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# Phase Transformation Monitoring by Laser Ultrasound & by Dilatometry during Cooling of DP780 & QP Steel Grades

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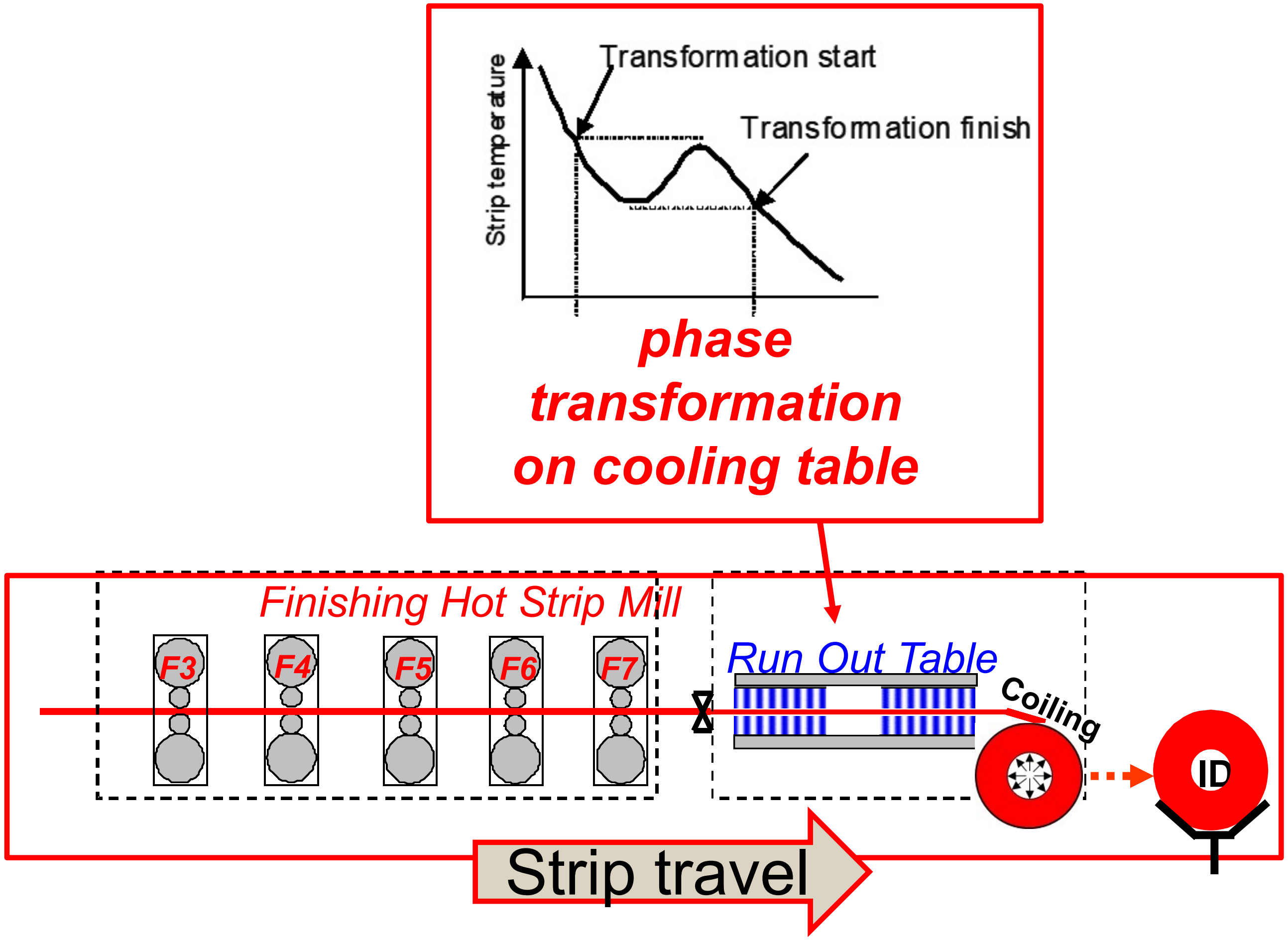
# Industrial Context



# Objectives

Compare **Dilatometry** and **Laser Ultrasonic techniques** to detect and monitor **phase transformation** during **cooling** of steel grades.

# Experimental conditions

- Materials selection

→ Two steel grades selected for evaluation:

*Chemical composition in major elements (Weight %)*

| Grade | C | Mn | Si | Cr | Al | Mo | B |
|---|---|---|---|---|---|---|---|
| DP780 grade | 0.136 | 2.09 | 0.208 | 0 | 0.027 | 0 | 0 |
| QP grade | 0.37 | 1.95 | 1 .95 | 0.35 | 0 | 0.12 | 0 |

# Experimental methods

## Dilatometric tests: **lever rule method**

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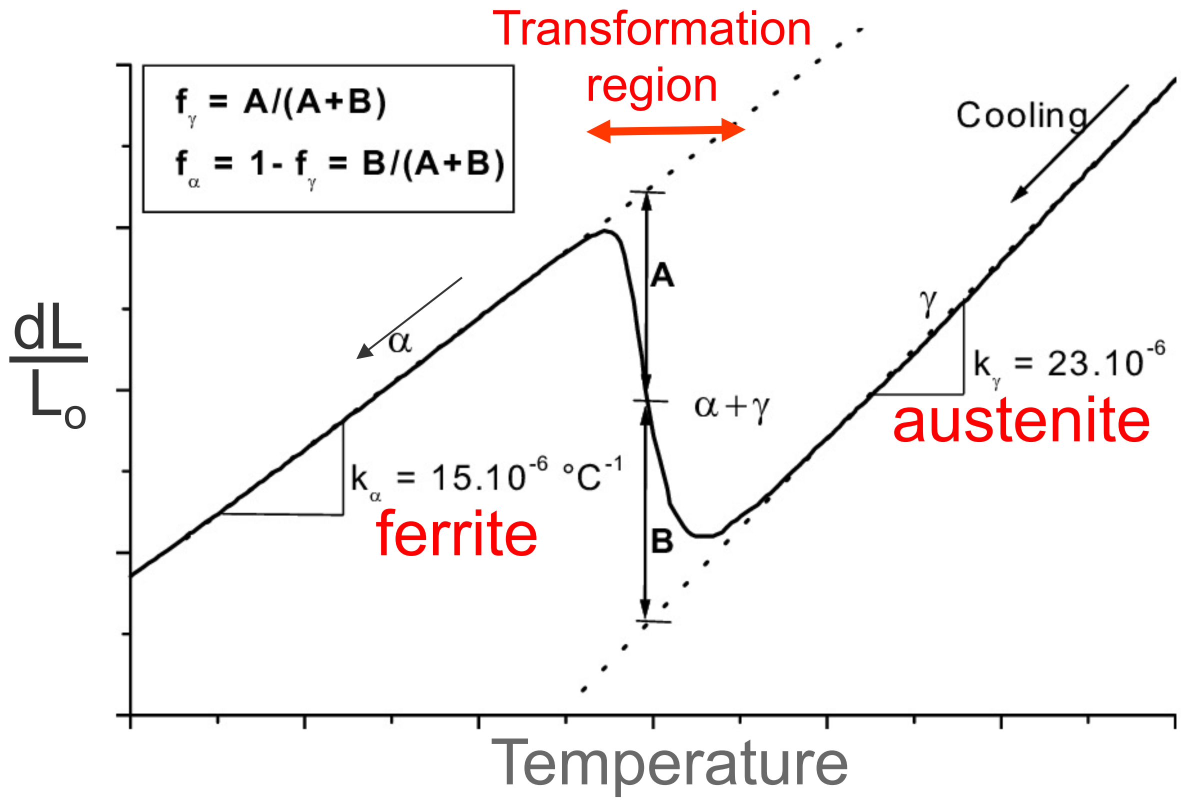


Bahr Dilato DIL805L

**Cooling rates:**

0.1 °C/sec.
1 °C/sec.
5 °C/sec.
10 °C/sec.

Assumptions for Austenite to ferrite/pearlite transformations:

→ **Austenite enrichment in Carbon (coming from ferrite) is neglected**

→ **Difference of Volume between ferrite and pearlite is neglected**

# Bibliographic Analysis

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## Lattice parameters for ferrite, austenite & pearlite(1/3)

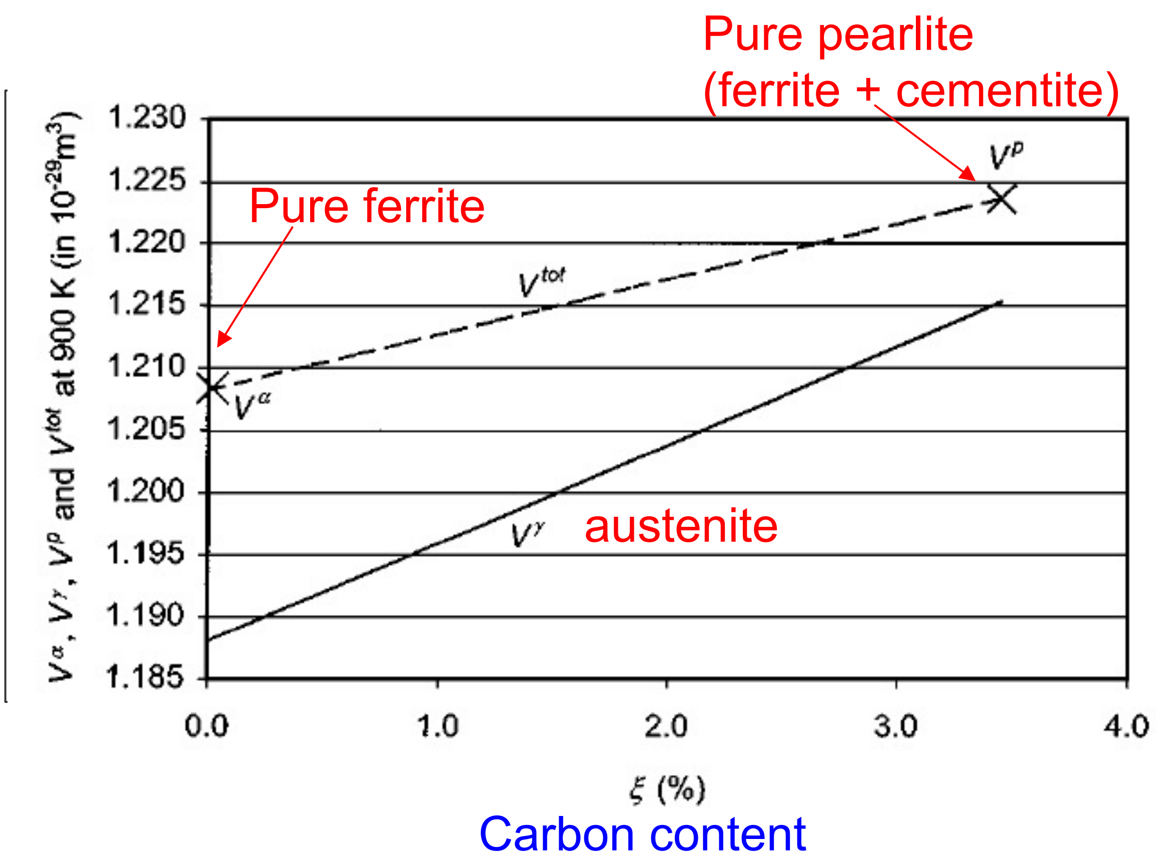
- Kop et Al. 2001:

| Phase | Lattice parameters (Å) |
|---|---|
| ferrite → $\alpha$ | $a_\alpha = 2.8863\ \text{Å}\ (1 + 17.5 \times 10^{-6}\ \text{K}^{-1}\ [T - 800\ \text{K}])$<br>$800\ \text{K} < T < 1200\ \text{K}$ |
| austenite → $\gamma$ | $a_\gamma = (3.6306 + 0.78\xi)\ \text{Å}\ (1 + (24.9 - 50\xi)10^{-6}\ \text{K}^{-1}\ [T - 1000\ \text{K}])$<br>$1000\ \text{K} < T < 1250\ \text{K};\ 0.0005 < \xi < 0.0365$ |
| cementite → $\theta$ | $a_\theta = 4.5234\ \text{Å}\ (1 + \{5.311 \times 10^{-6} - 1.942 \times 10^{-9}\ \text{K}^{-1}\ T + 9.655 \times 10^{-12}\ \text{K}^{-2}\ T^2\}\text{K}^{-1}\ [T - 293\ \text{K}])$<br>$b_\theta = 5.0883\ \text{Å}\ (1 + \{5.311 \times 10^{-6} - 1.942 \times 10^{-9}\ \text{K}^{-1}\ T + 9.655 \times 10^{-12}\ \text{K}^{-2}\ T^2\}\text{K}^{-1}\ [T - 293\ \text{K}])$<br>$c_\theta = 6.7426\ \text{Å}\ (1 + \{5.311 \times 10^{-6} - 1.942 \times 10^{-9}\ \text{K}^{-1}\ T + 9.655 \times 10^{-12}\ \text{K}^{-2}\ T^2\}\text{K}^{-1}\ [T - 293\ \text{K}])$<br>$300\ \text{K} < T < 1000\ \text{K}$ |

$\xi$: carbon content

# Lattice parameters for ferrite, austenite & pearlite (2/3)

- Kop et Al. 2001:



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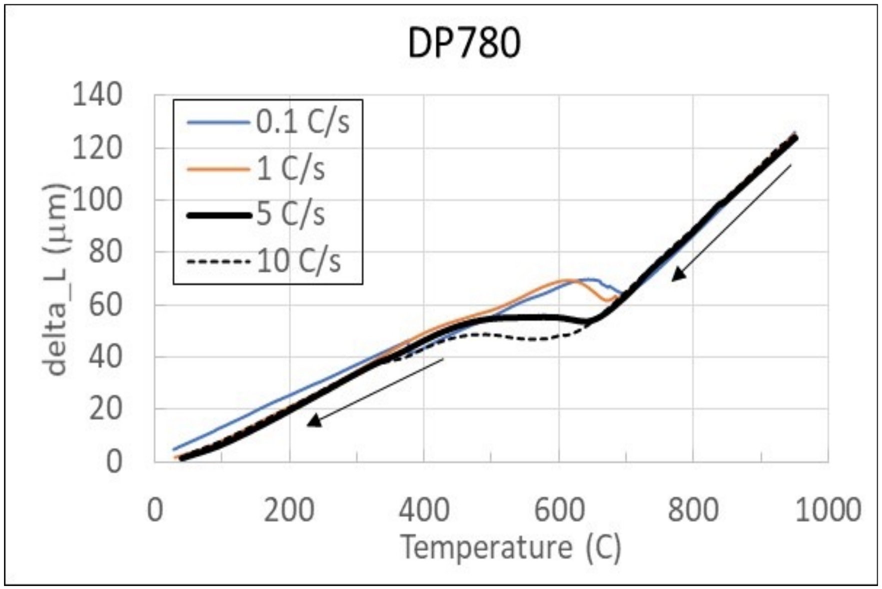
# Dilatometric tests: **corrected** lever rule method for Carbon containing alloys (3/3)





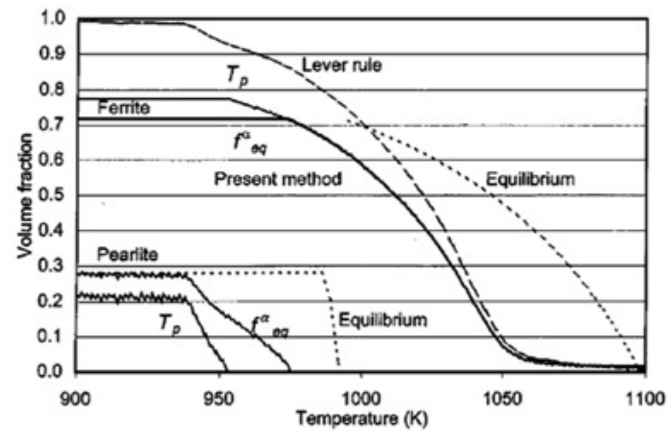




*Figure 11* The fraction curves obtained from a measurement by applying the present analysis (solid lines), once with the equilibrium ferrite fraction criterion ($f^{\alpha}_{eq}$) and once with the inflection point criterion ($T_p$). The results from applying the lever rule are represented by the dashed line. Furthermore fraction curves for sample C22 according to equilibrium (short dashed lines) are given.

## Mechanisms:

- **The austenite enriches in carbon** (redistribution) during ferrite formation,
- **The specific volume of austenite increases** (non-linear temperature dependence)
- Also, **Pearlite is formed with a higher volume** than ferrite

→ **overestimation of decomposed austenite** (lower austenite) of up to 25%

**Conclusion:** A non-linear analysis is found better than the 'lever-rule' method
Ref: T.A. Kop et al., J. Mater. Sci. 36, pp. 519-526 (2001)

# Experimental methods

# Laser ultrasonic tests: velocity method

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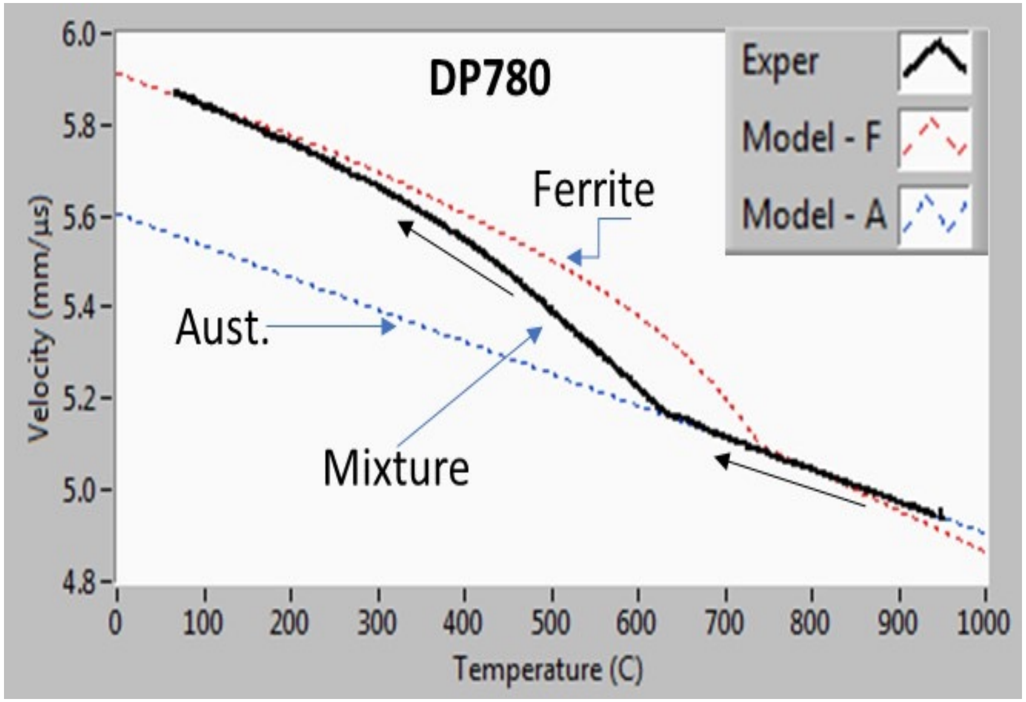


**Kruger et Al. 2006**

Gleeble 3500

**Cooling rates:**

0.1 °C/sec.
1 °C/sec.
5 °C/sec.
10 °C/sec.

Law of mixture on ultrasonic velocity

$$V_{mixture} = V_{\alpha}.(1-f_{\gamma}) + V_{\gamma}.f_{\gamma} \Rightarrow f_{\gamma} = \frac{V_{mixture} - V_{\alpha}}{V_{\gamma} - V_{\alpha}}$$

**Ferrite velocity**

**Austenite velocity**

**Austenite fraction**

# Experimental results

## DP780 grade

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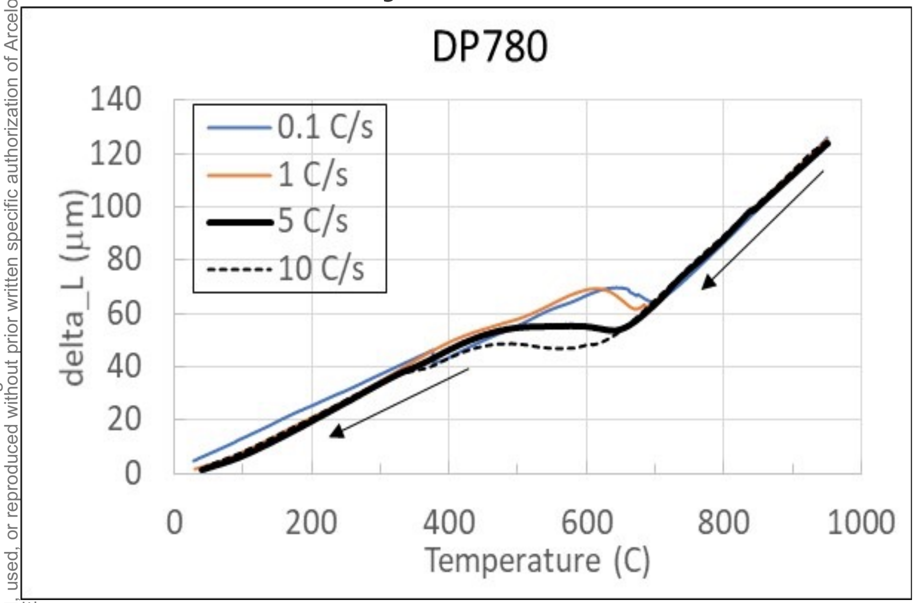
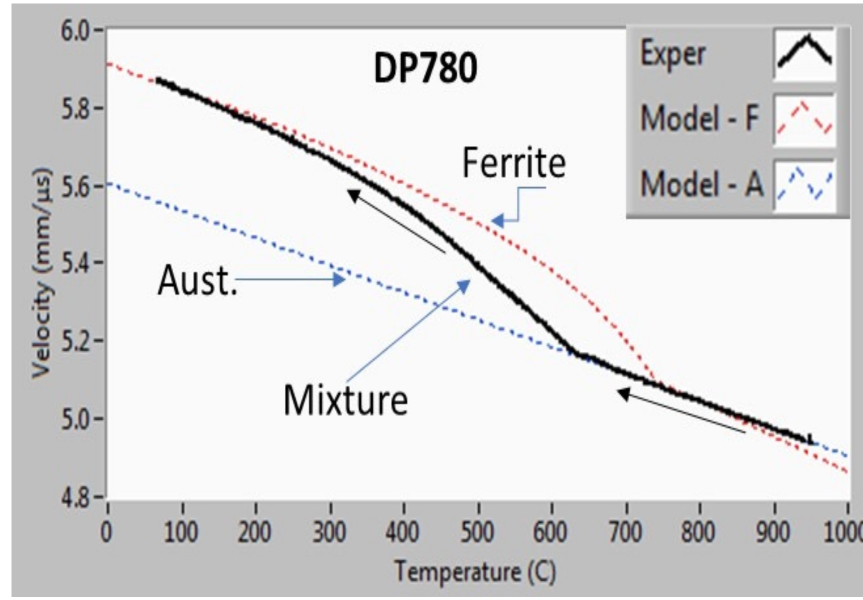
### Dilatometry




### Laser ultrasound @ -5 C/s



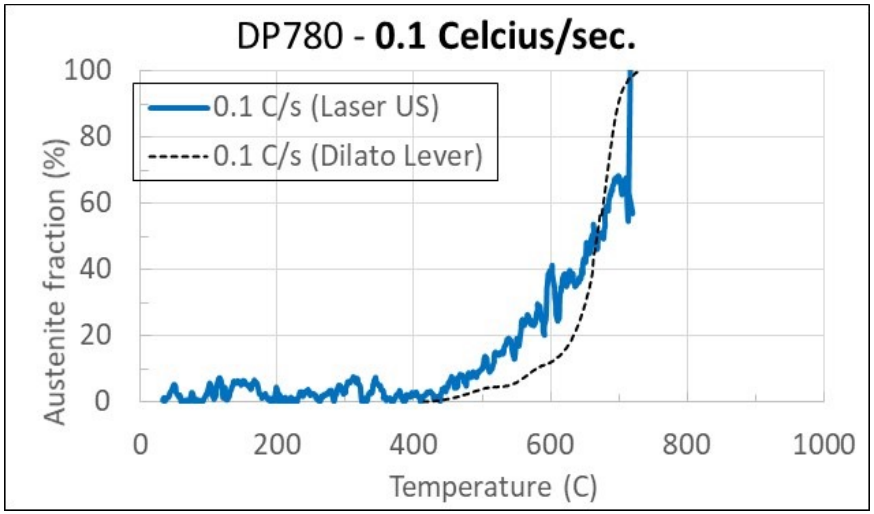

- ***Remark:*** *cooling of DP780 leads to ferrite and probably to pearlite and martensite (no metallography was done). But for sake of simplicity of the present analysis, only pearlite and ferrite are considered.*

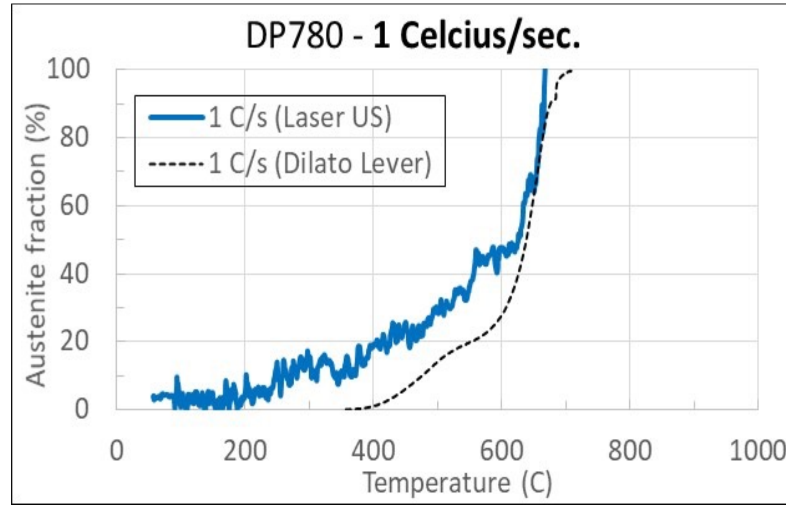
**Experimental results**

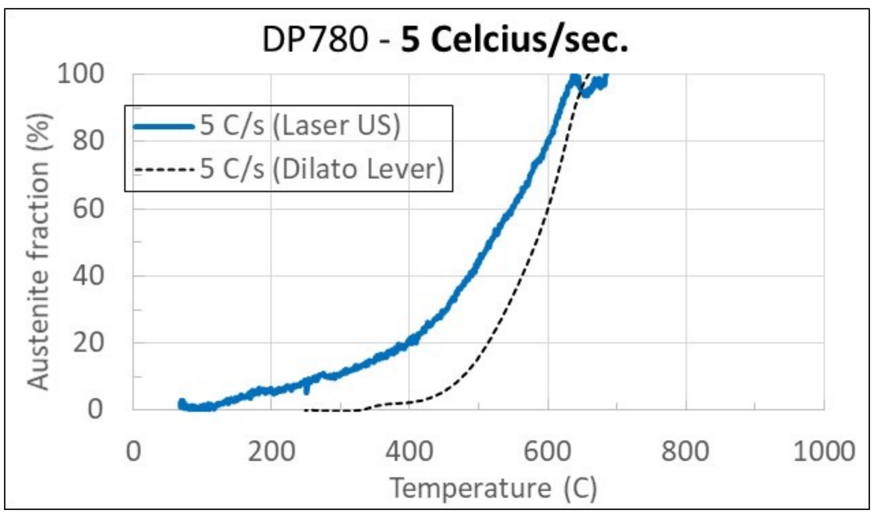
# Dilatometry **without** correction (Lever rule) vs Laser Ultrasound – **DP780**

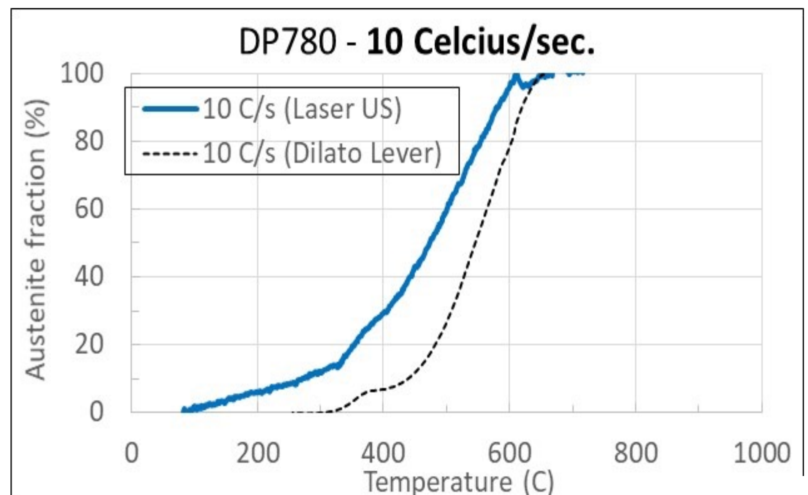
Laser US
Dilato Lever Corrected





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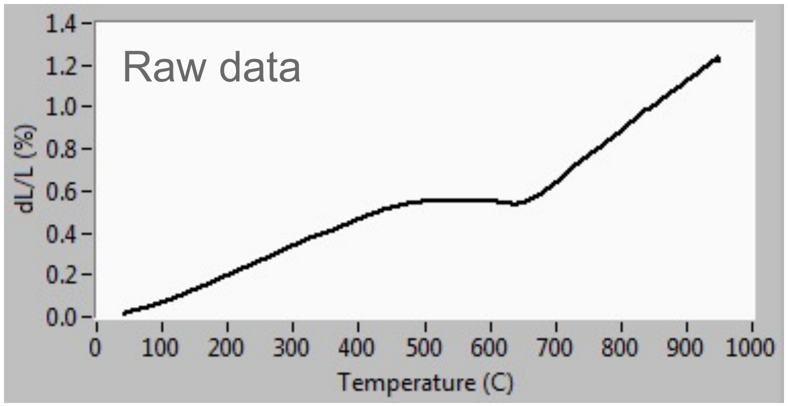
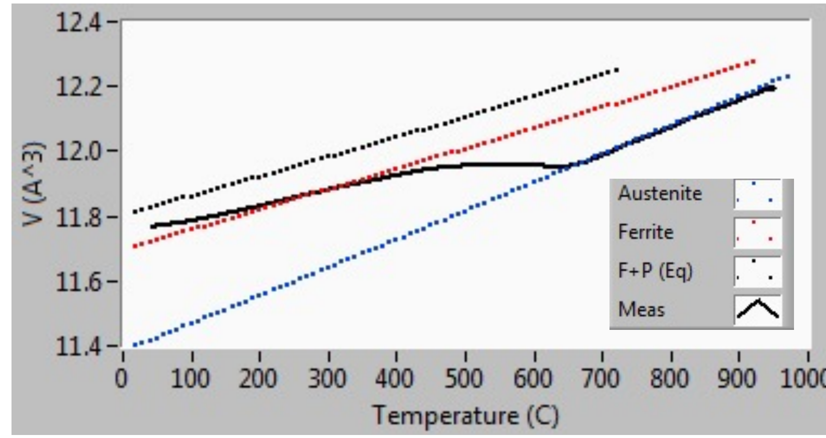
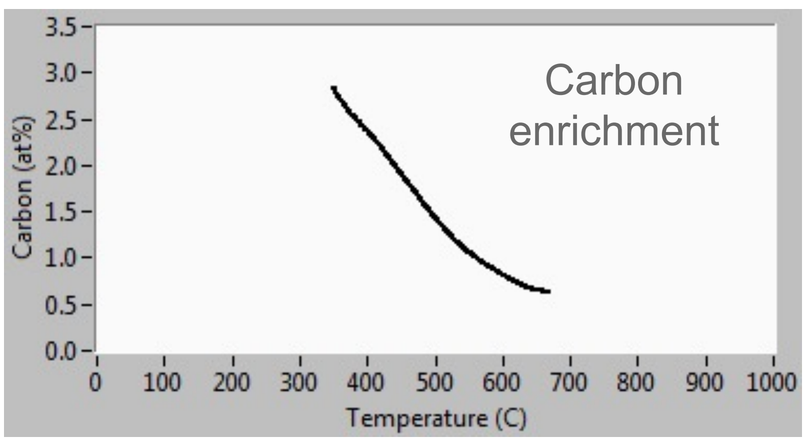
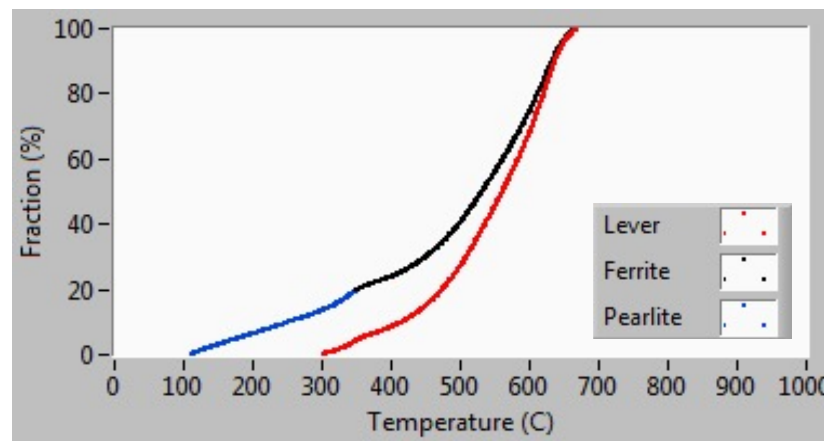
# Dilatometry **with** correction: DP780 @ -5 C/s





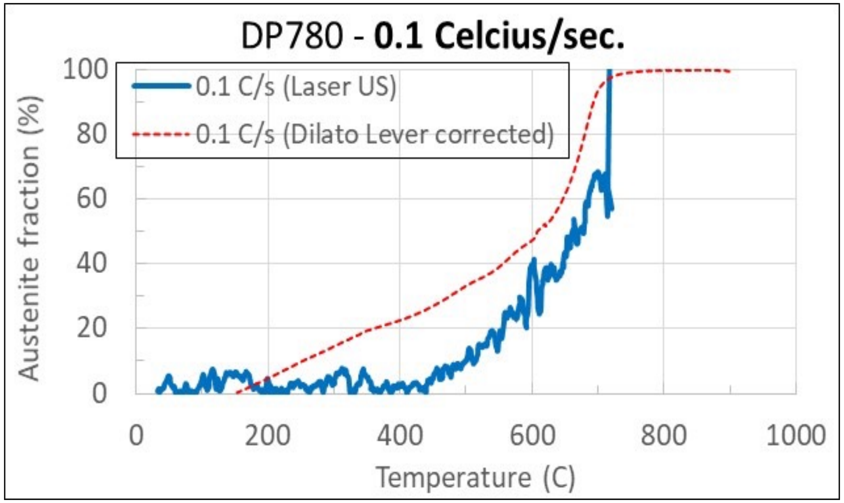

For DP780: 0.136 wt% or 0.63 at%

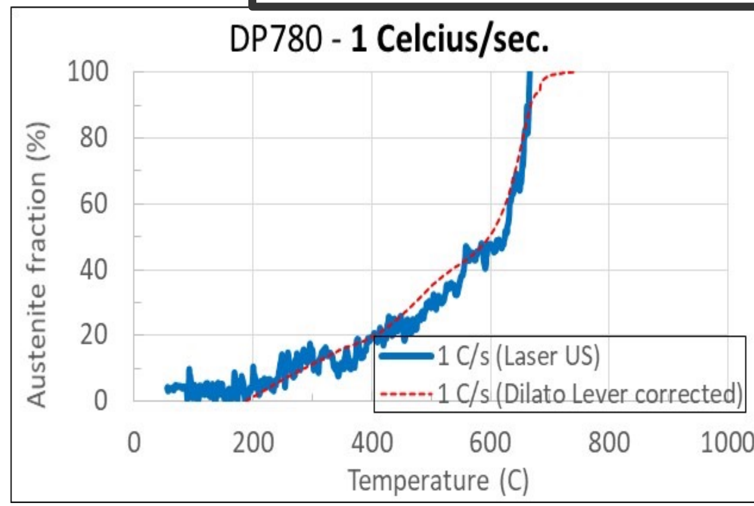
End of stage 1: Ts= 350ºC, C=2.82 at%
End of transfo : P=20%, F=80% (as expected)

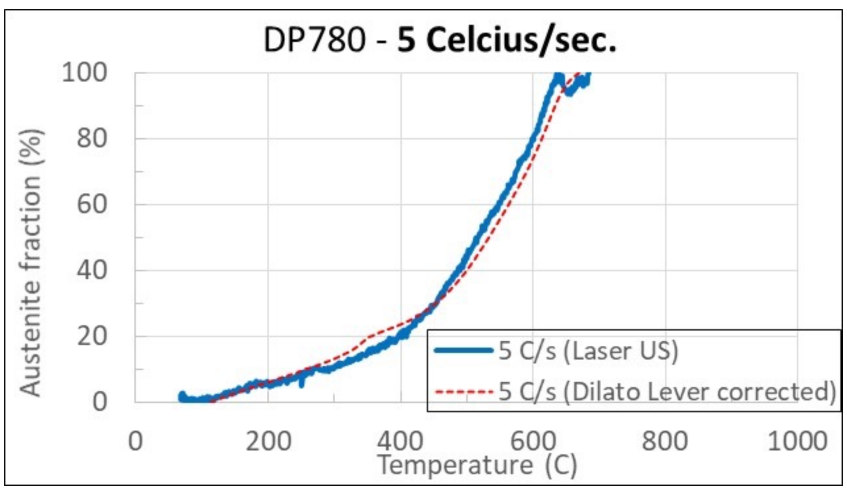
# Experimental results

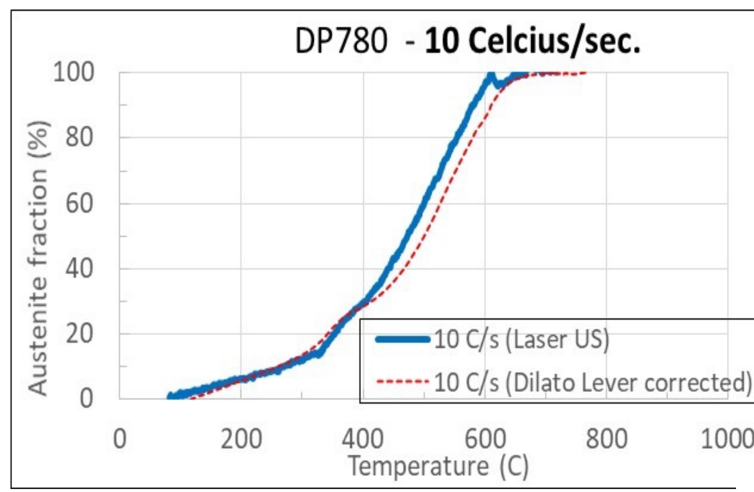
# Dilatometry **with** correction vs Laser Ultrasound – **DP780**

Laser US
Dilato Lever Corrected



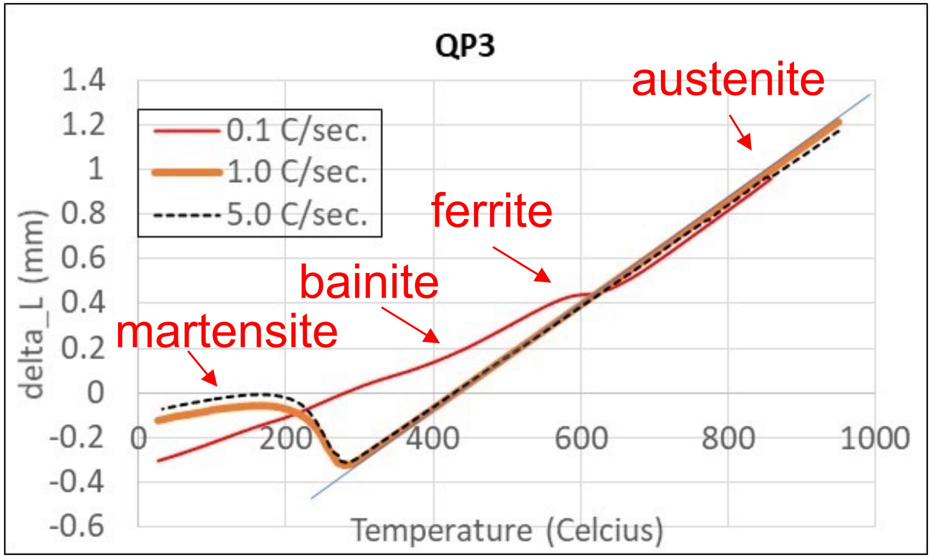



# Experimental results

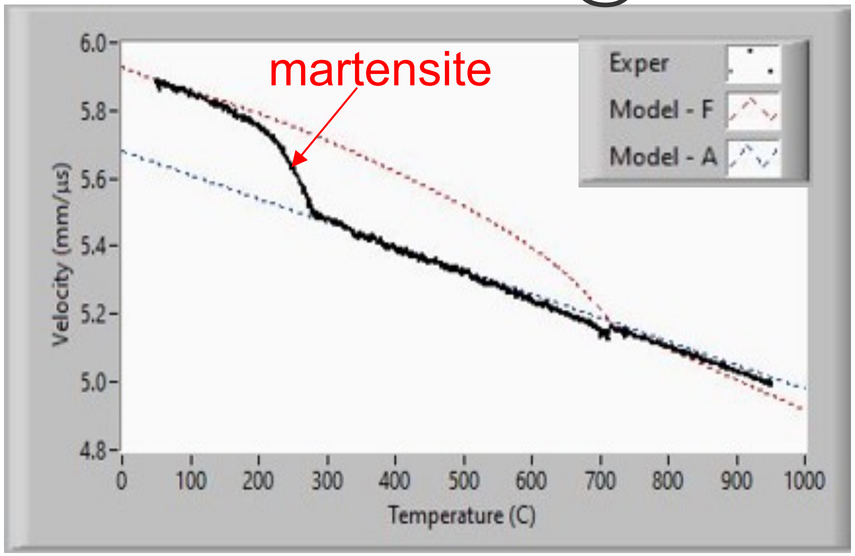
## QP grade



Dilatometry




Laser ultrasound @ -5 C/s



# Experimental results

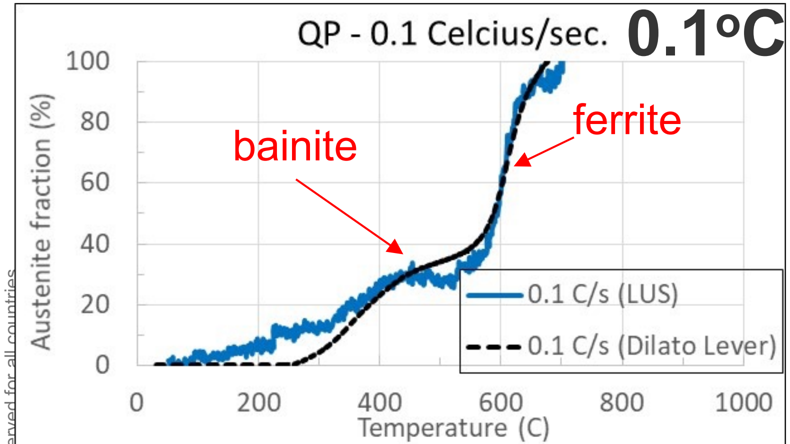
## QP grade

**Dilato. Lever Rule**

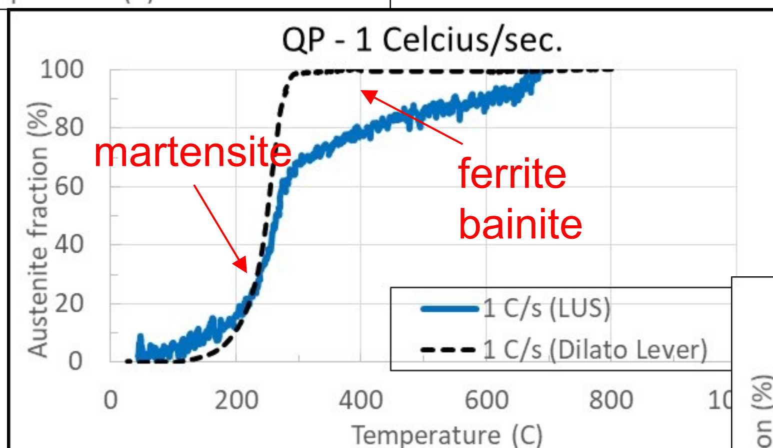
Vs

**Laser Ultrasound**

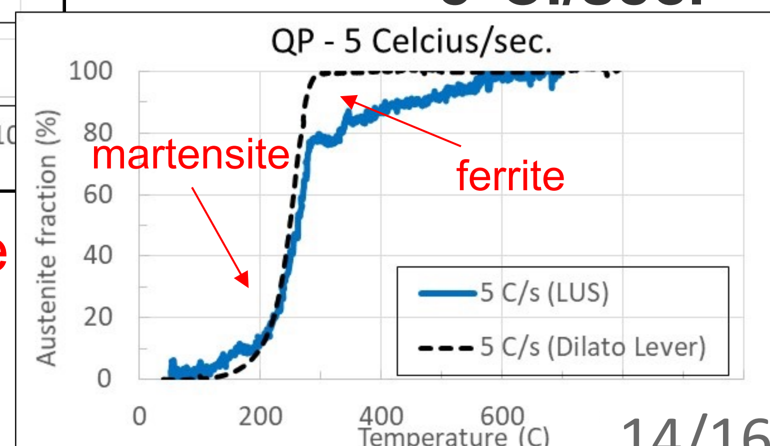
**$0.1^oC$./sec.**




**$1^oC$./sec.**




**$5^oC$./sec.**




**NO correction** for lever Rule Martensite because **NO enrichment of Carbon** in Austenite.

# Experimental results

## QP grade results

## Metallography

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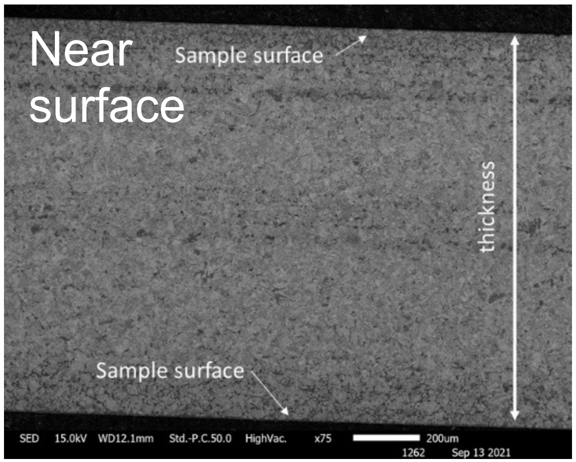
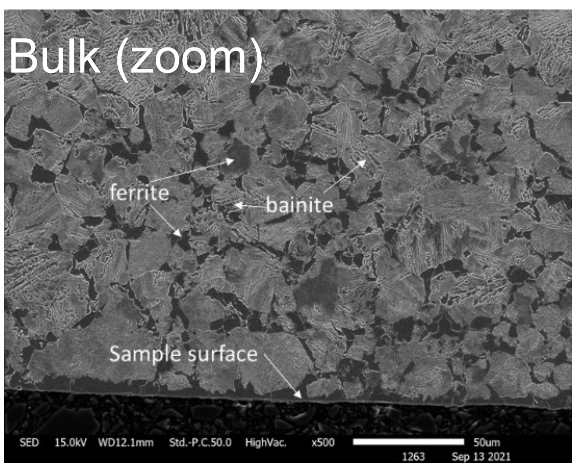
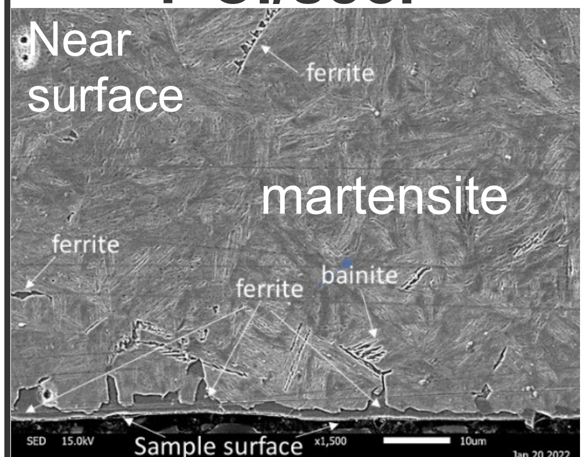
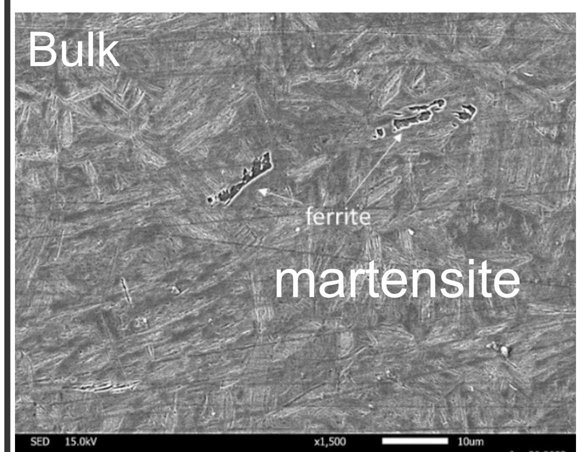
### 0.1°C./sec.



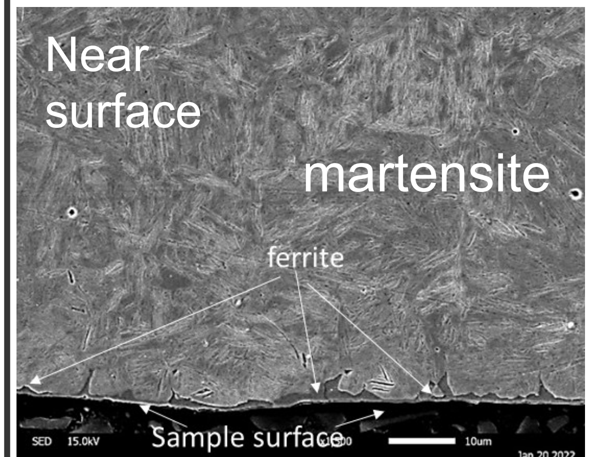



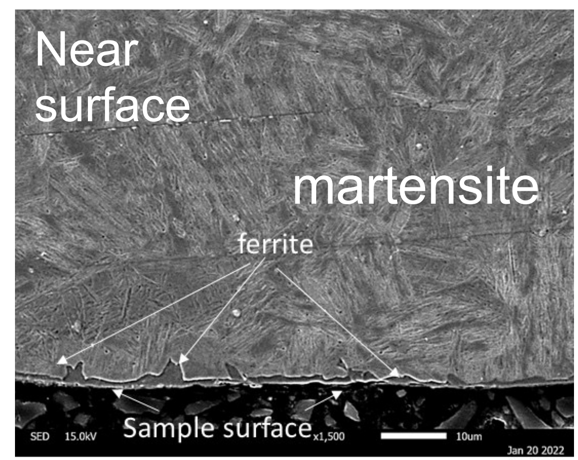

### 1°C./sec.




### 5°C./sec.



# 4- Conclusions

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- **DP780 grade:** classic **Lever rule method** needs correction to consider **Carbon enrichment in Austenite (**1, 5, 10 °C/sec. (unclear for 0.1 °C/sec.) and be in agreement with **Laser US**.

- **QP grade:**
  - Prior to martensite formation, **Laser ultrasound** detects **ferrite and bainite formation (confirmed by metallo.),** while the **classic Lever Rule method (dilato.) does not.**

  → **The classic Lever Rule method** can be improved by considering a **calculated volume change** instead of measured slope.

  - Both **laser ultrasound** and **classic Lever Rule monitor martensite formation correctly** *(NB: The Classic Lever rule does not need correction because NO Carbon enrichment).*