Ferrite Grain Size Control Via Two-Stage Cooling for Structural Steel Tubes

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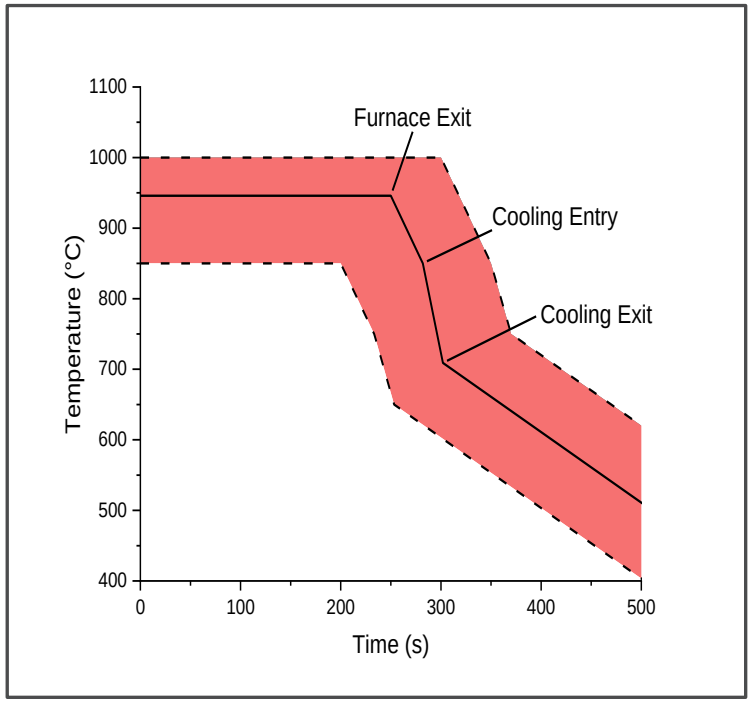
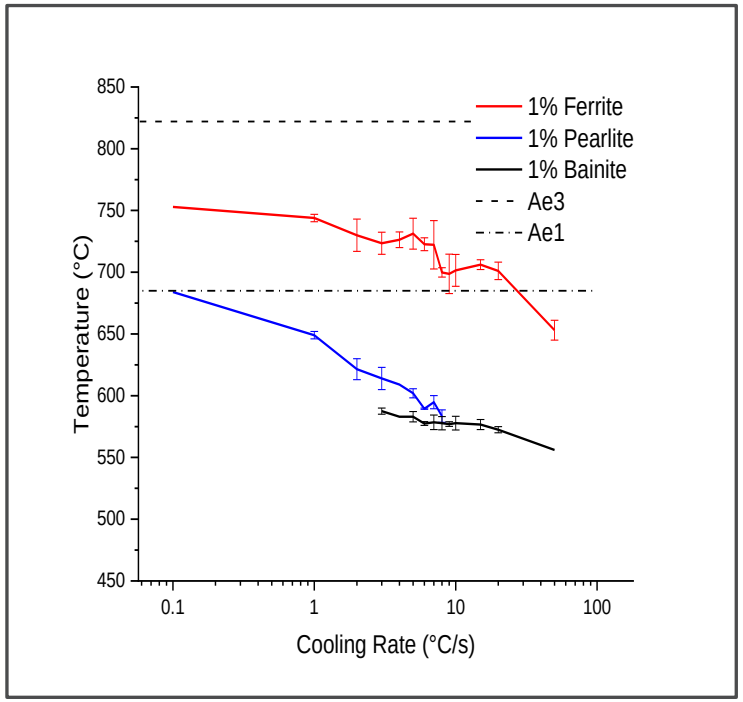
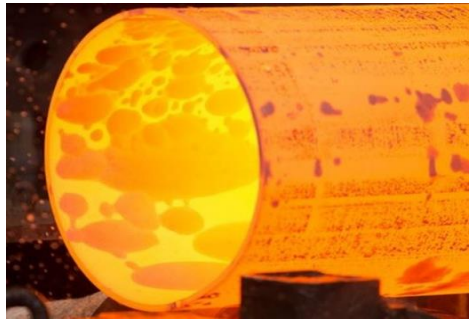
Contents

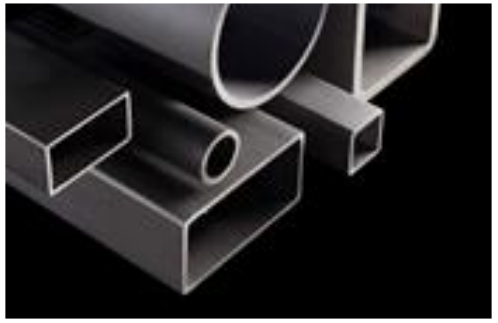
Tube Manufacturing

- **Structural Steel Tubes are produced in a range of shapes, diameters and thicknesses.**
- **Designed to attain varying yield strengths ranging from 275 MPa to 460MPa.**
- **A ferrite – pearlite microstructure is required.**
- **Final product is produced using a two – stage cooling process.**
  - **Tubes are initially water cooled at cooling rates varying from 1°C/s to 10 °C/s.**
  - **Tubes are water cooled to temperatures above bainite formation (550 - 600 °C)**

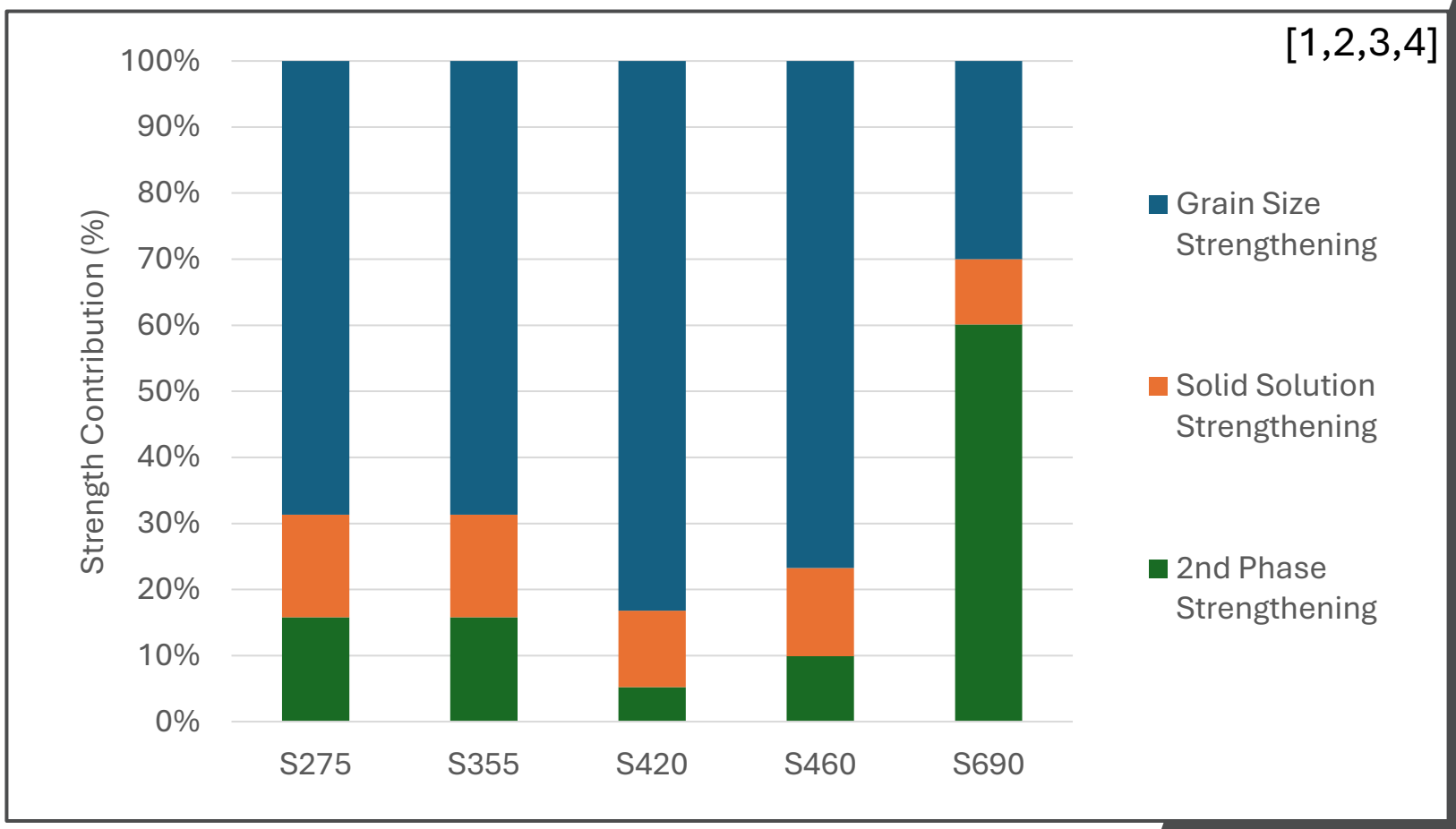






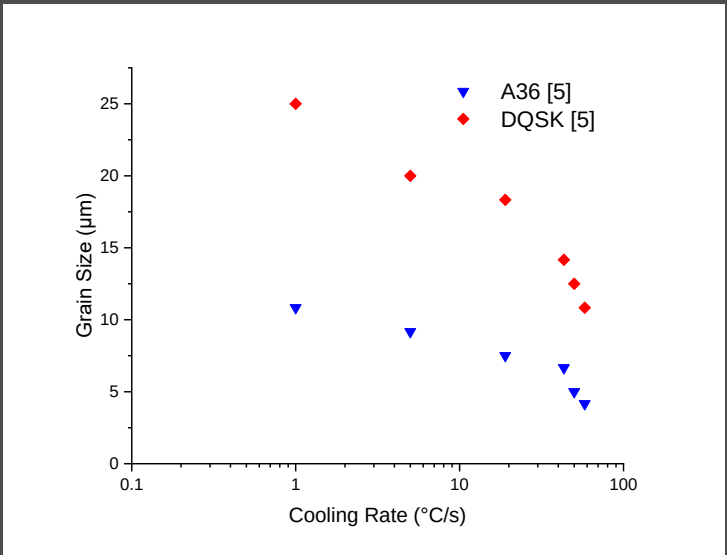


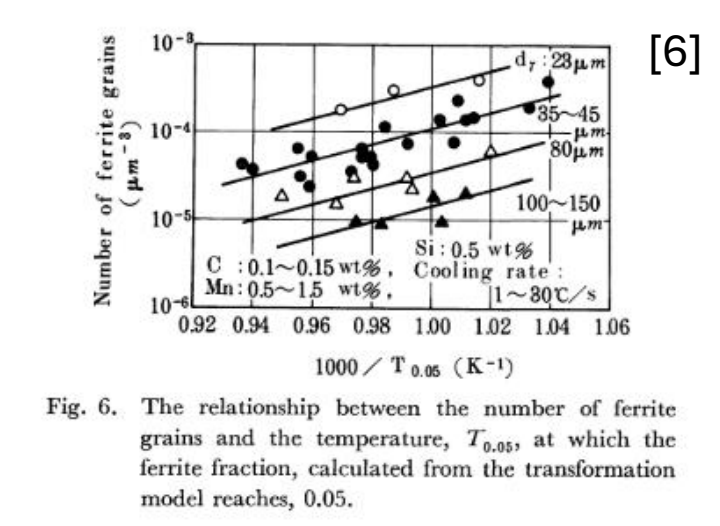
Grain Size Strengthening in S-Grade Steels



- Ferrite Grain Size accounts for ≈ 70% of yield strength.
- For higher strength grades, bainite and martensite are used.
- Controlling ferrite grain size is essential in producing a wide range of S-Grade Steels below 690 MPa YTS.

Literature: Grain Size Control





[6]

Fig. 6. The relationship between the number of ferrite grains and the temperature, $T_{0.05}$, at which the ferrite fraction, calculated from the transformation model reaches, 0.05.

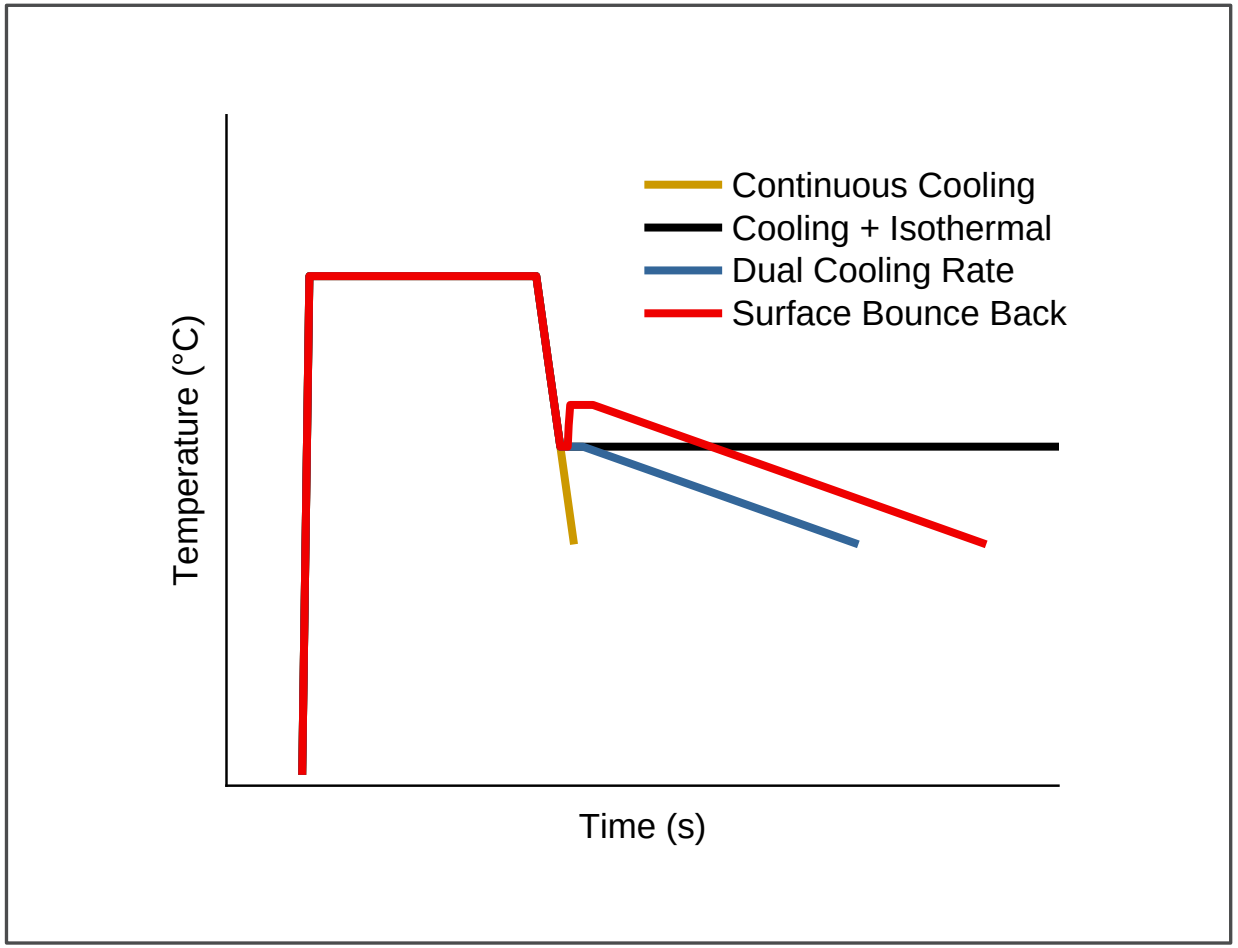
- Well known link between increased cooling rate and grain size refinement.
  - Greater cooling rates produce greater undercoolings, which increases the nucleation rate.
  - Lower transformation temperatures reduce ferrite growth rates.
- Final ferrite grain size has been linked to the undercooling required to form 5% ferrite during continuous cooling.
  - Allows for final ferrite grain size predictions through the use of CCT's.

Aims

- Understand the level of ferrite grain size refinement achievable during:
  - Conventional transformations.
  - Two - stage tube manufacturing.
- Identify the amount of ferrite formation required to determine the final ferrite grain size.

Methodology

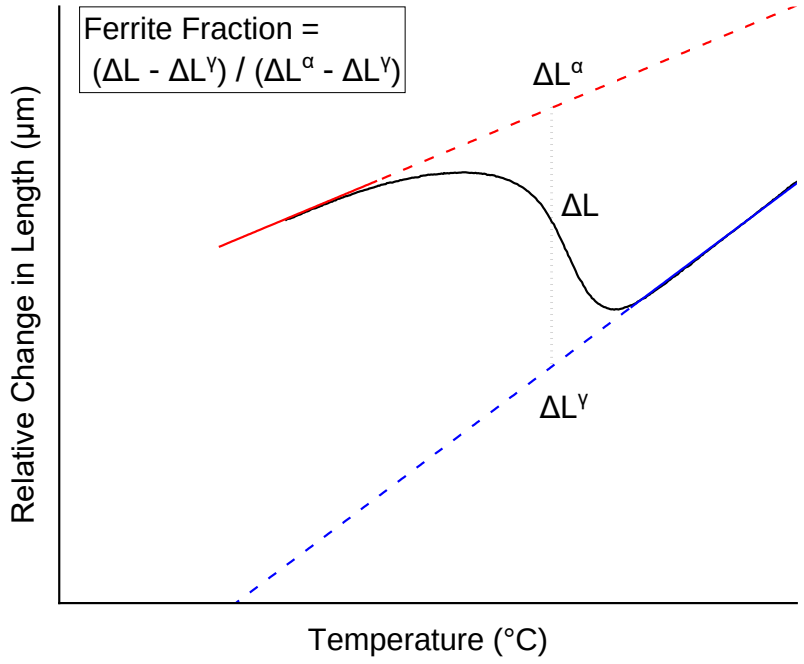
- 15.2 mm hot rolled strip S355 has been studied.
- Bähr DIL 805A/D differential dilatometer used to recreate a range of thermal profiles.
  - Standard 4 mm x 10 mm cylindrical samples used.
  - Samples annealed at 950 °C for 5 minutes.
  - Cooled at rates ranging from 0.1 °C/s to 50 °C/s. Cooling rates were achieved using helium gas.
  - Cooling was interrupted at temperatures ranging from 730 °C to 580 °C.
  - After interruption, samples were fully transformed using isothermal transformation, slow cooling at 0.5 °C/s or via reheating and then slow cooling.
- Ferrite – pearlite microstructures measured using optical imagery taken from 2% nital etched samples.
- Ferrite grain sizes have been determined via grain contouring of 400 – 500 grains.
- Average equivalent circle diameters are used for ferrite grain size.
- Ae3 calculated from ThermoCalc.

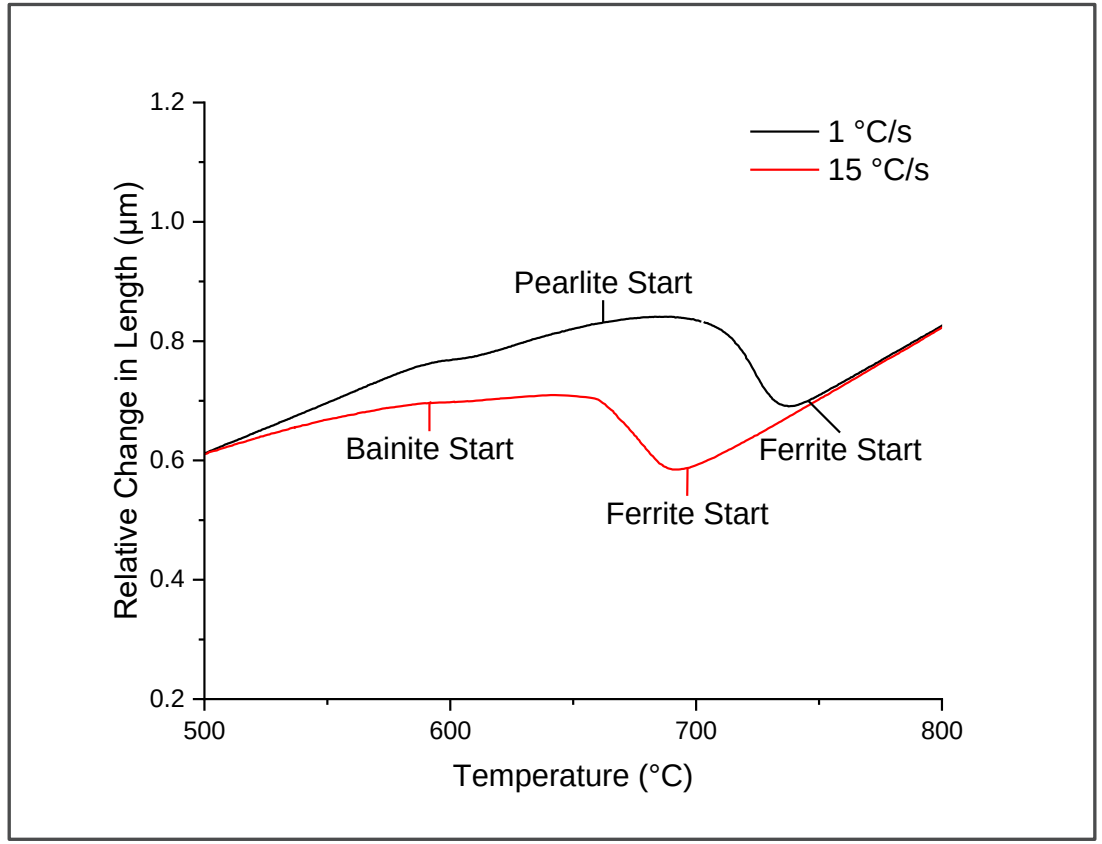


Grade	C (Wt%.)	Si (Wt%.)	Mn (Wt%.)	Nb (Wt%.)	Ae3
S355	0.14	0.20	1.40	0.03	822 °C

Methodology

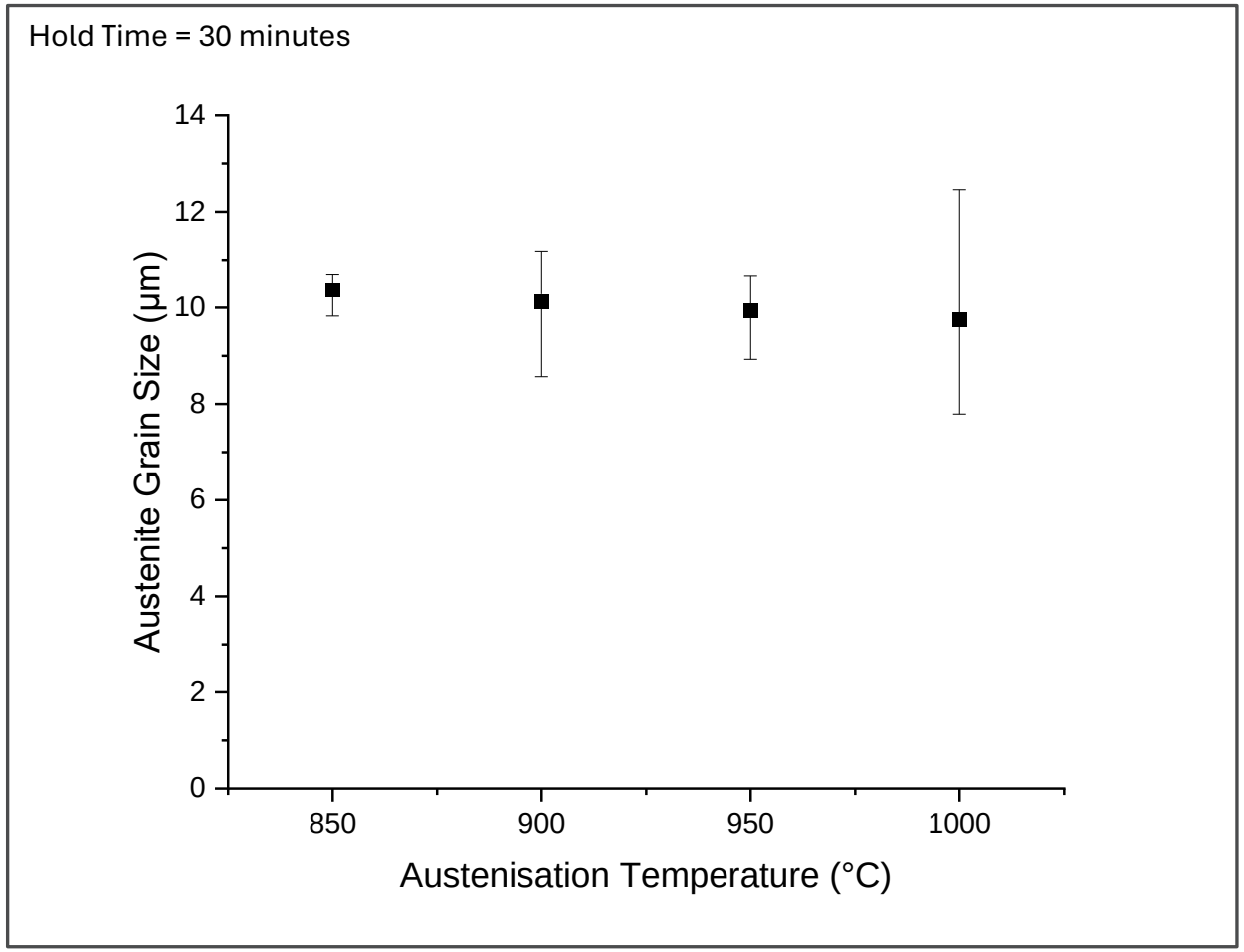
Lever Rule:





- Ferrite fractions have been attained using the dilatometry lever rule.
- Dilatometry traces allow for the identification of phase formation start temperatures
- This identifies the temperature at which X amount of ferrite has formed for each transformation.

Austenite Grain Size Produced via Normalisation

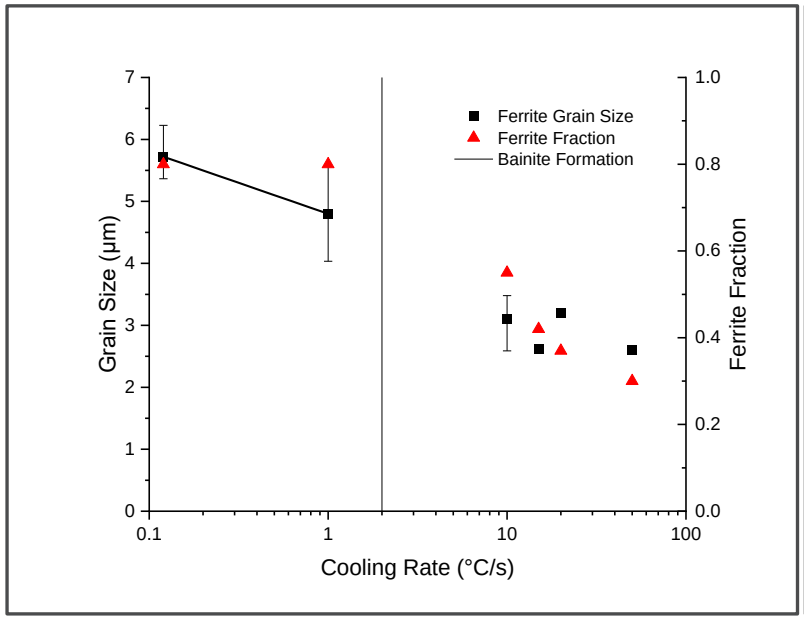


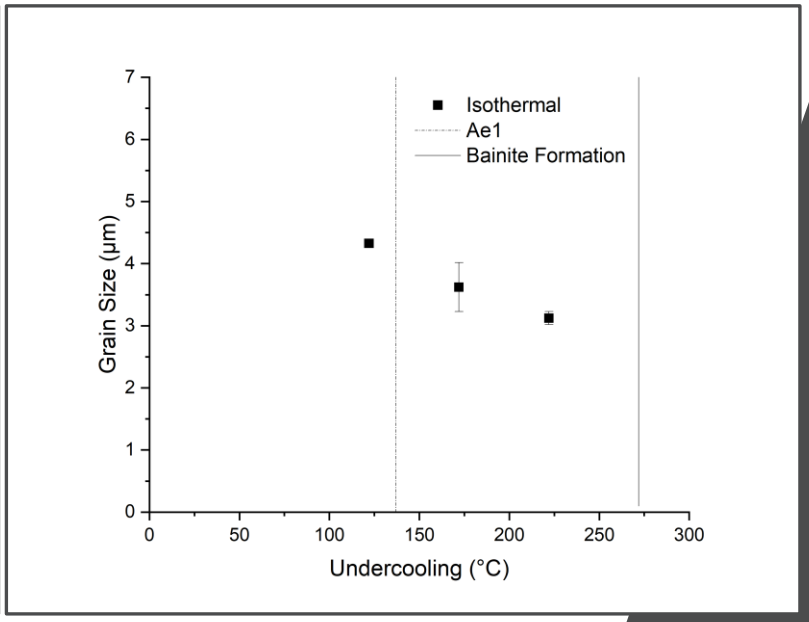
Error bars shown above and throughout presentation represent the ranges from repeat tests

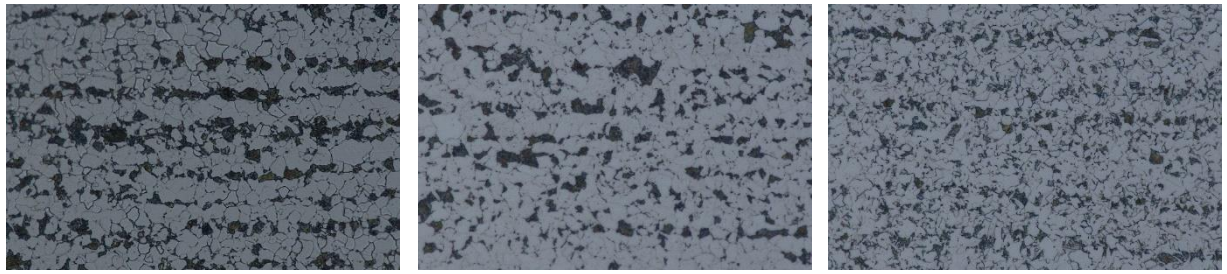
- Austenite grain sizes are consistently fine, ranging from 7.8 µm to 12.5 µm
- A normalisation schedule of 950 °C for 5 minutes produces a comparable grain size of 9.9 µm

15.2 mm thickness sample held at 850 °C for 30 minutes. Etched using Bechet and Beaujard's reagent.

Grain Size Control During Conventional Transformation Methods







100 µm

Samples isothermally transformed at (a) 700 °C (b) 650 °C (c) 600 °C

- Average grain sizes required for S355 standard, range from 5 µm to 3.5 µm.
- Grain size refinement achievable during continuous cooling is limited by bainite formation.
- Isothermal transformations are capable of significant grain refinement. However, limited by industrial production process.

Grain Size Control During Two-Stage Cooling

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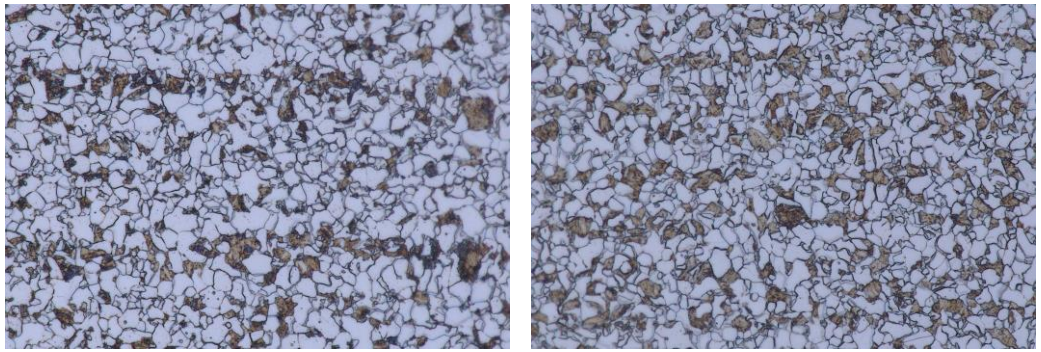
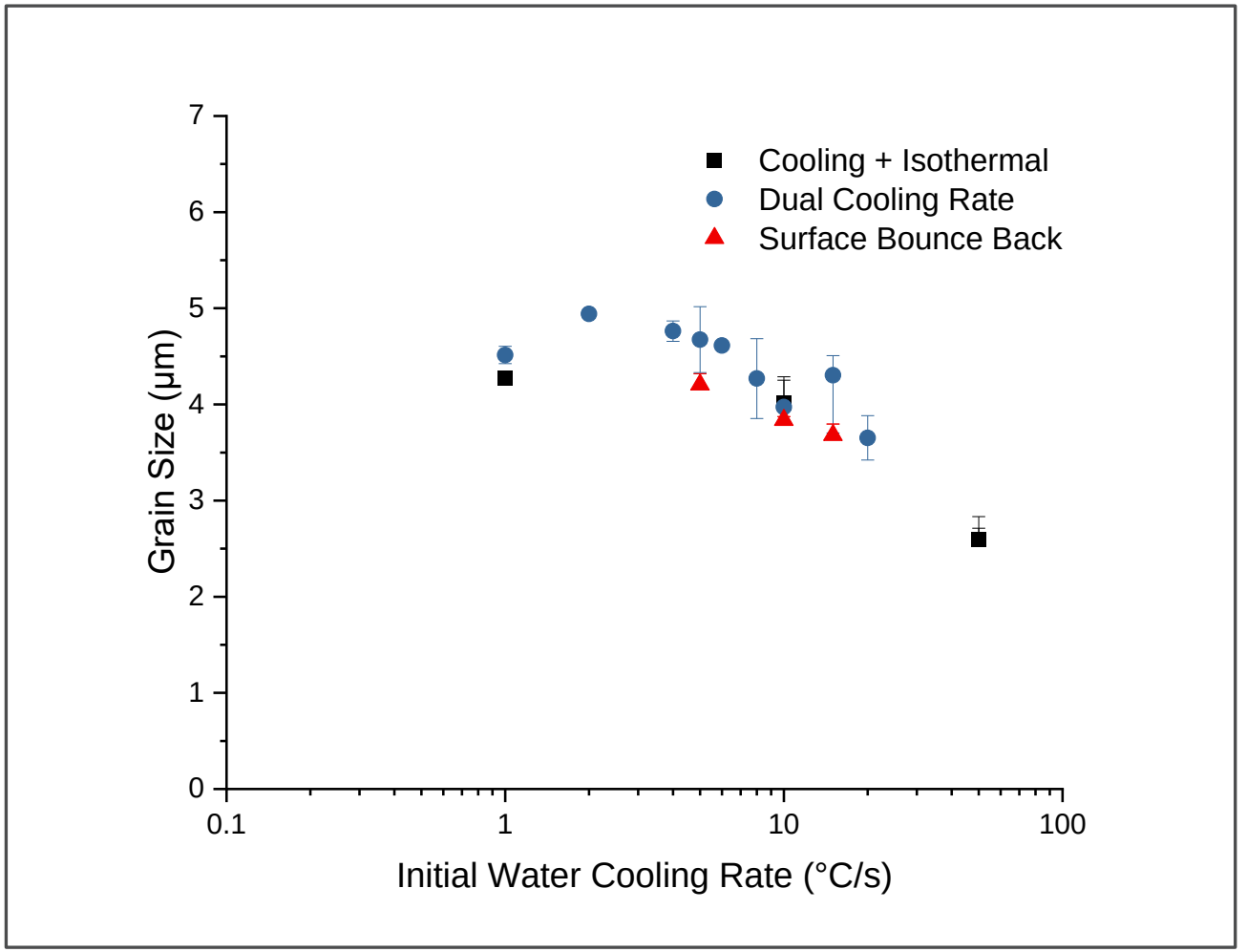
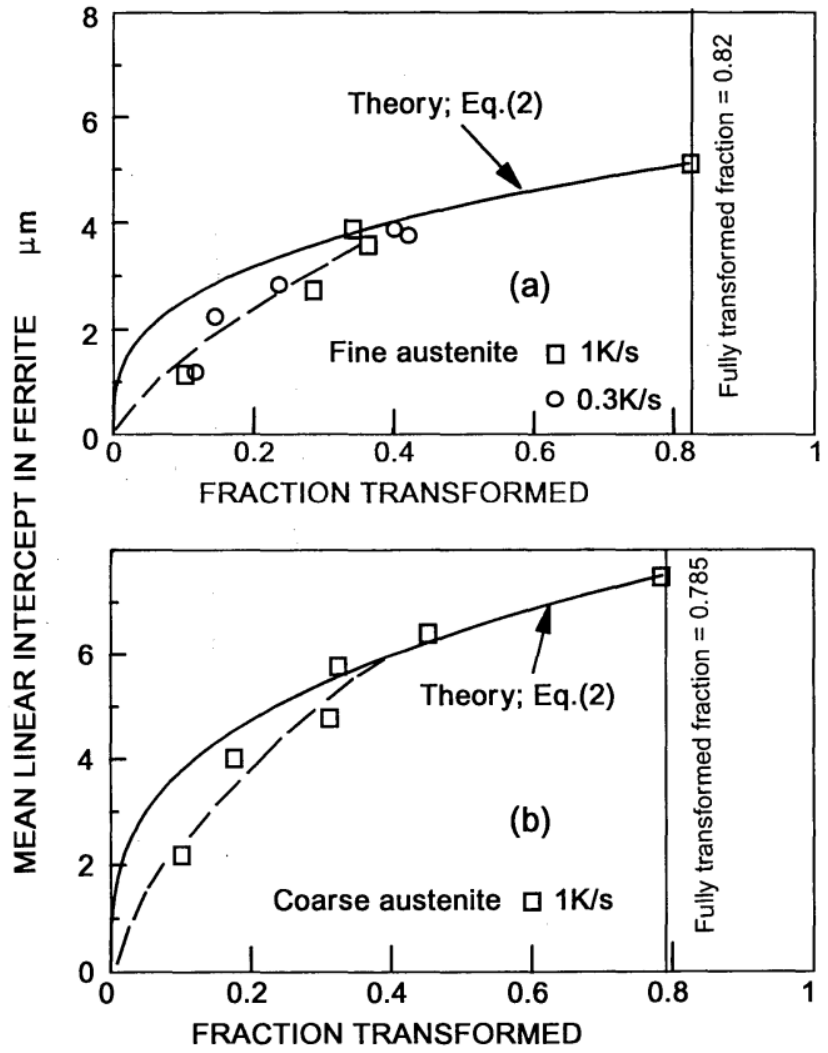
- **Samples have been cooled to form ferrite amounts ranging from 15% to 75% during the initial water cooling.**
- **Regardless of subsequent cooling method, grain size links strongly to initial water-cooling rate.**
- **Significant grain size refinement, from 5.7 µm to 2.6 µm is possible by increasing the water-cooling rate from 1 °C/s to 50 °C/s**



Samples cooled at (a) 10 °C/s and (b) 50 °C/s to 632 °C and isothermally held for 5 minutes.



Literature: Determining of Ferrite Grain Size

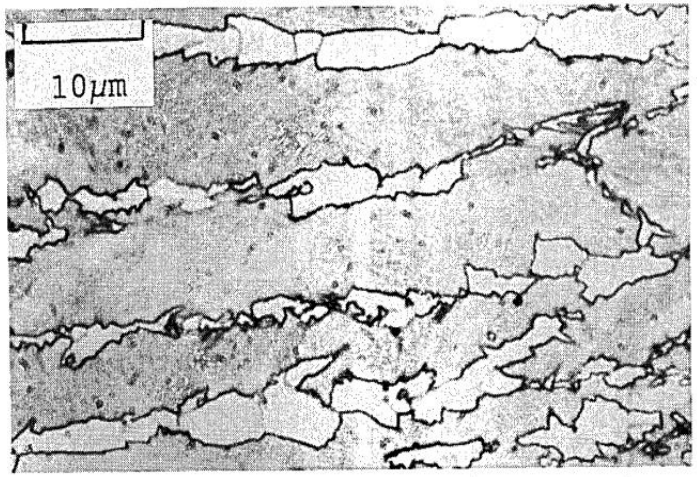


[7]

7 Mean linear intercept in ferrite phase during transformation

How much ferrite needs to be formed during the initial water cooling to determine the ferrite grain size?

- Priestner and Hodgson observed that the grain size is determined after 35% ferrite is formed.
- Once 35% is formed, nucleation sites are saturated, grain coarsening has occurred and transformation becomes growth and impingement dominated.



[7]

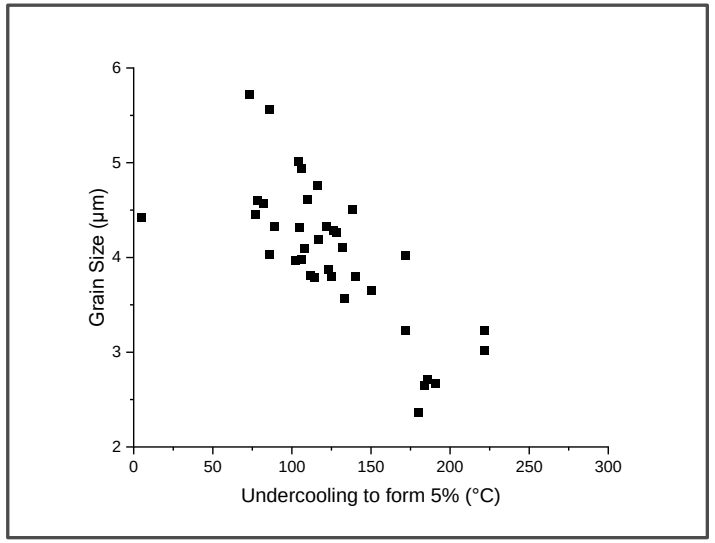
4 Finer grained austenite cooled at 1 K s^{-1} and quenched from 720°C (optical micrograph)

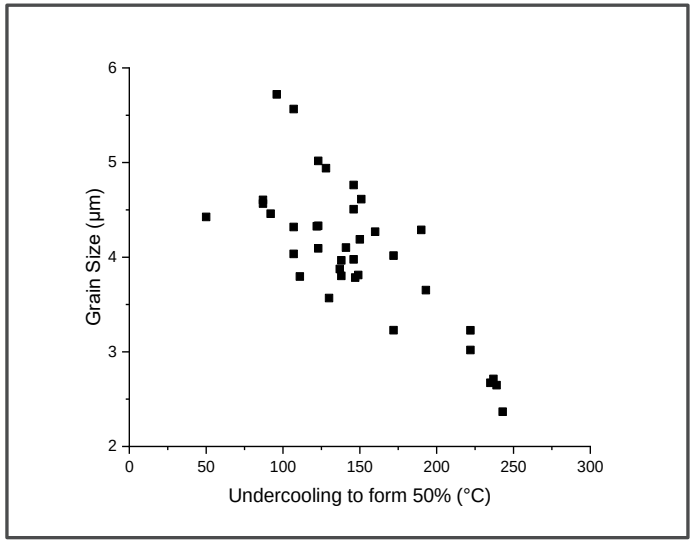
Link Between Final Ferrite Grain Size and Undercooling

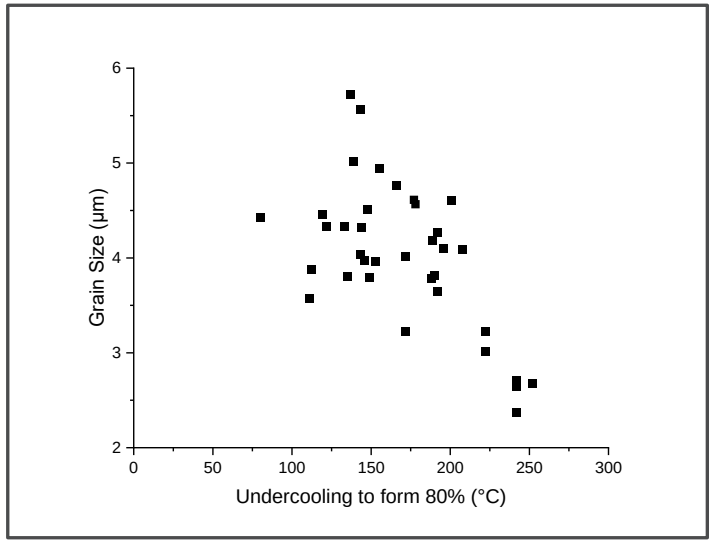
- We know from Suehiro [6] that ferrite grain size links to the undercooling (ΔT) required to form 5% ferrite.
- The ferrite grain size / grain density (N) can be correlated with the undercooling required to form X percentage of ferrite.
- The fitting equation used is:

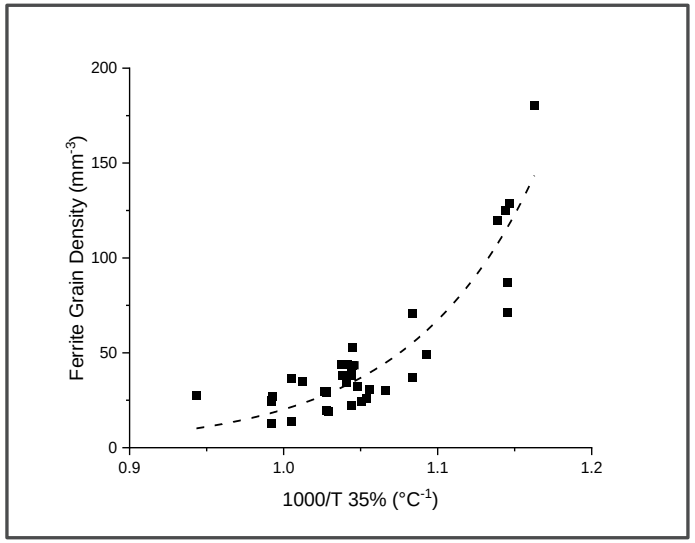
$$N = A\,exp\,(\frac{1000}{\Delta T}B)$$

- By quantifying the correlations, the critical ferrite amount can be determined.



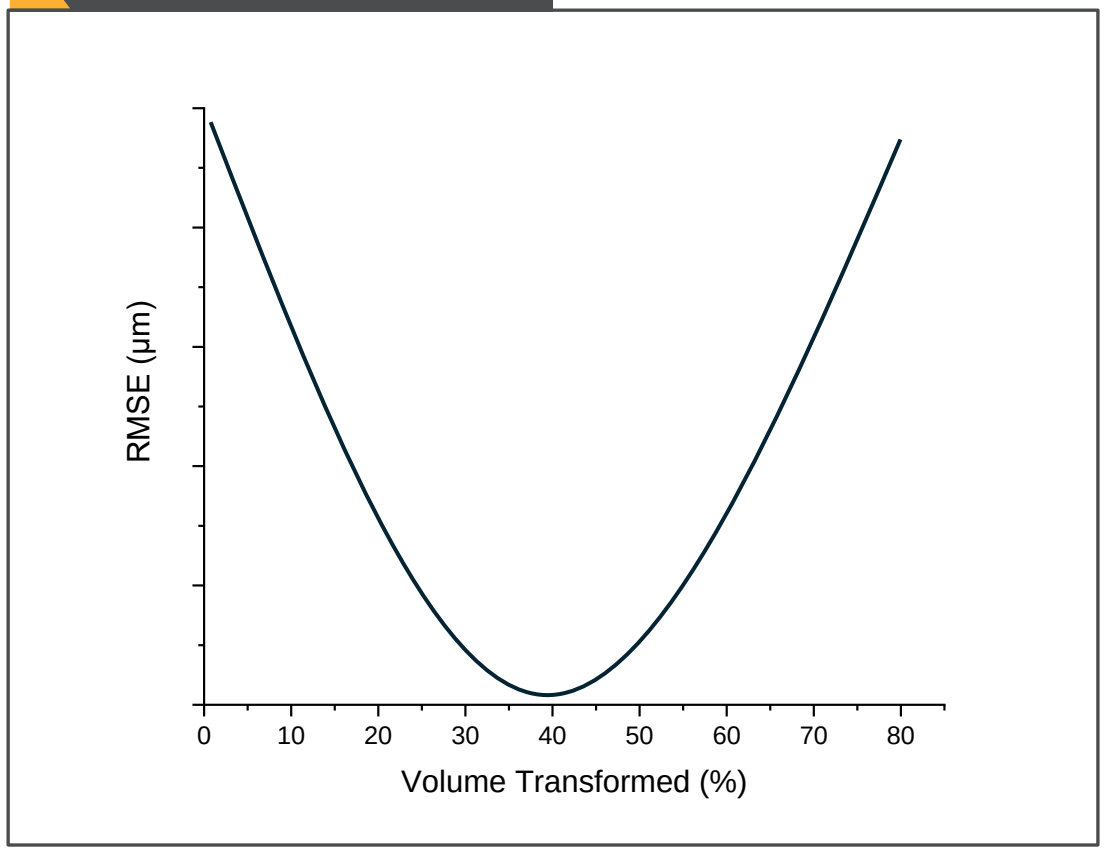






Ferrite Phase Volume Required to Determine Grain Size

Theoretical

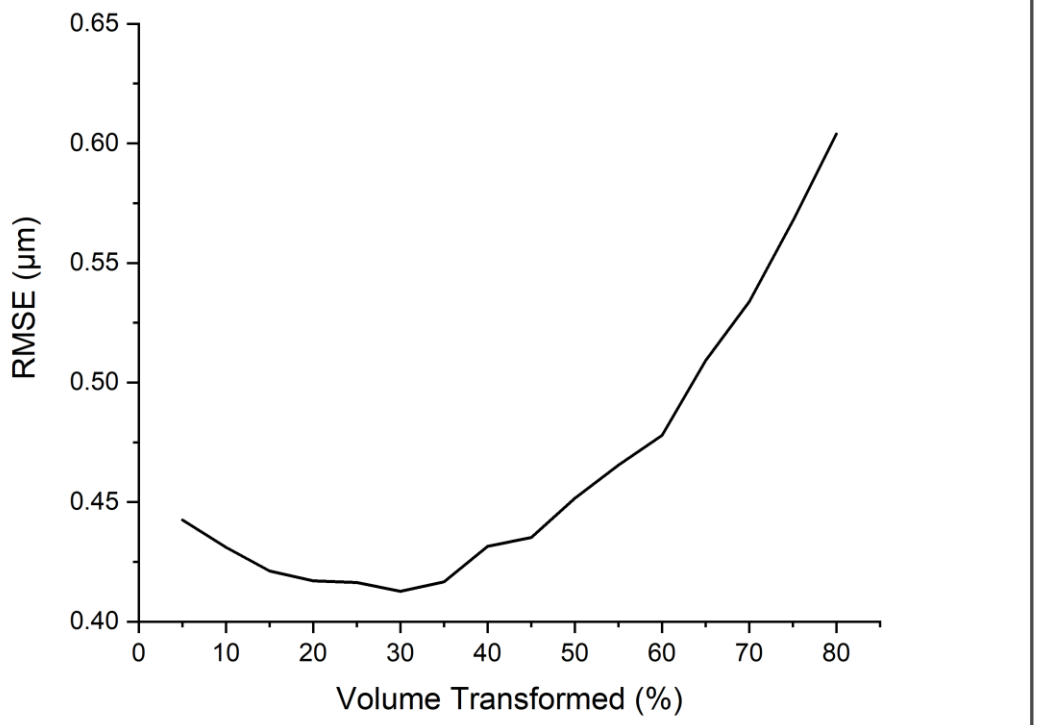


- A trough is expected when error is plotted against the volume transformed.
- A poor agreement is expected for lower ferrite fractions since the ferrite grain size has not been determined.
  - Changes in thermal profile prior to grain size determination will alter ferrite nucleation and growth behaviors.
- A poor agreement is expected at higher ferrite fractions.
  - During complex cooling, full transformation can be achieved via many thermal profiles.

Ferrite Phase Volume Required to Determine Grain Size

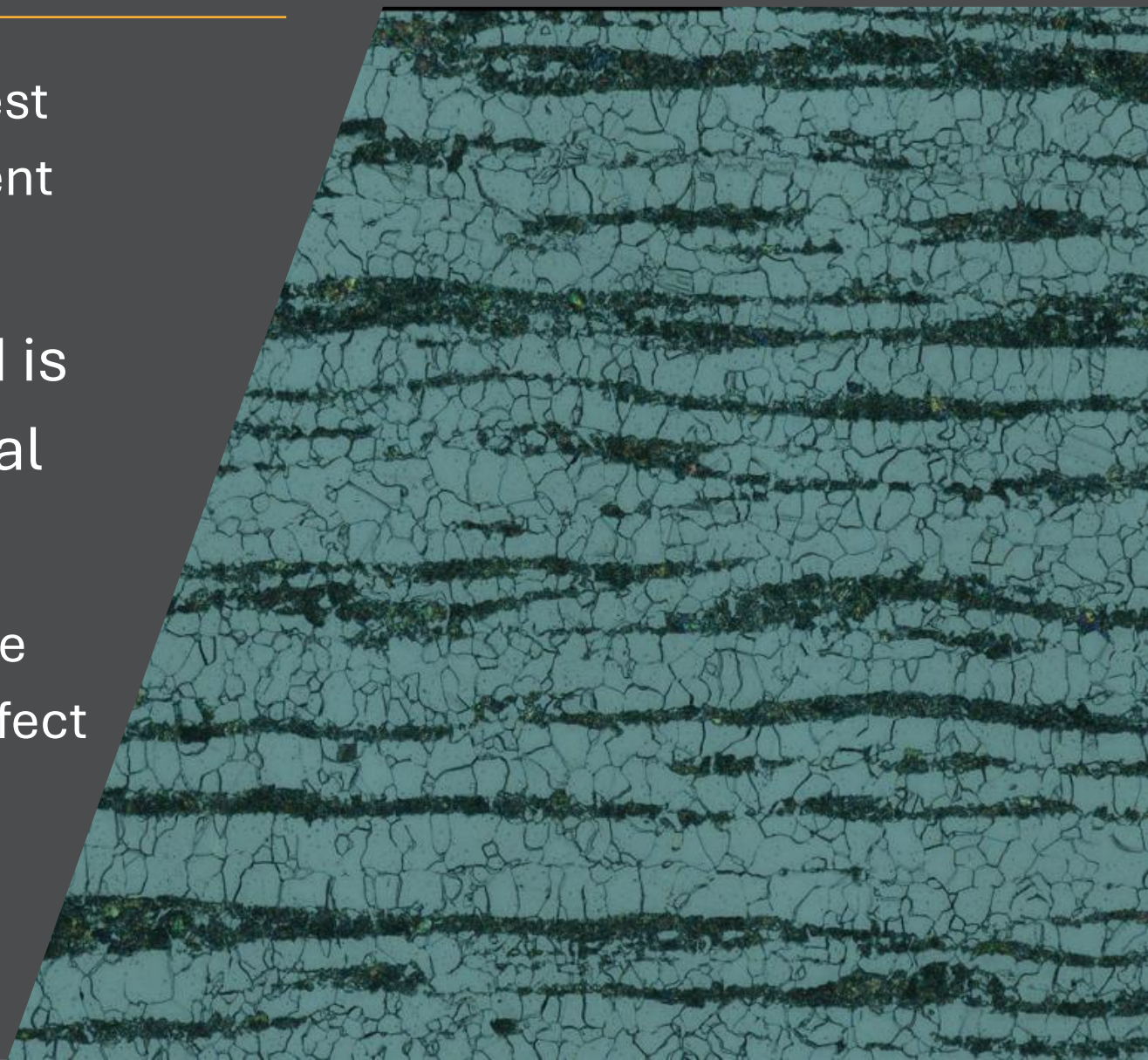
- **A trough is present at 25-35% ferrite. This agrees with Priestner and Hodgson [7].**
- **The undercooling at which 30% ferrite has formed is a good indicator of the final ferrite grain size.**
- **To maximise the benefits of two-stage cooling. The first 30% of ferrite formation should be achieved at high undercoolings.**
- **Once 30% ferrite has been achieved, the subsequent thermal profile will not have a detrimental effect on grain size.**

Experimental

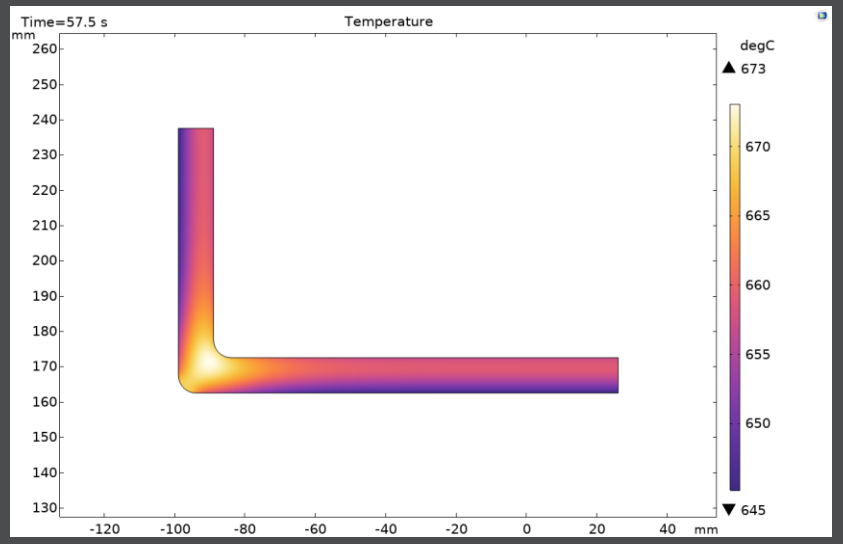


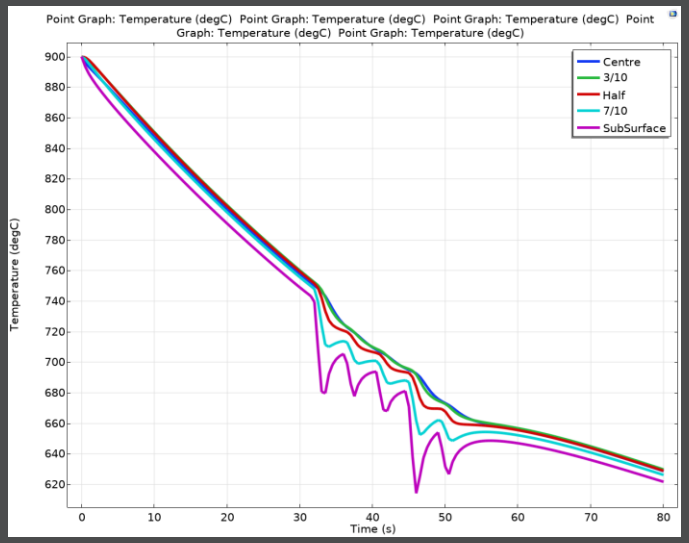
Conclusions

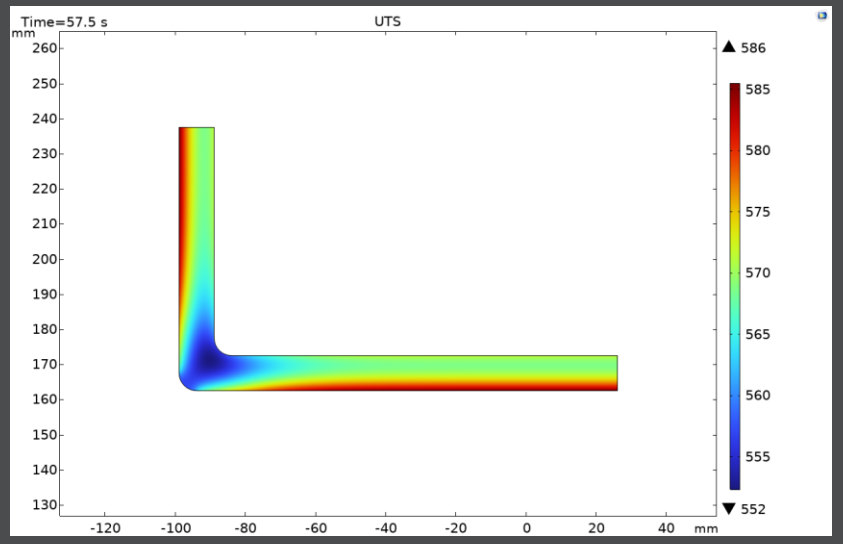
- Dilatometry testing has been used to test the extents of ferrite grain size refinement achievable during tube manufacturing.
- Undercooling at 30% transformed is the best indicative measure of final grain size.
- Any subsequent ferrite formation can be achieved slowly, with no detrimental effect on ferrite grain size.

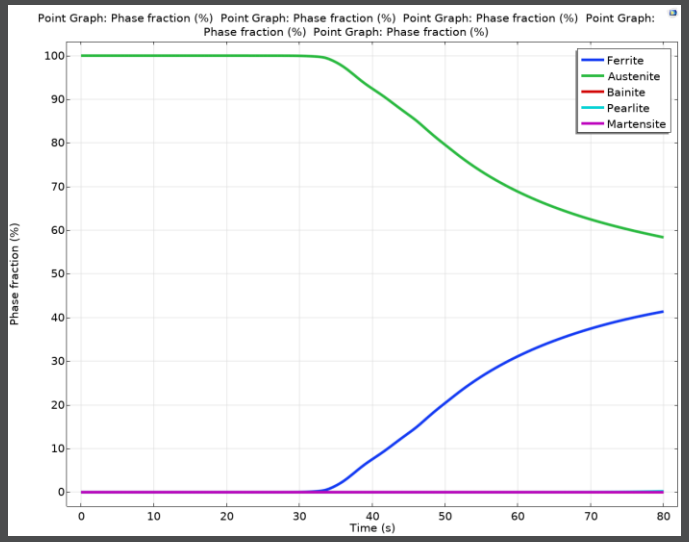


Future Work: COMSOL Modelling









Do you have any questions?

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