

Advancing Induction Heating Technology for Sustainable Processing and Property Enhancement for Advanced High Strength Sheet Steels

AIST Sustainable Technologies for Steel Manufacturing Program

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Project Objectives

- To advance electrified induction heating technology for sustainable (energy-efficient and clean) steel processing
- To explore the feasibility of induction heating to (entirely) replace conventional gas-fired furnaces in continuous annealing line while enhancing steel performance, with a focus on the rapid induction heating applications to AHSS.
- Computational and laboratory induction annealing simulations
- Student engagement with the steel industry

Background: Industrial Electrification

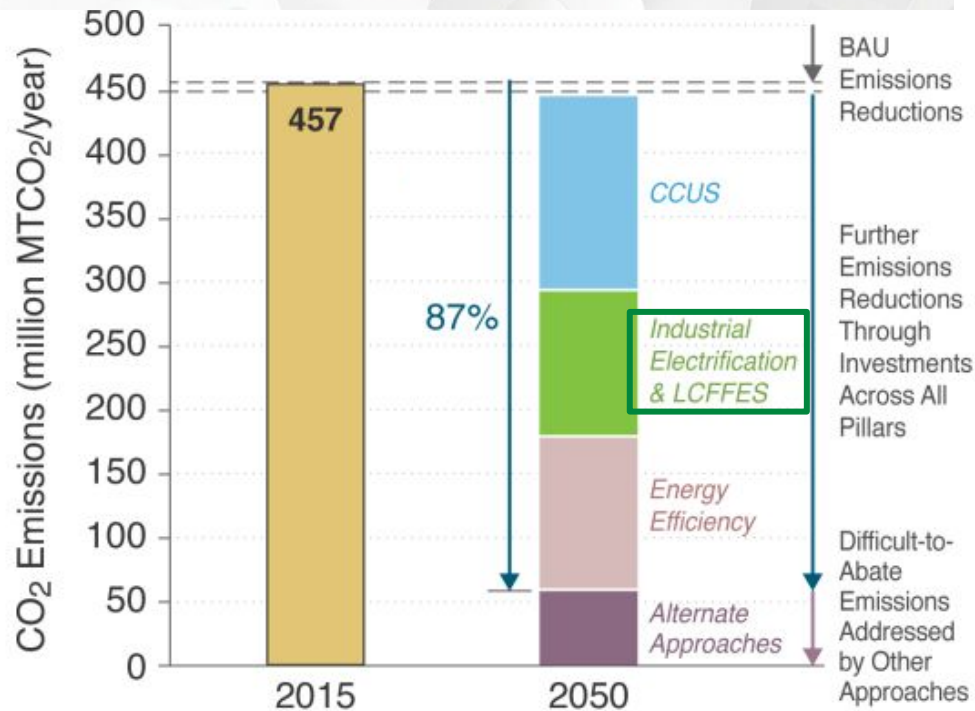
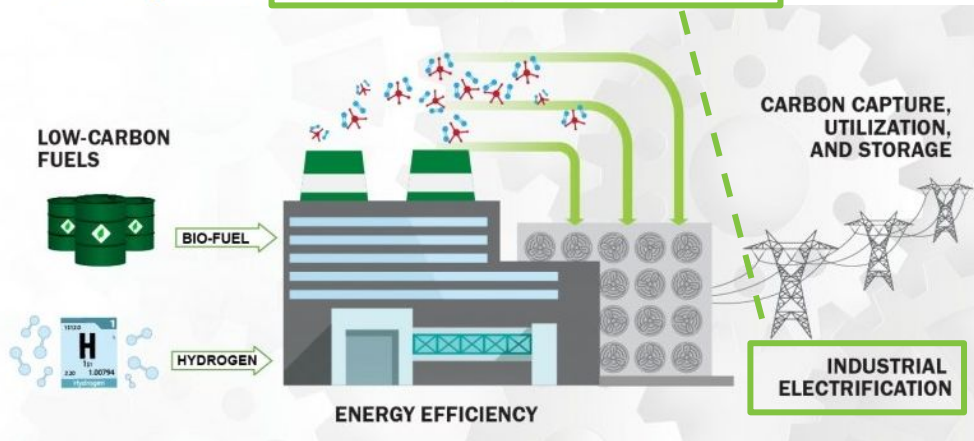


Industrial Decarbonization Roadmap

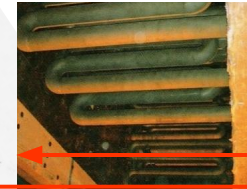
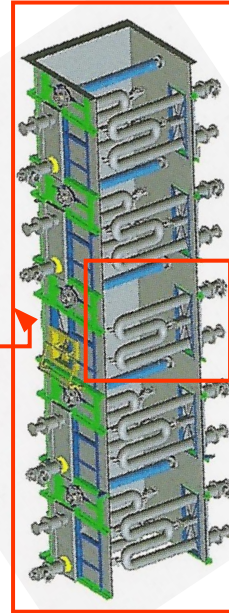
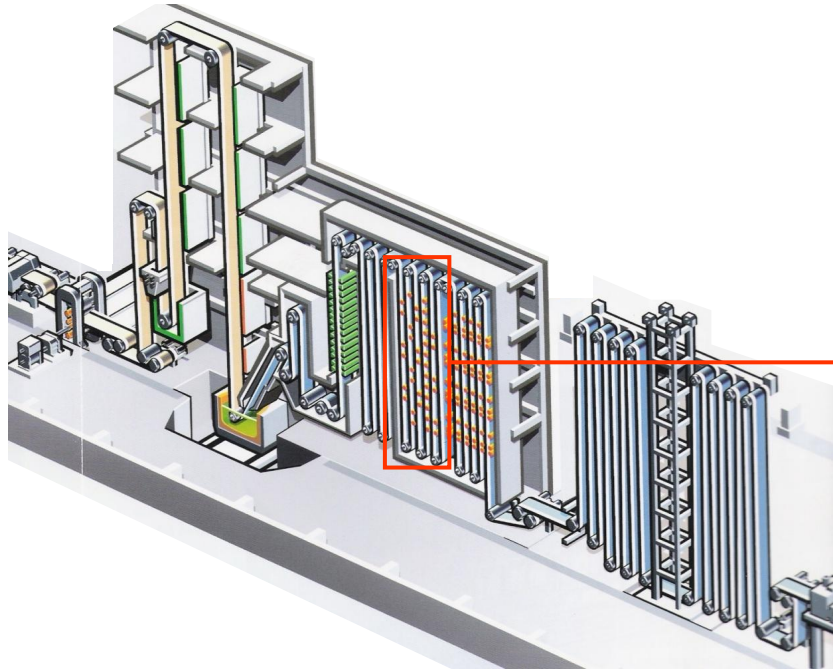
DOE/EE-2635
September 2022

United States Department of Energy
Washington, DC 20585

Strategies for Decarbonizing U.S. Industries

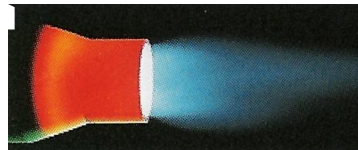


Continuous Annealing Line and Combustion Heat



*Current Use of
Gas Fired Furnaces*

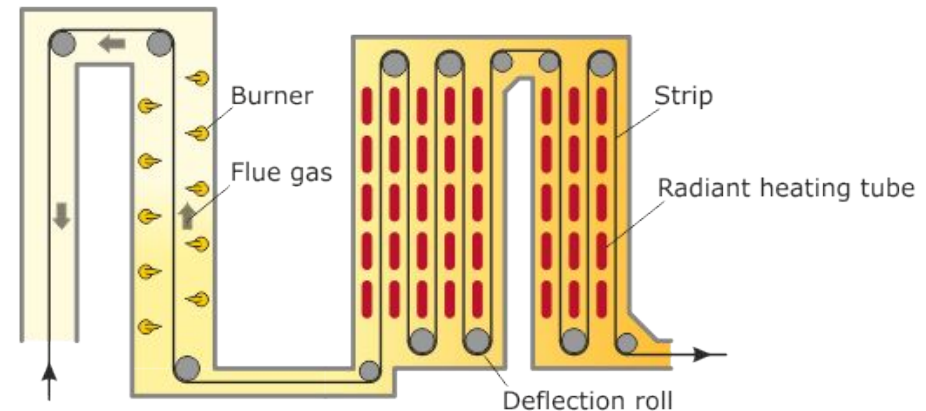
Direct Fired Furnace + Radiant Tube Furnace



Direct-fired furnace

Indirect-fired furnace

acin.tuwien.ac.at



Key Challenges and Opportunities

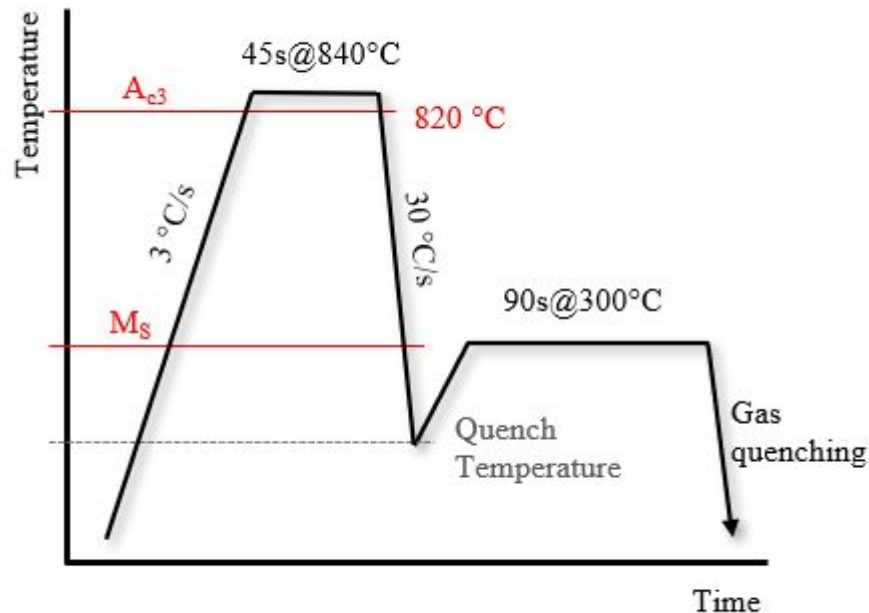
- Metallurgical Aspects and Opportunities
 - Processing-Microstructure-Property relationship optimization needed across various steel grades
 - Emphasis on initial microstructure, e.g. cold-rolled reduction
- Processing, Operation, and Maintenance
 - Different processing windows/routes
 - Magnetic permeability versus energy input
 - Temperature uniformity (e.g. edge of sheet)
 - Temperature measurement and control
 - Steel strip feeding rate compatible with desired heating rate
 - Cost of electricity
- Surface quality control
 - Scale reduction and selective oxidation on uncoated and coated products
 - Re-optimize gas atmosphere conditions (e.g. dew point)

CSMMAC Meeting (April 17, 2024)

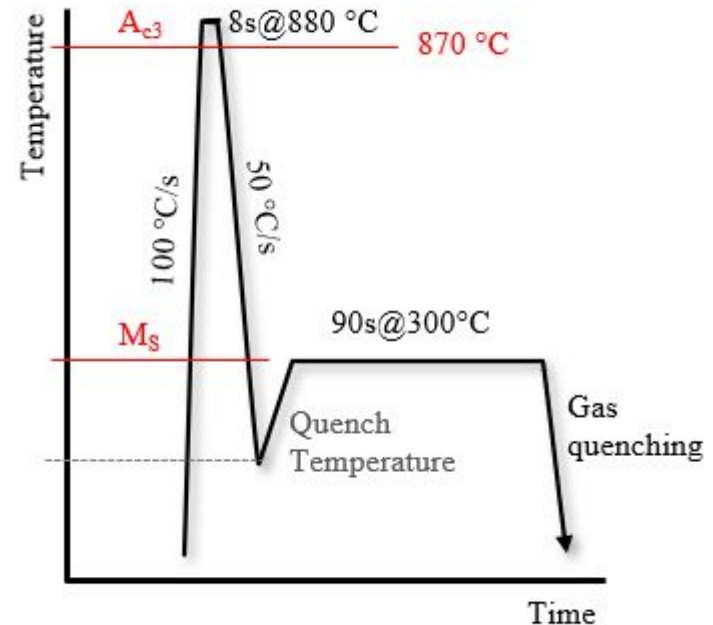
Discussion between ASPPRC and industrial mentors (U.S. Steel, Cleveland-Cliffs, and Fluxtrol)

Compare Conventional Q&P versus Q&P Involving Induction Heating

- Medium Mn (3-5%) steels, provided by POSCO
- Designed industrially relevant conventional and induction Q&P cycles



Conventional Q&P



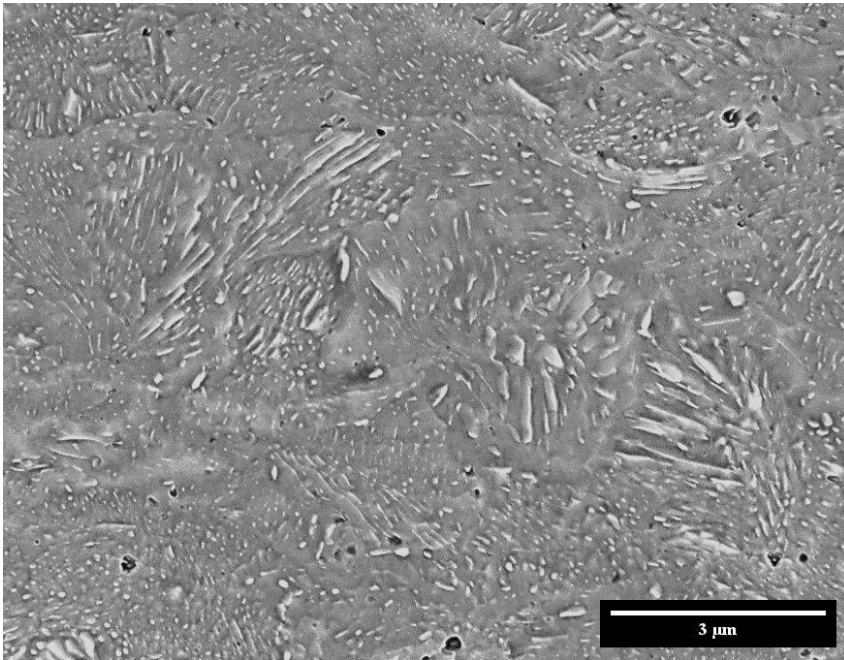
Rapid Induction Q&P

- For the Fe-0.3C-5Mn-1.6Si-1.0Cr alloy, soaking temperatures used were 830 °C for conventional and 850 °C for rapid.

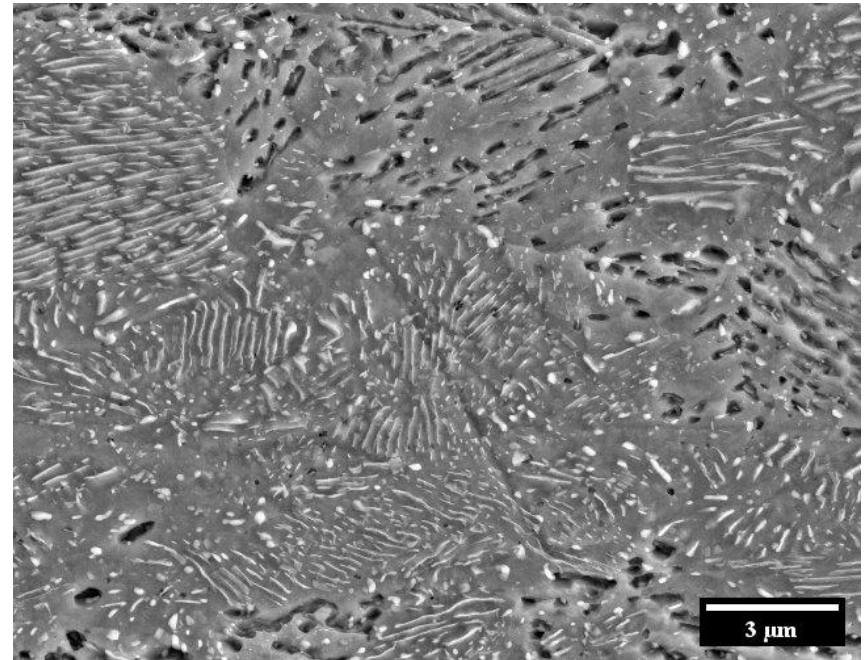
As-Received Microstructures

- Cold-rolled condition.
- Microstructure likely consisting of bainite, retained austenite, and fine cementite.
- Vickers hardness: 370 ± 4.5 HV (3Mn)

3Mn Sample

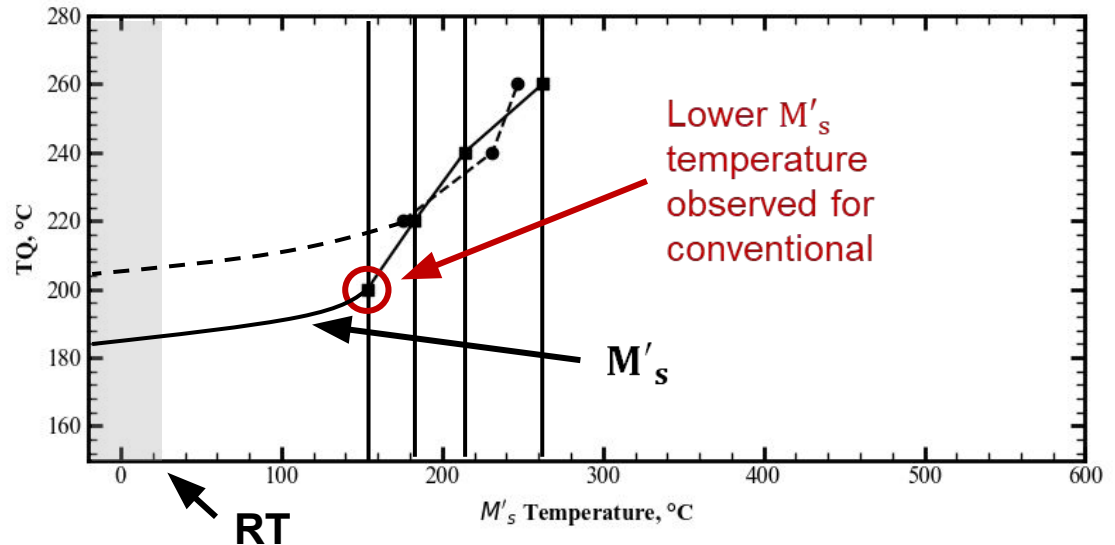
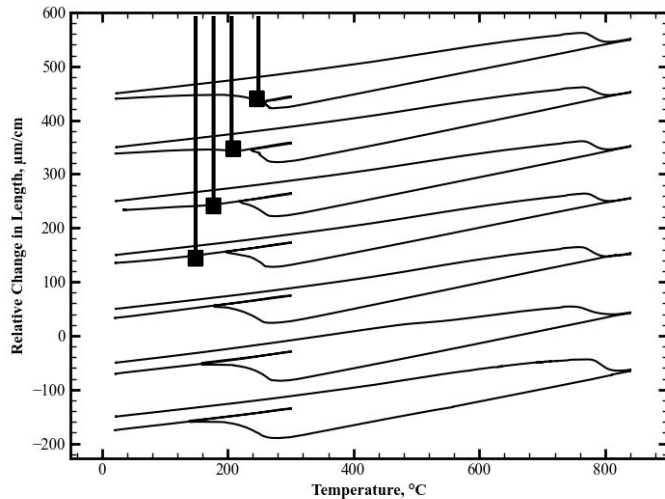


5Mn Sample

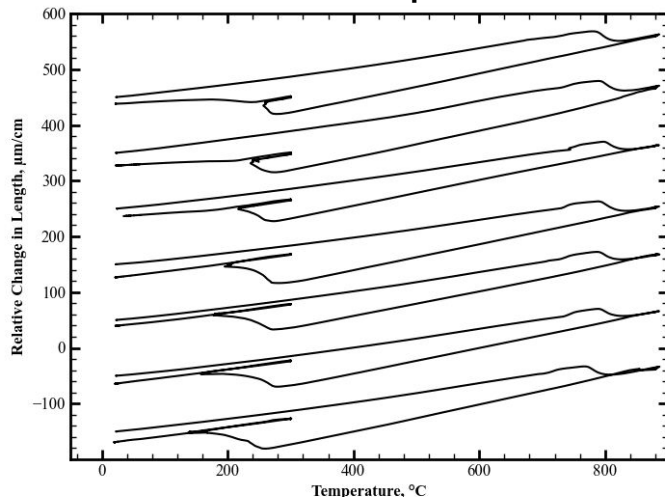


Dilatometry and M'_s Temperature (3Mn)

3Mn Conventional

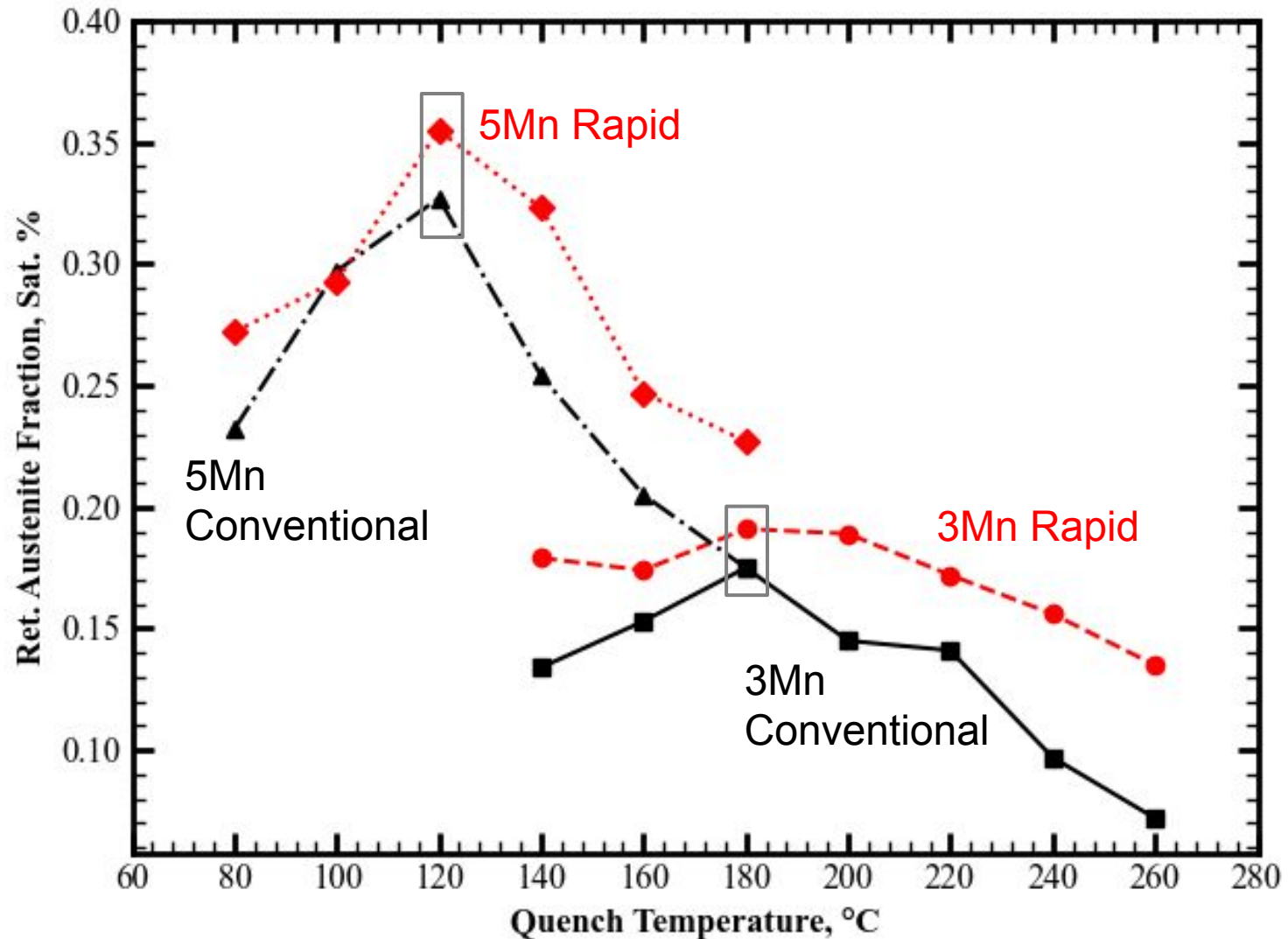


3Mn Rapid



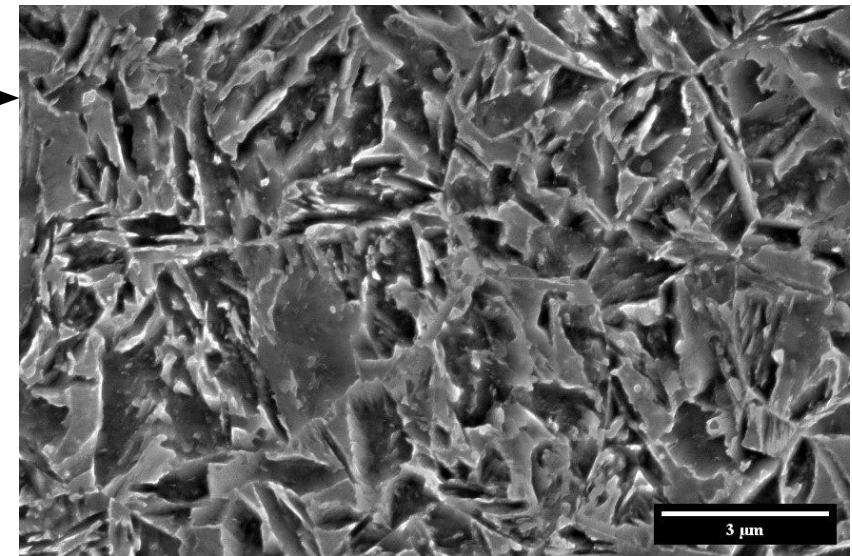
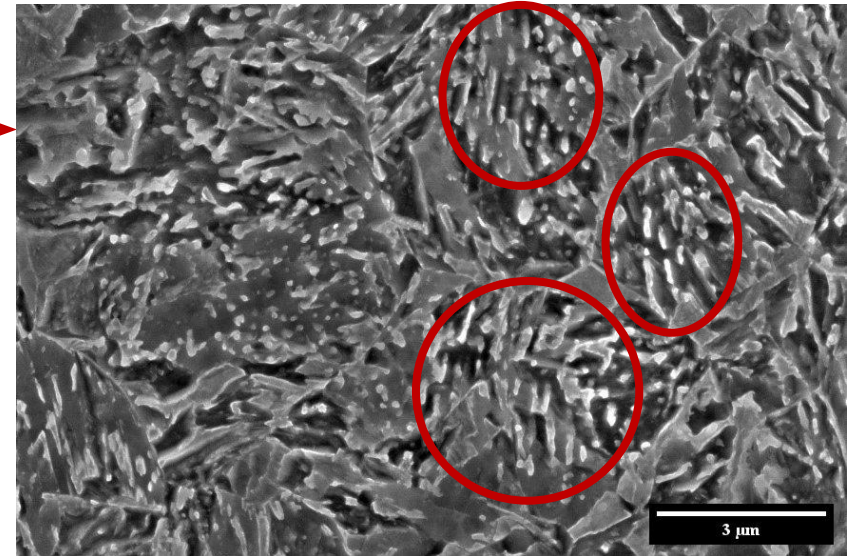
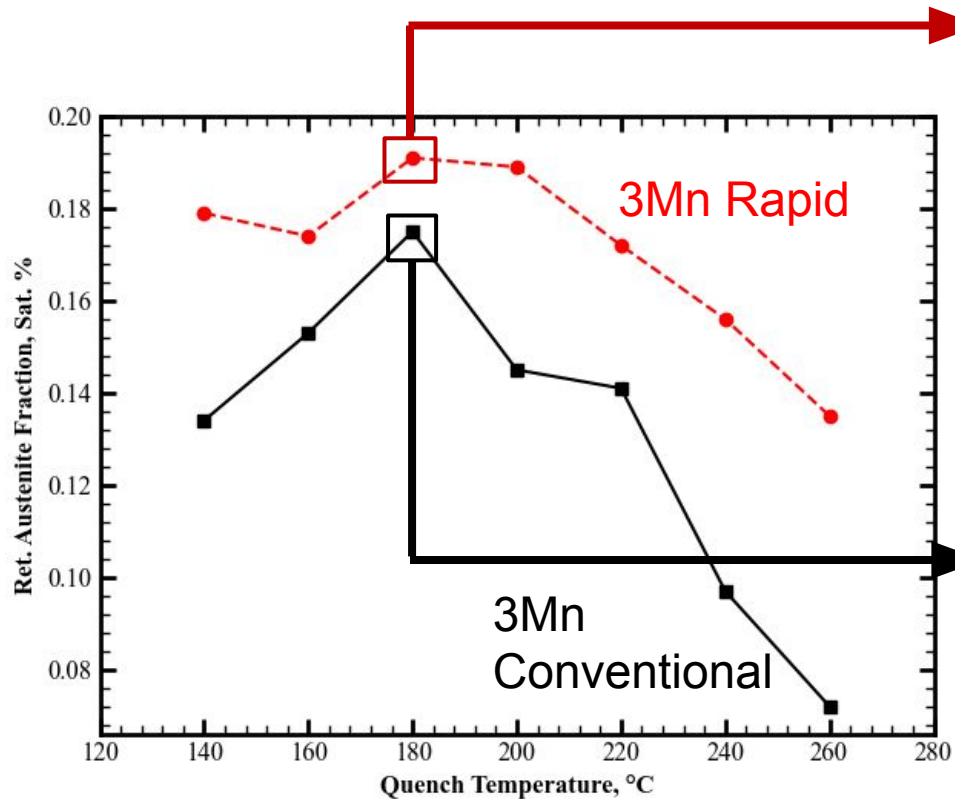
- Secondary martensite start temperature M'_s decreases with decreasing quench temperature.
- Secondary martensite formation observed at a lower QT (200°C) for conventional compared to 220°C for rapid.

Retained Austenite Stability



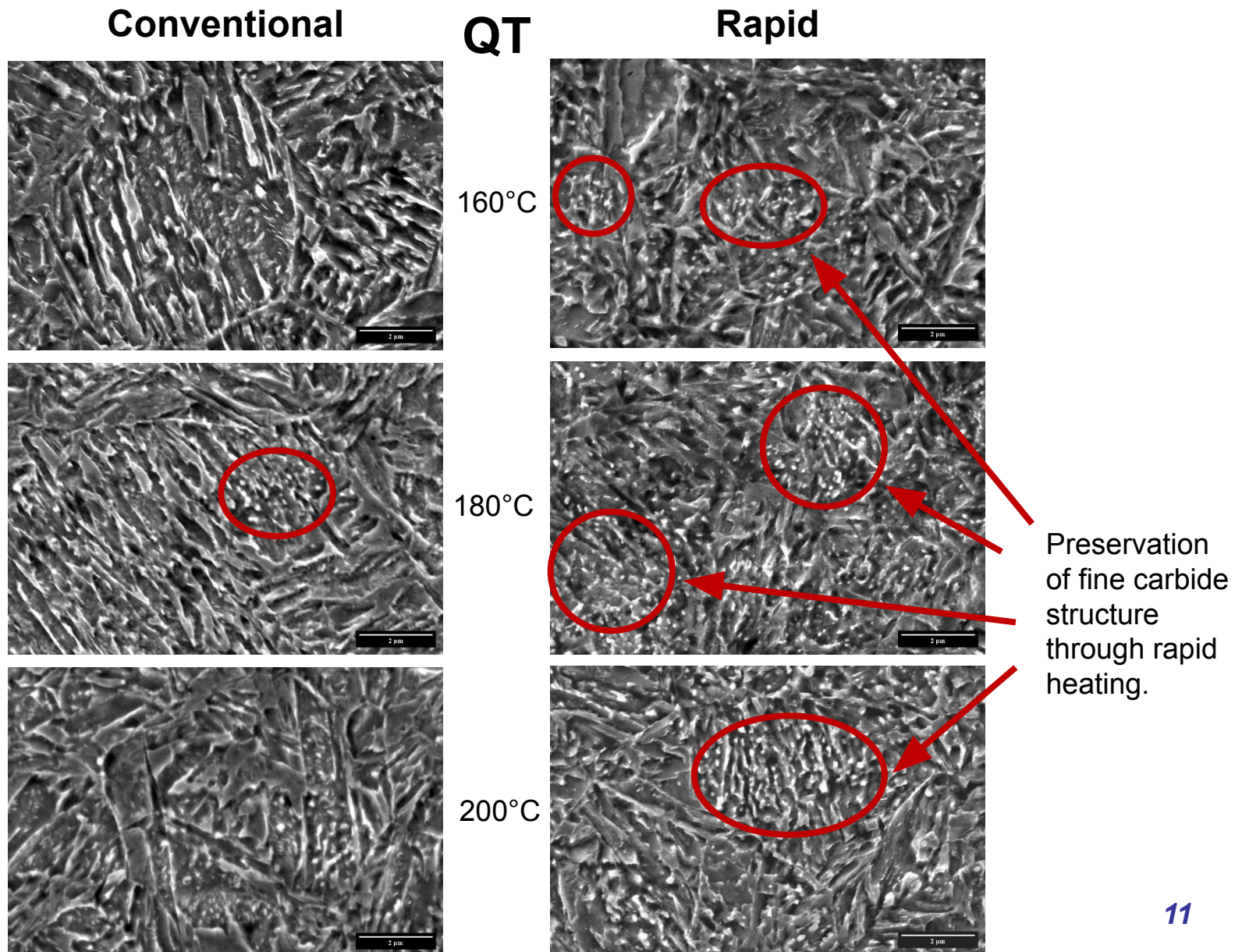
Quenched and Partitioned Microstructure

- Fe-0.3C-3Mn-1.6Si-1.0Cr alloy



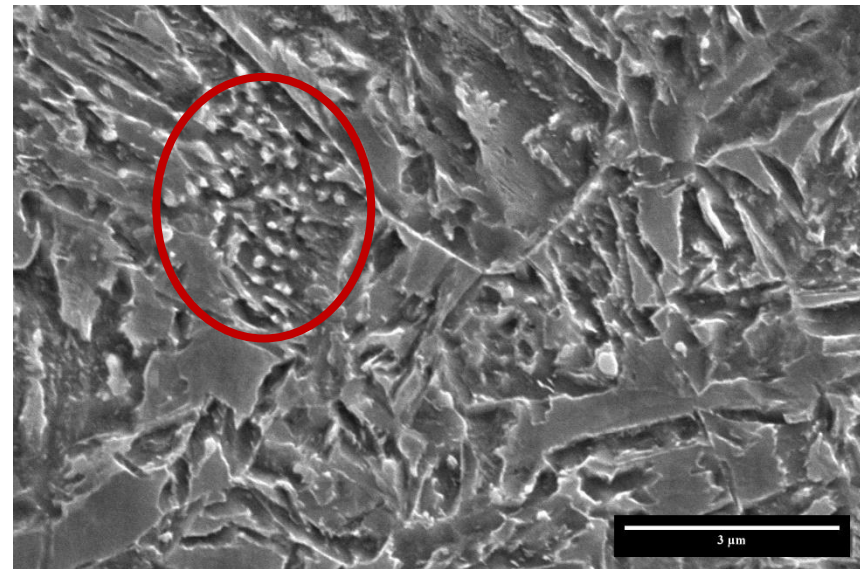
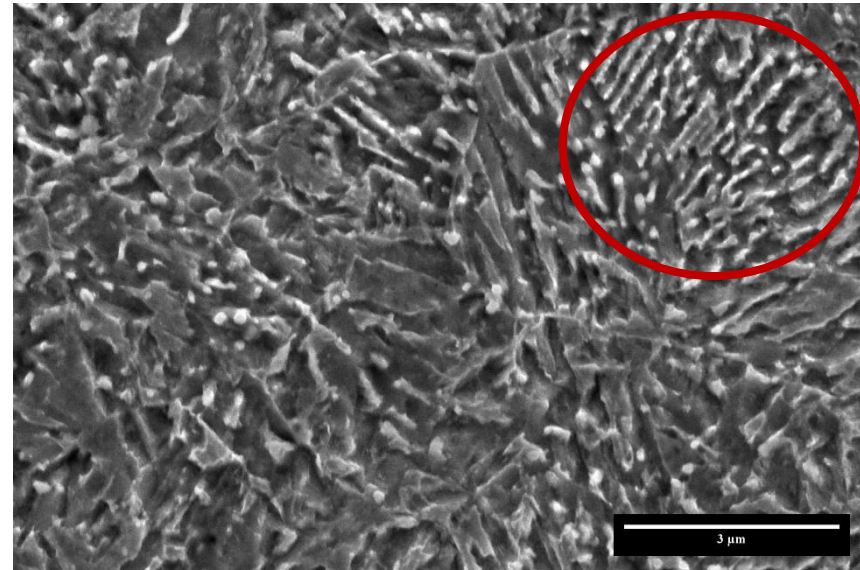
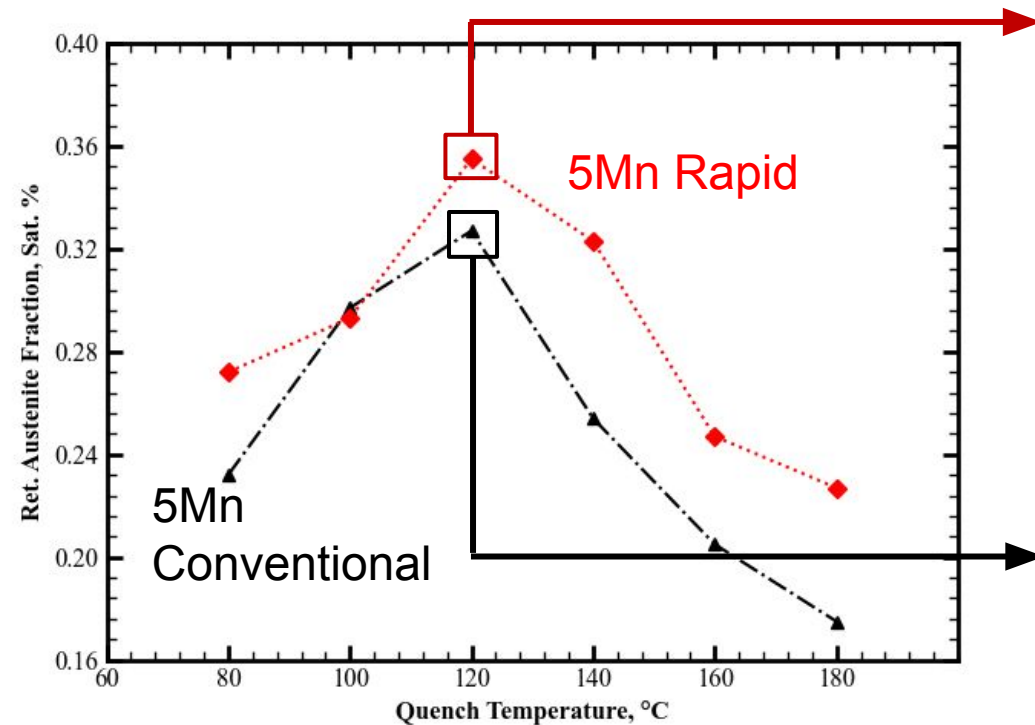
- Increased ret. austenite fraction can be stabilized through rapid heating.

Quenched and Partitioned Microstructure 3Mn



Quenched and Partitioned Microstructure (5Mn)

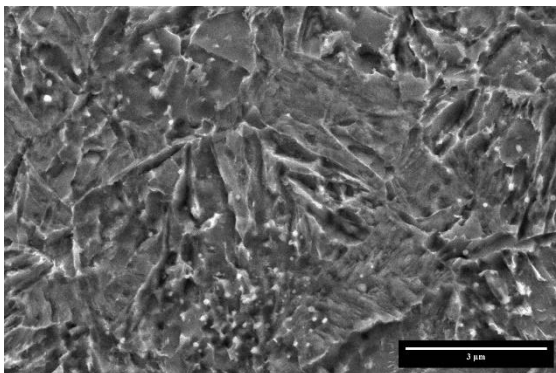
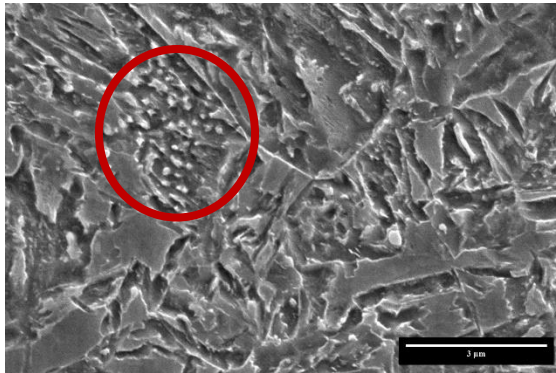
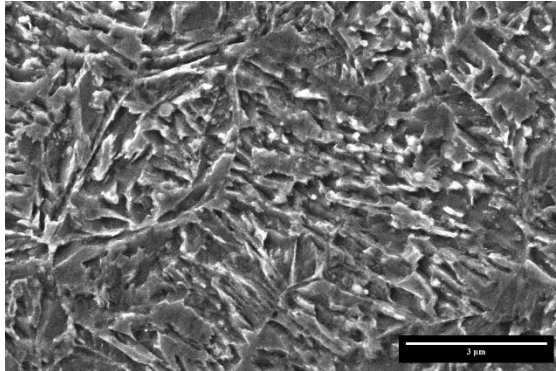
- Fe-0.3C-**5Mn**-1.6Si-1.0Cr alloy



- Increased ret. austenite fraction stabilized from rapid heating cycle for 5Mn alloy.

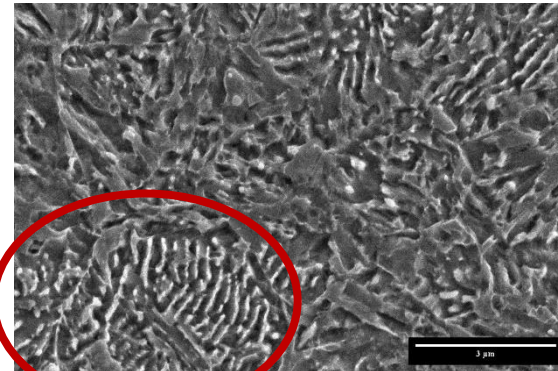
Quenched and Partitioned Microstructure 5Mn

Conventional

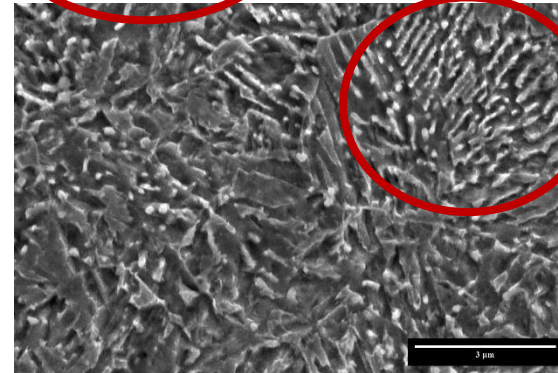


QT

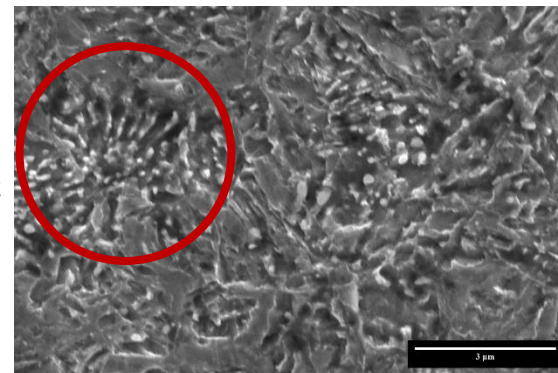
100°C



120°C



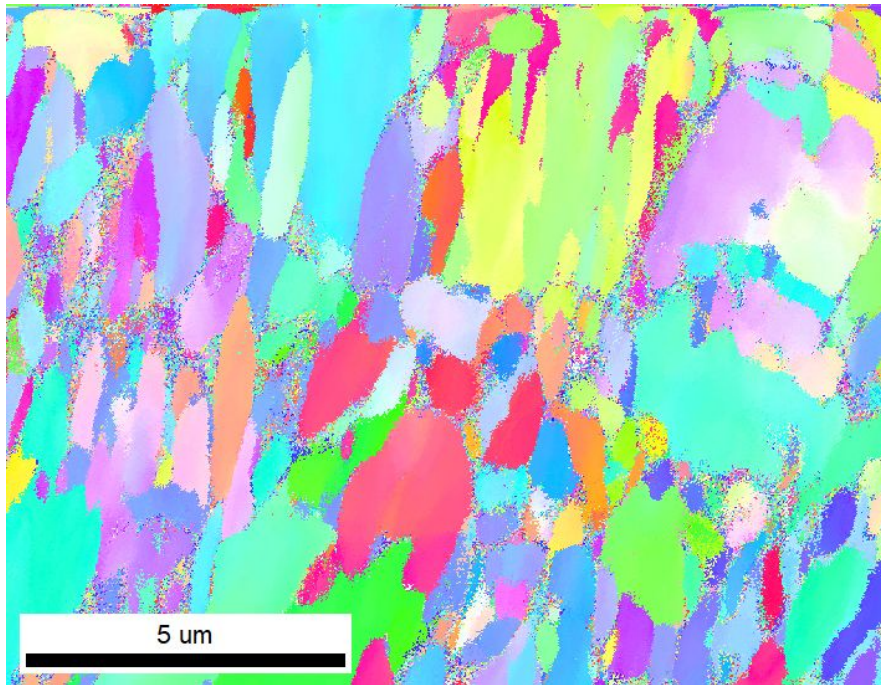
140°C



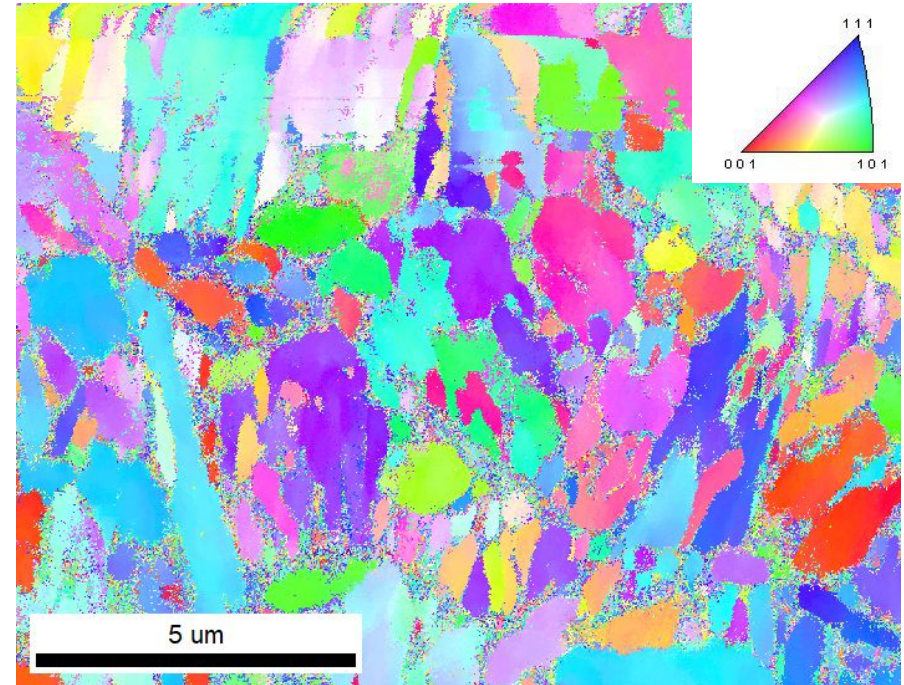
Rapid

EBSD Mapping of Ret. Austenite (5Mn)

- Inverse pole figure comparing conventional and rapid cycles at the $QT_{\max}$ (120°C) condition.

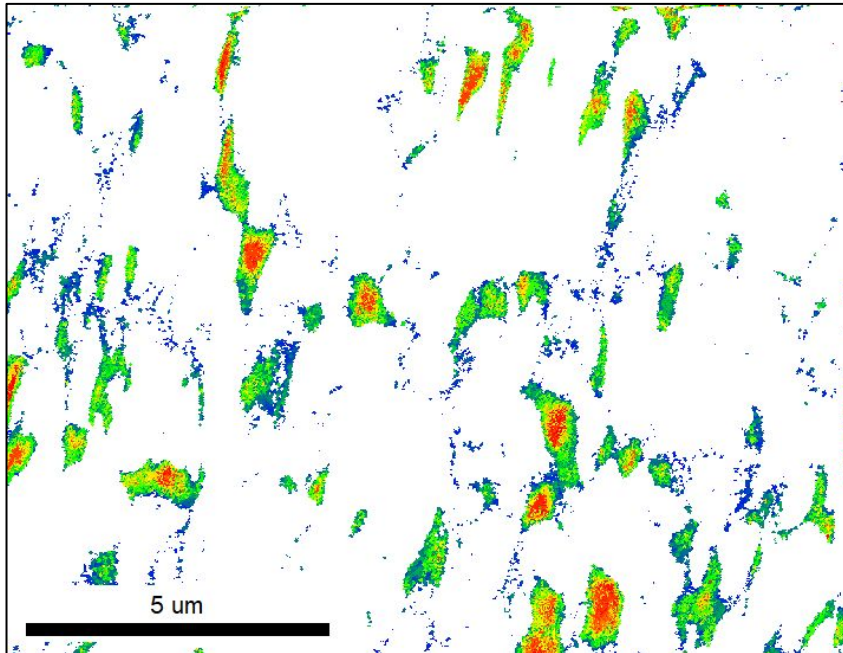


Conventional



Rapid

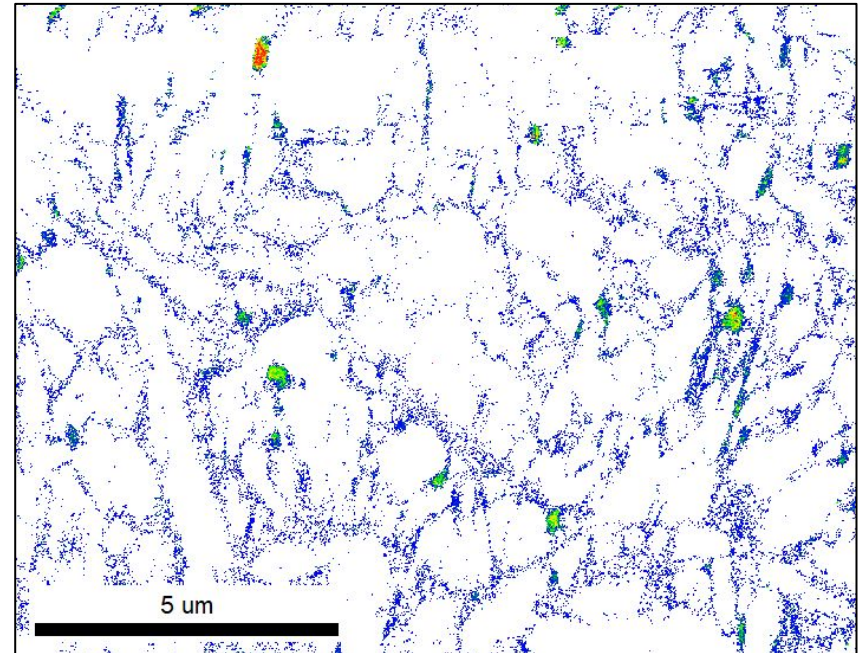
Conf. Index Mapping Showing Retained Austenite Morphology (5Mn)



Conventional

Color Coded Map Type: Confidence Index

	Min	Max	Total Fraction	Partition Fraction
	0	0.929	0.123	1.000



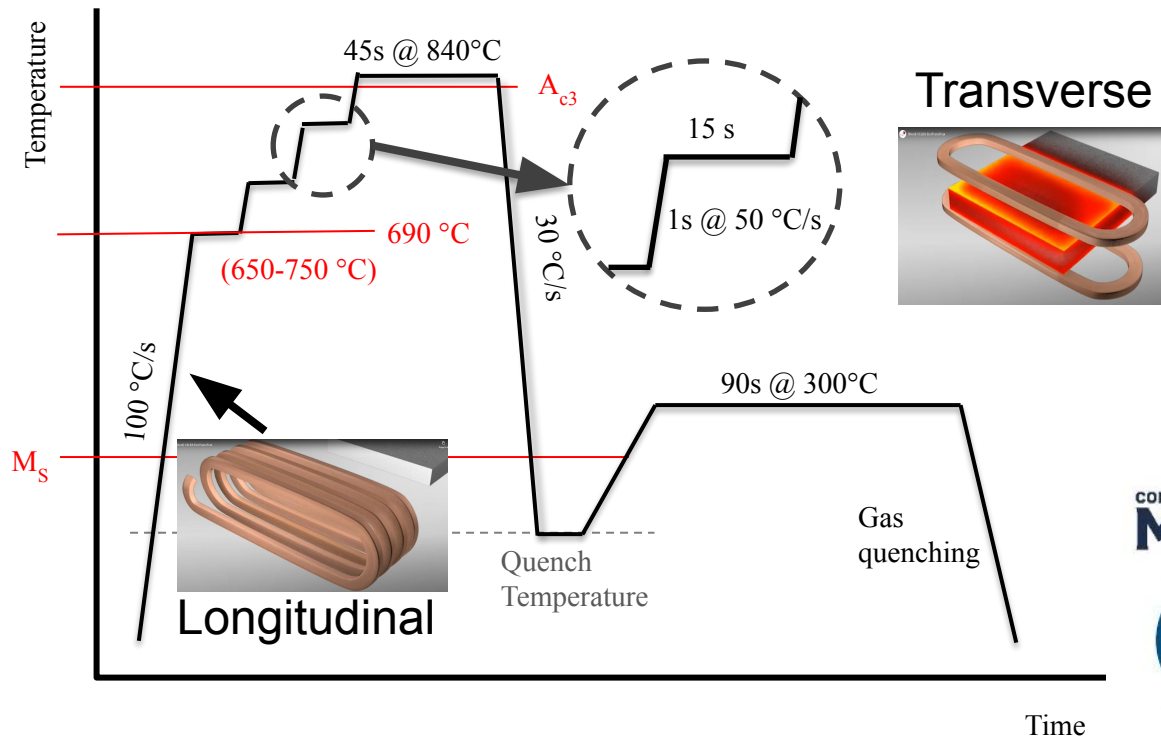
Rapid

Color Coded Map Type: Confidence Index

	Min	Max	Total Fraction	Partition Fraction
	0	0.929	0.094	1.000

Electrifying Current Lines

- Computational ELTA simulation for multi-stage strip heating to determine the optimal induction processes.
- Thermal and electric efficiency during stage heating investigated for longitudinal and transverse flux.
- Significant efficiency benefit to heating with transverse flux at and above Curie temperature.

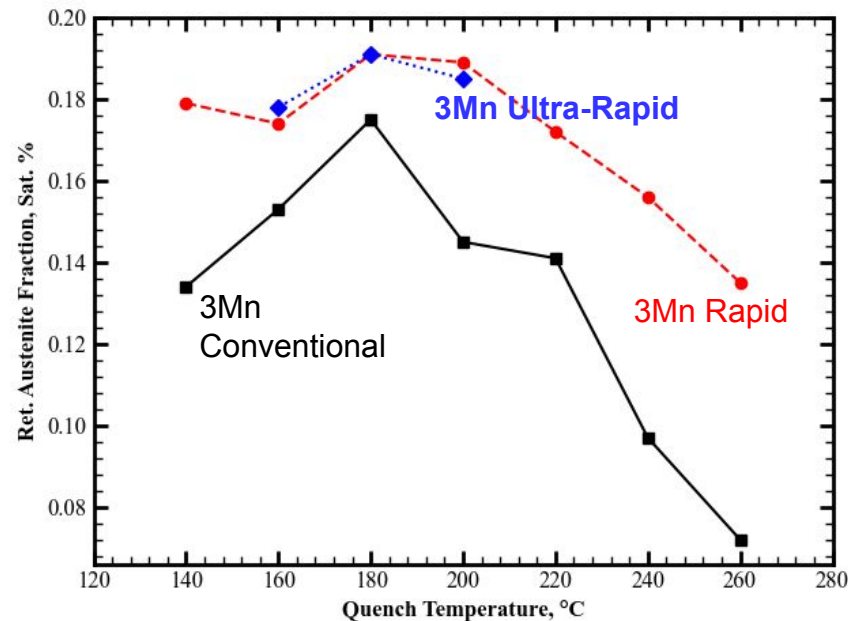
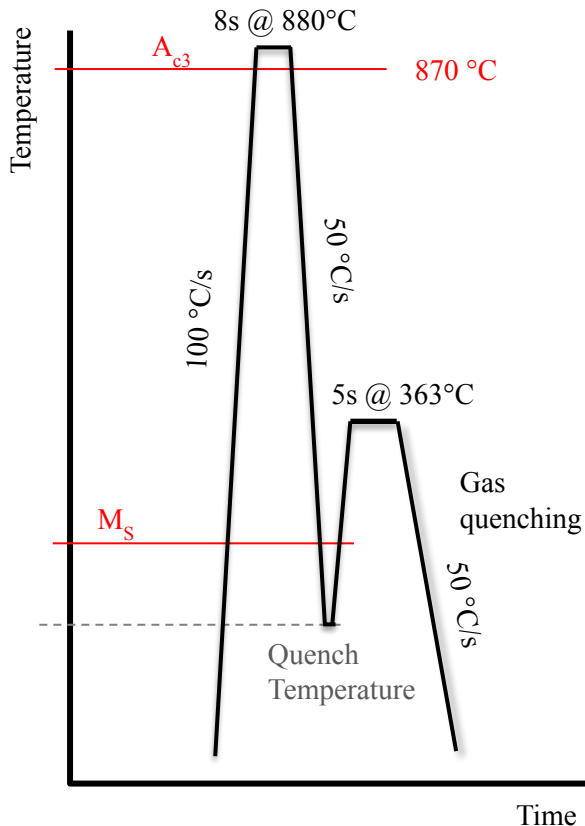


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Ultra-Rapid Q&P Opportunities

- Equivalent diffusion calculations were used to determine an equivalent rapid partitioning step.
- Sensitivity between 1-5s will be investigated.
- An equivalent ret. austenite fraction can be stabilized.



$$D(T, C) = (0.146 - 0.036C) \cdot \exp\left(-\frac{144.3 - 15.0C + 0.37C^2}{R_{kJ}T}\right)$$

Seok-Jae Lee et al. for carbon diffusivity in austenite.

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fives

Conclusions

- This project explores the feasibility of induction heating to (entirely) replace conventional gas-fired furnaces in continuous annealing lines, with a focus on the rapid induction heating applications to AHSS.
- Q&P involving rapid induction heating stabilizes higher fractions of retained austenite compared to conventionally continuous-annealed microstructures
- Rapid heating could result in finer distributions of retained austenite due to inhomogeneous microstructures.
- Rapid partitioning can effectively stabilize equivalent fractions of retained austenite.

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