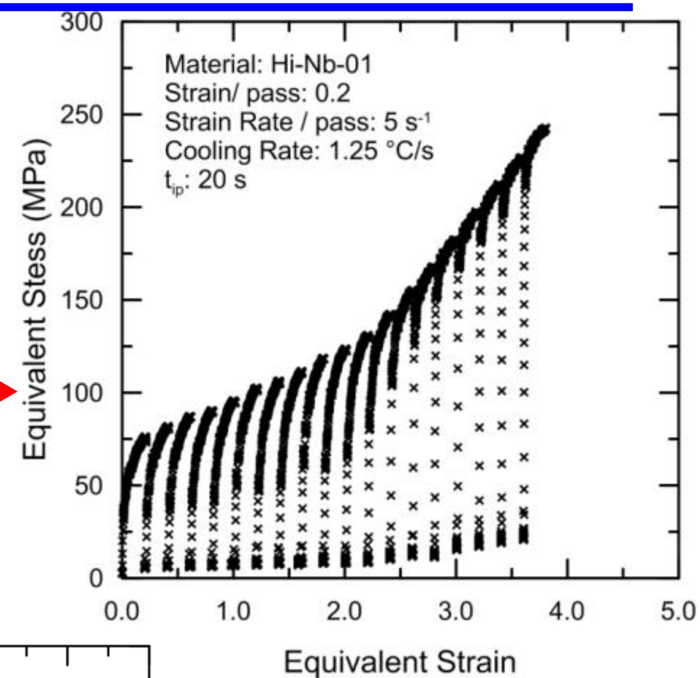
Images courtesy of: (1) B.M. Whitley, "Thermomechanical Processing of Microalloyed Bar Steels for Induction Hardened Components," PhD Thesis, Colorado School of Mines, 2017. (2) J.K. Benz, "The Effects of Vanadium and Other Microalloying Elements on The Microstructure and Properties of Bainitic HSLA Steels," PhD Thesis, Colorado School of Mines, 2019. (3) Todd Bonesteel, VP, Dynamic Systems Inc.(September 2019)

Example Torsion Data to Determine T_{NR}

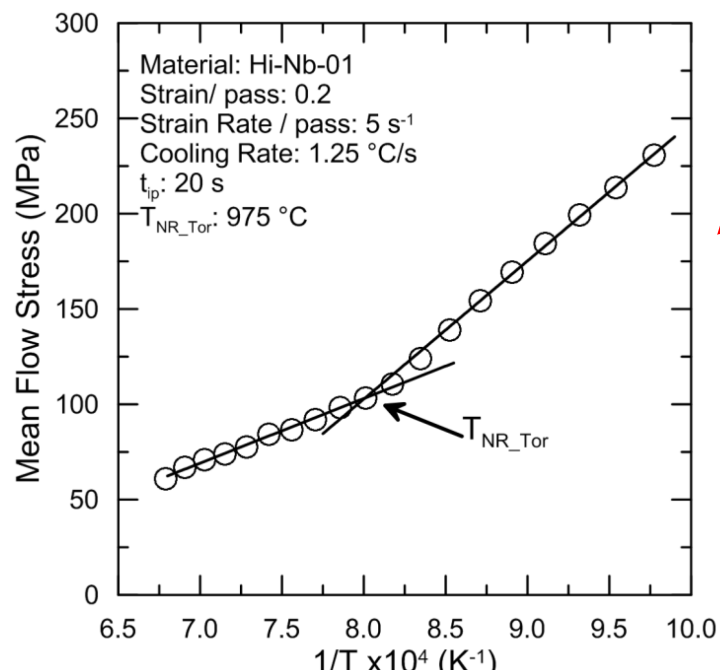


$$\sigma = \frac{3\sqrt{3}T}{2\pi a^3}$$

$$\varepsilon = \frac{0.724 a\theta}{\sqrt{3} l}$$



T = torque
a = radius
l = gage length
Θ = angle of rotation



Mean Flow Stress

$$MFS = \bar{\sigma} = \frac{1}{\varepsilon_2 - \varepsilon_1}\int_{\varepsilon_1}^{\varepsilon_2} \sigma d\varepsilon$$

In C.N. Homsher, “Influence of Processing Parameters and Alloying Additions on the Mechanically Determined No-Recrystallization Temperature in Niobium Microalloyed Steels,” PhD Thesis, Colorado School of Mines, 2016.

Simulation of Multi-stand Bar Mill

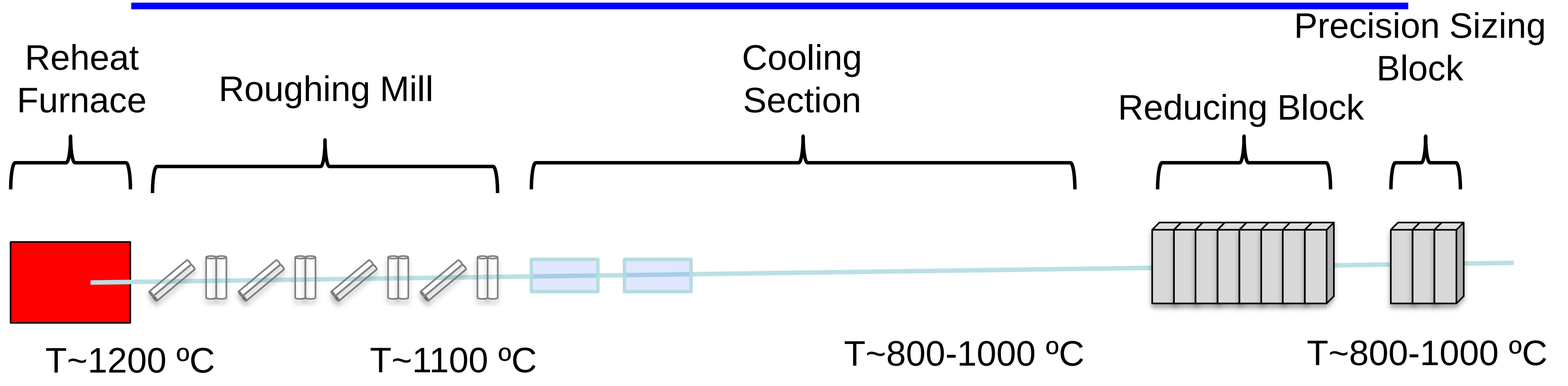
- **Apply Gleeble torsion testing to evaluate commercial multi-stand bar mill**
- **Determine how microalloying and thermomechanical processing affect high temperature strength and microstructural evolution during bar rolling**

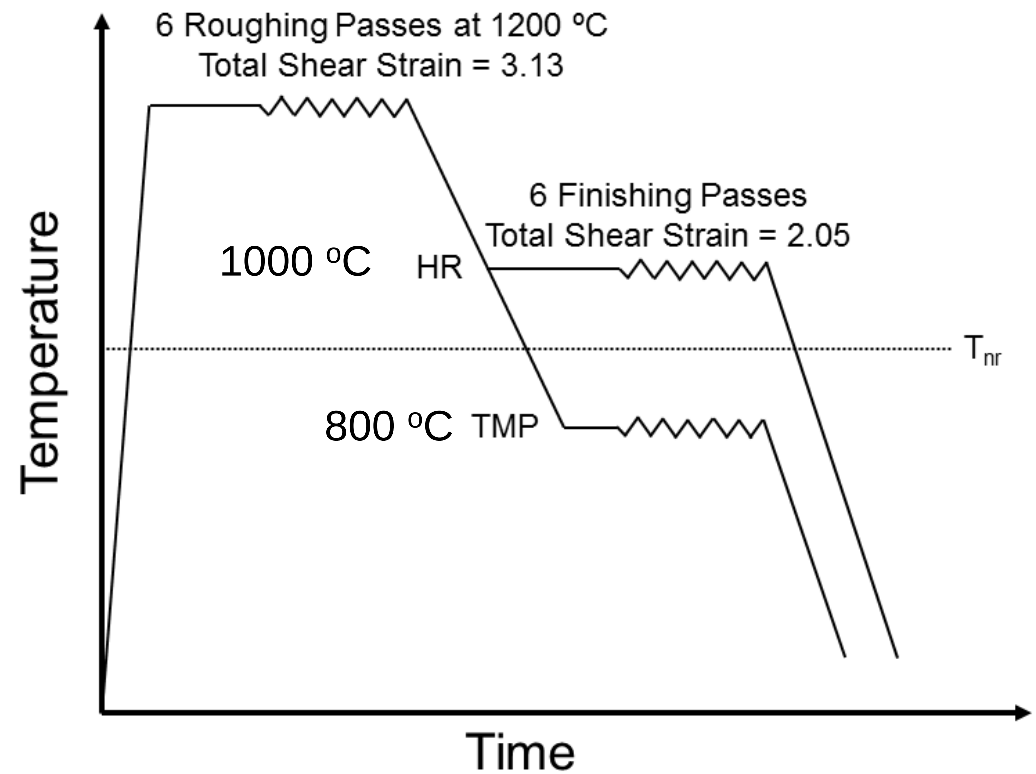
Alloy	C	Mn	Nb	V	Al	N
1045 Al	0.45	0.72	0.001	0.003	0.021	0.0097
10V45	0.45	0.82	0.001	0.089	0	0.0127
10V45 w/ Nb	0.46	0.85	0.02	0.092	0	0.0124

- **Compare mill and laboratory results for conventional rolling and TMP**
- **Use Gleeble to simulate subsequent induction heat treating**

B.M. Whitley, "Thermomechanical Processing of Microalloyed Bar Steels for Induction Hardened Components," PhD Thesis, Colorado School of Mines, 2017

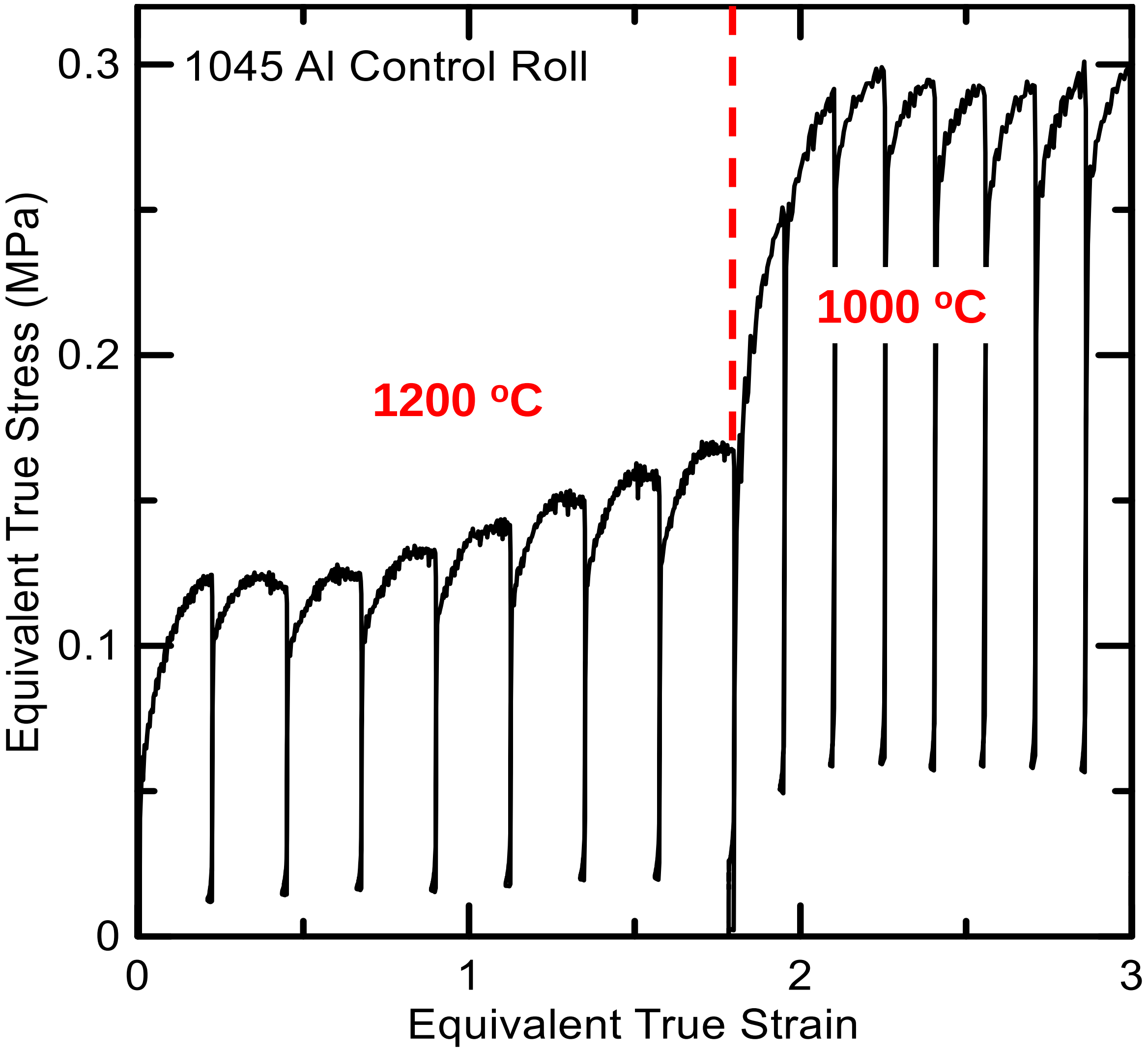
Simulation of Multi-stand Bar Mill





B.M. Whitley, "Thermomechanical Processing of Microalloyed Bar Steels for Induction Hardened Components," PhD Thesis, Colorado School of Mines, 2017

Example Results: Stress-strain

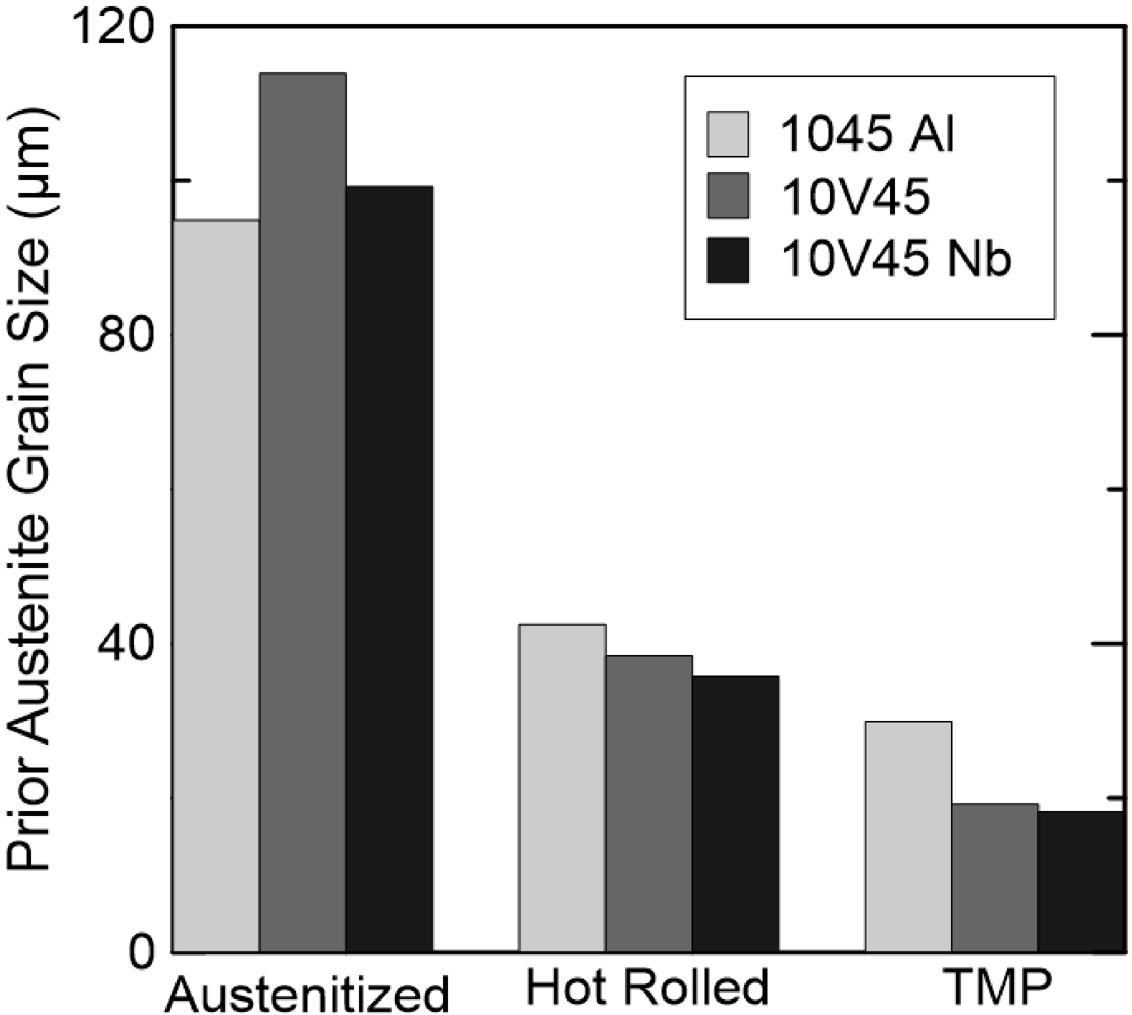


- **Conventional rolling, 1000 ºC finishing**
- **Hardening observed during roughing steps.**
- **Combination of hardening and softening observed during finishing steps.**

B.M. Whitley, "Thermomechanical Processing of Microalloyed Bar Steels for Induction Hardened Components," PhD Thesis, Colorado School of Mines, 2017

Example Results:

Quench to reveal prior austenite grain size

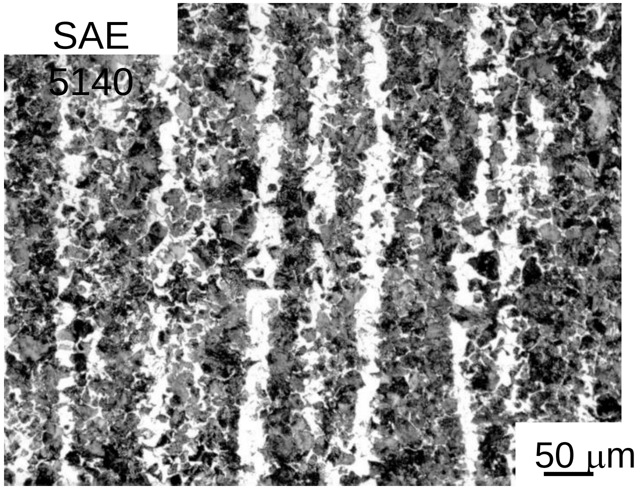


Refinement by:

- Rolling
- TMP processing (Low T Rolling)
- Microalloying

B.M. Whitley, "Thermomechanical Processing of Microalloyed Bar Steels for Induction Hardened Components," PhD Thesis, Colorado School of Mines, 2017

Applications of the Laboratory Rolling Facility at CSM
Simulation of Other Processes
Banding in Steel



D.K. Matlock, R.J. Johnson, E. De Moor, and J.G. Speer, "Microstructural Simulations via Thermal Processing of Roll Bonded Steel Laminates," *Inter. J. of Metall. Engr*. 2013. vol. 2, no. 1, pp. 10-17.

T.F. Majka, D.K. Matlock, G.Krauss, "Development of Microstructural Banding in Low-Alloy Steel with Simulated Mn Segregation," *Metall. and Mat. Trans*., Vol. 33A, 2002, pp. 1627-1637

Banding: Application of Laminates

- **Purpose:** **Evaluate Properties of Artificially Banded SAE 5140**
- **Alloy selection**
  - **Based on *measured* composition variations**
  - **SAE 5140 with 0.82 wt. pct. Mn**
  - **SAE 5140M (modified) with 1.82 wt. pct. Mn**

Grade	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al
5140	0.39	0.82	0.01	0.02	0.22	0.16	0.17	0.81	0.04	0.03
5140M	0.41	1.83	0.02	0.02	0.22	0.16	0.17	0.81	0.04	0.03

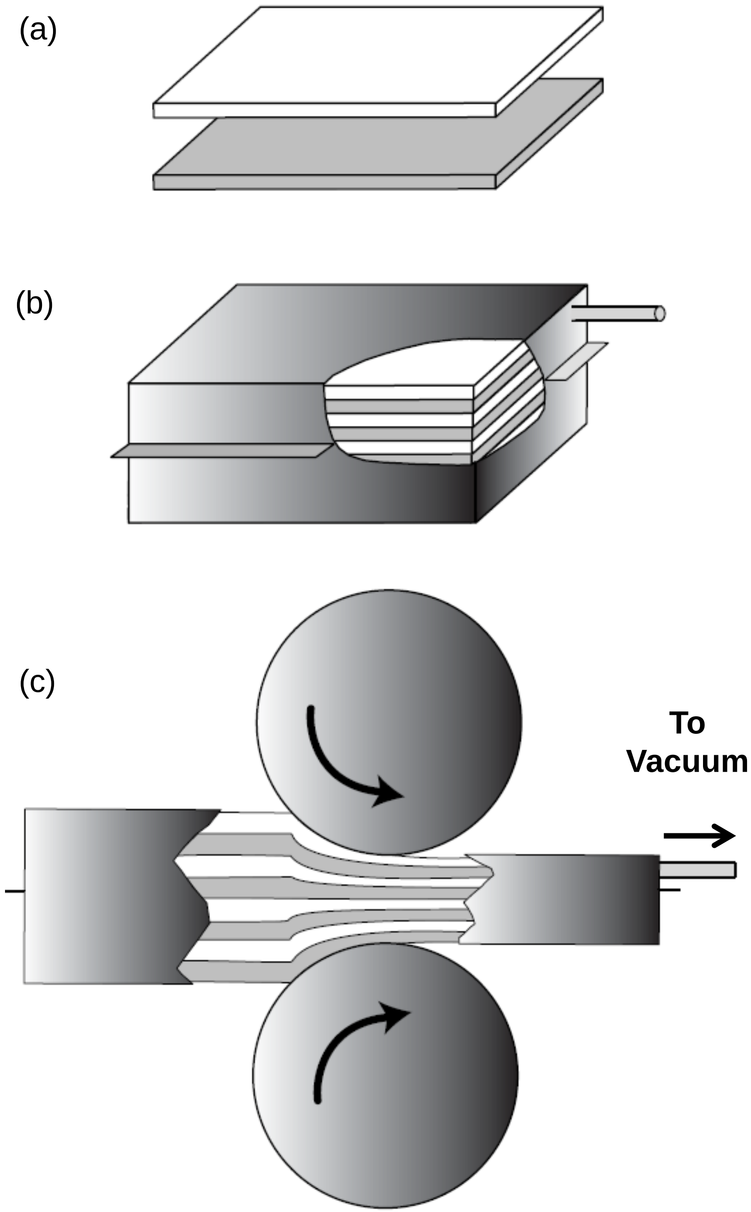
T.F. Majka, D.K. Matlock, G.Krauss, "Development of Microstructural Banding in Low-Alloy Steel with Simulated Mn Segregation," *Metall. and Mat. Trans.*, Vol. 33A, 2002, pp. 1627-1637.

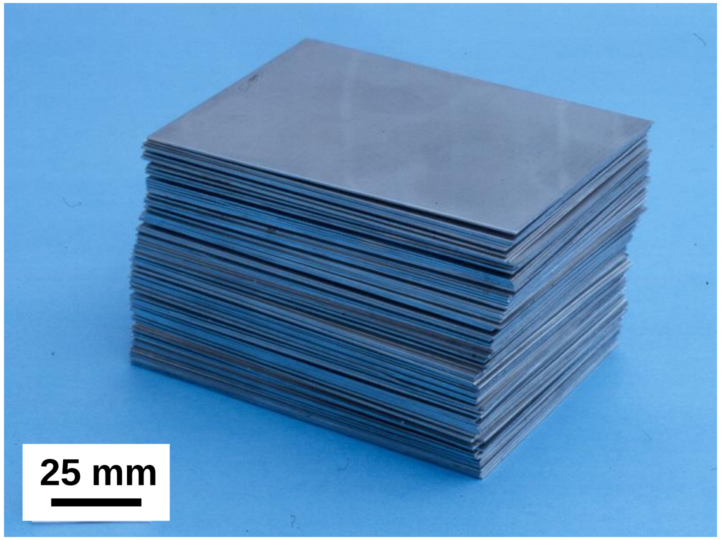
Banding: Application of Laminates

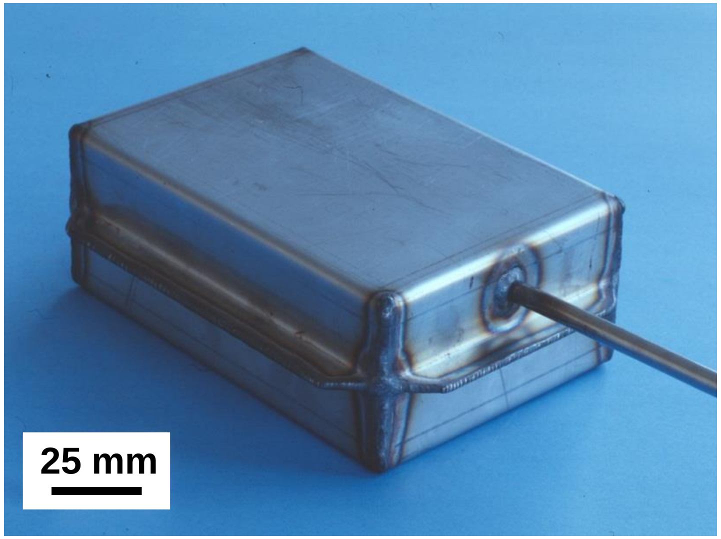
- **Approach:** **Prepare roll-bonded laminates of steels with alternating Mn content layers**
- **Band Thicknesses:**
  - **10 μm to 320 μm**
- **Thermal process**
  - **Austenitize at 850 ^oC for 10 min**
  - **Control cool at six rates between 83 ^oC/s and 0.5 ^oC/min**
- **Evaluation**
  - **Tensile properties**
  - **Microstructures (light optical)**

T.F. Majka, D.K. Matlock, G.Krauss, "Development of Microstructural Banding in Low-Alloy Steel with Simulated Mn Segregation," *Metall. and Mat. Trans.*, Vol. 33A, 2002, pp. 1627-1637.

Production of Steel Laminates



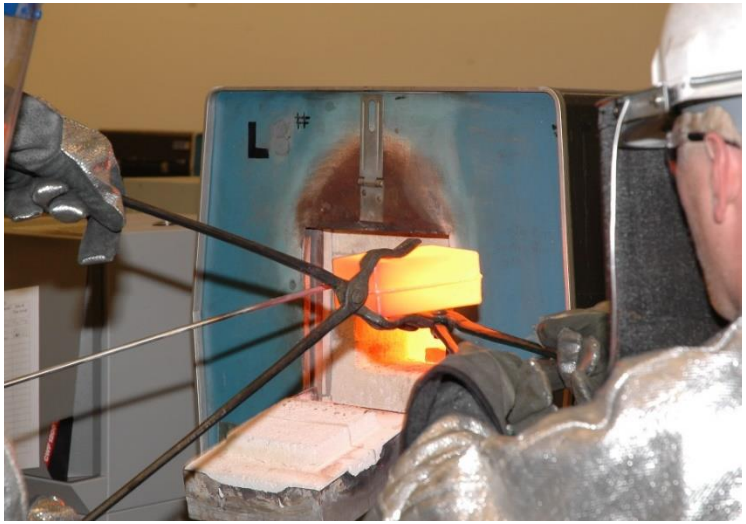


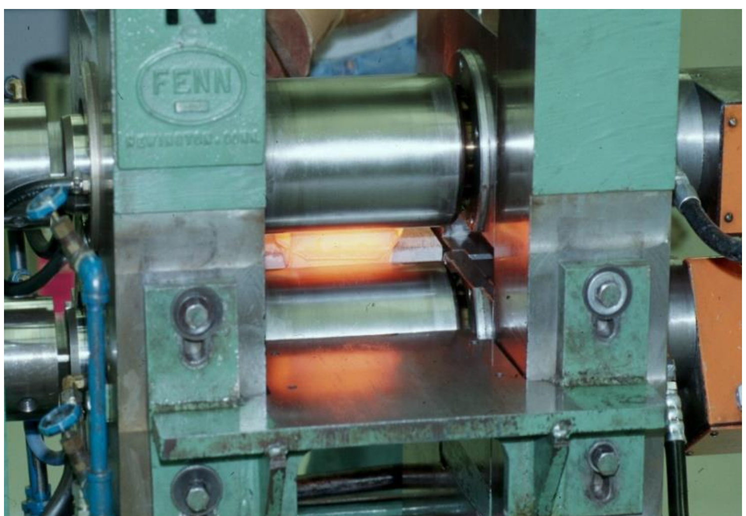


T.F. Majka. "Tensile Deformation Behavior and Microstructural Evolution in an Artificially Banded SAE 5140," MS Thesis, Colorado School of Mines, 2000.

Production of Steel Laminates

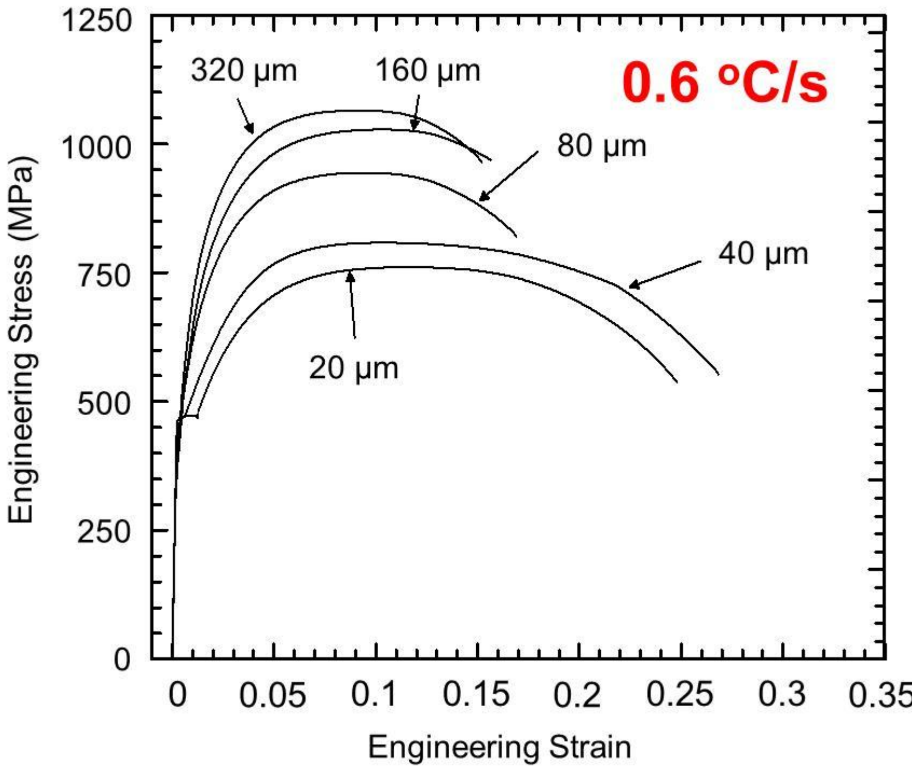
Laboratory hot rolling facilities in Hill Hall at the Colorado School of Mines

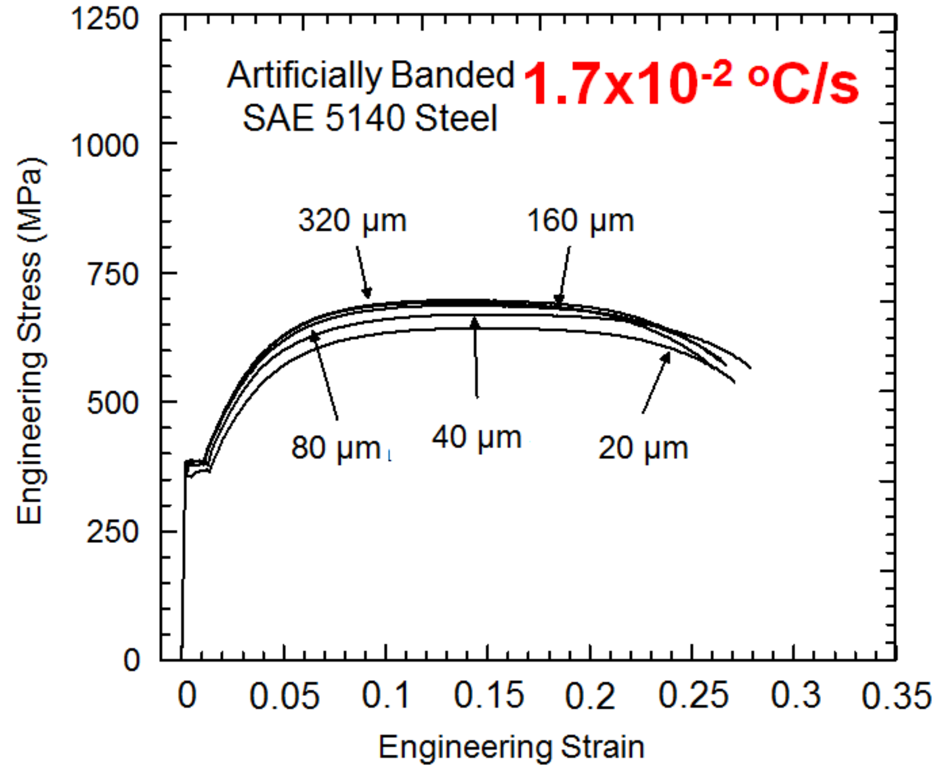




D.K. Matlock, R.J. Johnson, E. De Moor, and J.G. Speer, “Microstructural Simulations via Thermal Processing of Roll Bonded Steel Laminates,” images from presentation at SimPro’12, Ranchi, India, October 12, 2012; text published in *Inter. J. of Metall. Engr*. 2013. vol. 2, no. 1, pp. 10-17.

Banded 5140 Steel: Tensile Properties

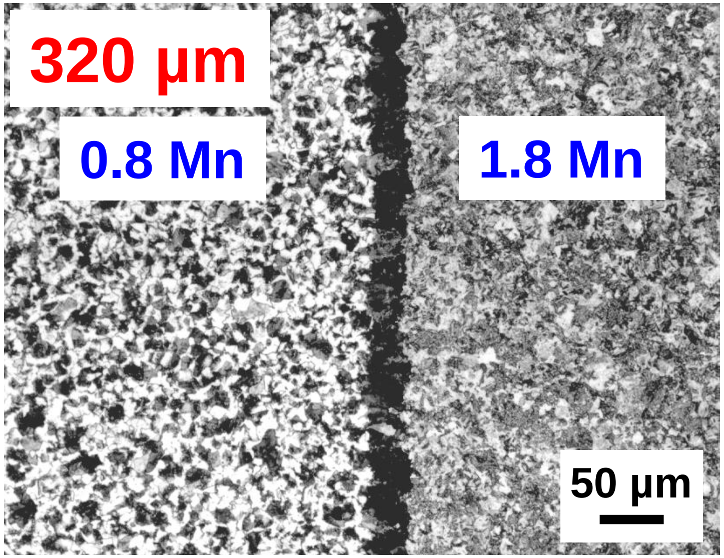


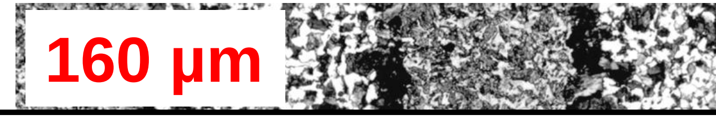


- **Tensile properties independent of band width**
    - **As-Quenched and slow cooled**
- **Tensile properties dependent on band width**
    - **Intermediate cooling rates.**

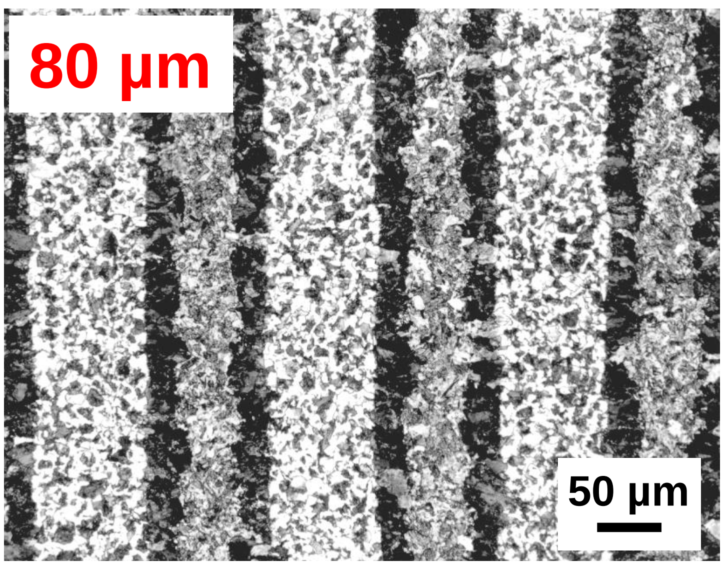
T.F. Majka, D.K. Matlock, G.Krauss, “Development of Microstructural Banding in Low-Alloy Steel with Simulated Mn Segregation,” *Metall. and Mat. Trans.*, Vol. 33A, 2002, pp. 1627-1637.

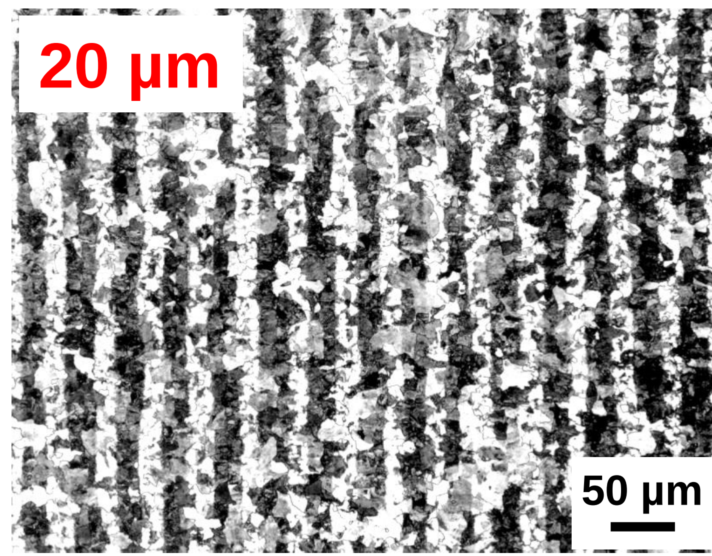
Microstructures: 0.6 $^{o}C/s$





- 1.8 Mn Layer – bainitic with constant thickness interfacial pearlite layer
- Amount of bainite increases with an increase in layer thickness = higher strength





T.F. Majka, D.K. Matlock, G.Krauss, “Development of Microstructural Banding in Low-Alloy Steel with Simulated Mn Segregation,” *Metall. and Mat. Trans.*, Vol. 33A, 2002, pp. 1627-1637.

Sulfide Inclusions:
Effects of Reduction Ratio

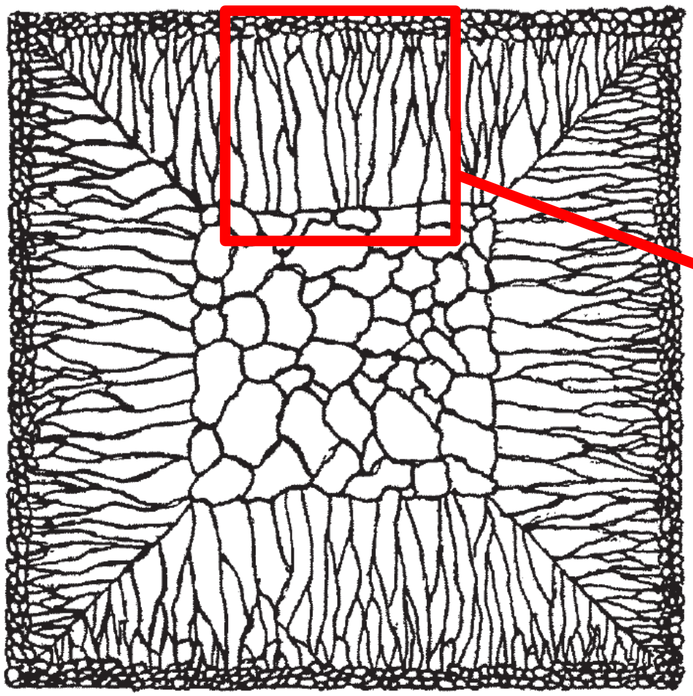
Sulfide Inclusions in Bar Rolling

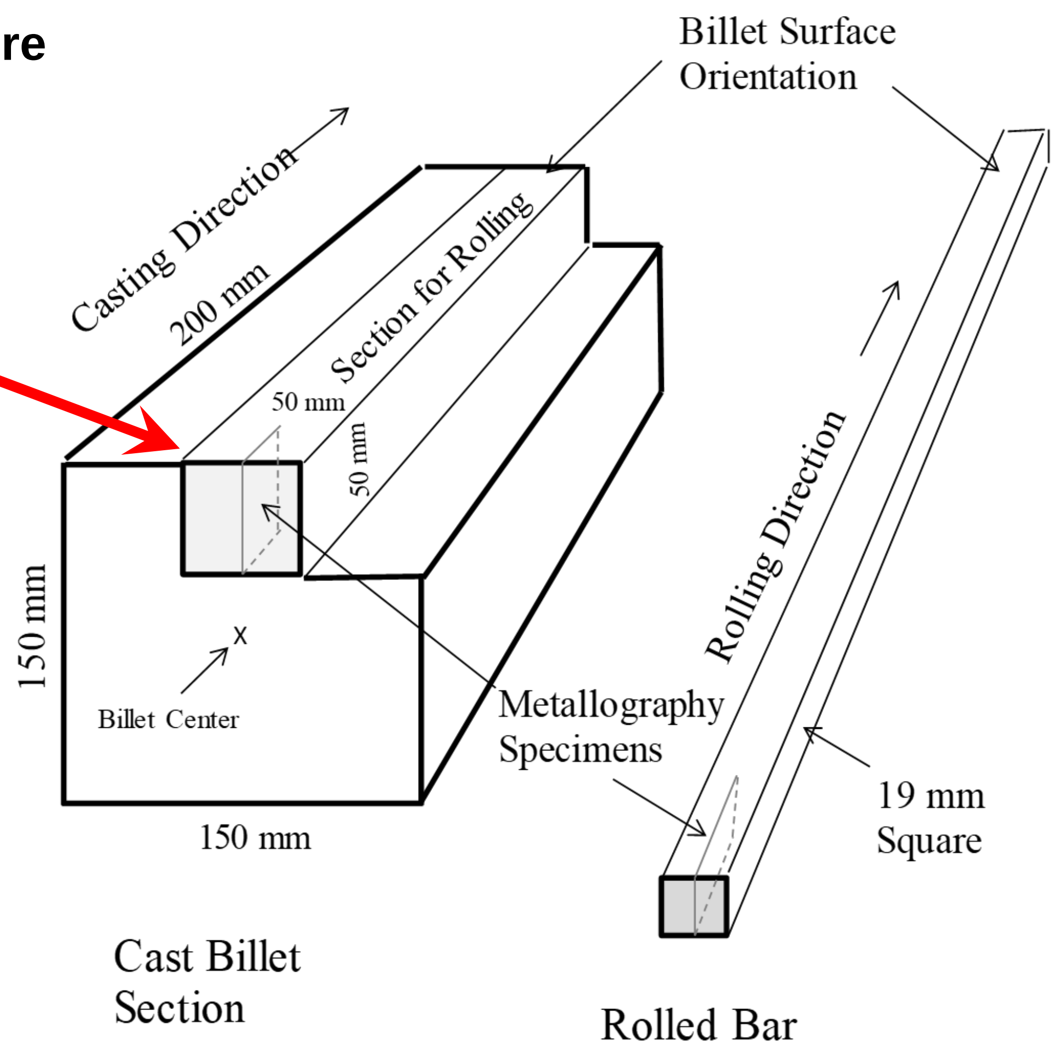
- **ASPPRC Study:** **Effects of Mn content, dendrite size, and hot rolling on sulfide inclusions in medium carbon steel bars**
  - **Medium carbon steels at 0.02 to 0.03 wt pct S**
  - **Three Mn levels**
    - **L = 0.55 Mn, 0.30 C**
    - **M = 0.96 Mn, 0.41 C**
    - **H = 1.49 Mn, 0.41 C**
  - **Hot roll to different reduction ratios**
  - **Hot roll at 800 ^{o}C, 1000 ^{o}C, and 1200 ^{o}C**
  - **Characterize macrostructures**
  - **Assess changes in sulfide inclusions**

Professor Robert Cryderman
ASPPRC, Colorado School of Mines
personal communication, 2019.

Sulfide Inclusions in Bar Rolling

Billet Solidification Macrostructure

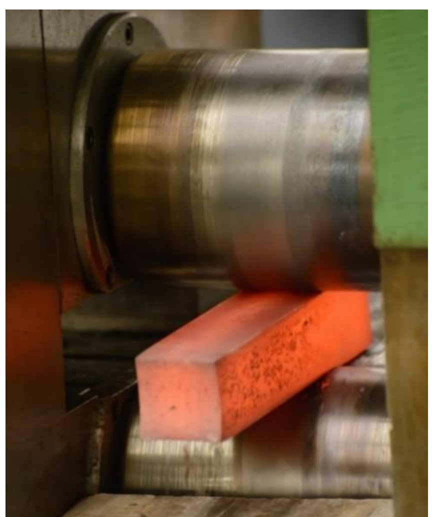




R. L. Cryderman, "Classification of Long Steel Products," The Making, Shaping and Treating of Steel, 11th Edition– Long Products Volume, Chapter 1, AIST, 2017, pp. 11, 31.

Hot Rolling – Bar and Rod

Rolling of square bars in the hot rolling laboratory in Hill Hall at the Colorado School of Mines



Professor Robert Cryderman, ASPPRC, Colorado School of Mines, personal communication, 2019.

Hot Rolling – Bar and Rod

Rolling of square bars to different final reduction ratios (RR) in the hot rolling laboratory in Hill Hall at the Colorado School of Mines

<u>As Cast - 50 mm Square Samples</u>

<u>Heating Temps:</u>

800 °C

1000 °C

1200 °C

<u>Flat Pass Rolling</u>

41 mm Square (RR 1.5 : 1)
30 mm Square (RR 2.9 : 1)

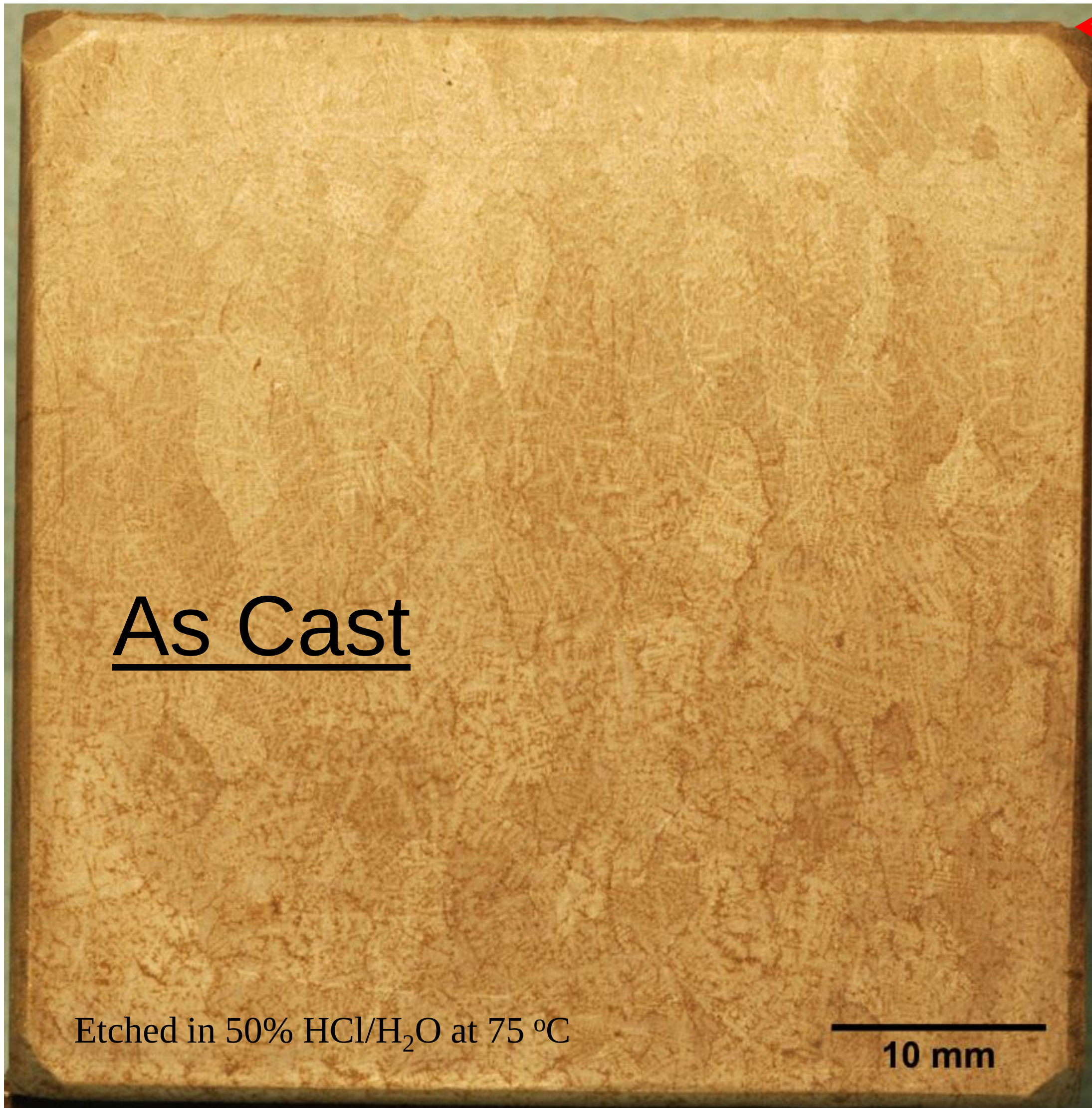
<u>Groove Rolling</u>

19 mm Square (RR 7.2 : 1)
13 mm Square (RR 15 : 1)

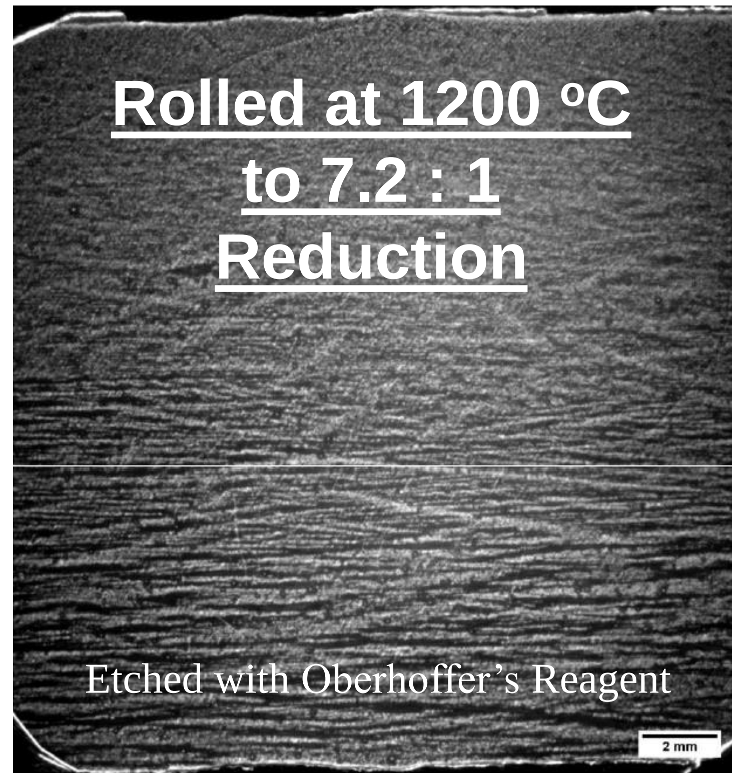
Professor Robert Cryderman, ASPPRC, Colorado School of Mines, personal communication, 2019.

Example Result

Dendrite size and Orientation



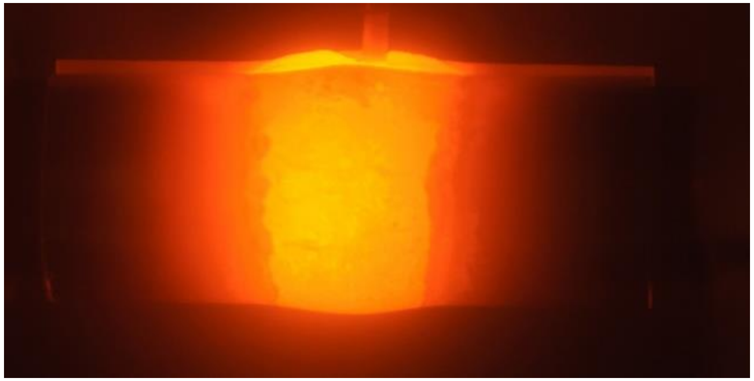
Cast Surface (Top)



R. L. Cryderman, "Classification of Long Steel Products," The Making, Shaping and Treating of Steel, 11th Edition– Long Products Volume, Chapter 1, AIST, 2017, pp. 11, 31.

Closing Comments

- Multiple examples presented to illustrate opportunities for physical simulation of hot rolling operations.
- Applications of specialized equipment and laboratory rolling facilities
- Multiple other examples….



Julian Stock, "Microalloy Precipitation and Dissolution in Hot-Charged Slabs," MS Thesis, Colorado School of Mines, 2013.

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