Effective Exploration of New 760°C Capability Steels for Coal Energy

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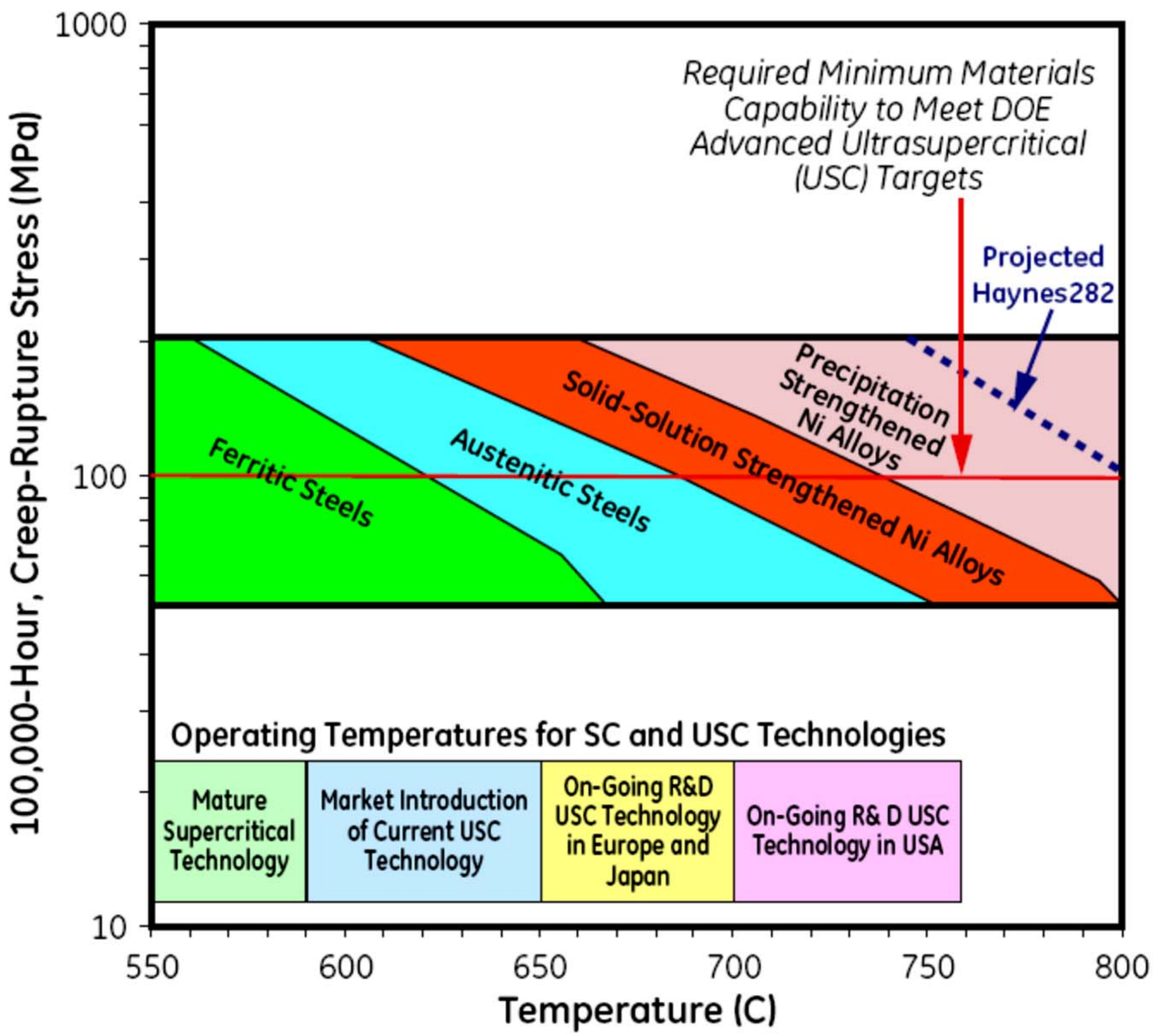
Outline

1. Background and Project Objectives
2. Technical Approach
3. Ferritic Steels
4. Austenitic Steels
5. Summary & Future Work

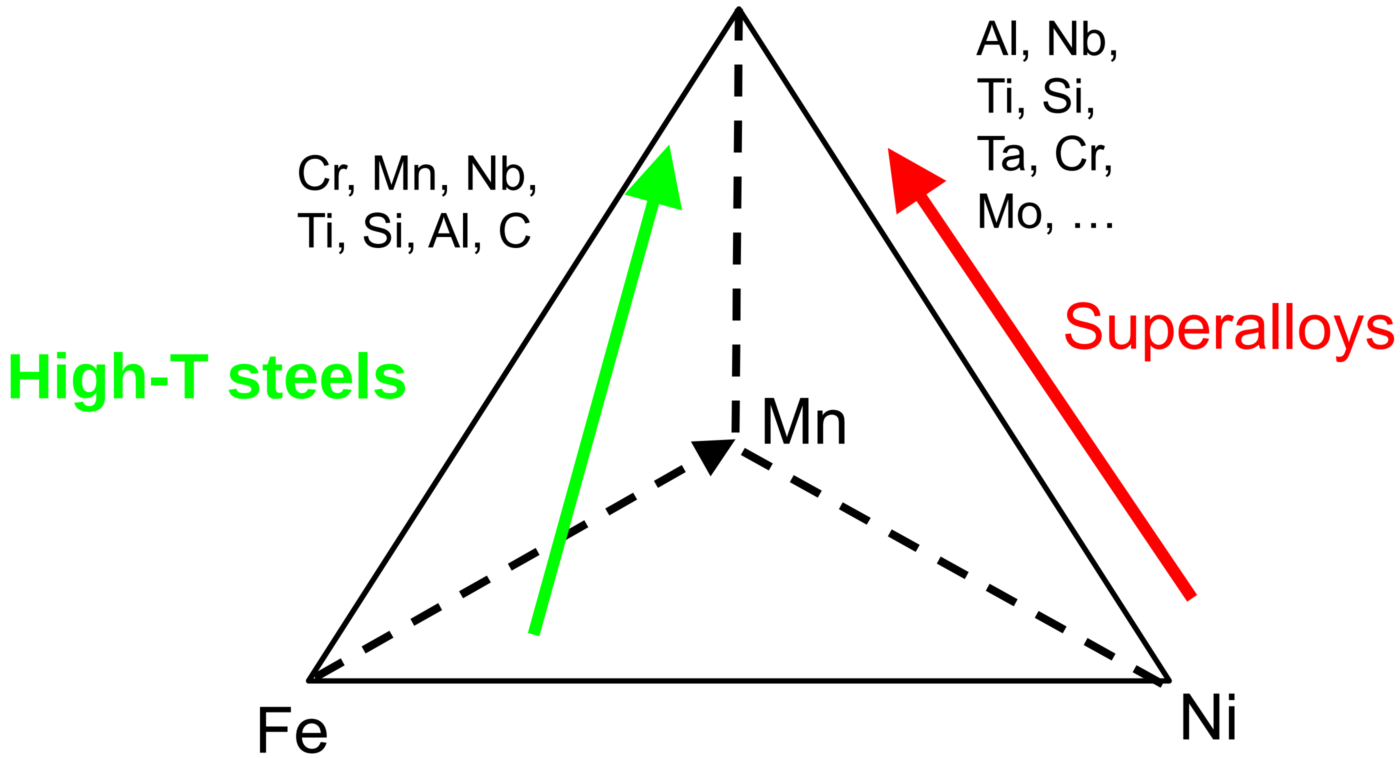
1. Background and Project Objectives



L. Jiang, 2011

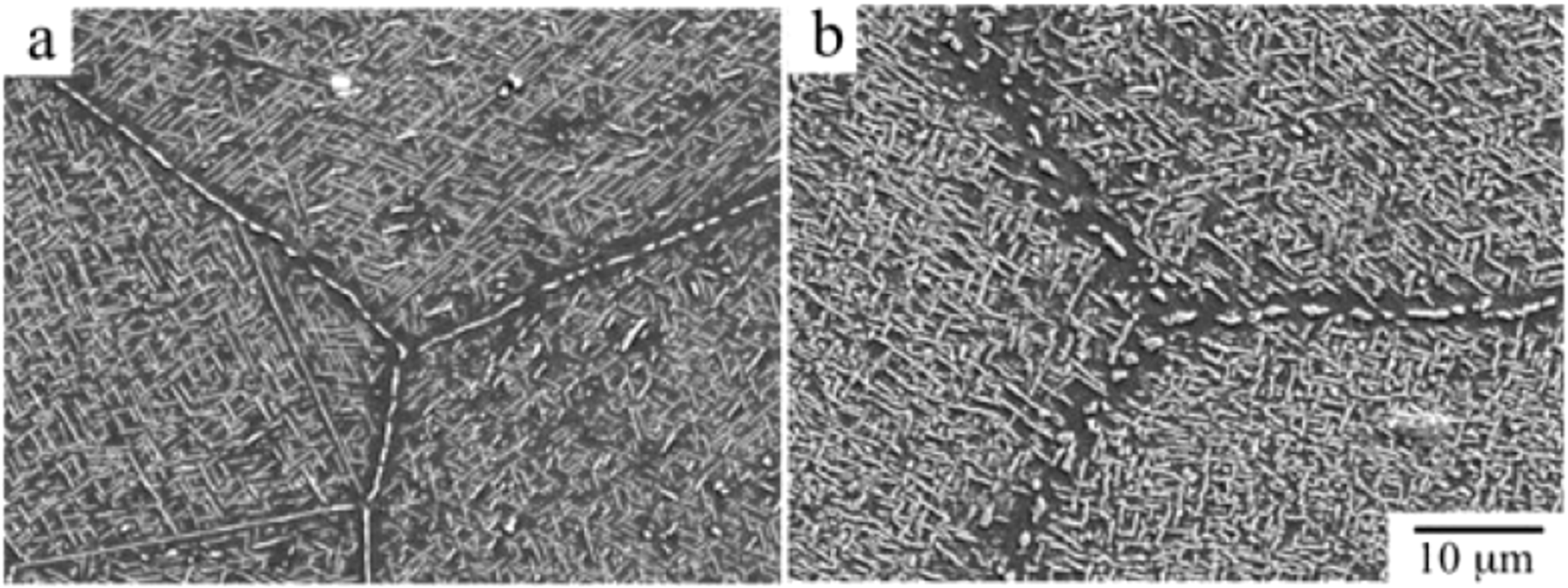
- Martensite strengthening no longer workable at 760 °C.
- New strengthening mechanism is sought.

1. Background and Project Objectives



- Identification of new strengthening phases through high-throughput exploration together with computational thermodynamics.
- Cost-effective steels for AUSC clean coal systems.

1. Background and Project Objective

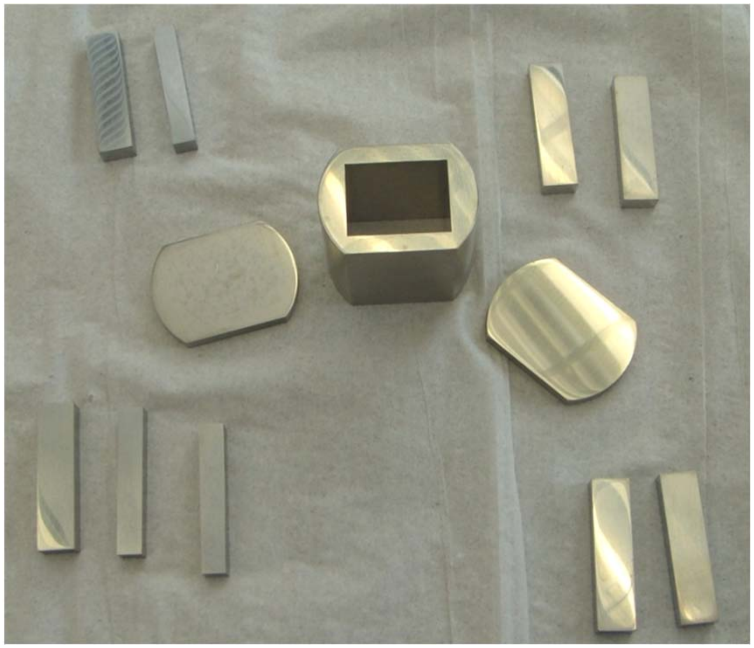


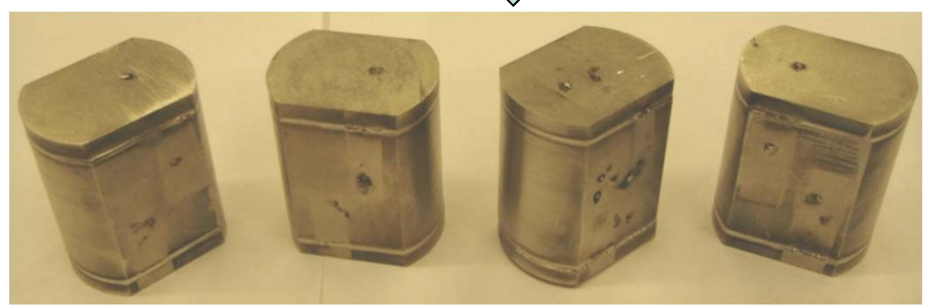
Finely dispersed Laves phase in a Fe-20Cr-30Ni-2Nb (at.%) steel after a creep test at 700°C and 120 MPa: (a) boron-doped steel, and (b) boron-free steel (Takeyama et al.)

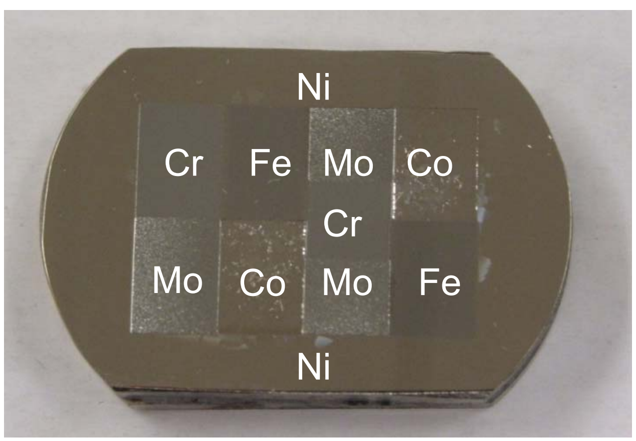
- Laves phase has demonstrated good properties.
- Sluggish precipitation kinetics.
- Grain boundary precipitates key to good creep strength.
- High enough Cr for hot corrosion resistance.

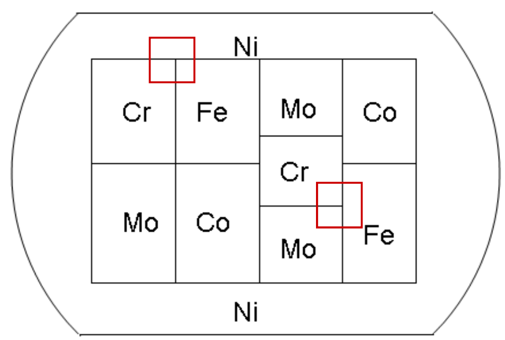
2. Technical Approaches

Diffusion-multiple approach





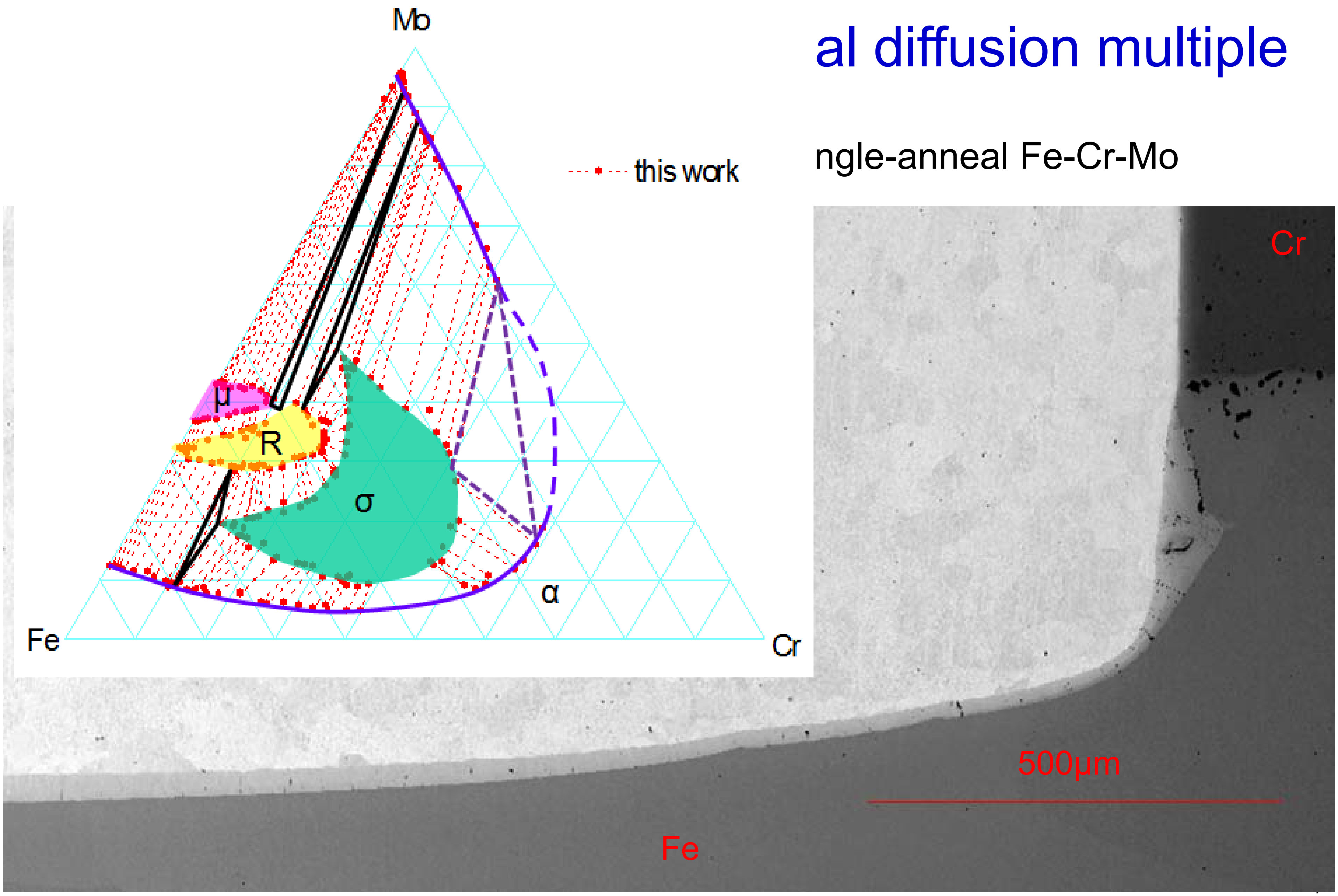


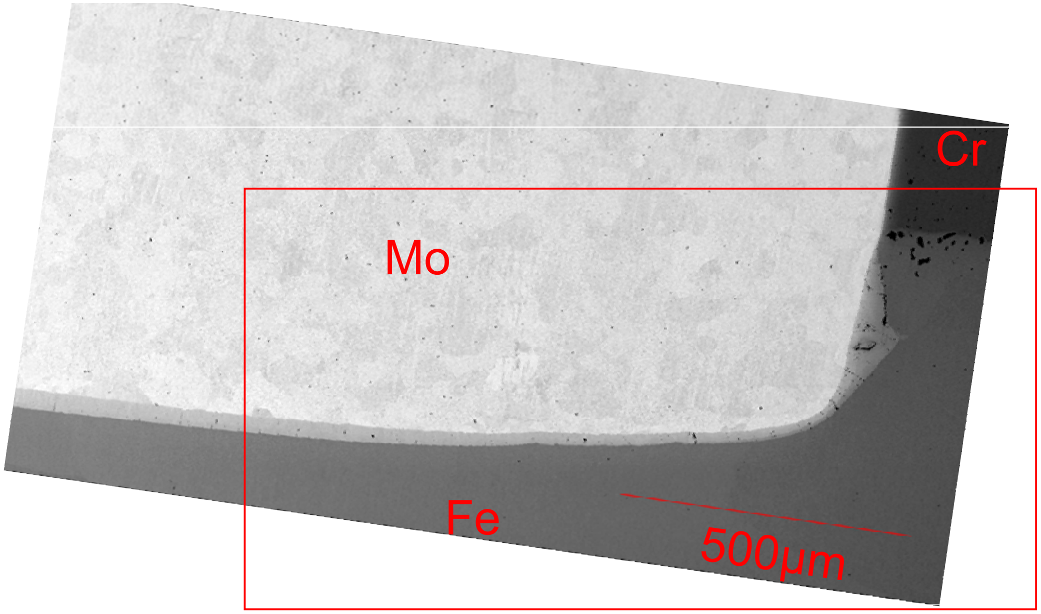


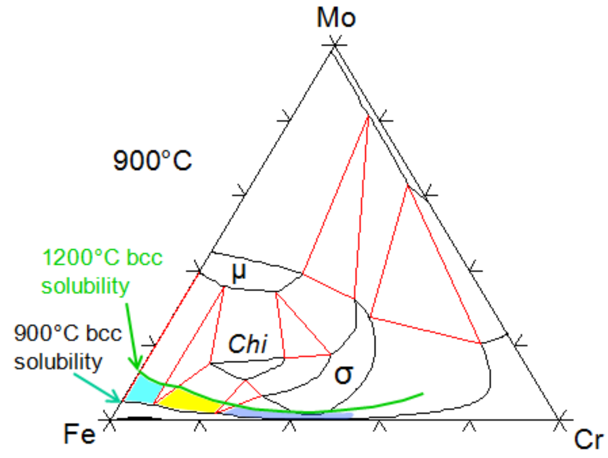
2. Technical Approaches

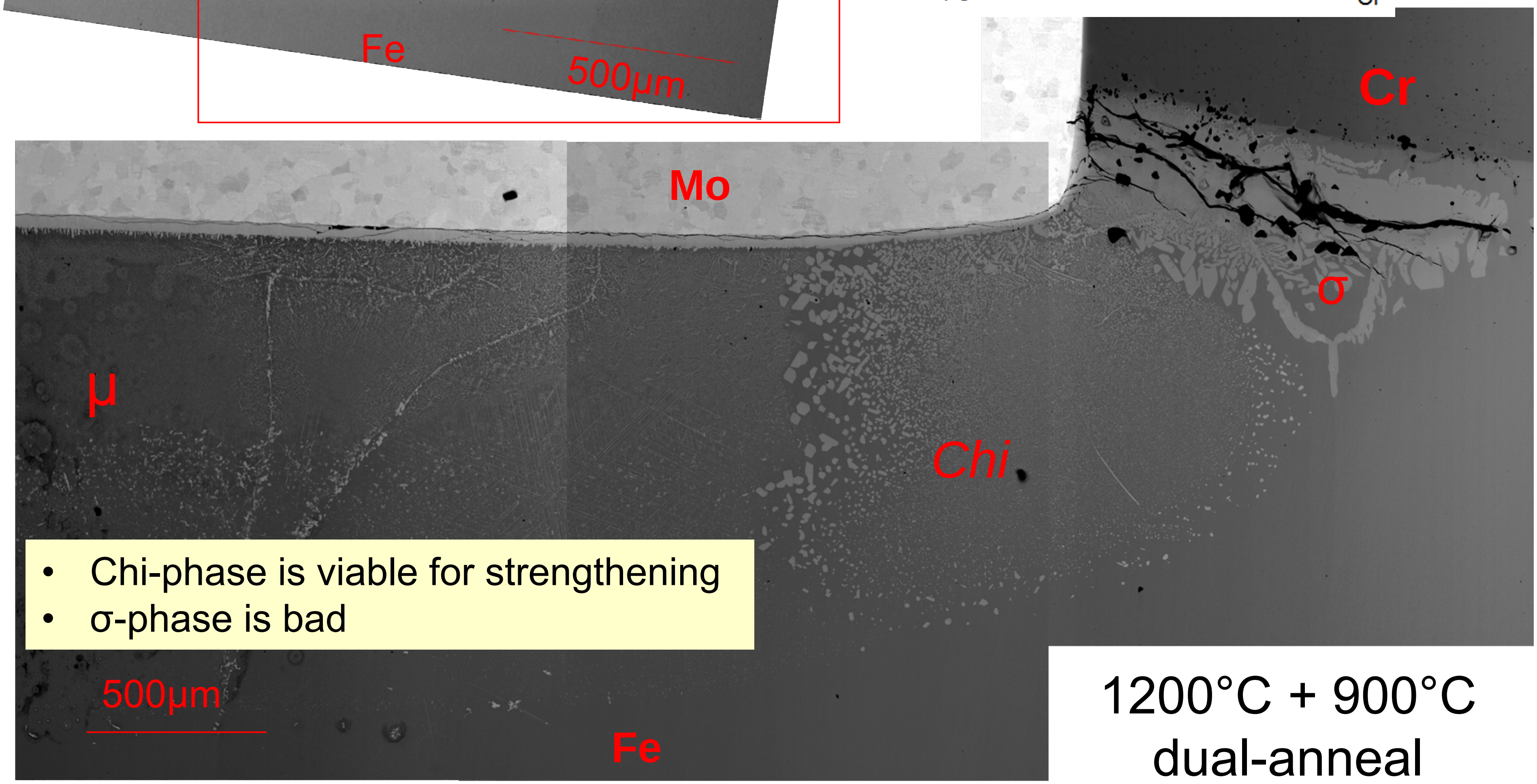
al diffusion multiple

ngle-anneal Fe-Cr-Mo







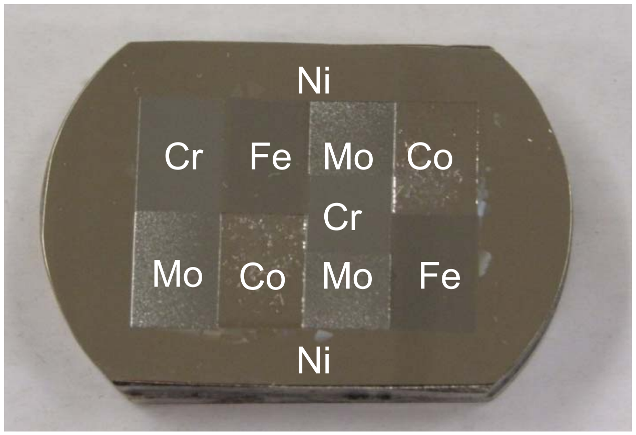


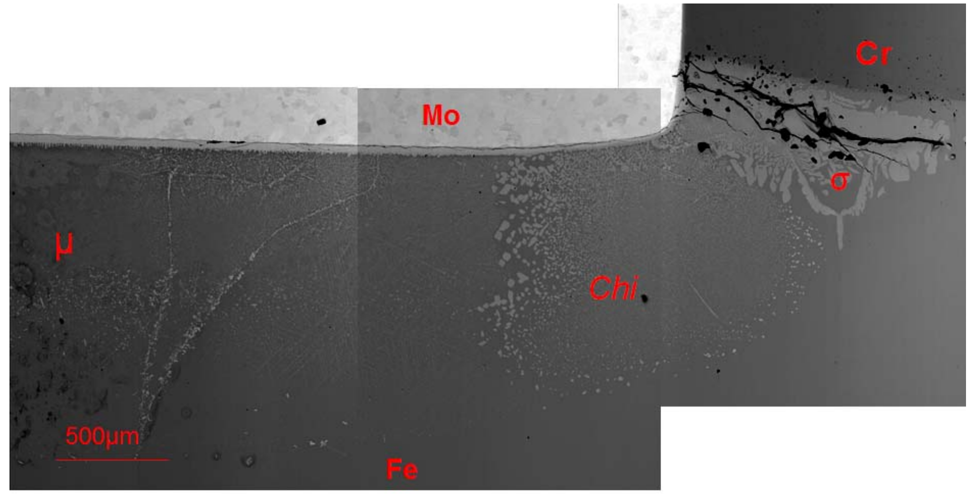
- Chi-phase is viable for strengthening
- σ-phase is bad

1200°C + 900°C dual-anneal

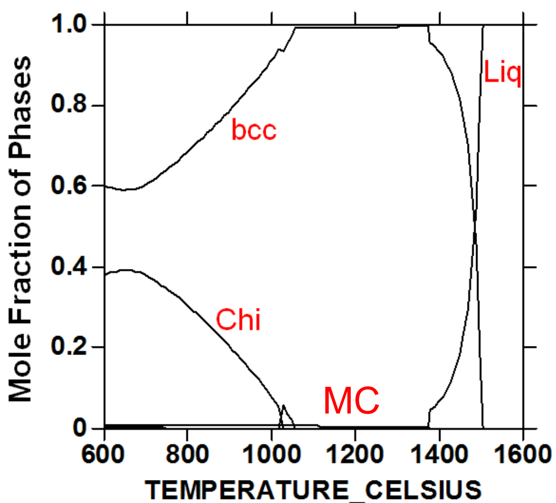
2. Technical Approaches

Dual-Anneal Diffusion Multiple → Viable Strengthening Phase





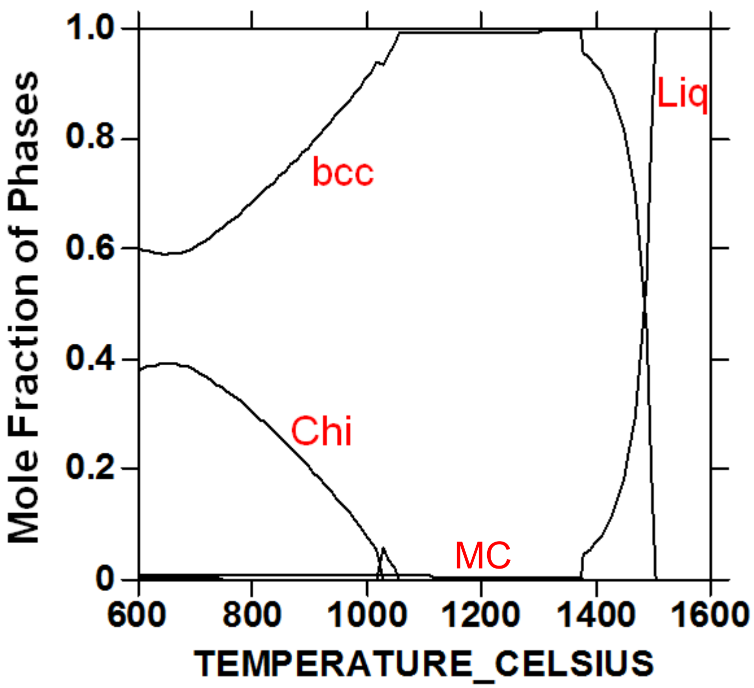
Computational Thermodynamics → Design of Alloys for Property Balance



- Multicomponent alloys
- Volume fractions of phases
- Grain boundary phases
- Oxidation resistance consideration
- Cost and other requirements

3. Ferritic Steels

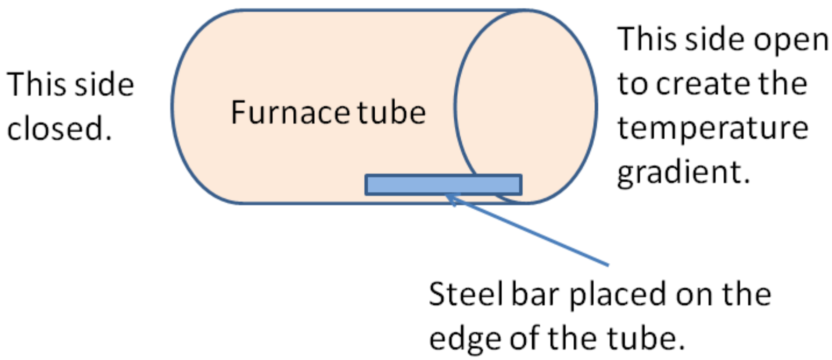
- Designed a Chi-phase strengthened steel using Thermo-Calc
- Induced MC carbide for grain boundary pinning during solution annealing
- Induction melted the alloy (24 lbs) and processed to 1” plate
- Performed systematic study of solution annealing and precipitation annealing

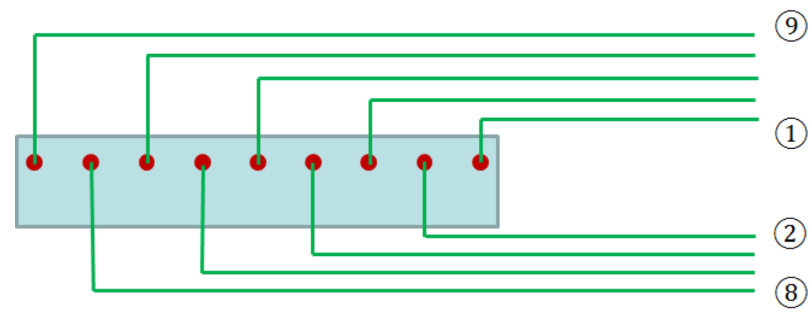


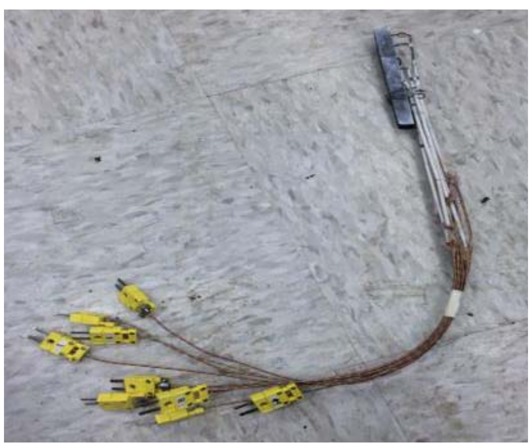
- 24 pound cast ingot
- Hammer forged to 1” thick plate

3. Ferritic Steels

Gradient Temperature Heat Treatment to quickly find the optimum precipitation heat treatment



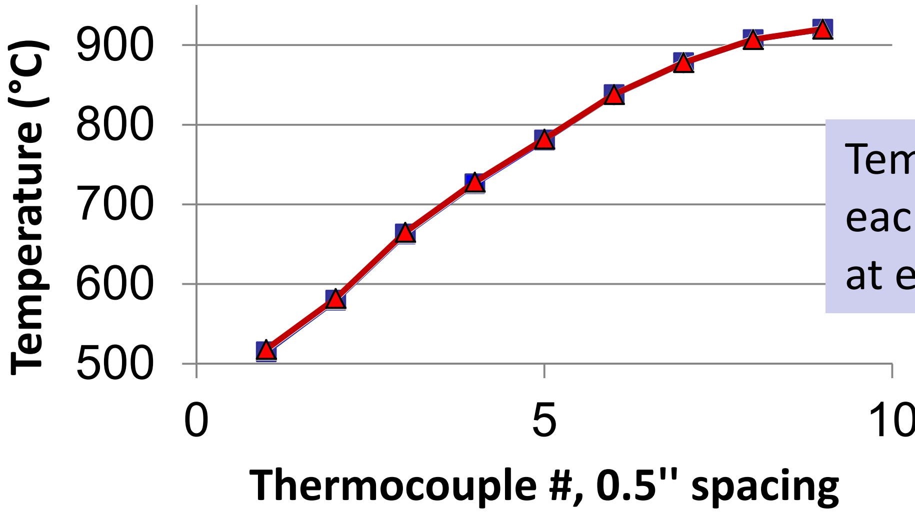




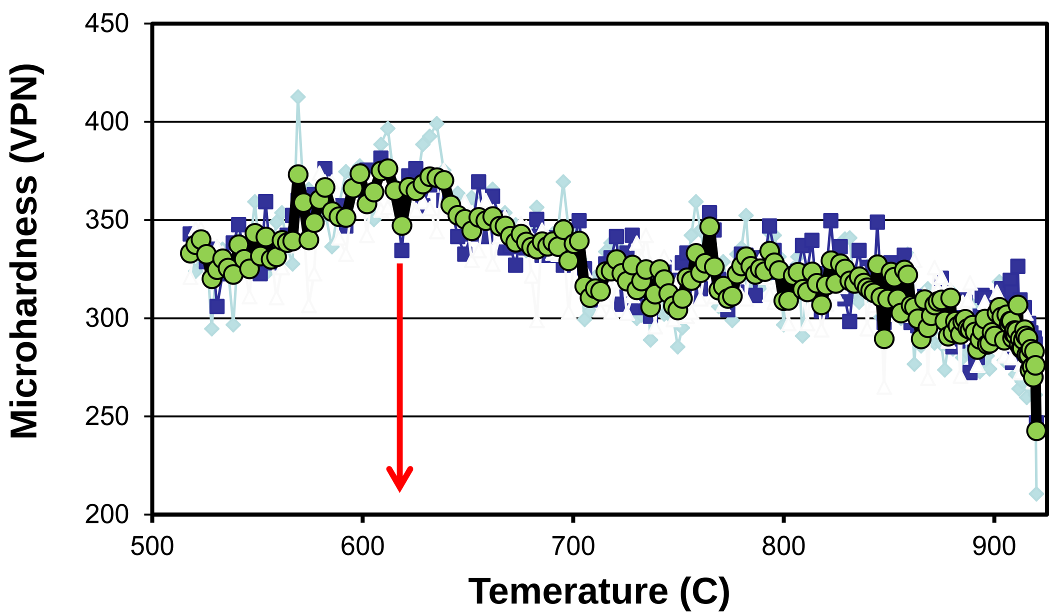
9 type-K thermocouples were attached to the steel bar at an equal spacing.

The steel bar was placed to an open end tube furnace at 1000°C (center) for 10 hrs.

3. Ferritic Steels

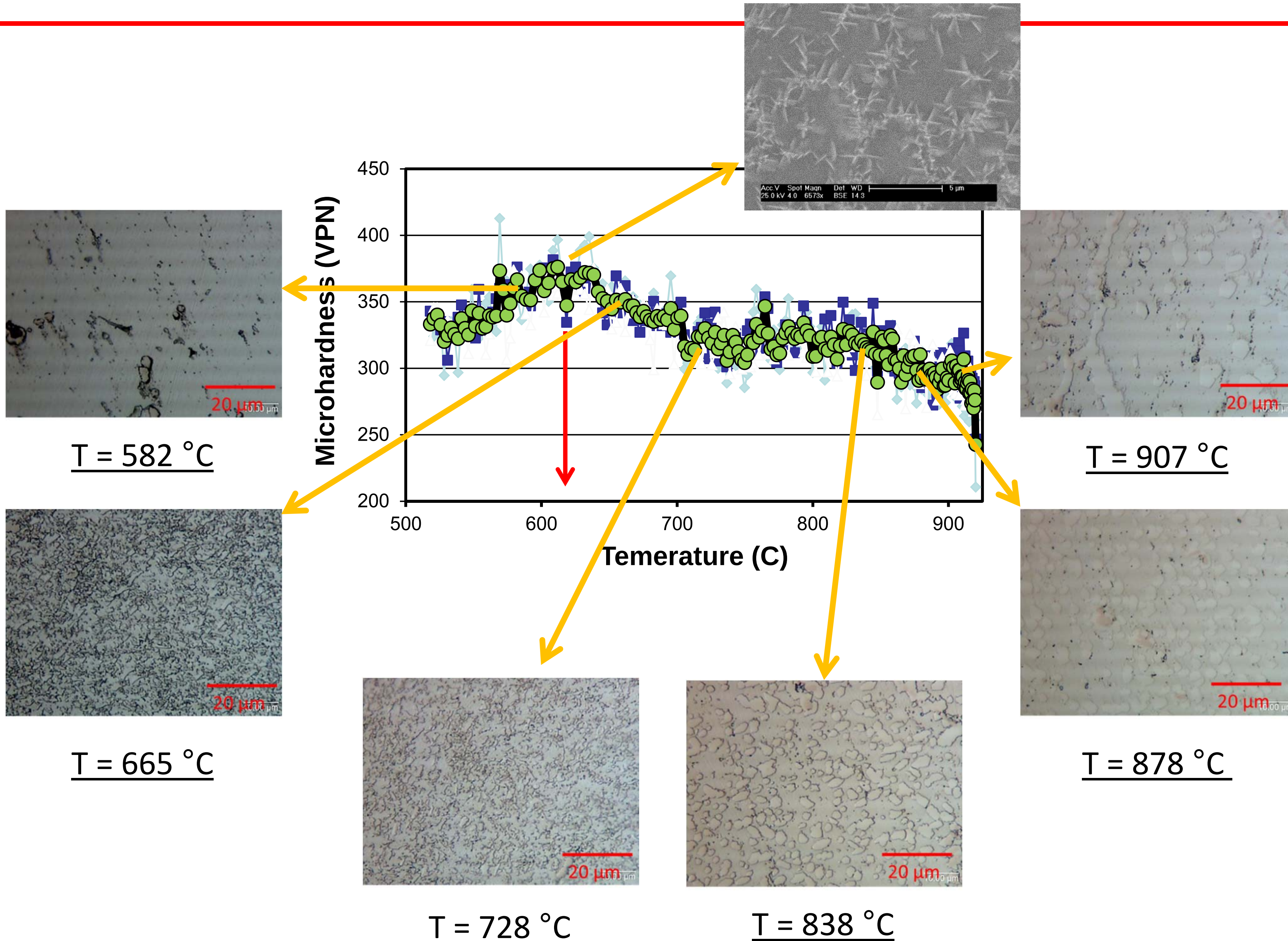


Temperature is stable at each location. The variation at each location is ±3°C.



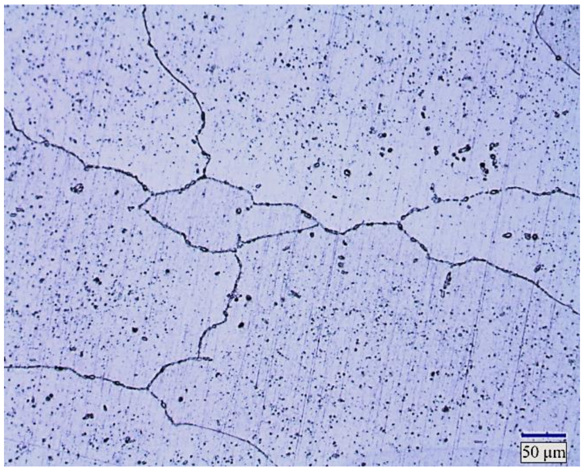
Microhardness as a function of T shows a peak hardness at ~620 °C.

3. Ferritic Steels

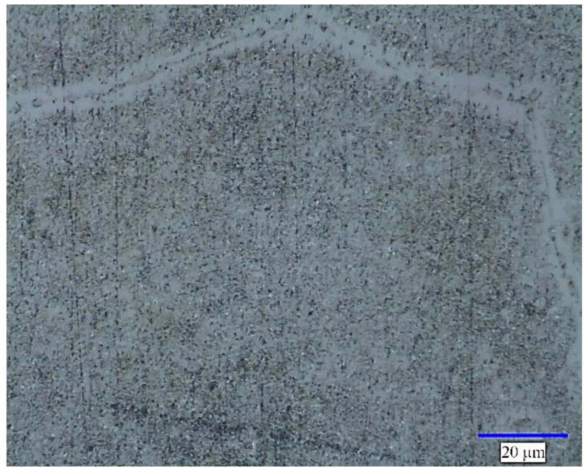


3. Ferritic Steels

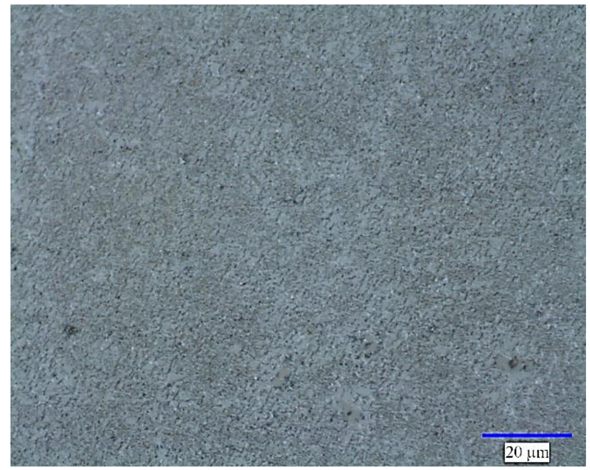
Gradient Temperature Heat Treatment (GTHT)



1200 °C 8 hr Solution H/T
Microhardness (VPN): 237



Solutionization + 620 °C 18 hr
Microhardness (VPN): 349

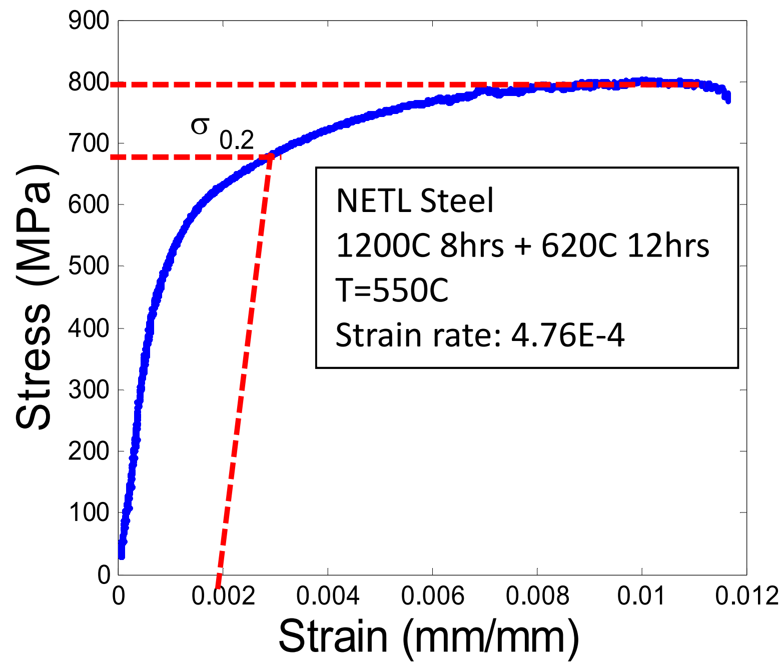


Solutionization+ 620 °C 75 hr
Microhardness (VPN): 335

Optimum precipitation annealing condition is identified from high-throughput experiment and confirmed with individual samples.

3. Ferritic Steels

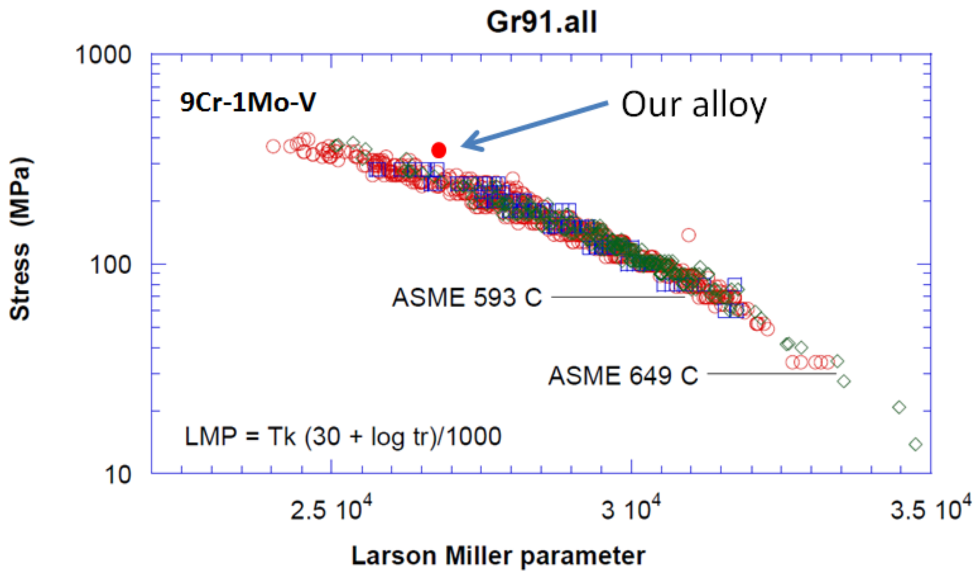
Tensile test at 550 °C

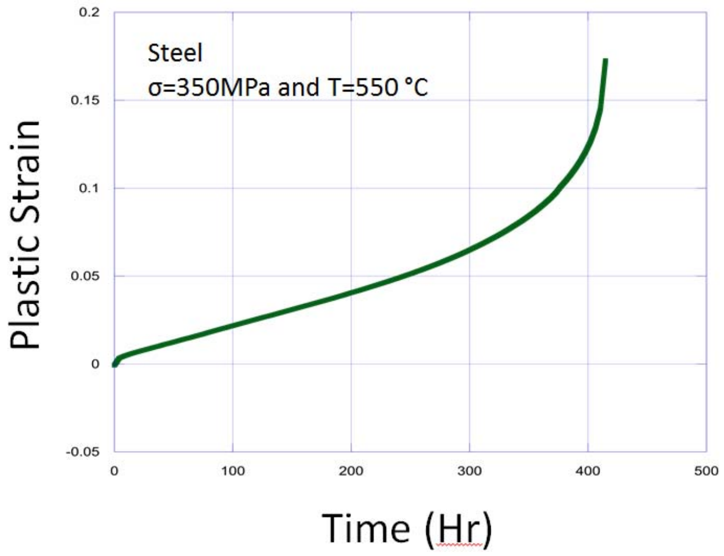


$\sigma_{0.2}$ ≈ 680 MPa (at 550 °C)

3. Ferritic Steels

Creep test at 550 °C, 350MPa



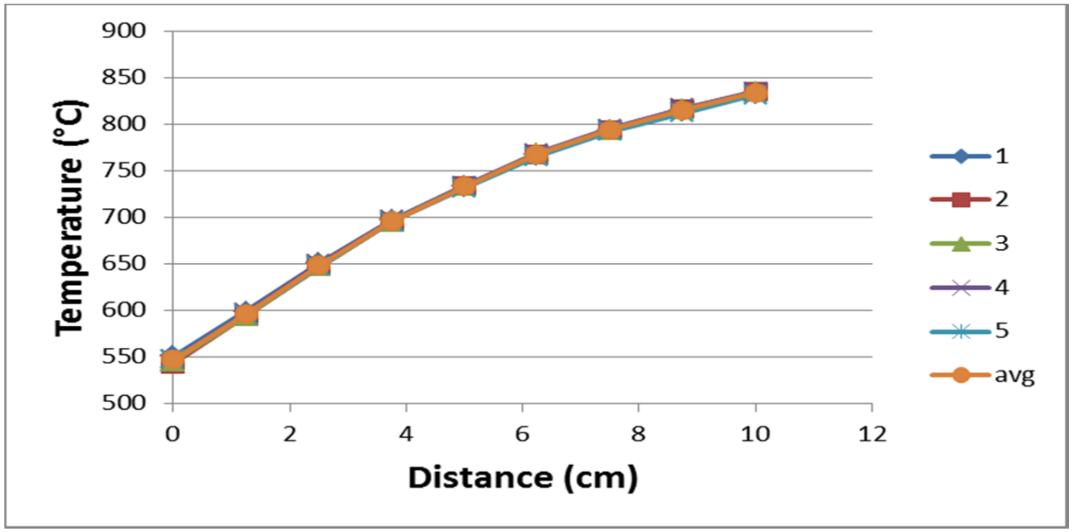


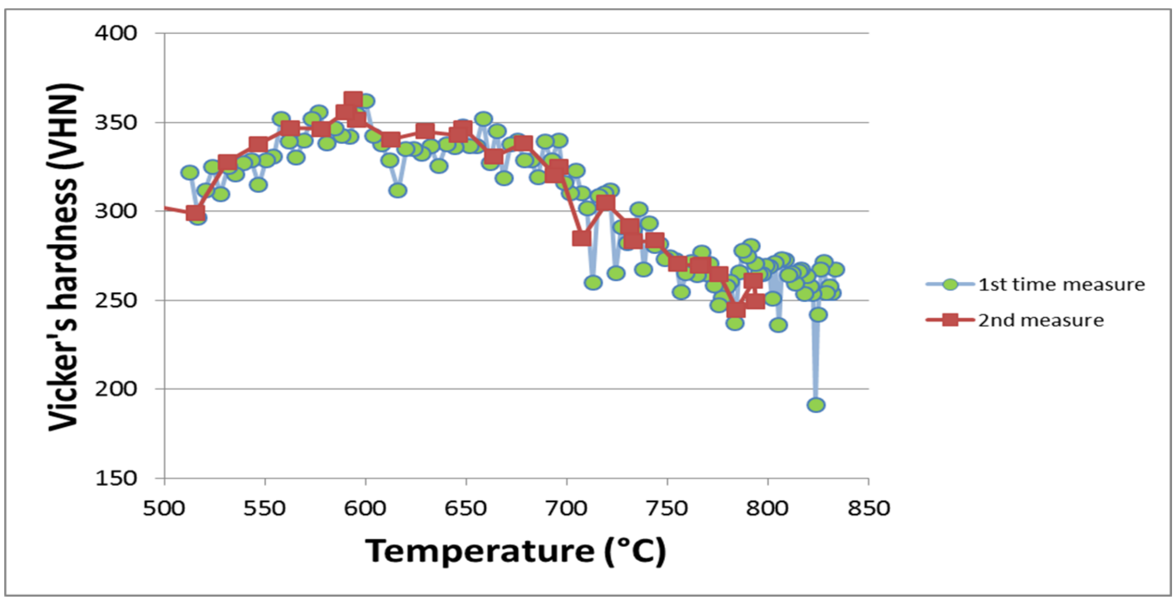
Calculated Larson-Miller parameter and compared with high temperature ferritic steel Fe-9Cr-1Mo-V in literature.

Data from Michael Gold at http://web.ornl.gov/~webworks/cppr/y2001/rpt/119036.pdf

3. Ferritic Steels

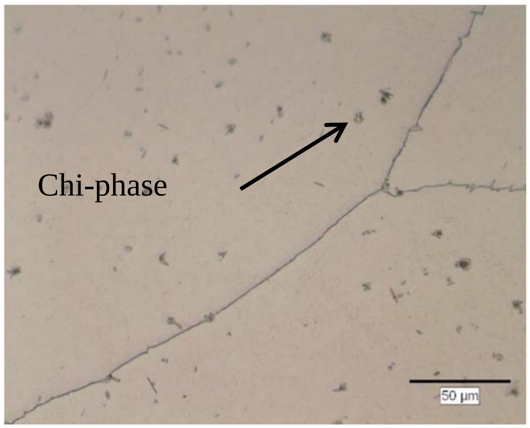
Gradient Temperature Heat Treatment for ferritic steel #2



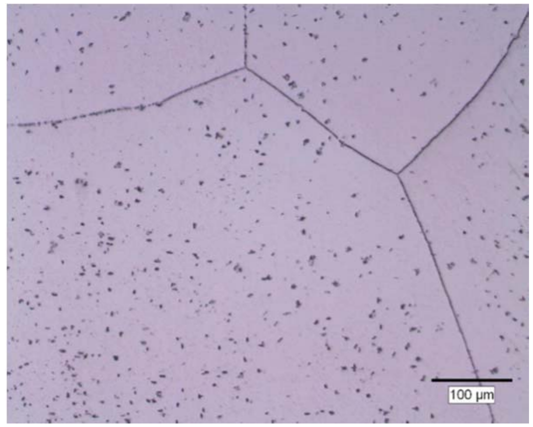


3. Ferritic Steels

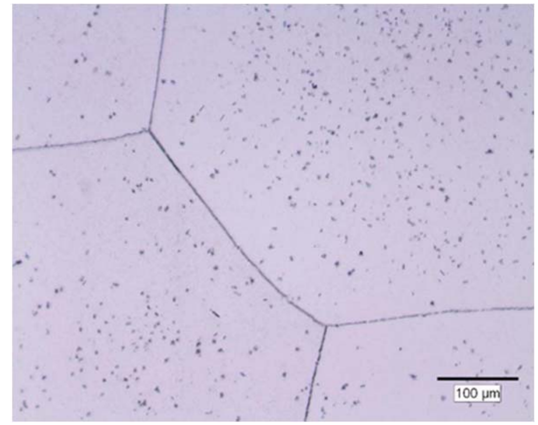
Optical images (after etch) at different locations



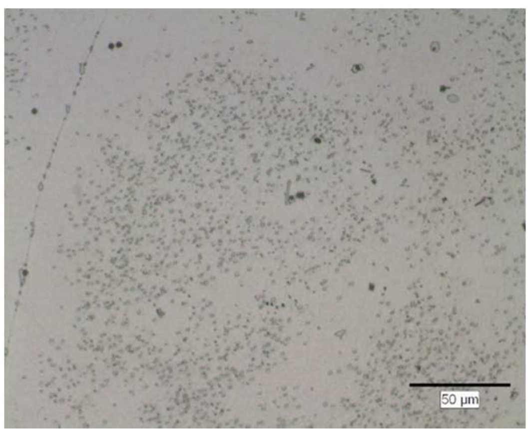
T = 733 ° C



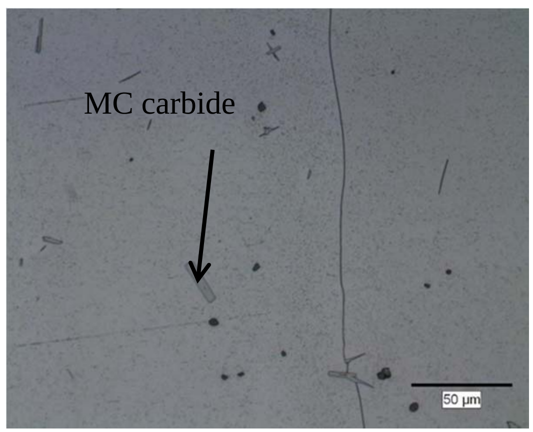
T = 715 ° C



T = 689 ° C



T = 654 ° C

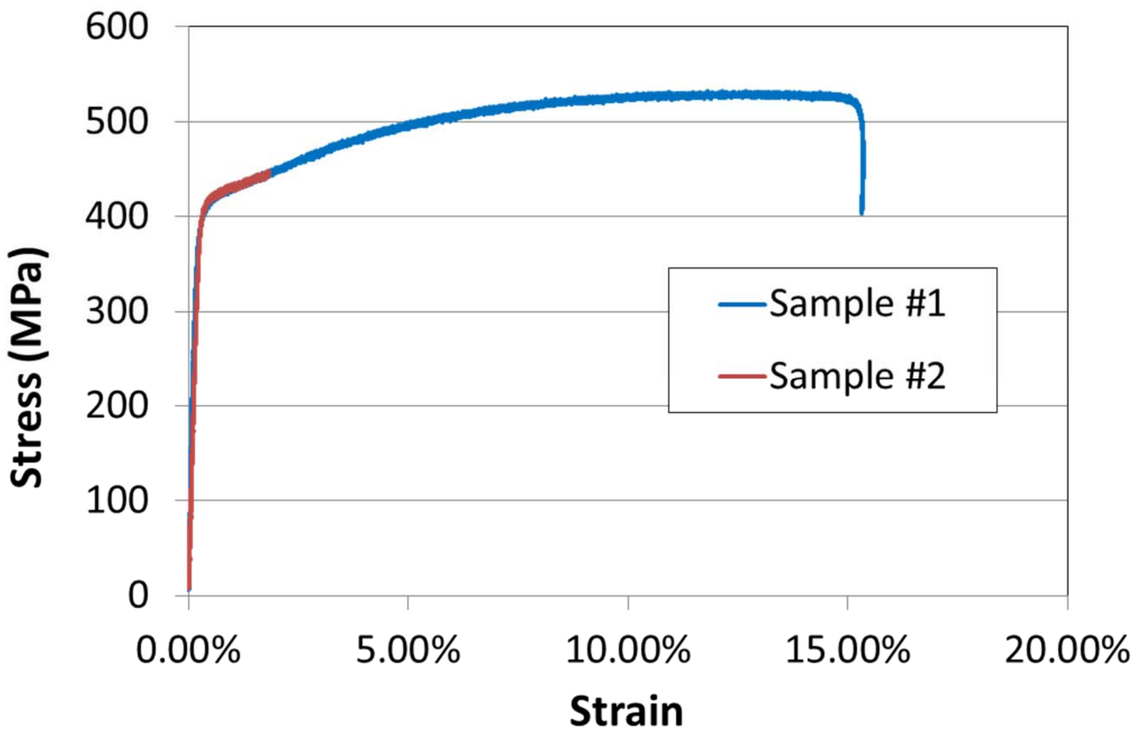


T = 611 ° C

T = 566 ° C

3. Ferritic Steels

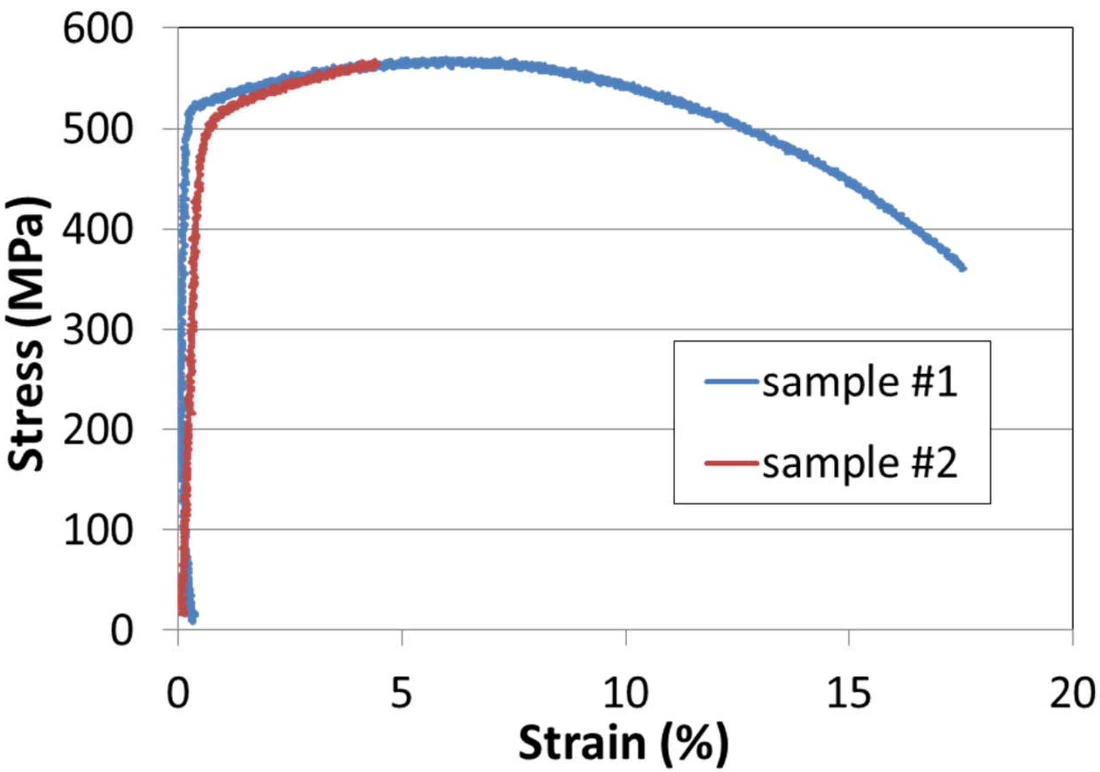
Tensile tests of “as-received” ferritic steel #2



Induction melting + hammer forging (no additional heat treatment)

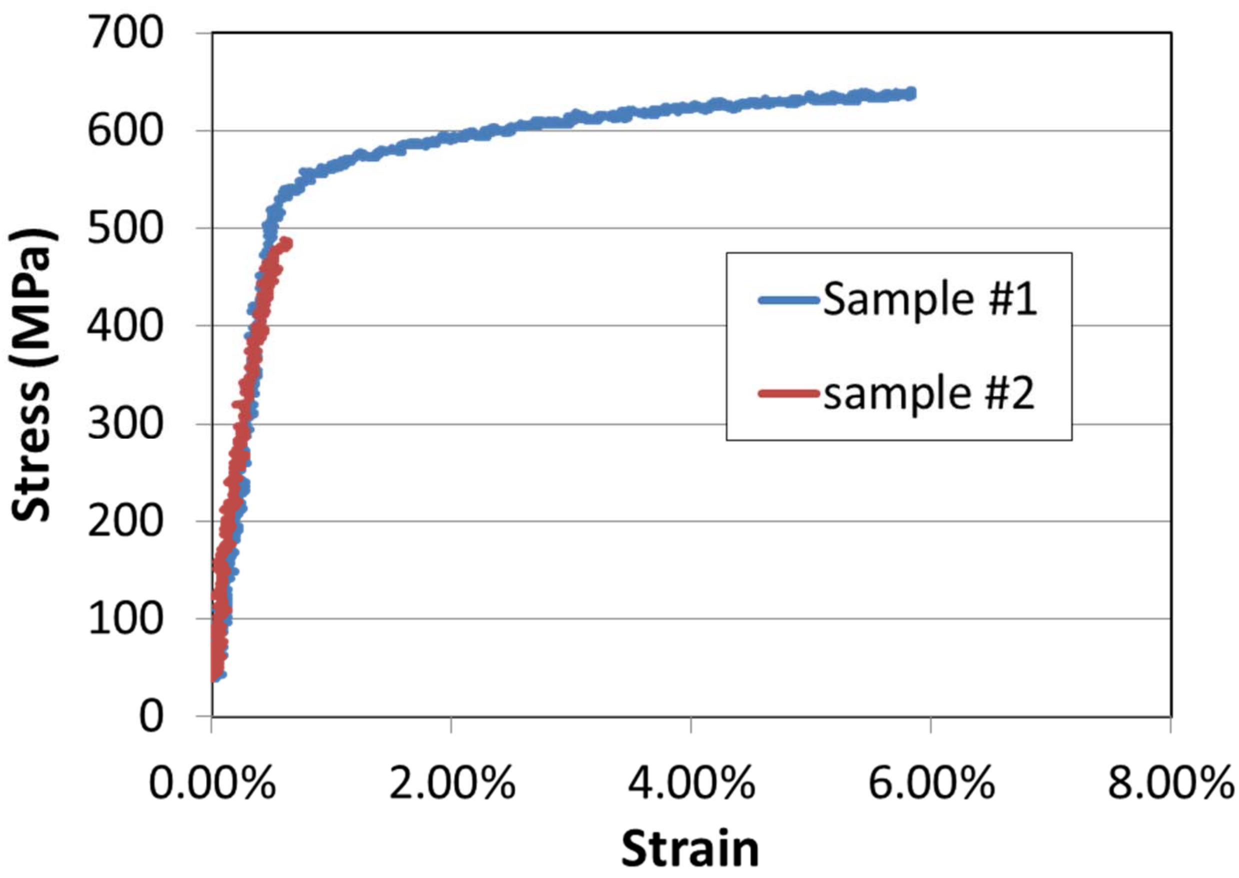
3. Ferritic Steels

Tensile tests of steel #2 after 1200 °C for 8 h heat treatment



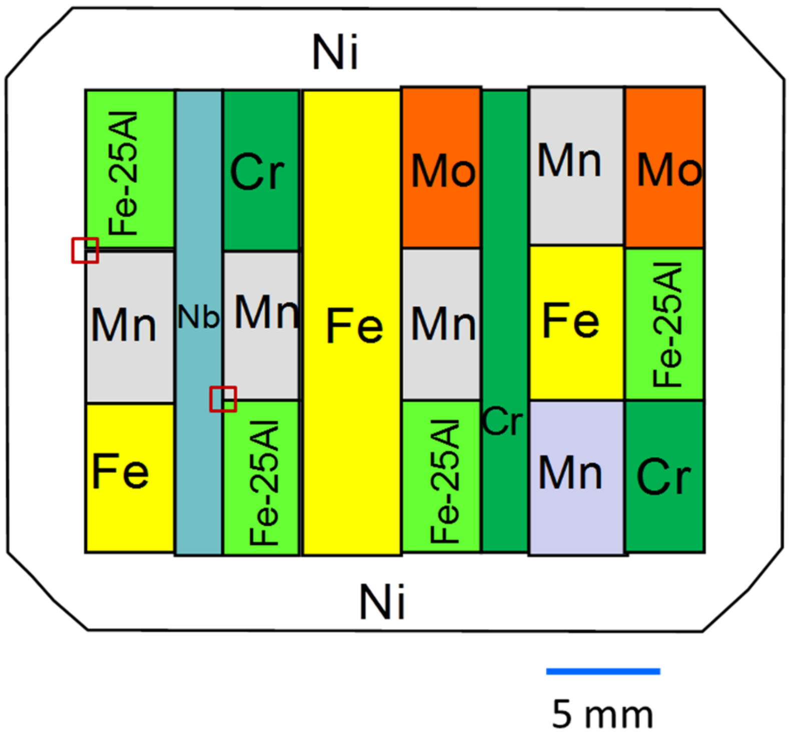
3. Ferritic Steels

Tensile tests after heat treatment at
1200 °C 8 hr + 600 °C 12 hr



4. Austenitic Steels

Diffusion multiple



Fe-Mn-Cr
Fe-Mn-Al
Fe-Mn-Ni
Fe-Mn-Mo
Fe-Mn-Nb
Fe-Ni-Al
Fe-Ni-Mo
Fe-Ni-Nb
Fe-Cr-Ni
Fe-Cr-Nb
Ni-Mn-Cr
Ni-Mn-Mo
Ni-Mn-Nb
Ni-Mo-Nb
Ni-Cr-Nb

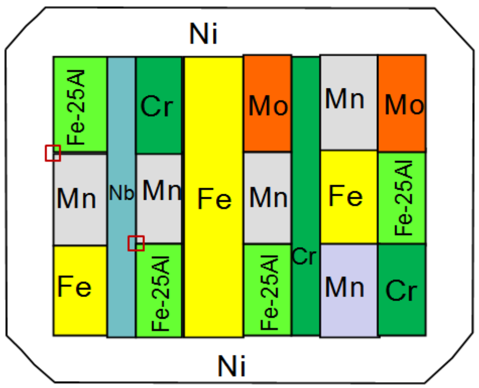
15 ternary systems +
6 quarternary systems

Fe-Mn-Ni-Al
Fe-Mn-Nb-Al
Fe-Mn-Cr-Al
Fe-Ni-Mo-Al
Fe-Ni-Cr-Al
Fe-Ni-Nb-Al.

- Four such diffusion multiples are made for different temperature treatments
- Looking for high Mn and high Cr compositions with fine stable precipitates

4. Austenitic Steels

Diffusion-multiple manufacturing process



Design

Grind and assemble

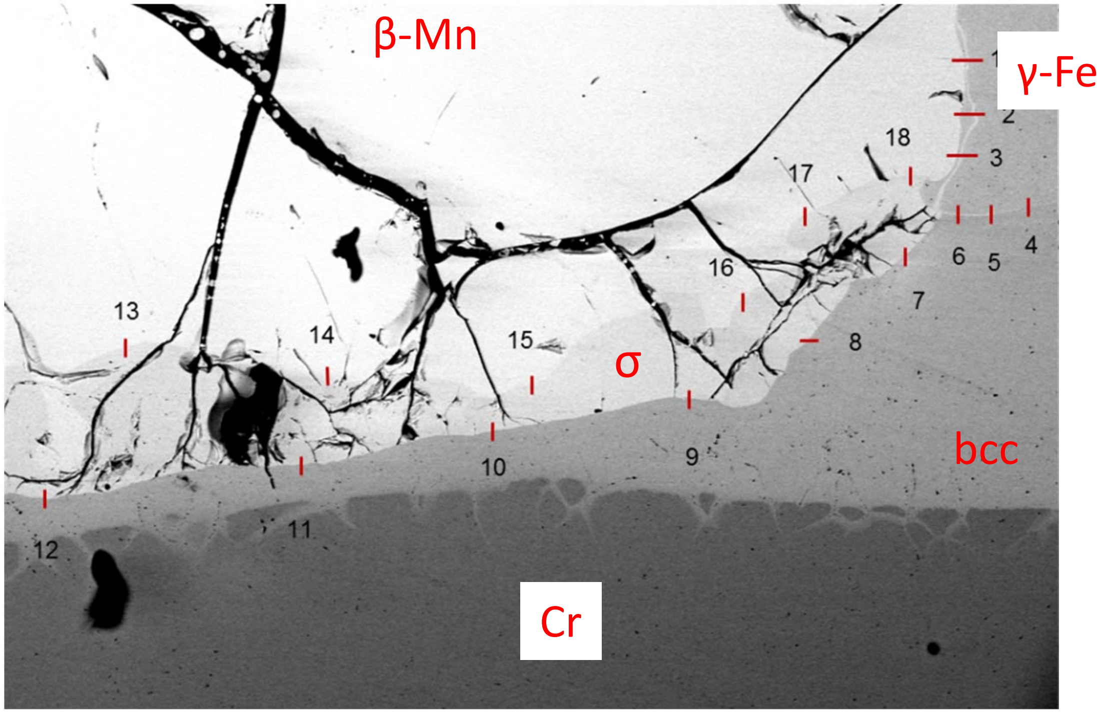
EB welding

Hot-isostatic pressing

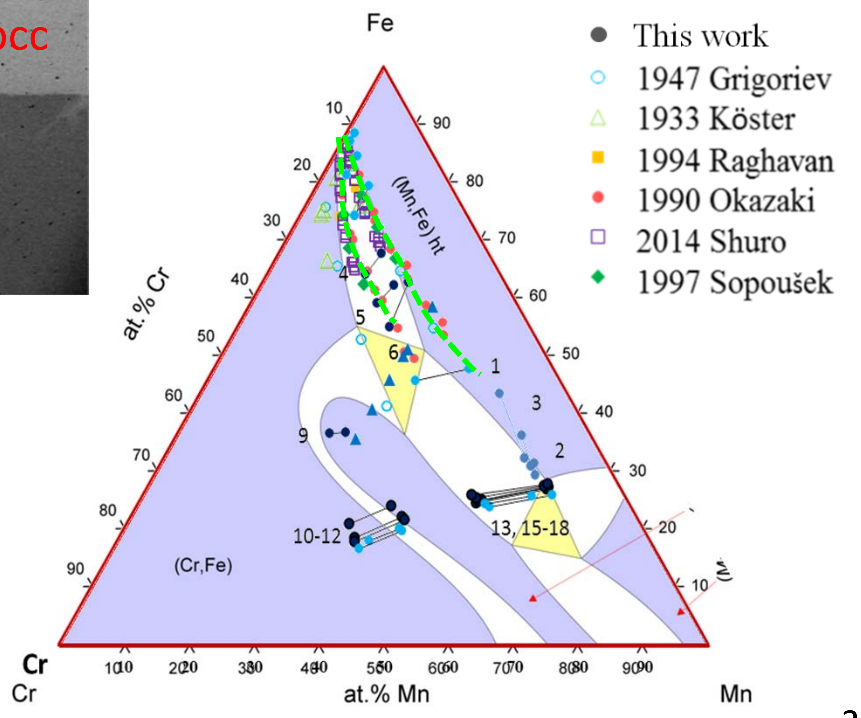
Encapsulation & annealing

Mounting/polishing

4. Austenitic Steels

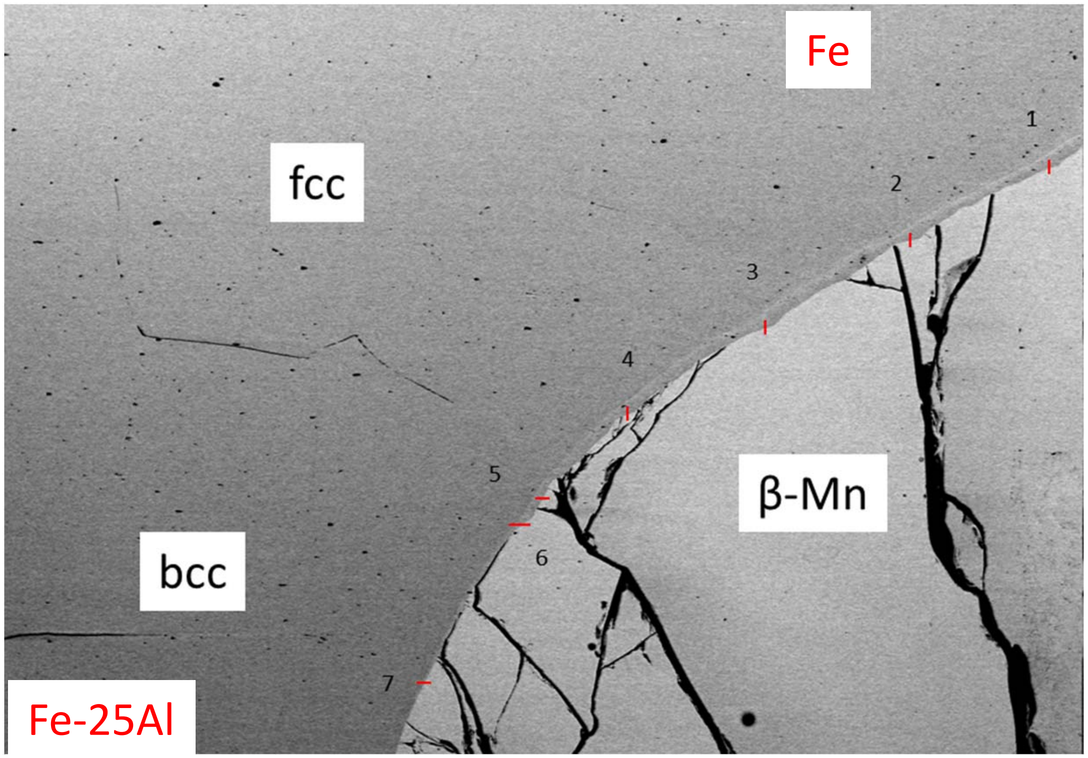


Fe-Mn-Cr (1000 °C 500 hrs)

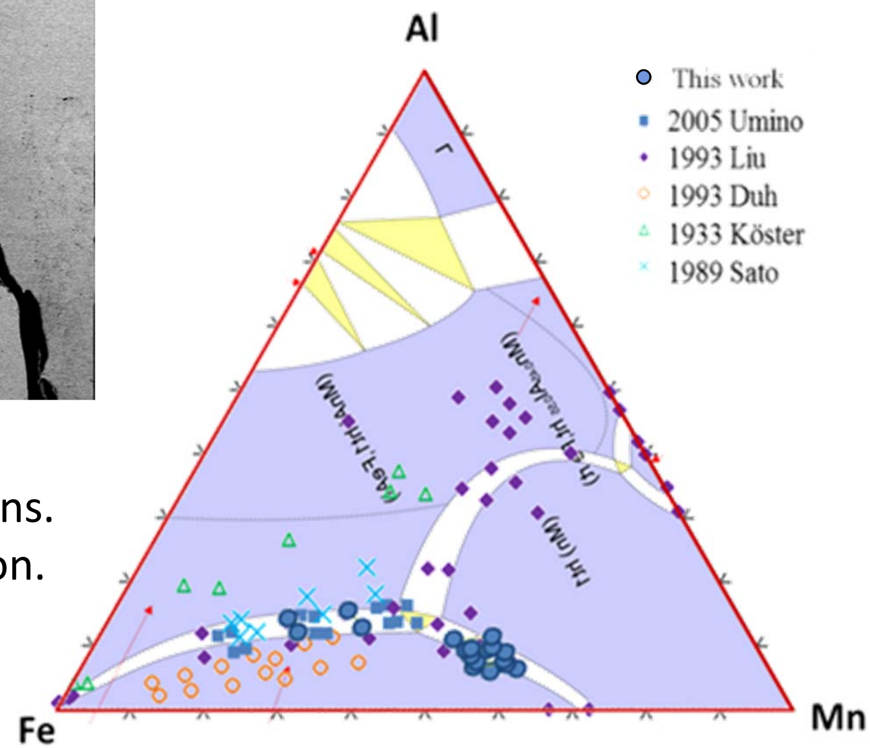


Phase equilibria:
Fe-Mn-Cr

4. Austenitic Steels

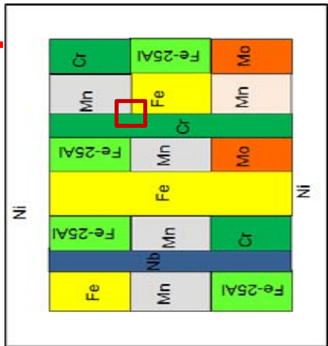


Fe-Mn-FeAl ternary junction

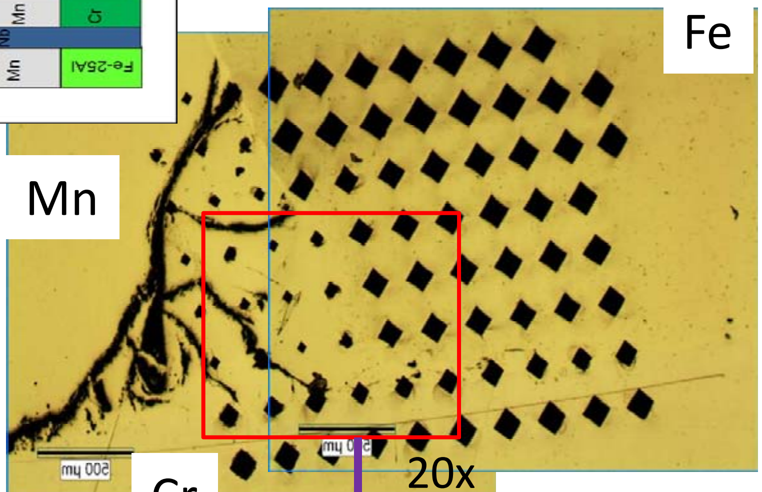


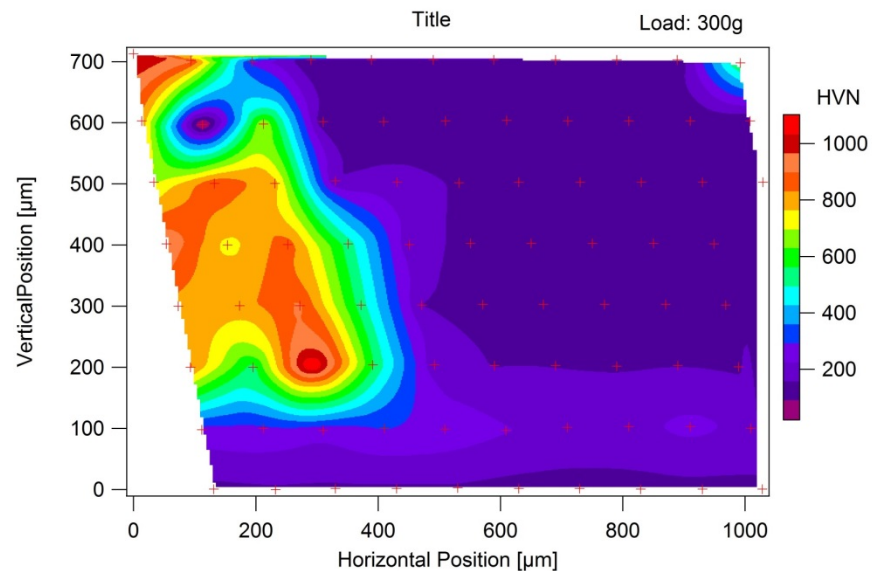
- Efficiently establish the phase-equilibria relations.
- High fidelity thermodynamic database validation.
- Guidance to the design of high-Mn austenitic steels.

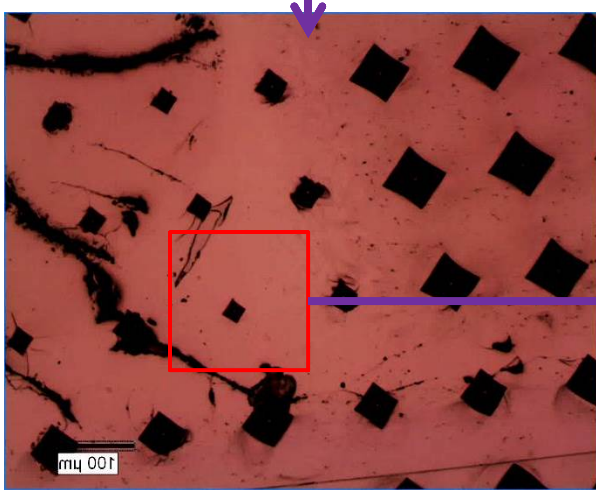
Microhardness map



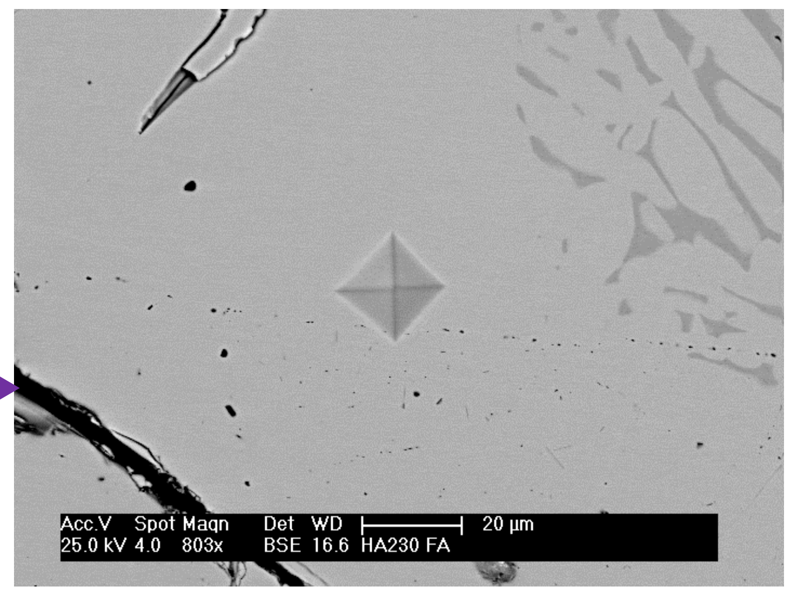
Fe-Cr-Mn

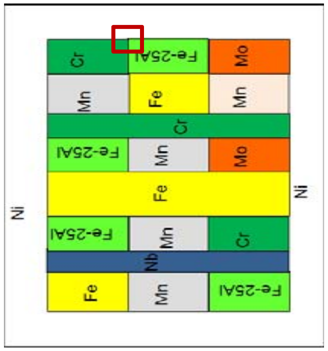




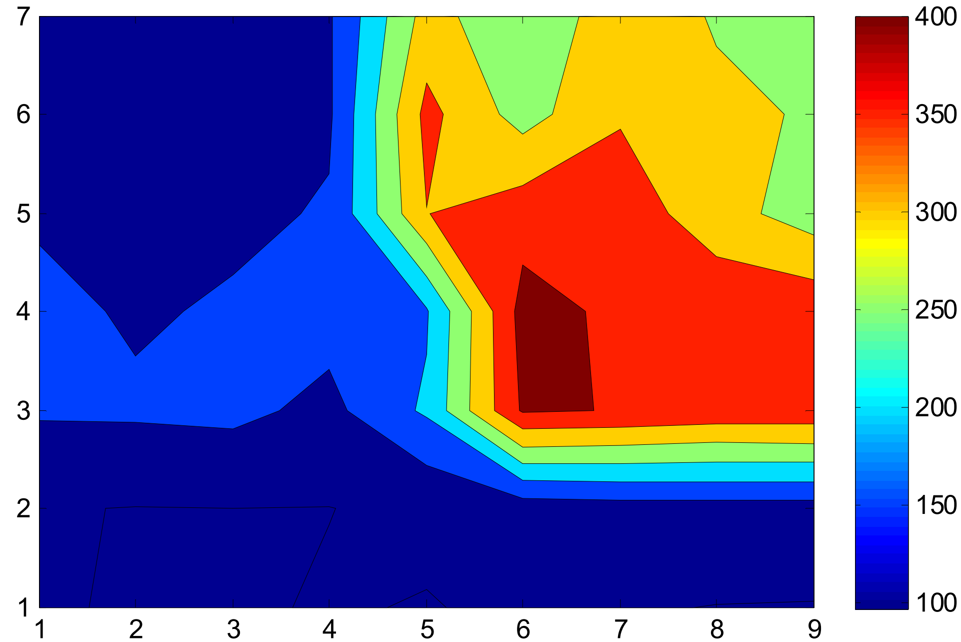


SEM




Cr
Fe-25Al
Mo
Mn
Fe
Mn
Cr
Fe-25Al
Mn
Mo
Fe
Ni
Ni
Fe-25Al
Mn
Cr
Nb
Fe
Mn
Fe-25Al

FeAl-Ni-Cr


7
6
5
4
3
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1
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4
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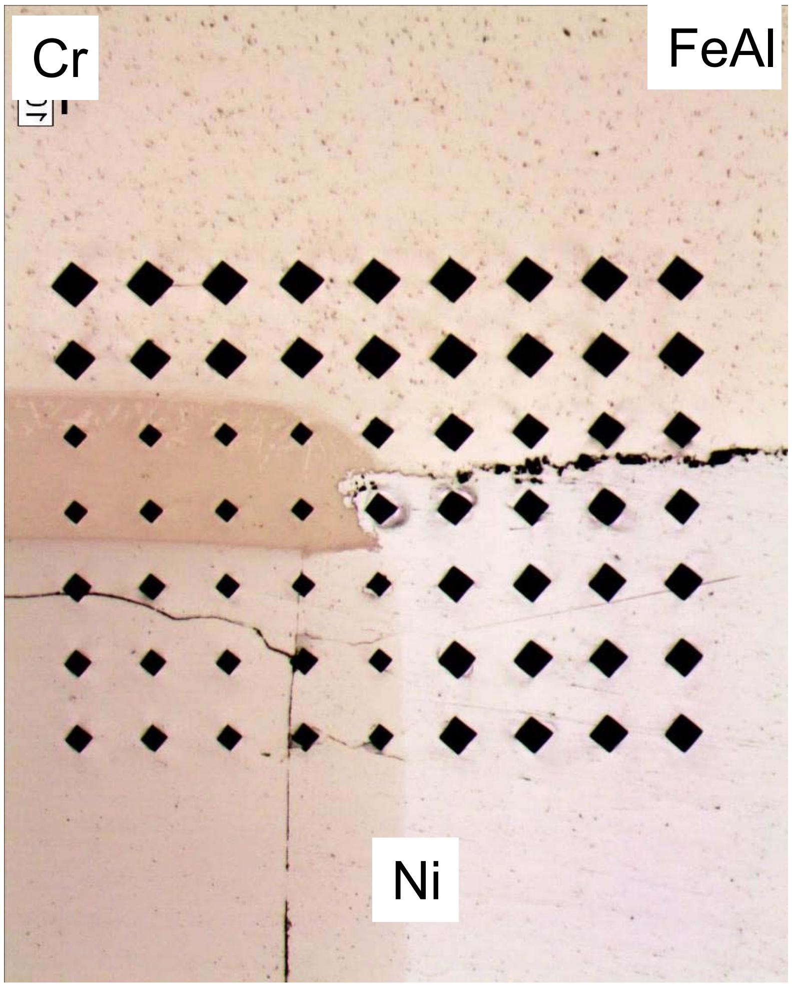
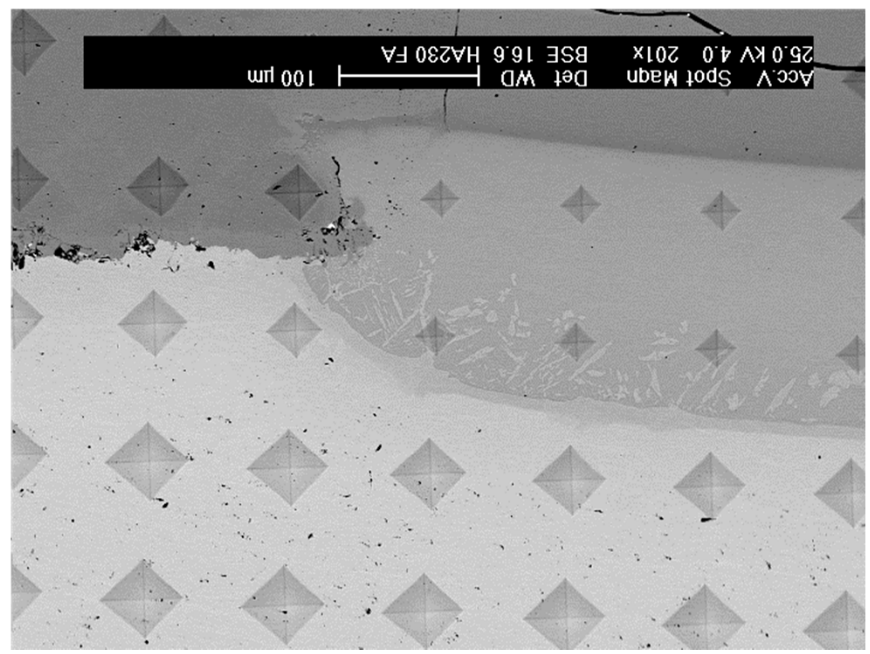
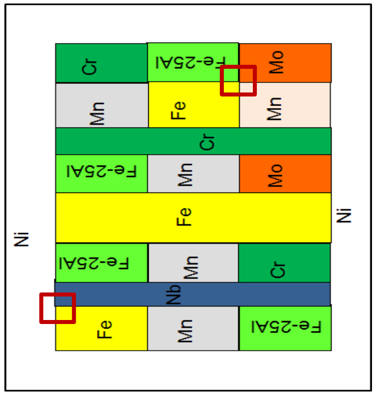
7
8
9
400
350
300
250
200
150
100


Cr
FeAl
Ni


Acc.V Spot Magn Det WD 100 µm
25.0 kV 4.0 201x BSE 16.6 HA230 FA

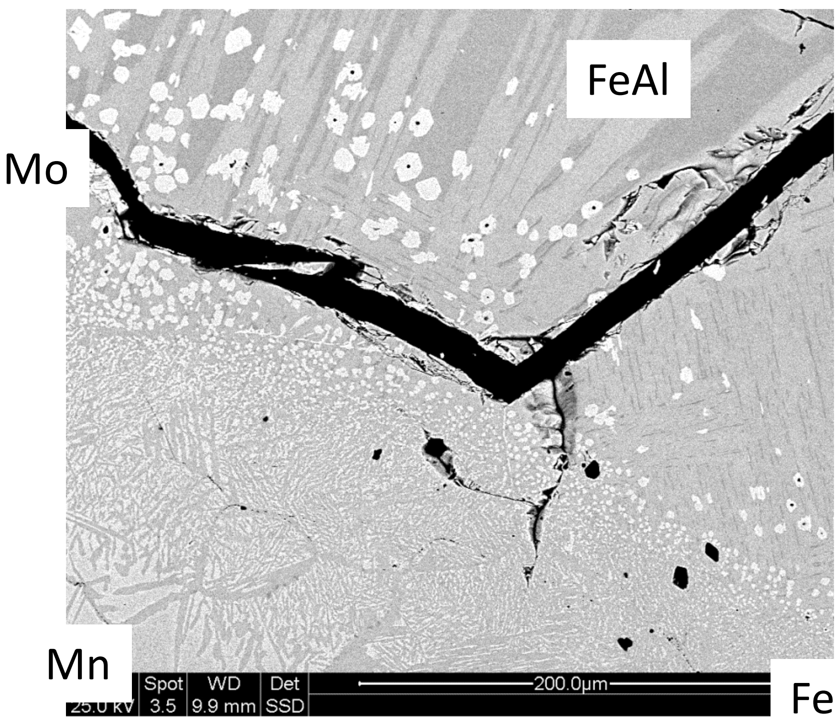
4. Austenitic Steels



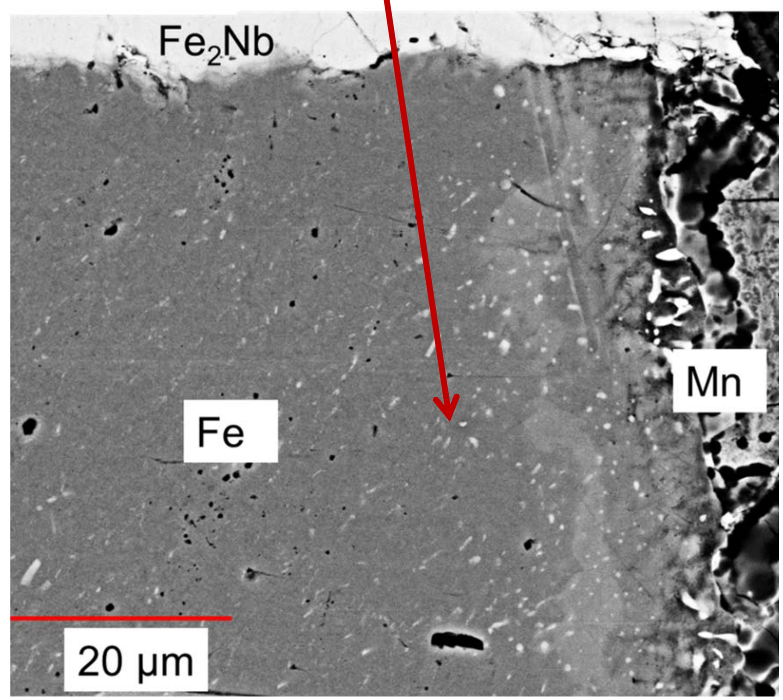
Dual-Anneal Diffusion multiple: precipitates screening

Annealed at 1000°C for 500 hrs+760°C for 200 hrs

Fine Fe_2Nb laves-phase precipitates



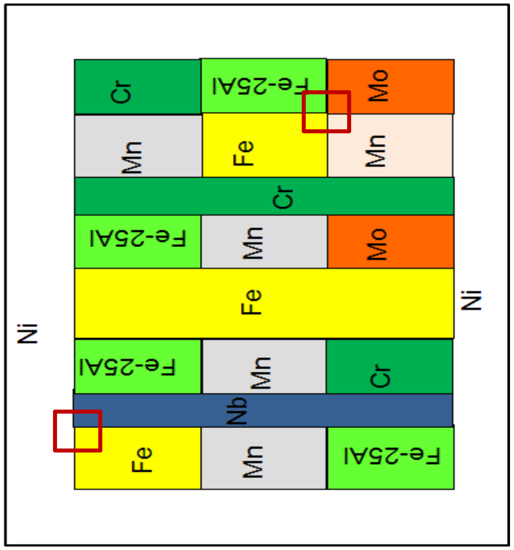
FeAl-Mo-Mn-Fe quarternary system

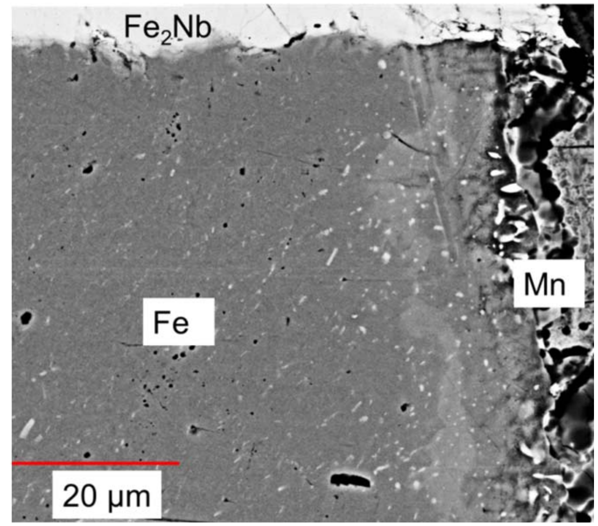


Fe-Mn-Nb ternary system

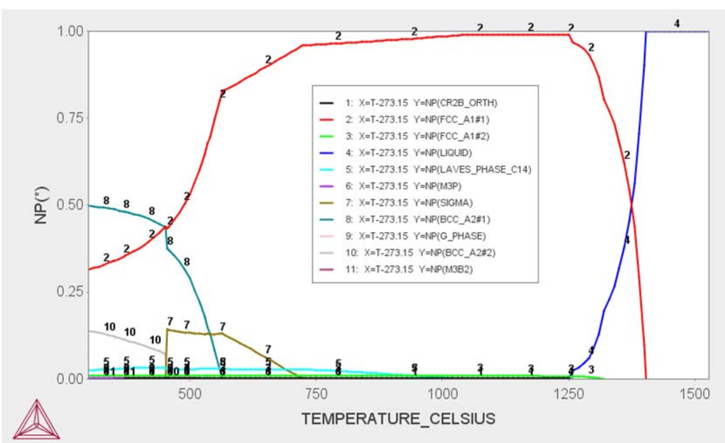
4. Austenitic Steels

Dual-Anneal Diffusion Multiple → Viable Strengthening Phase





Computational Thermodynamics → Design of Alloys for Property Balance



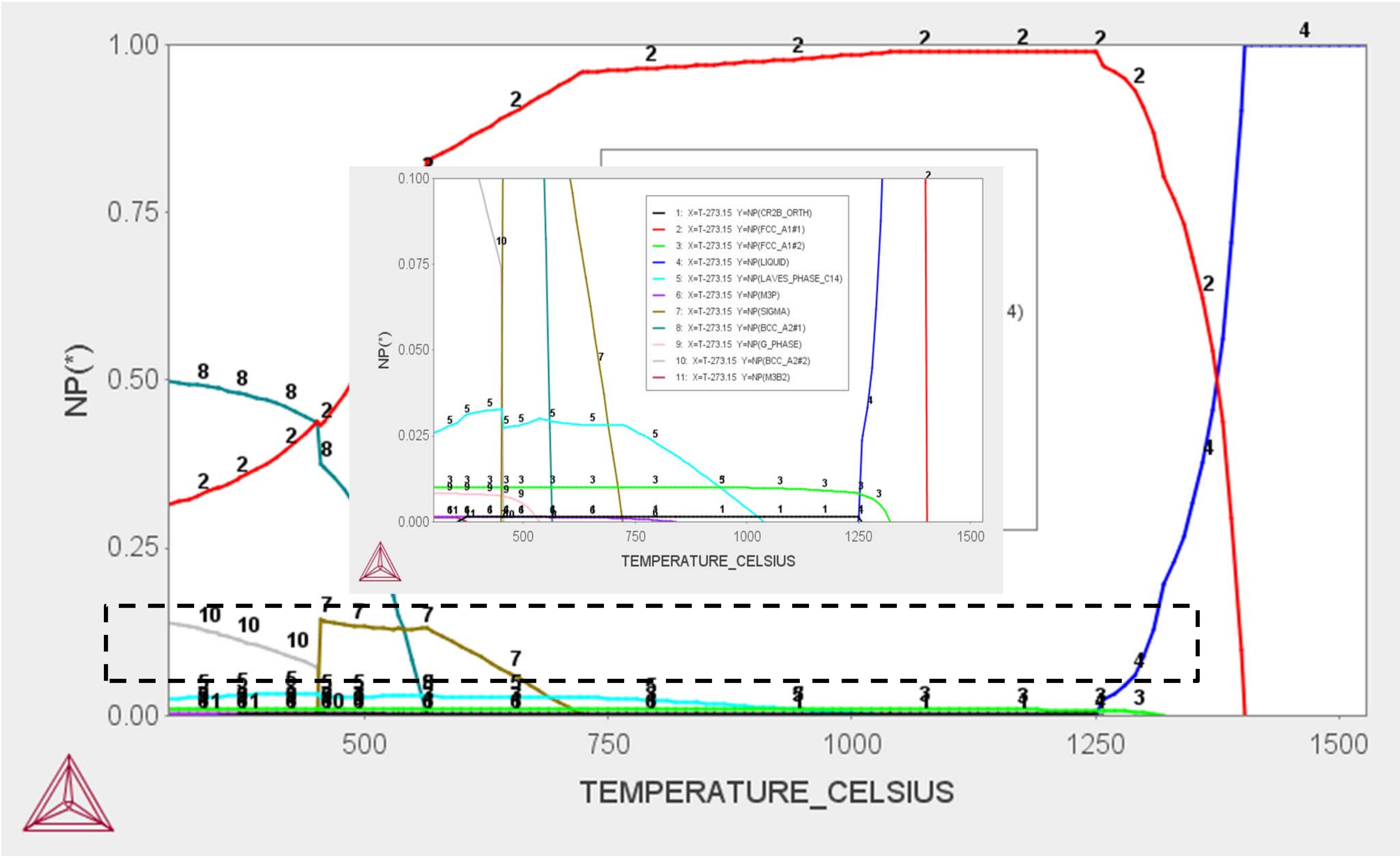
- Multicomponent alloys
- Volume fractions of phases
- Grain boundary phases
- Oxidation resistance consideration
- Cost and other requirements

4. Austenitic Steels

Design of Laves-strengthened Mn-containing austenitic steels

- Target use temperature: 760°C.
- Bcc/fcc transition temperature < 760°C; sigma phase start temperature < 760°C.
- Enough Cr (or Al) for a good oxidation resistance at target temperature.
- Optimal Nb content
- Additional of Mo or W for creep resistance enhancement
- C, B, P for grain boundary engineering during casting and forging
- TCFE7 database was used in Thermo-Calc for the thermodynamics calculation. JMatPro was also employed to check certain calculations

4. Austenitic Steels



5. Summary & Future Work

Brief Summary of Fe-Cr-Mo Chi-strengthened ferritic steel

- Fine stable Chi-phase precipitates observed in a dual-anneal diffusion multiple was confirmed by a cast ferritic steel
- Fe-Cr-Mo Chi-phase strengthened steel was ductile at high temperature (hammer-forged from round ingot to flat plate)
- High-throughput gradient temperature tests are very effective in identifying the optimum precipitation annealing temperature
- The Chi-strengthened steel has good strength at high temperature (e.g., $\sigma_{0.2} \approx 680$ MPa at 550 °C)
- Current alloys too brittle:
  - Need to further reduce Chi phase volume fraction
  - Need to engineering grain boundaries
- More work is needed to figure out the cause of brittleness

5. Summary & Future Work

Brief Summary of Fe-Mn-Cr-Al-Ni-Mo-Nb diffusion multiples

- Fe-Mn-Cr-Al-Ni-Mo-Nb diffusion multiples made to effectively explore potential strengthening phases in Mn-containing austenitic steels
- Significant amount of phase diagram information related to high Mn and high Cr (or Al) austenitic compositions was obtained from the diffusion multiples
- Fe_2Nb-based Laves phase was identified as a viable strengthening phase in Mn-containing austenitic steels
- A new multicomponent Mn-containing and Laves phase strengthened steel is designed and made
- Precipitation kinetic study and property testing are underway

Thank you!