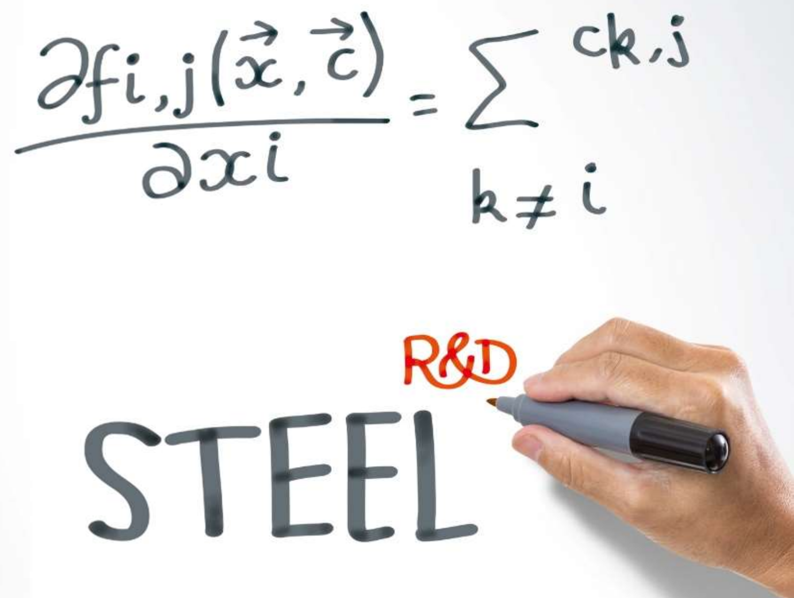
LUS Development for Microstructure Monitoring during Annealing

Global Research and Development

7th Workshop on Laser-Ultrasound for Metals



21/05/2026

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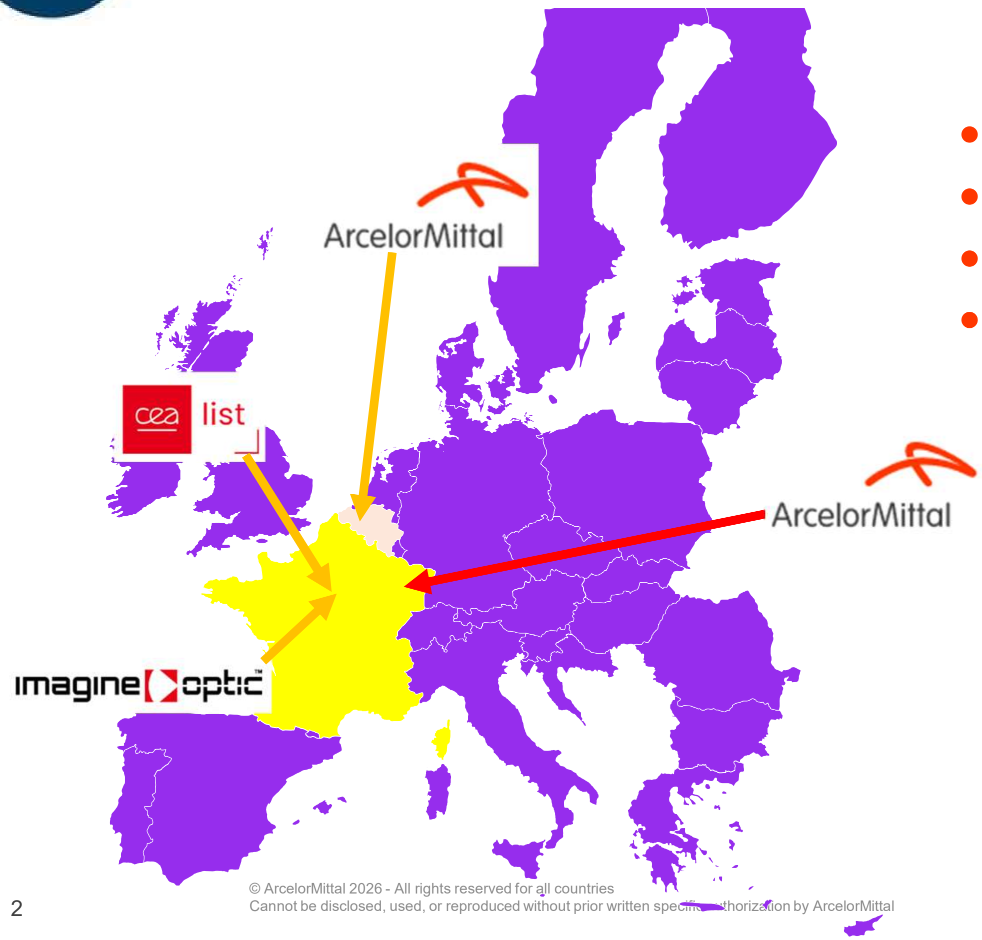
C. Kerschbaummayr, C. Gruensteidl, E. Scherleitner

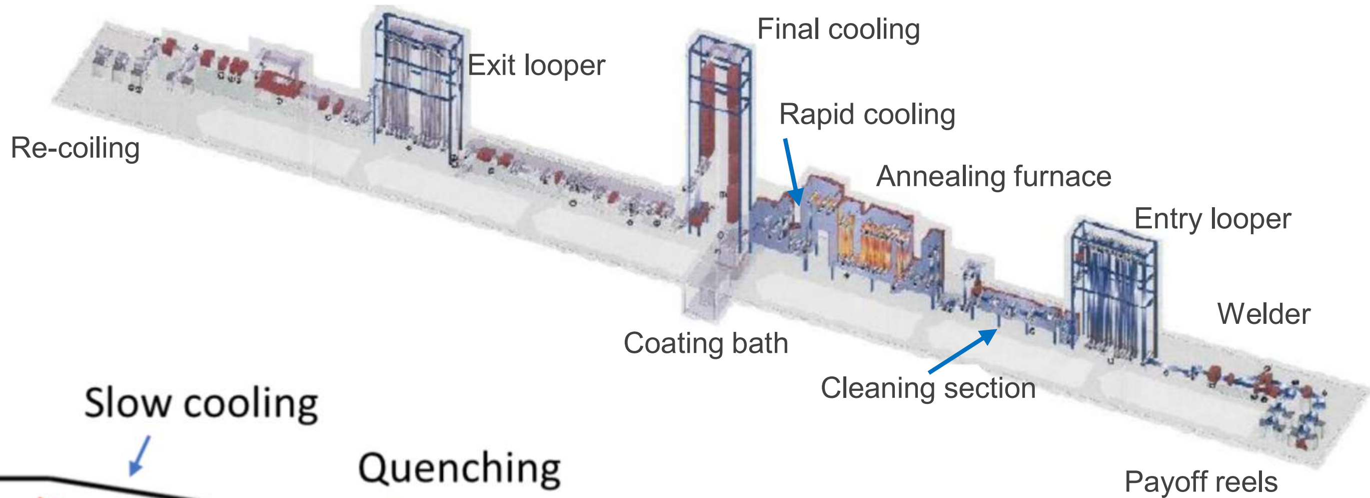
Monitoring Metallurgical Properties of Strips inside Annealing Furnace with Laser Ultrasonics

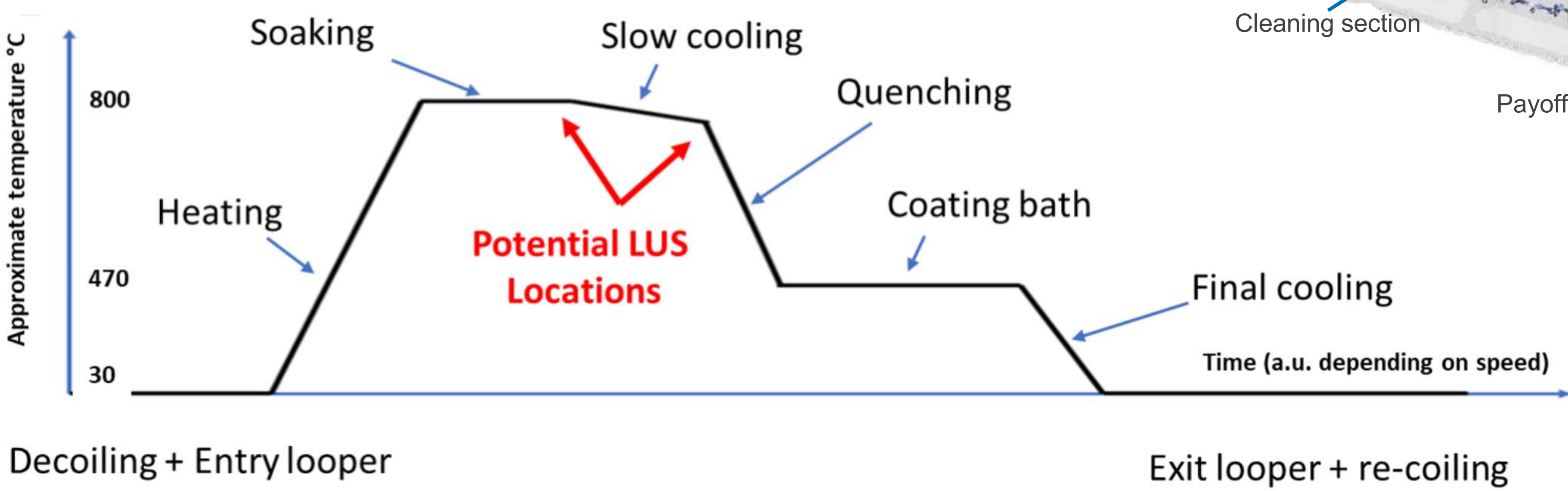


- **RFCS Project 101157601 (ANNEAL-LUS)**
- Coordinator: Philip MEILLAND
- Start date: 01/07/2024
- End date:31/12/2027

Co-funded by the European Union

Context – Objectives (I)





Typical thermal cycle in an annealing and galvanizing line
Objective to check if thermal (energy) path up to soaking / slow cooling allows reaching adequate metallurgical features before quenching

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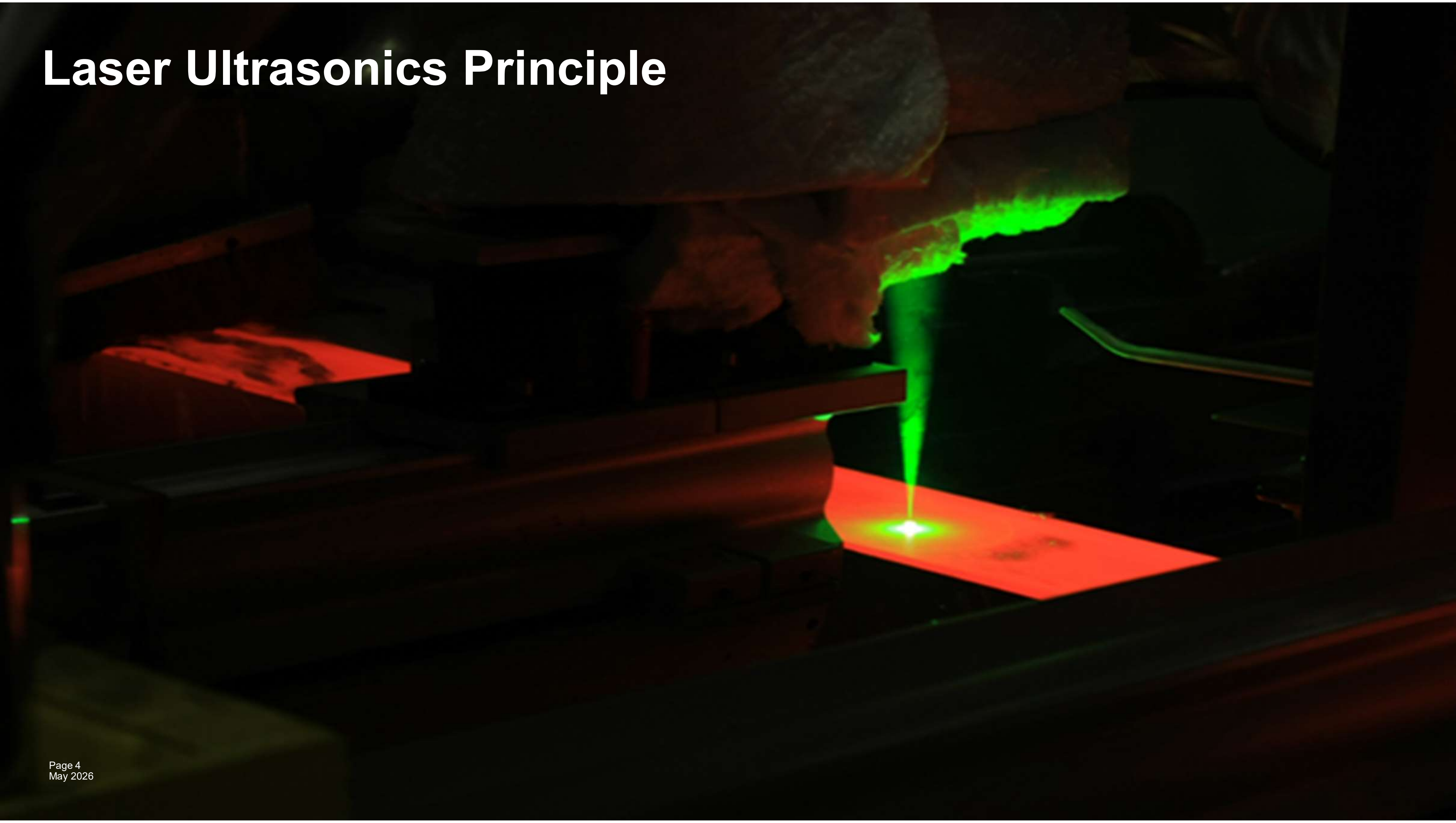
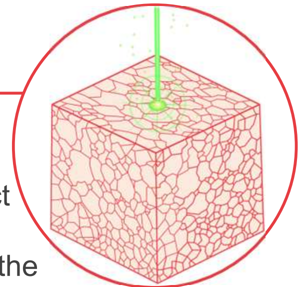
Laser Ultrasonics Principle

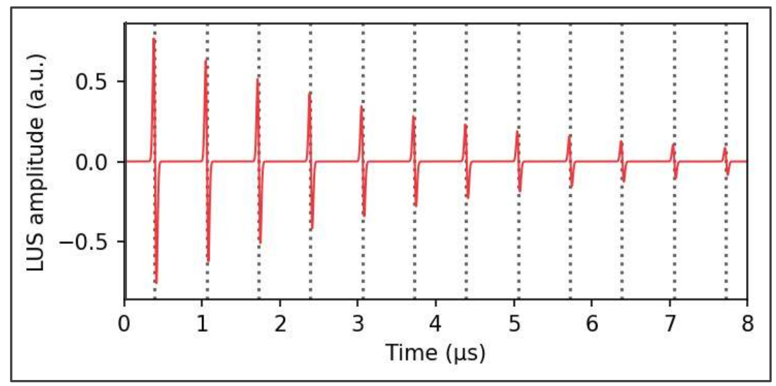


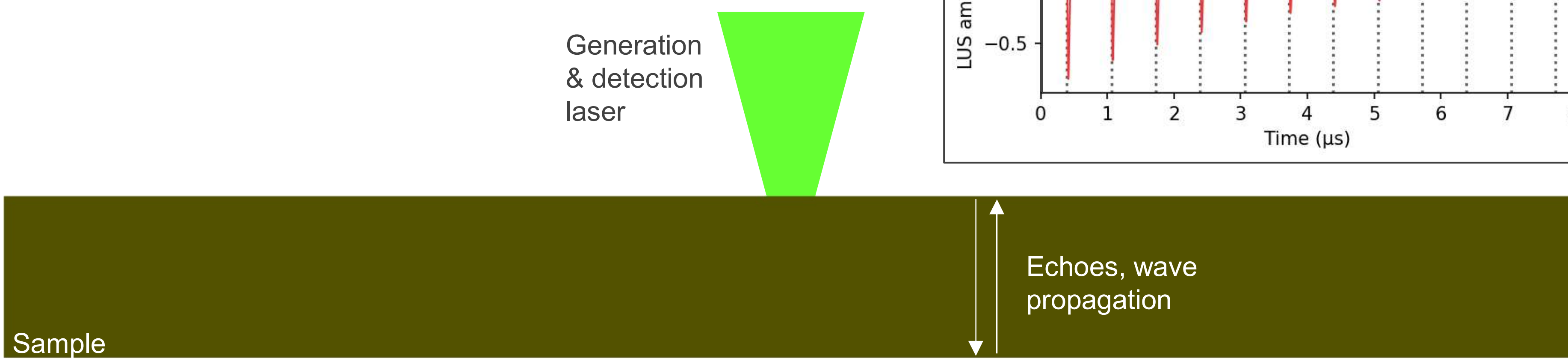
Laser Ultrasonics Evaluation of Metallurgical State



Laser ultrasonics is a non-contact technique used to generate and detect ultrasonic waves in materials. Here's a brief overview of how it works:

1. Generation of Ultrasound: A high-energy laser pulse is directed onto the surface of the material. This pulse can generate ultrasound through two main mechanisms: Thermoelastic Expansion, Ablation
2. Detection of Ultrasound: A second laser, often a continuous-wave laser, is used to detect the ultrasonic waves. The surface vibrations caused by the ultrasonic waves modulate the laser light, which is then analyzed to extract information about the material.





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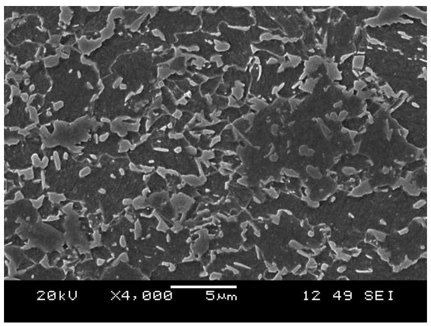
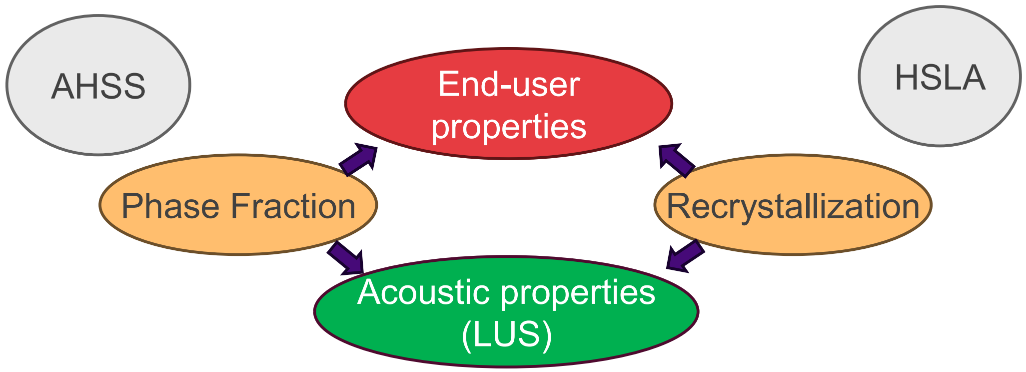
Context – Objectives (II)

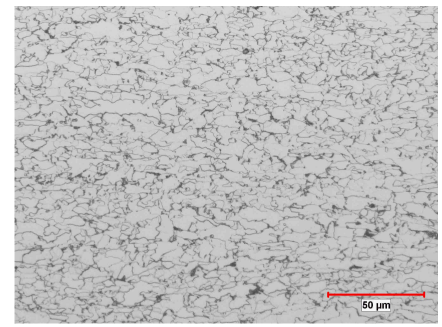
Purpose to improve control of end-user properties at annealing stage

DP780





HSLA420



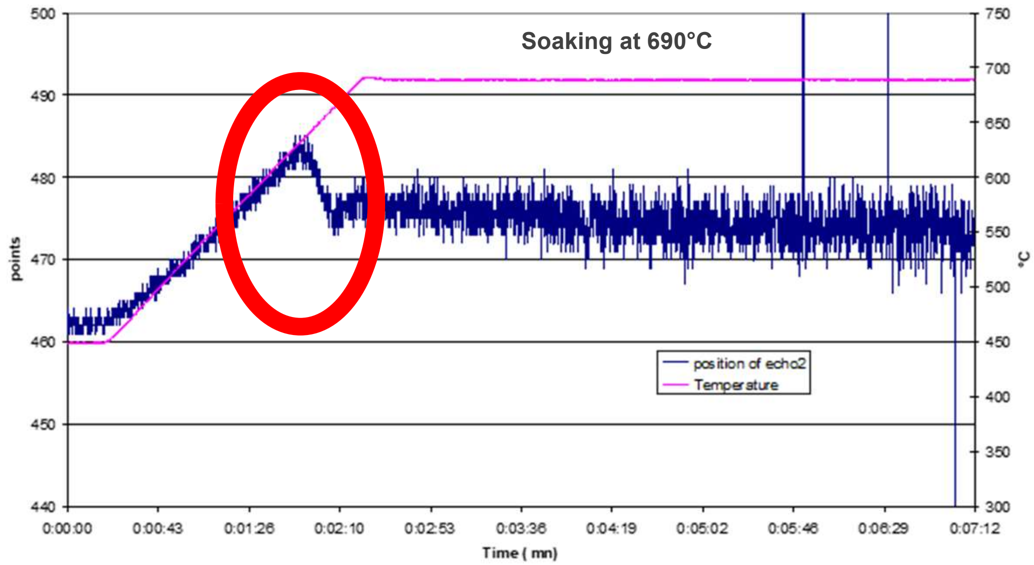
- Non-reversible transformations
  - **Advanced High Strength Steels (AHSS): Austenite fraction at soaking end is of prime importance**
  - **High Strength Low Alloy (HSLA): Recrystallization (Rex) expected to be main impacting factor at soaking end**

Acoustic properties accessible at high temperature with LUS are expected to provide information of metallurgical phenomena :

- c_L, velocity of pressure (longitudinal) waves
- c_T velocity of shear (transverse) waves
- Attenuation

From literature, effect of recrystallization on pressure wave velocity

Evolution of P-wave time-of-flight* with recrystallization for IF steel ***time of flight = $2d/c_L$**

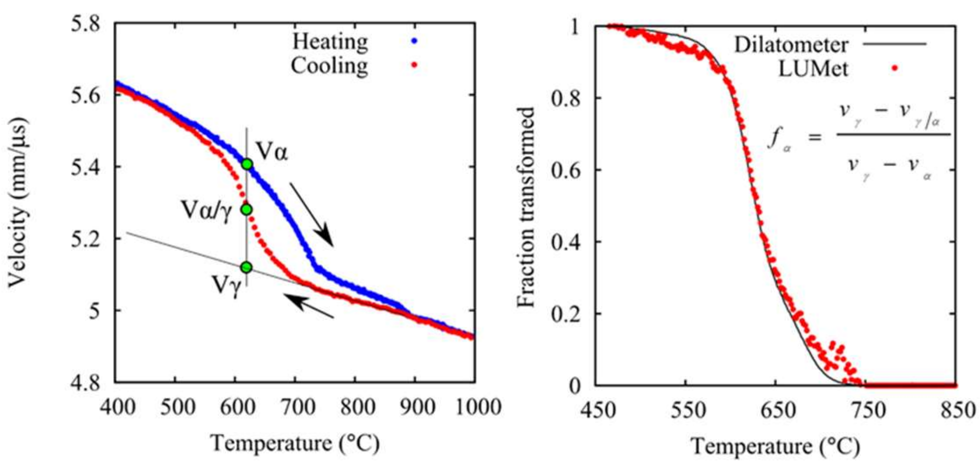


- Impact of recrystallization : inversion of the trend during heating in the range 620°C – 680°C
- Associated to a change in texture (crystalline orientation distribution function)
- Known to be a sluggish metallurgical transformation

- *European Commission, Directorate-General for Research and Innovation, Midroit, F., Damoiselet, F., Nogues, M., New approaches to non-destructive characterisation of microstructure and applications to online control of steel quality (NANDACS), Publications Office of the European Commission, 2006*

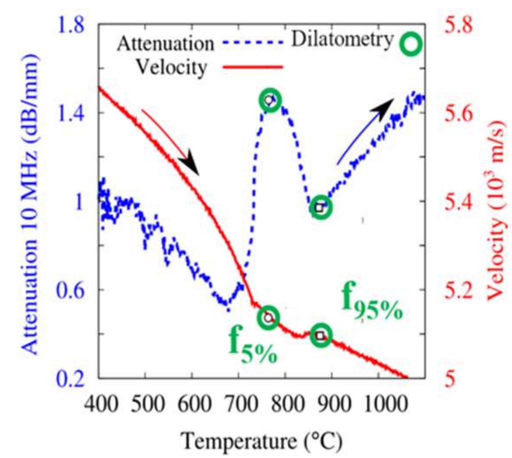
From literature, effect of phase transformation on pressure wave velocity

Evolution of P-wave velocity below Curie Point
during heating / cooling (DP 780)



European Commission, Directorate-General for Research and Innovation, Satyanarayan, L., Legrand, N., Meilland, P., et al., *Combined online microstructure sensor and model for better control of hot rolling conditions and final products Properties (phase 2) (MicroControl-PLUS) : final report*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2848/836170

Evolution of P-wave attenuation above Curie point
(pipeline steel)



Millitzer M., Garcin T., Kulakov M., Poole W., Laser ultrasonics for in-situ monitoring of microstructure evolution in steels,
Proceedings of the 5th Baosteel Biennial Academic Conference, Beijing, China, 2013.

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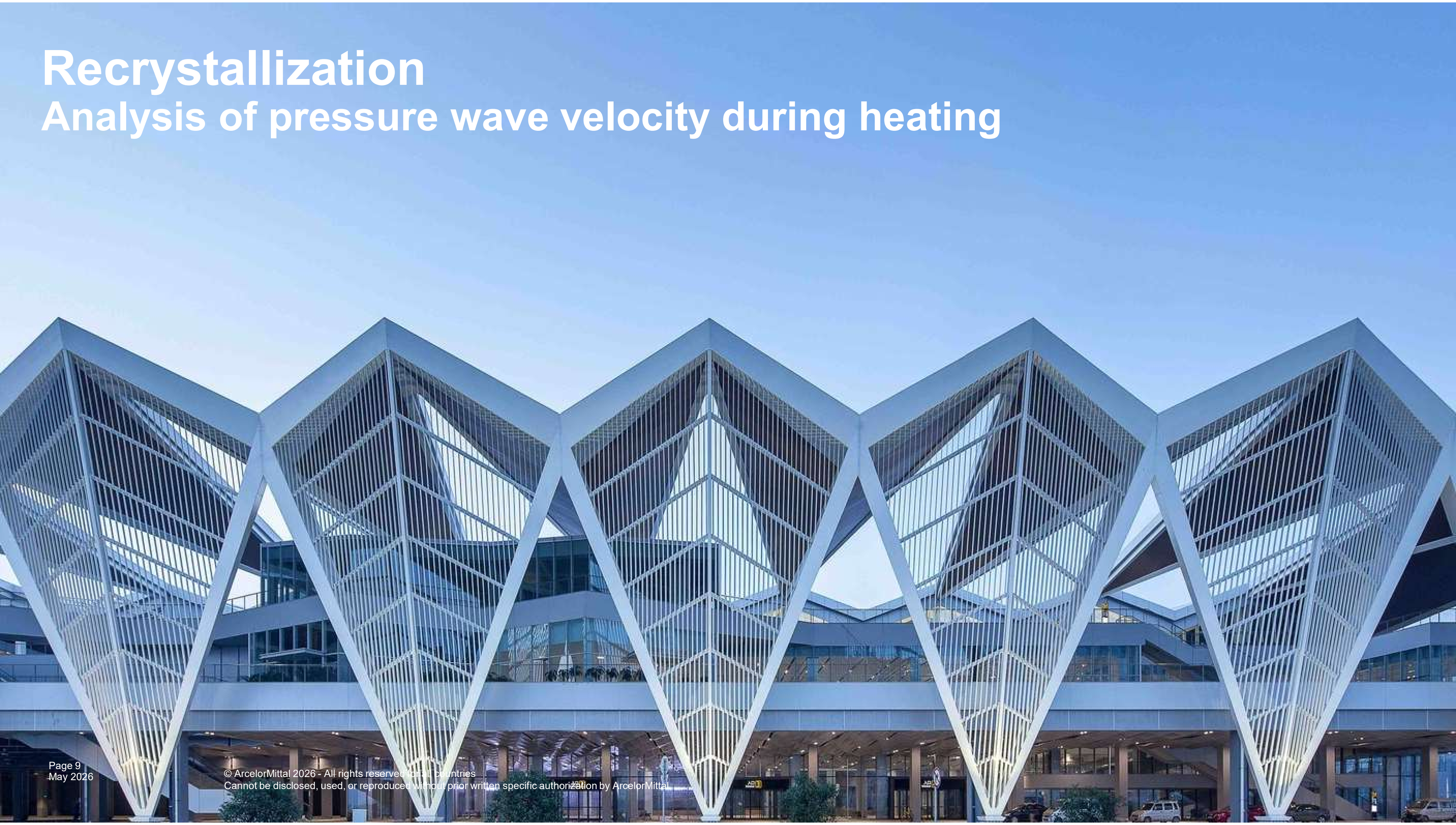
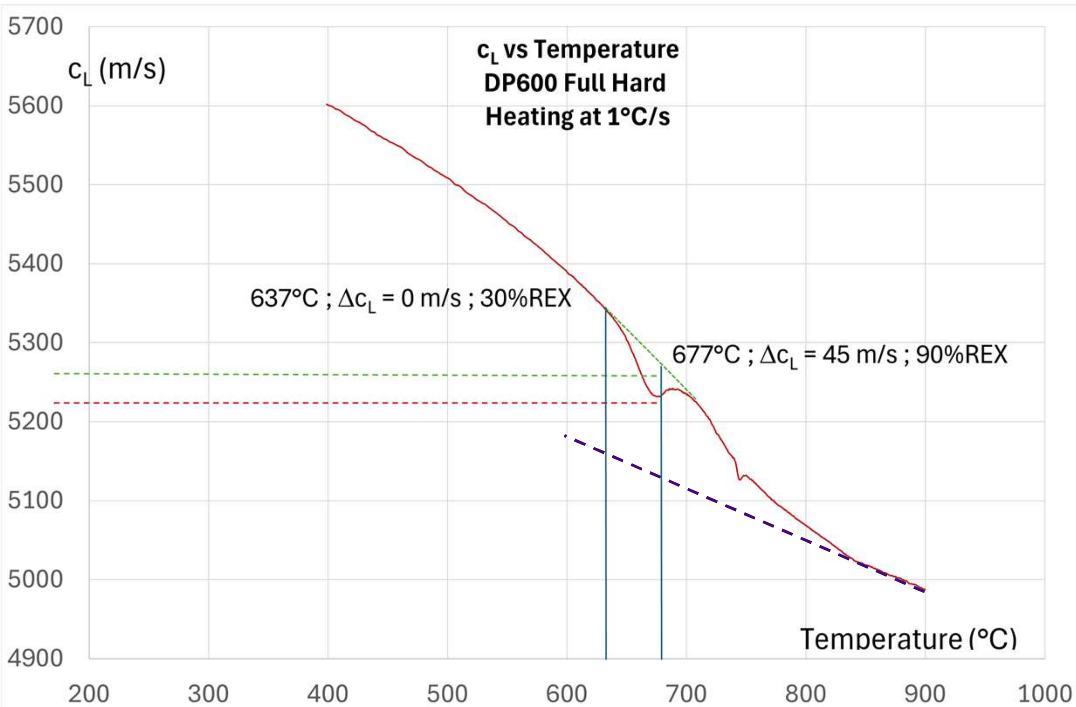
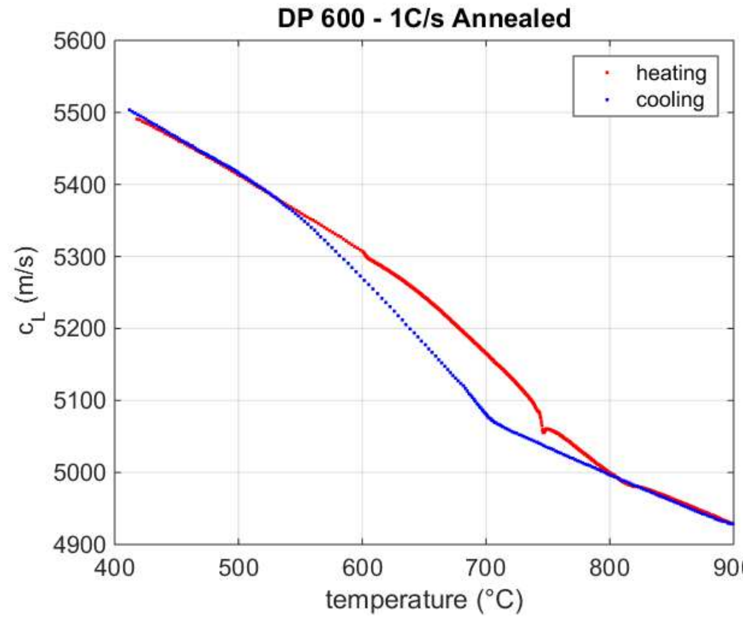
Recrystallization
Analysis of pressure wave velocity during heating



Experimental results : Recrystallization





- Local minimum appearing for full hard material at 673°C, but not on annealed material
  - Confirmed with metallurgical investigations (quench-interrupted cycles and EBSD)
  - Most likely dependent on heating rate (recrystallization is sluggish)

Consistent with literature : Militzer M., Garcin T., Poole W., **In-situ measurements of grain growth and recrystallization by laser Ultrasonics,** *Materials Science Forum, Vol. 753, pp 25-30, 2013, doi:10.4028/www.scientific.net/MSF.753.25*

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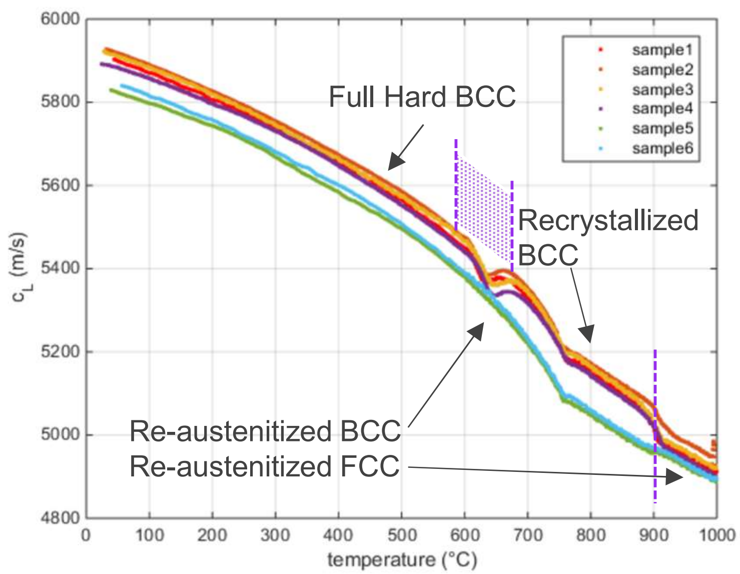
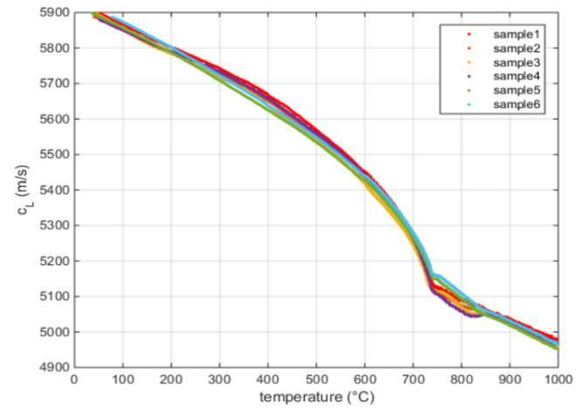
Experimental results : Recrystallization

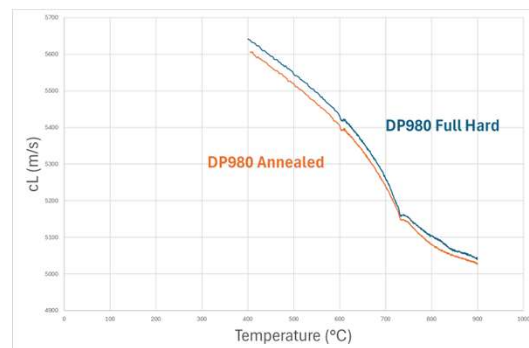
HSLA 240



HSLA 460



DP 980



- Local minimum appearing for full hard HSLA 240, at ~650°C,
  - ~40 m/s difference between Full Hard and Annealed HSLA 240 at T< 600°C could be explained by difference in texture (Crystalline Orientation Distribution Function), Investigations required to confirm hypothesis
  - Presence of 3 different textures : Full Hard (below 600) ; 1st Recrystallization (Full Hard between 700 and 900°C) ; Re-austenitized

- **No visibility at all on HSLA 460 – DP980**
  - Is there a significant texture for full hard product in these grades?
  - How does austenite formation interfere with recrystallization process?
    - Thermodynamic calculations show austenite is expected to appear and grow at lower temperatures than for HSLA240

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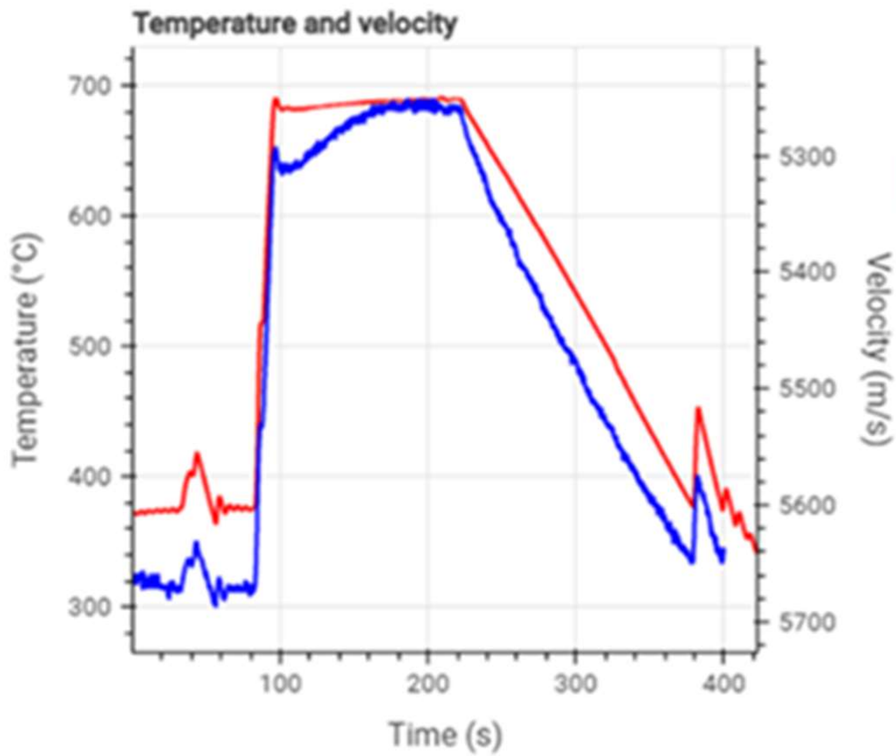
Experimental results : Sluggish behaviour of Recrystallization

Evolution of P-wave velocity
with recrystallization for HSLA 240



~60s drag in P-wave velocity before reaching asymptote, matching almost complete recrystallization

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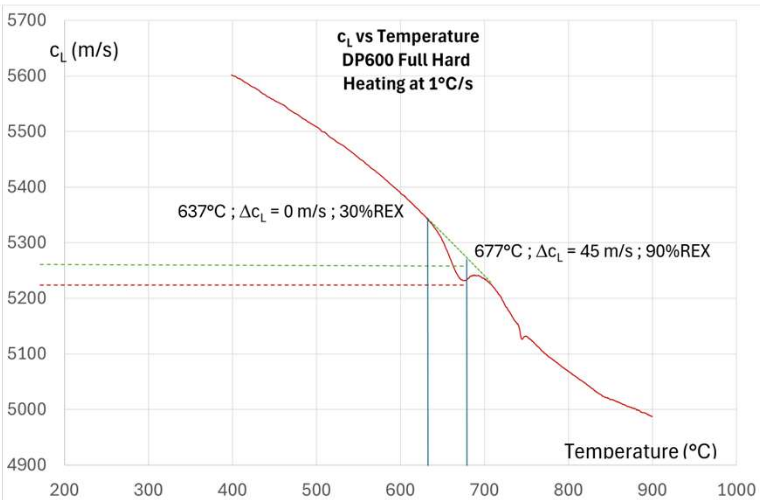
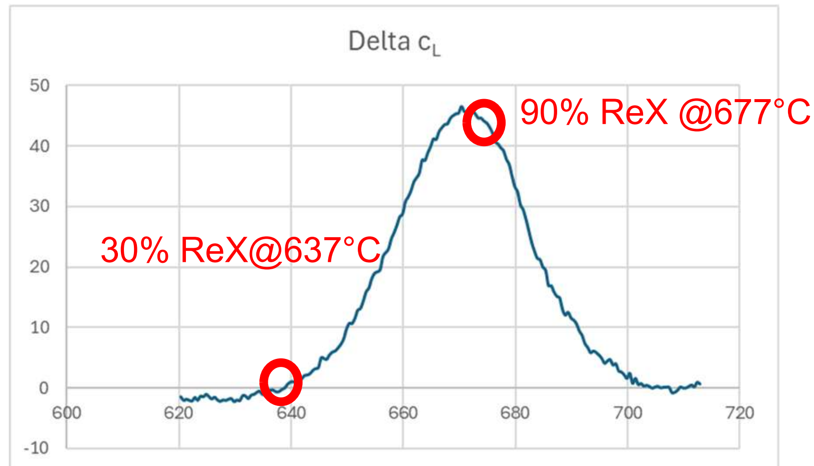
Estimation of recrystallization





- No sensitivity up to 30 % ReX?
- Non monotonous effect with a maximum amplitude apparently for ReX rate of ~90%

Grade	IF	HSLA 240	DP600*	HF1180*
Max Δc_L (m/s)	50	50	45	22
Temperature (°C) for Max Δc_L	720	635	673	685

* Recrystallization is not the actual metallurgical target for DP600 and HF1180

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CONCLUSIONS and next steps for HSLA recrystallization monitoring

- Pressure wave velocity c_L displays evidence of recrystallization
- Presence of a particular trough at around 673°C for DP600
  - 90% Recrystallization at 677°C checked for DP600
  - c_L features high monotonous sensitivity in the 90 – 100% recrystallization range
- **Seems well fitted to allow guaranteeing 95% recrystallization rate**
- Need to customize model behaviour to each grade / heating rate
  - Sluggish behaviour of recrystallization process

- Finalize investigations for all HSLA grades for which recrystallization is the primary target

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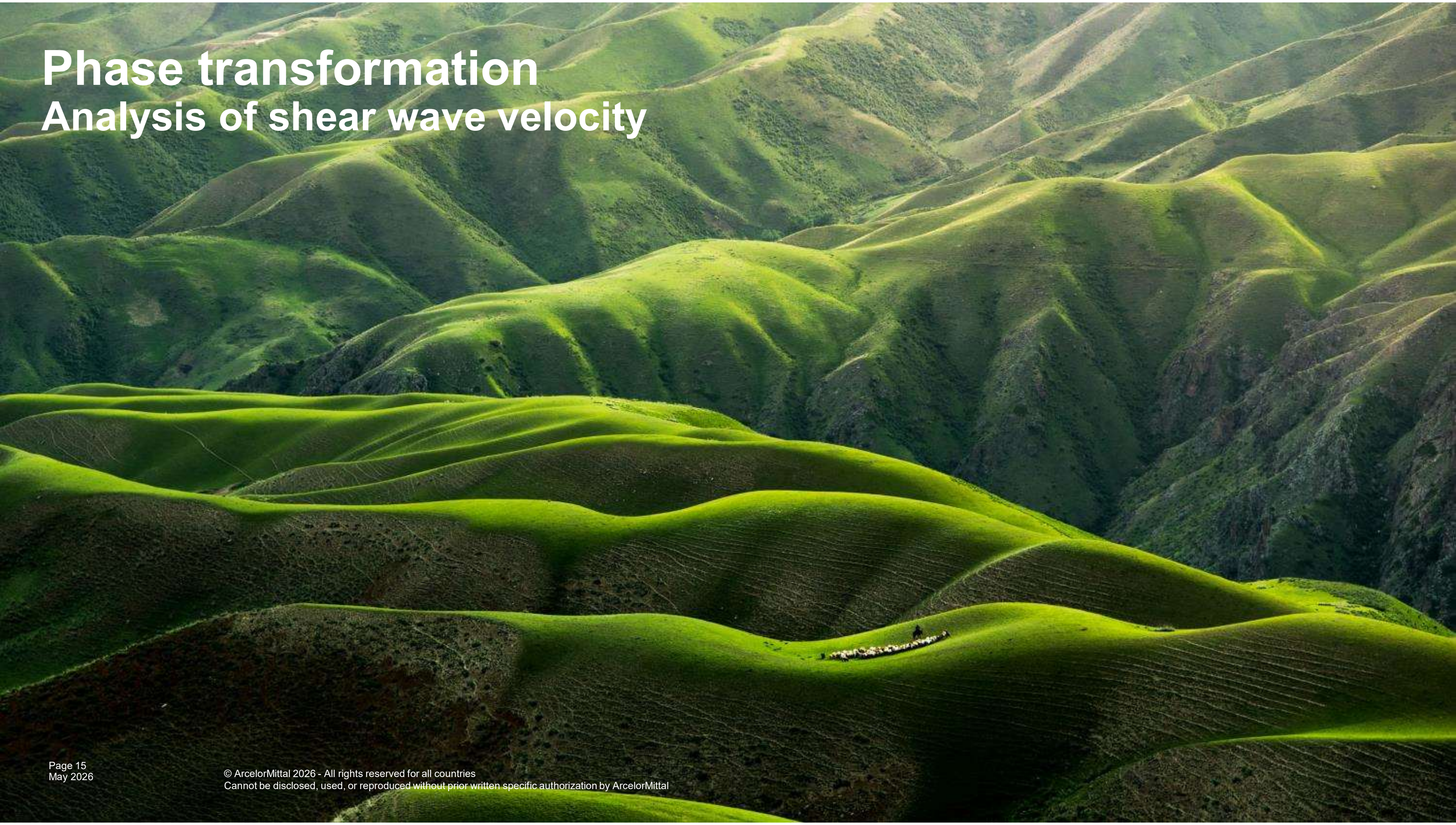
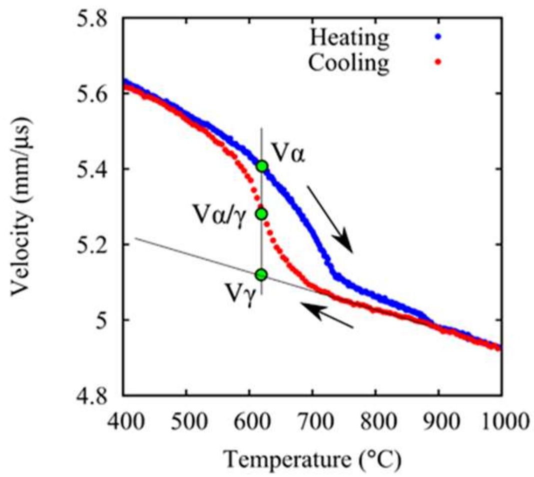
Phase transformation
Analysis of shear wave velocity



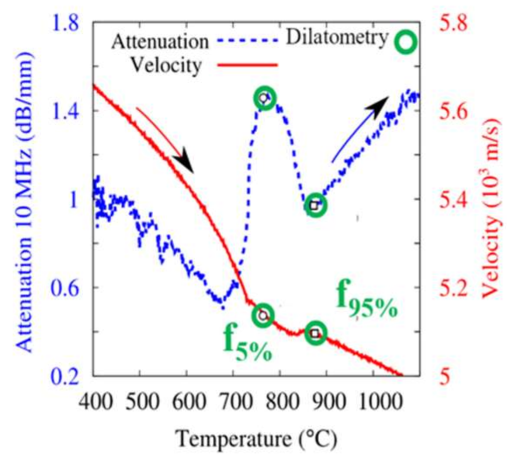
Pressure wave velocities of BCC and FCC iron are almost equal above Curie point

Evolution of P-wave velocity below Curie Point during heating / cooling (DP 780 at Gleeble)



European Commission, Directorate-General for Research and Innovation, Satyanarayan, L., Legrand, N., Meilland, P., et al., *Combined online microstructure sensor and model for better control of hot rolling conditions and final products Properties (phase 2) (MicroControl-PLUS) : final report*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2848/836170

Evolution of P-wave attenuation above Curie point (pipeline steel)



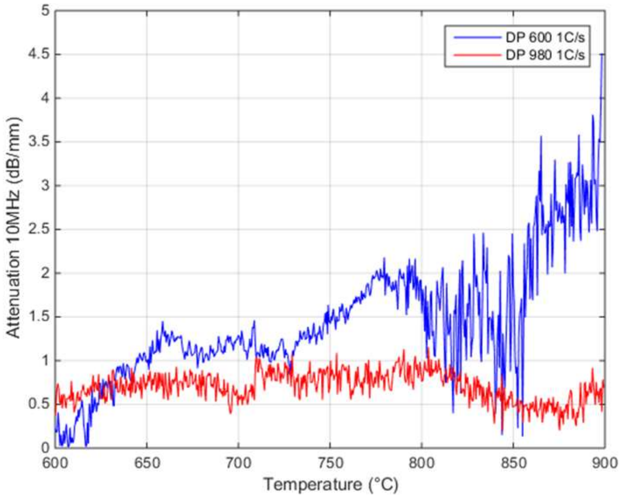
Millitzer M., Garcin T., Kulakov M., Poole W., Laser ultrasonics for in-situ monitoring of microstructure evolution in steels,
Proceedings of the 5th Baosteel Biennial Academic Conference, Beijing, China, 2013.

In all cases for AHSS, soaking temperature is in the intercritical domain, above 750°C

=> Focus on P-wave attenuation in a first step

Experimental results : Attenuation vs Phase transformation

Evolution of P-wave attenuation for DP600 & DP980 during heating at 1°C/s



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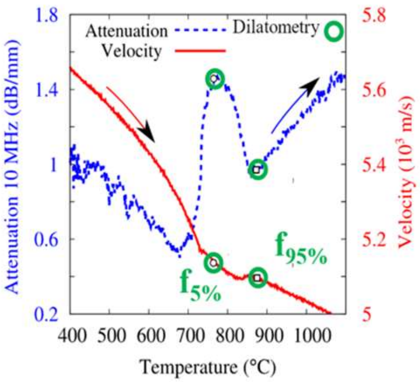


Millitzer M., Garcin T., Kulakov M., Poole W., Laser ultrasonics for in-situ monitoring of microstructure evolution in steels, Proceedings of the 5th Baosteel Biennial Academic Conference, Beijing, China, 2013.

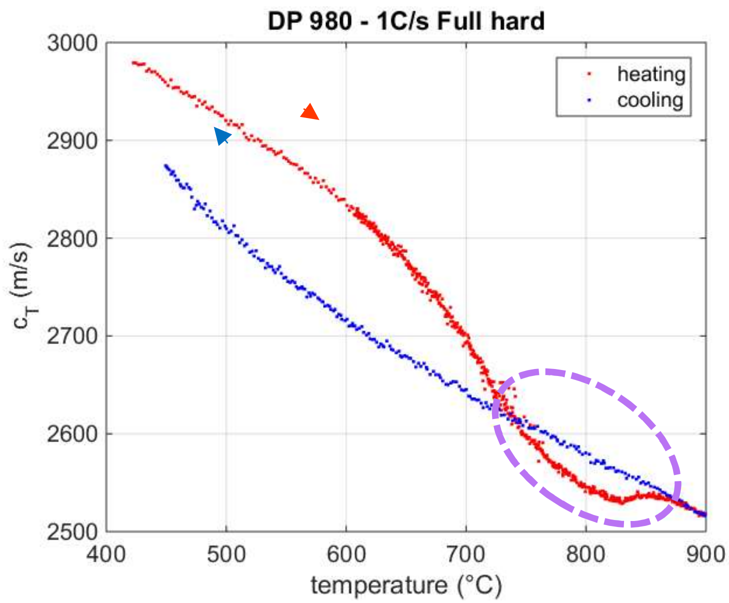
No observable attenuation peak corresponding to phase transformation in DP600 and DP980

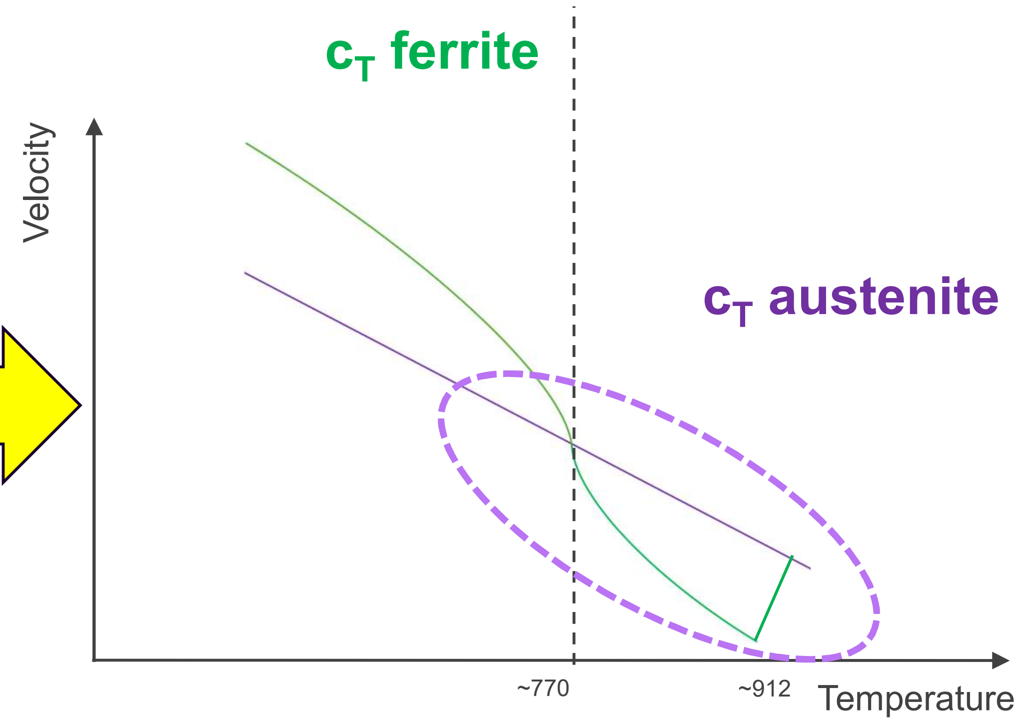
- Alternative found with the analysis of Zero Group Velocity waves
  - Stationary guided waves generated and detected with the same LUS set-up

Waltz G., Kerschbaummayr C., Schagerl M., Mitter T., Sonderegger B., Grünsteidl C., **In situ laser-ultrasonic monitoring of Poisson's ratio and bulk sound velocities of steel plates during thermal processes**, Acta Materialia 235 (2022) 118097, https://doi.org/10.1016/j.actamat.2022.118097

ZGV technique to derive shear wave velocity

Evolution of shear wave velocity for DP980





During cooling, phase transformation is retarded by boron (in DP980)
Behaviour of c_T above Curie point suggests sensitivity to phase transformation

Hypothesis on the evolution of shear wave velocity for pure iron

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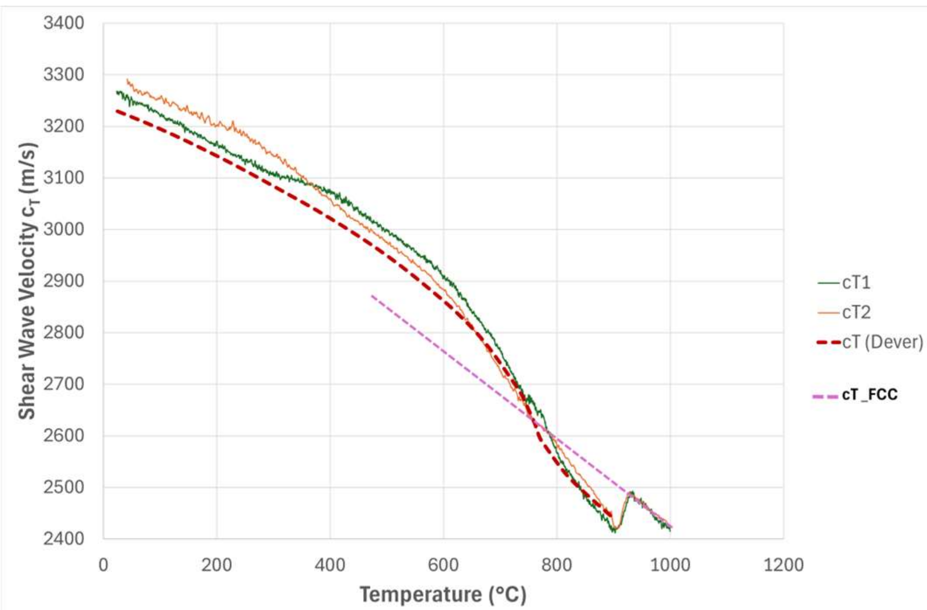
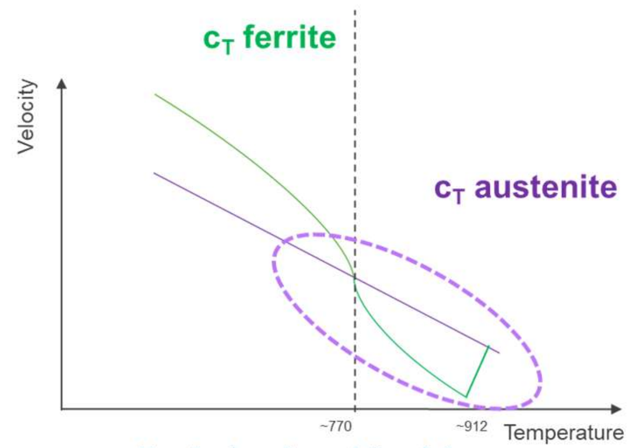
Model Ferritic material (BCC up to ~900°C) ? => ULC steel

- Ultra Low Carbon Steel (packaging applications), as hot-rolled
  - Slightly higher alloy content; BCC → FCC transition 907°C to 927 °C (slightly lower than for pure iron)
  - As hot rolled : last rolling pass is in full FCC domain, leading to a supposed (almost) isotropic BCC microstructure
  - Very good fit obtained for shear wave velocity vs temperature 😜, confirming assumption in preceding slide





Hypothesis on the evolution of shear wave velocity for pure iron

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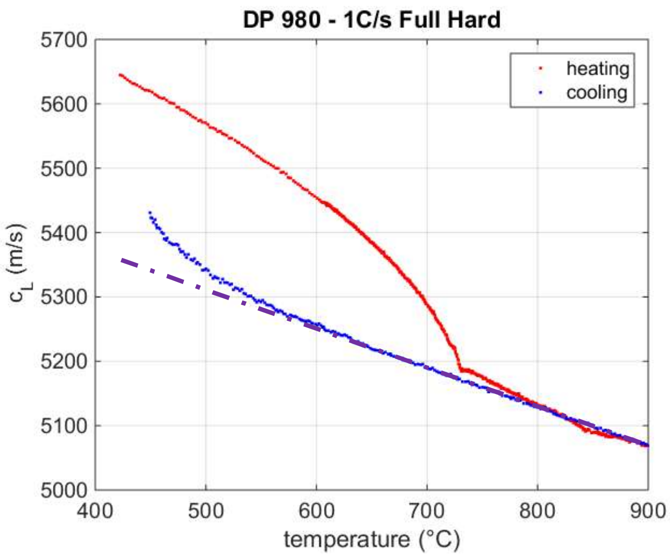
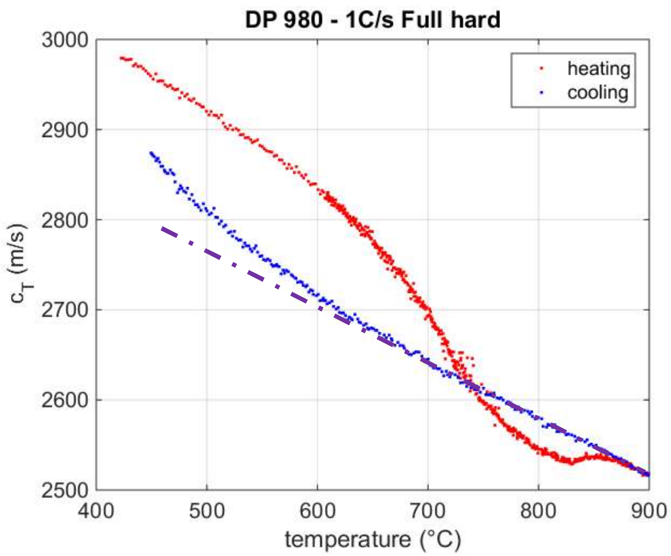
Model Austenitic material (FCC, down to 700 °C)

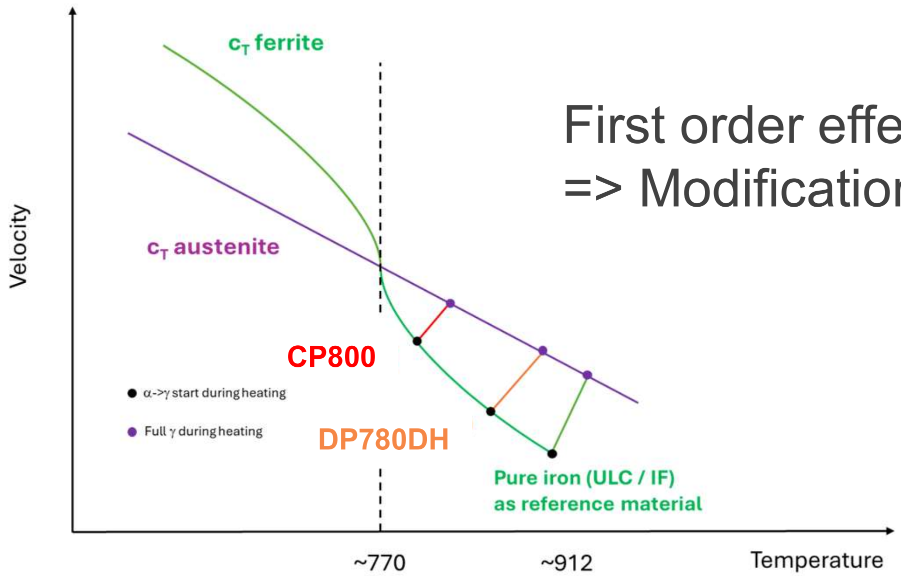
- No obvious solution with pure iron!
- Take advantage of DP980 modality containing Boron which retards phase transformation





Supposed c_L and c_T behaviours of FCC iron if it existed down to room temperature => straight lines

Proposal to verify evolution of velocity on a collection of grades
Such investigations never undertaken yet – examples of imaginable results



First order effect of alloying
=> Modification of full austenitization temperature

Grades selected according to priorities set with ArcelorMittal Sidgal 3.5

Possible derivation of austenite /ferrite ratio with an inverse segment method?
(similar to calculation with P-wave velocity below Curie point)

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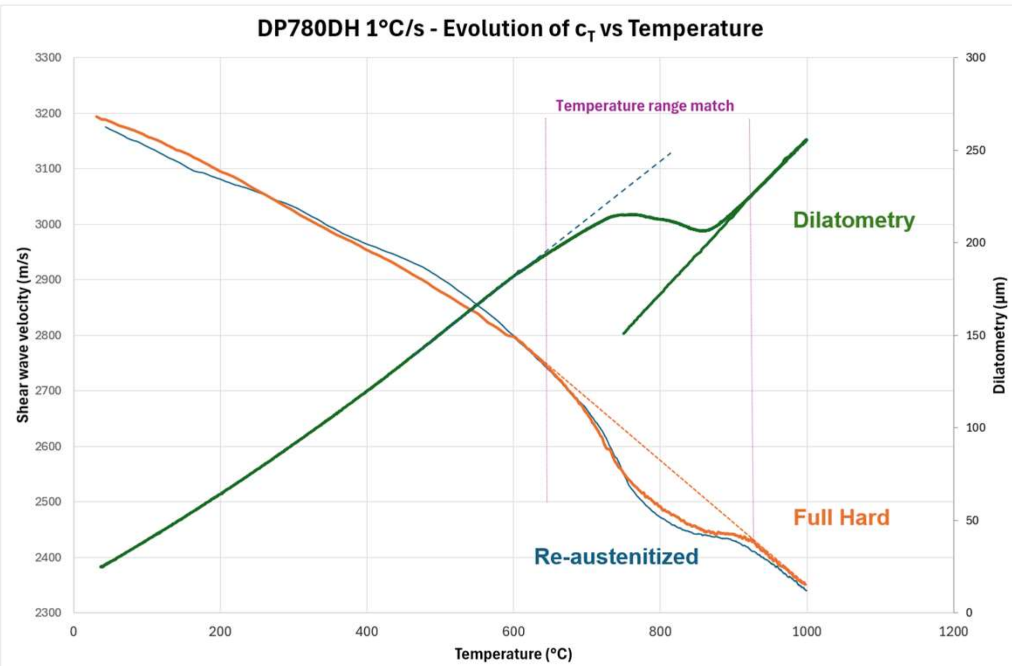
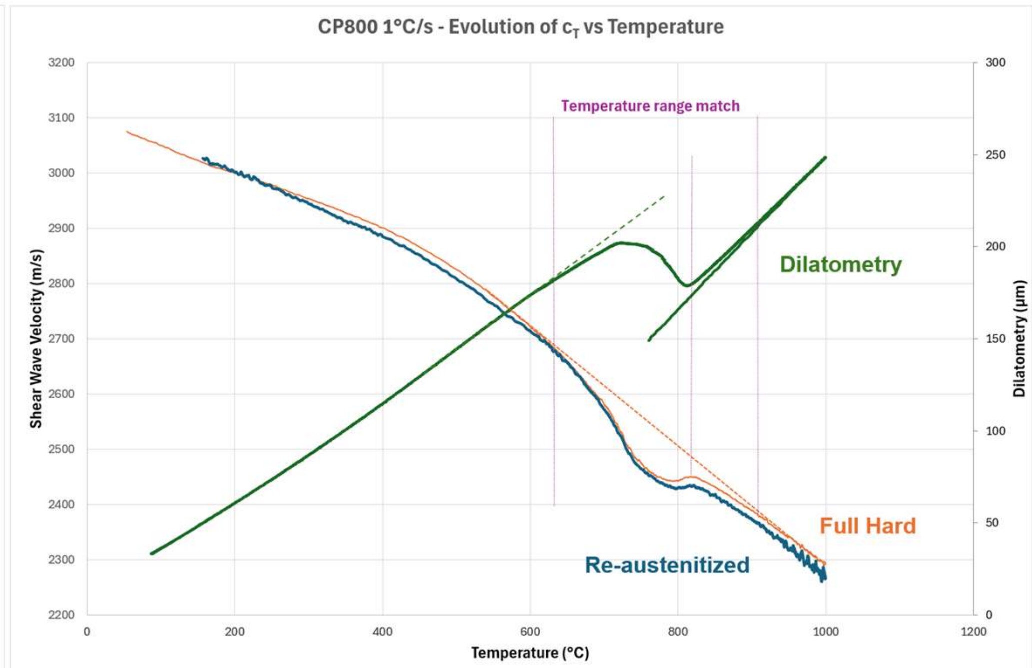
Results for AHSS selection





- Temperature ranges of interest : 650 -910°C for DP780DH ; 650 – 825 °C for CP800 ;
  - Consistent for both full hard and re-austenitized states
- **Very good match with the temperature ranges displayed by dilatometry in the BCC → FCC phase transformation**
  - Ongoing investigations for quantified confirmation : quench interrupted heating cycles with metallographic analyses

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CONCLUSIONS and next steps for AHSS – Phase transformation monitoring

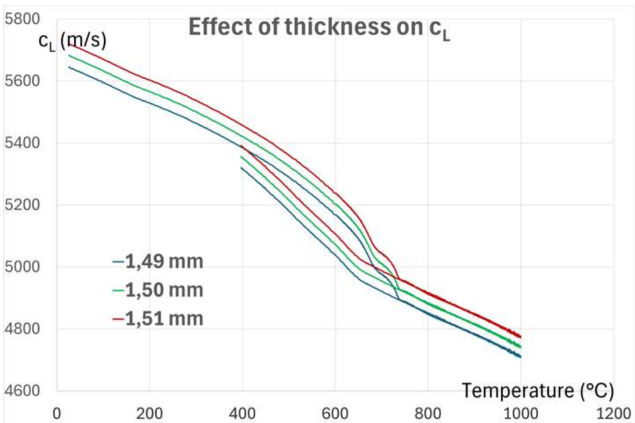
- **No observable sensitivity of pressure wave attenuation to phase transformation**

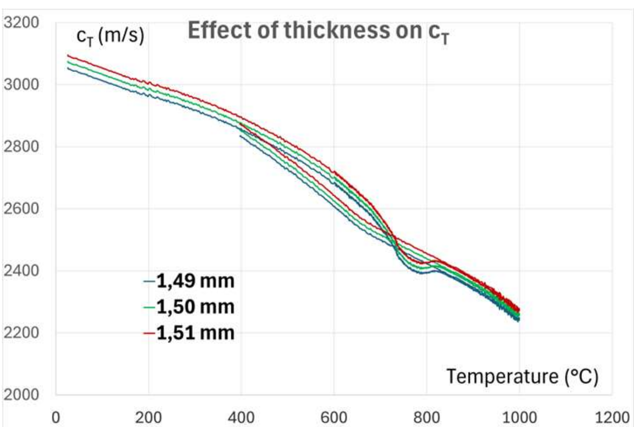
- **Shear wave velocity expected to be sensitive to phase transformation**
  - Good temperature range match with region of interest for shear wave velocity and dilatometry:
  - Observed for DP600 ; DP980 ; CP800 ; DP780DH

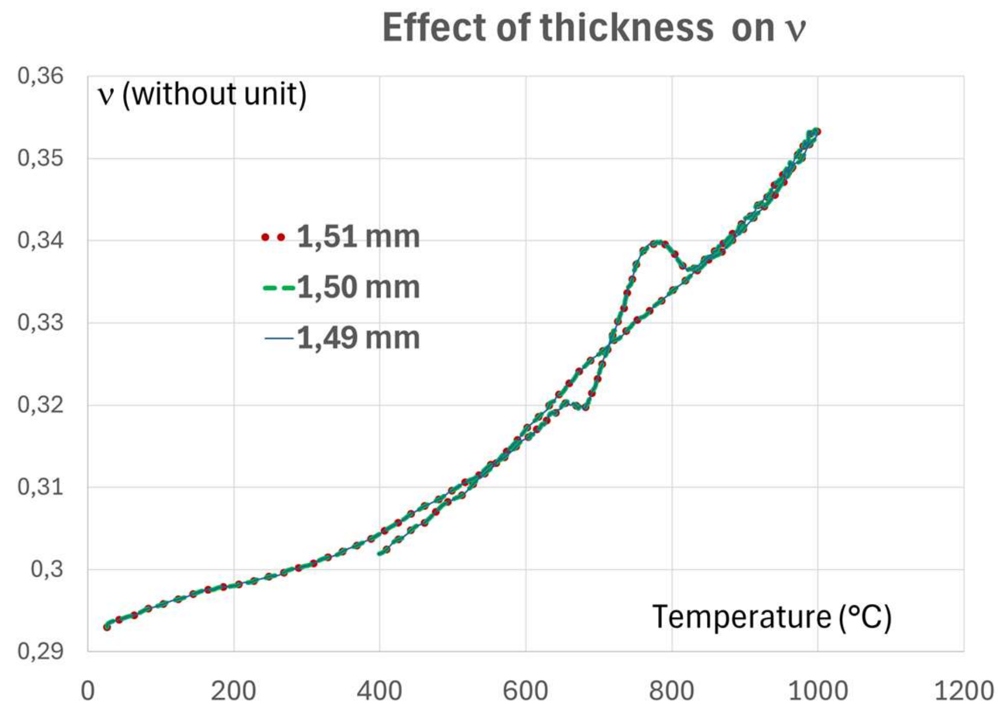
- **In the perspective of industrial application (next two slides)**
  - **Poisson ratio ν doesn't depend on thickness**
    - From analysis of ZGV signals : ν derived from a ratio of frequencies which are inversely proportional to thickness
  - **Shows both phase transformation and recrystallization**

- **Need to finish quantification of phase transformation**
  - With quench interrupted thermal cycles and metallographic analyses
  - With derivations from dilatometry
  - Ongoing contract with LEM3 laboratory to finish work (S1/2026)

Effect of thickness change on c_L , c_T and Poisson Ratio – example of CP800







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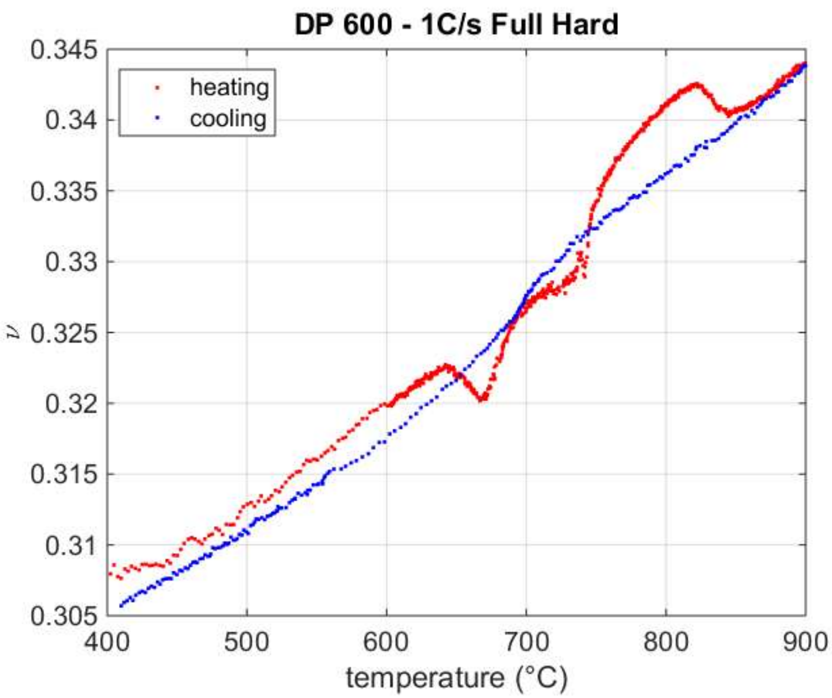
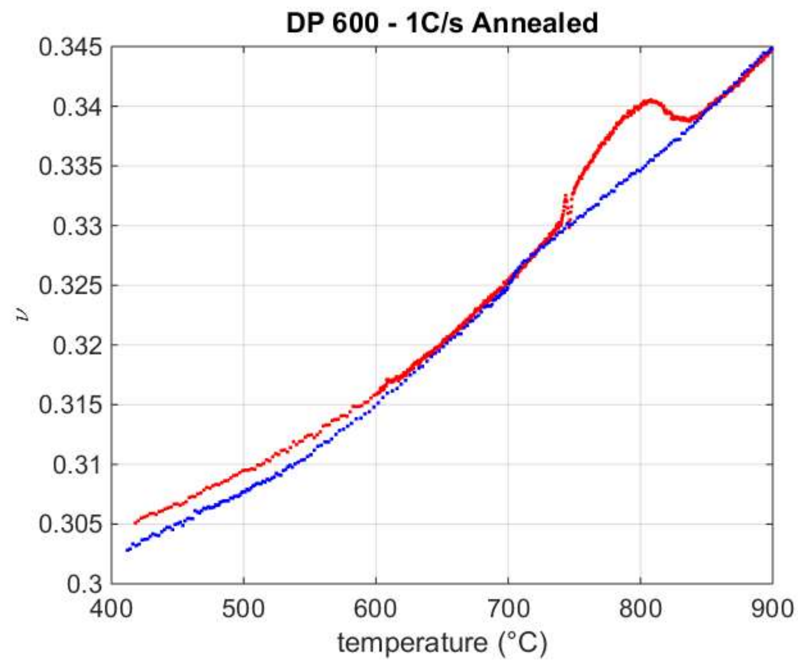
Poisson Ratio DP600





- Evidence of recrystallization (640 -700°C) as well as phase transformation (750 – 850°C) with one value

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$\Delta\nu$ vs temperature above Curie Point

Should allow accessing BCC/FCC proportions

- Customized models to build per grade

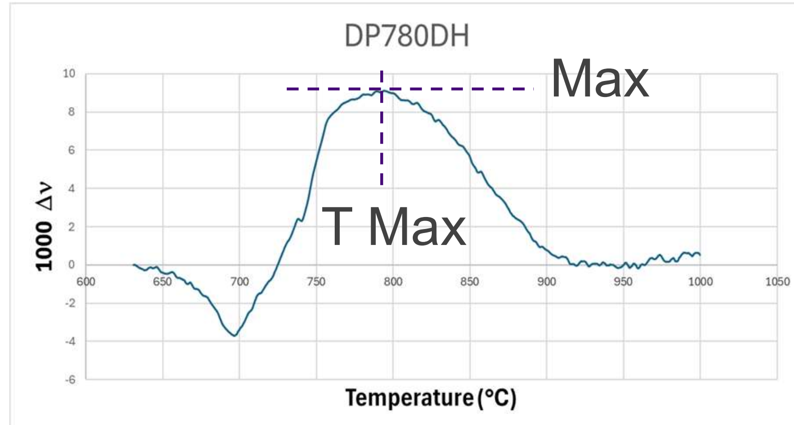

Illustration of selected values

Grade	HSLA460	DP600	DP780DH	CP800	DP980	HF1180
Max $\Delta\nu$ (10^{-3})	5.8	5.25	9.11	7.62	6.15	10
Temperature at Max $\Delta\nu$ (°C)	823	811	795	772	800	777

Overall Synthesis

LUS quantity		Recrystallization	Phase transformation	Observations
ν	Poisson Ratio	Below Curie point for some HSLA modalities	Above Curie Point	• Insensitive to Thickness Variations 😊 • Temperature dependent
c_L	Pressure wave velocity	Below Curie point for some modalities	Below Curie Point*	• Insensitive to phase transformation above Curie point 😟 • Sensitive to thickness variations 😟
c_T	Shear wave velocity		Above Curie Point	• Sensitive to ferritic phase above Curie point 😊 • Sensitive to thickness variations 😟
α	Pressure wave attenuation	No	No	😟 😟

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Next Steps

- Finalize Quantification of Recrystallization / Phase transformation
  - to build custom models for each of the target modalities
- Study applicability in industrial context, with main challenges:
  - Adapt optics to allow generating and detecting ZGV modes
  - Obtain a tight control of strip temperature measurement
- Go/NoGo Decision by plant to be taken in summer 2026
- If positive, target to run on-line trials in 2027 in Gent SidGal 3.5 line

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Thank you

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RECENDT
RESEARCH CENTER NON DESTRUCTIVE TESTING

cea list

imagine optic

LEM3

Questions?

Project RFCS-2023-101157601

Co-funded by the European Union

Research Fund for Coal & Steel