



In-situ evaluation of metallurgical phenomena using laser generated ultrasonic waves

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Motivations

Optical microscopy

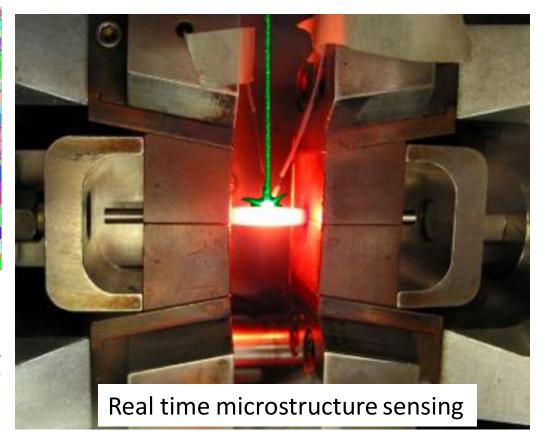
c: 5min

20

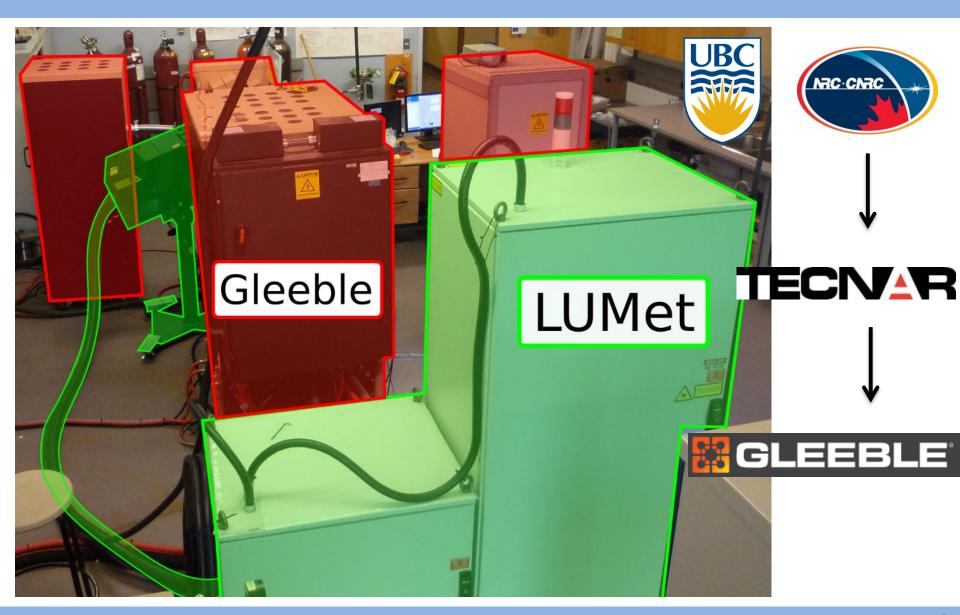
Electronic microscopy

Control of metallurgical processes in metals using laser-ultrasonic sensor

Ultrasonic wave propagation depends on microstructure



Gleeble + LUMet Technology



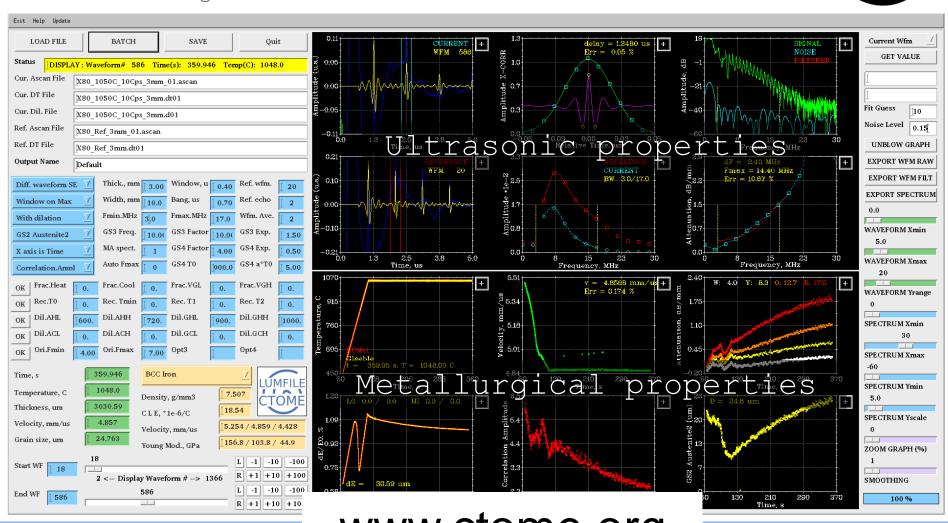
LUMet analysis software

CTOME

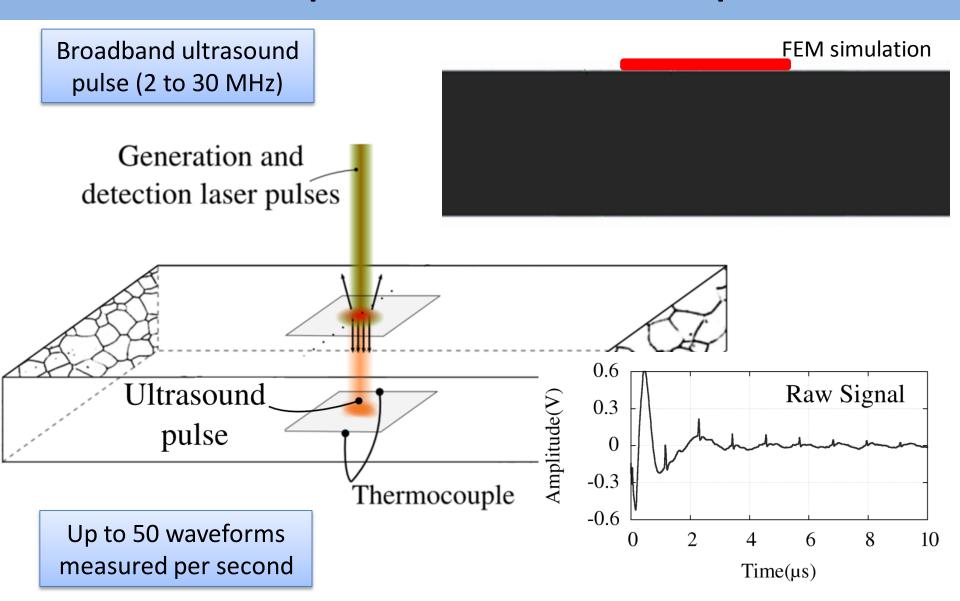
created in 2014 as UBC Spinoff company



Software & Consulting Inc.

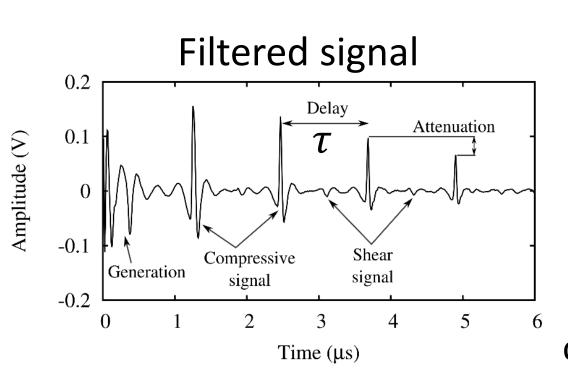


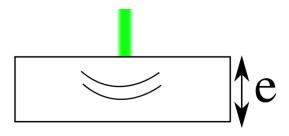
Principle of the technique



What parameters are measured?

- Time of arrival of echoes -> Velocity V
- Amplitude of echoes -> Attenuation $\alpha(f)$





$$V = \frac{2(e+\epsilon)}{\tau}$$

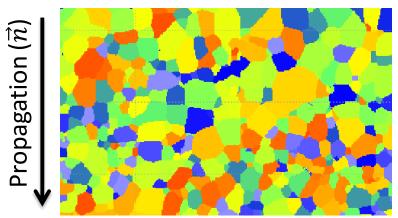
$$\alpha(f) = \frac{20}{2e} \log \left(\frac{A_{echo(i)}}{A_{echo(j)}} \right)$$

Velocity of ultrasonic wave in crystals

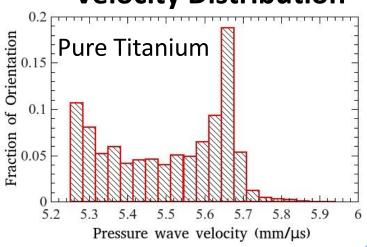
5.7

5.5 5.4

EBSD to **Velocity map** (mm/μs)



Velocity Distribution



Rotated Elastic Tensor

$$C_{ijkl} = \int c'_{ijkl} f(odf)$$
$$T_{ik}(\vec{n}) = C_{ijkl} \vec{n}_j \vec{n}_l$$

$$V = \sqrt{\sum_{Phases} \frac{K(odf)}{\rho}}$$

What can be investigated?

Phase transformation Second phase/Precipitation Recrystallization

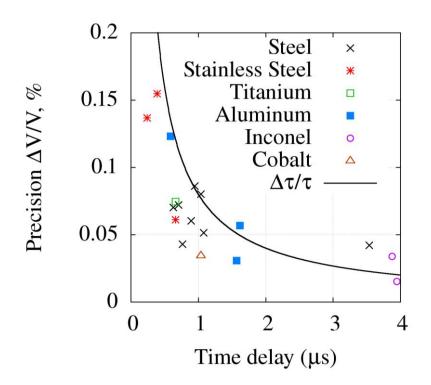
Velocity: Precision and Accuracy

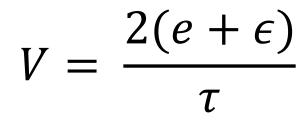
Absolute accuracy in velocity ≈ 1%

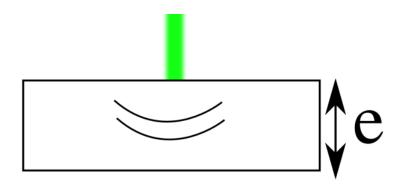
Limiting factor: thickness ($\Delta e = 10 \mu m$)

Precision < 0.1%

Limiting factor: time delay ($\Delta \tau = 1 \text{ ns}$)







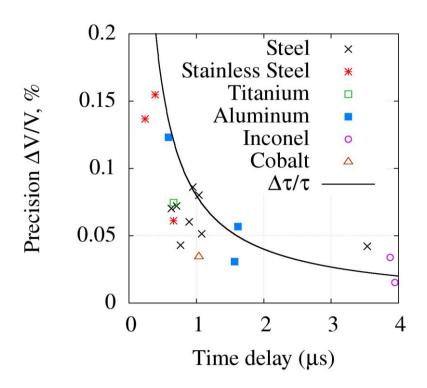
Velocity: Precision and Accuracy

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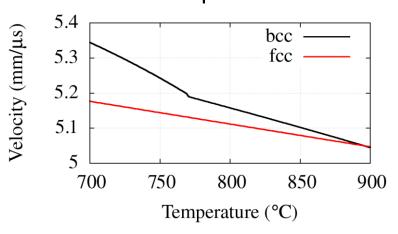
Limiting factor: thickness ($\Delta e = 10 \mu m$)

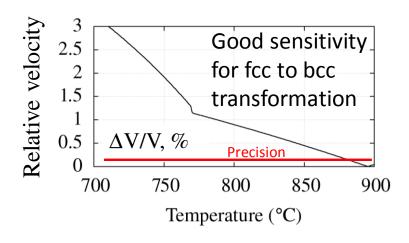
Precision < 0.1%

Limiting factor: time delay ($\Delta \tau = 1 \text{ ns}$)

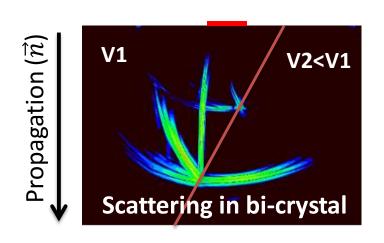


Example for iron bcc-fcc Isotropic case





Attenuation and Scattering by grains



Scattering depends on grain boundary disorientation and incidence angle and grain volume

Scattering depends on ultrasonic wavelength

Rayleigh Region $\alpha(D,\lambda) = C_r D^3 \lambda^{-4}, \lambda \gg D$

Stochastic Region $\alpha(D,\lambda) = C_s D \lambda^{-2}, \lambda \cong D$

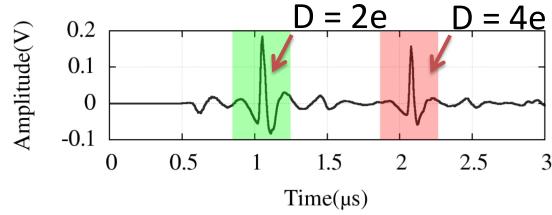
Diffusion Region $\alpha(D,\lambda) = C_d/D, \lambda \ll D$

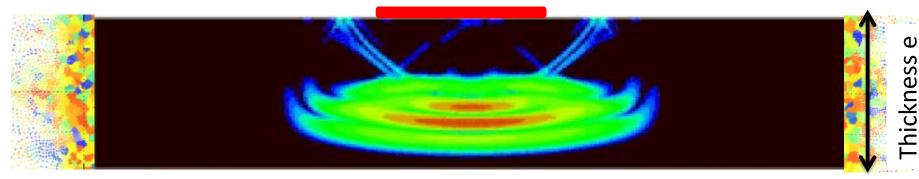
Nicoletti et al. 1994

Large grain size = High attenuation

Other sources of attenuation

TWO ECHO METHOD





Internal Friction/Gain Grain Scattering (sample geometry)
$$\alpha(f) = a + bf^n + cf^m$$

How to measure grain size?

- 1) Reference sample D_0
- 2) ONE ECHO METHOD

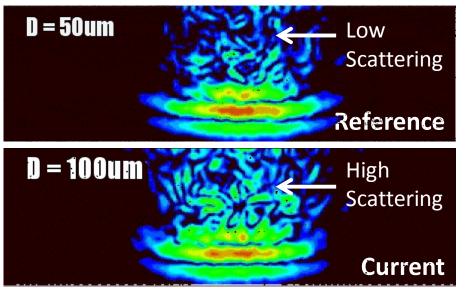
Isolate only grain scattering

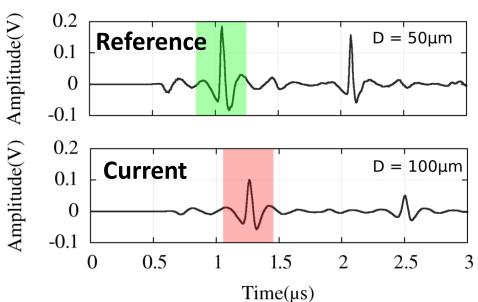
$$\alpha(f) = a + \mathbf{b}f^n$$

Frequency dependant grain size parameter

$$b = C(T) [D_i^2(t) - D_0^2(t_0)] f^3$$

Measurement precision < 10 %





Preliminary calibration is necessary

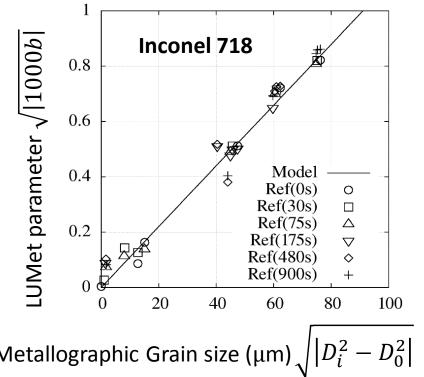
- 1) Reference sample D_0
- 2) Use one single echo

$$b = C(T) [D_i^2(t) - D_0^2(t_0)] f^3$$

Isolate only grain scattering

Measurement precision < 10 %

Correlation available: Austenite in Steel, Inconel, Cobalt, Copper

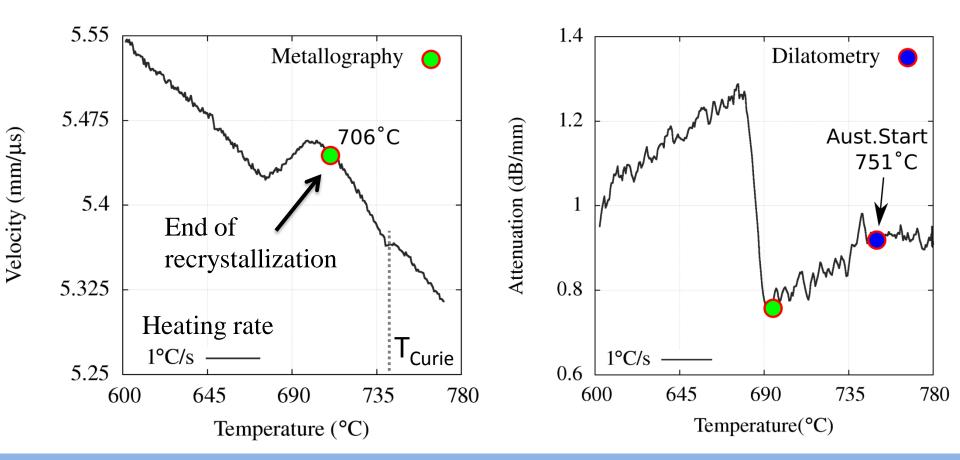


Metallographic Grain size (μm)

Recrystallization/Austenite formation

Dual Phase Steel 50% cold rolled (Intercritical annealing treatment) wt%: 0.105C-1.858Mn-0.157Si-0.012Ti-0.009Mo-0.006N

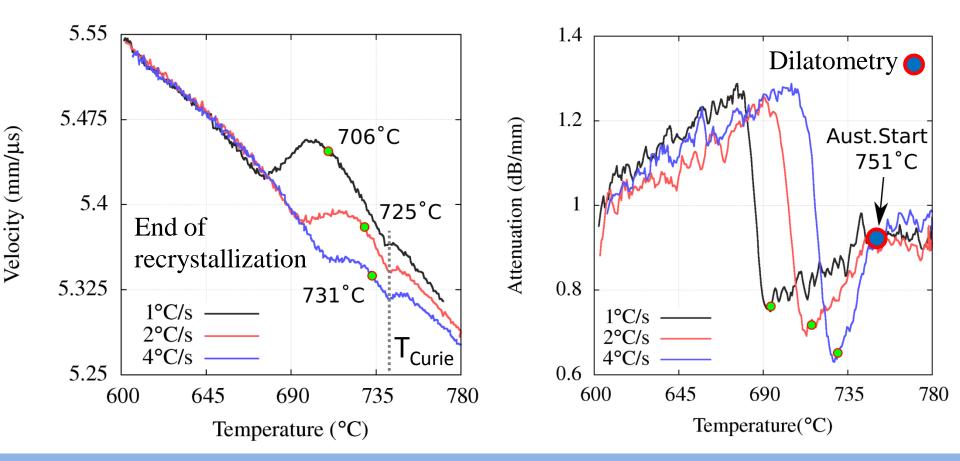
Interaction between ferrite recrystallization and austenite formation



Recrystallization/Austenite formation

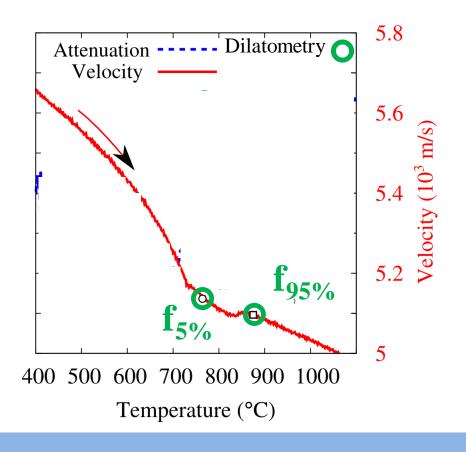
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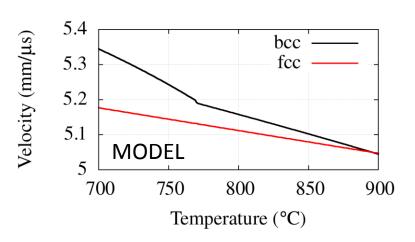


Austenite formation and grain growth

X80 microalloyed low carbon linepipe steel (Heating rate 100°C/s) wt%: 0.06C-1.65Mn-0.11Si-0.034Nb-0.014Ti-0.24Mo-0.005N

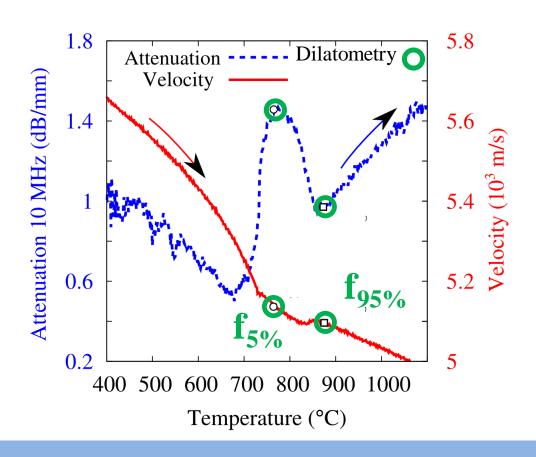


Small variation of velocity in the austenite formation temperature range



Austenite formation and grain growth

X80 microalloyed low carbon linepipe steel (Heating rate 100°C/s) wt%: 0.06C-1.65Mn-0.11Si-0.034Nb-0.014Ti-0.24Mo-0.005N

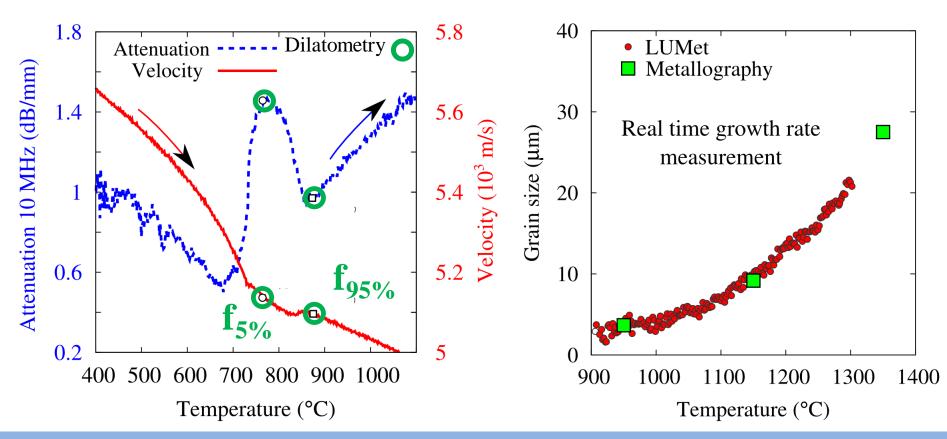


Important change of attenuation during magnetic transition and austenite formation

Austenite formation and grain growth

X80 microalloyed low carbon linepipe steel (Heating rate 100°C/s)

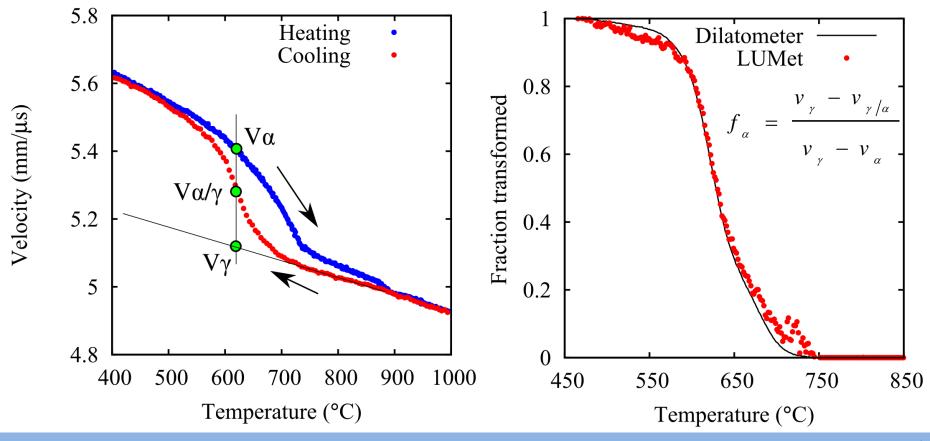
Subsequent austenite grain growth following austenite formation



Austenite decomposition

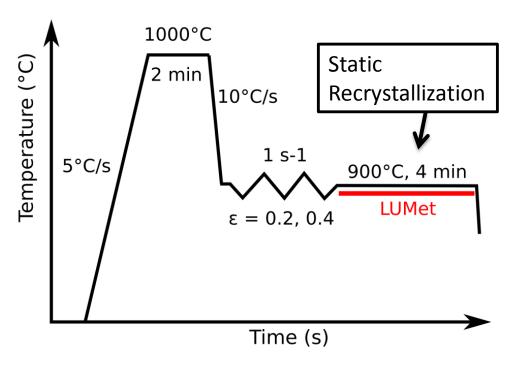
Low-carbon linepipe steel (Heating 100°C/s to 1150°C, cooling 3°C/s) wt%: 0.06C-1.49Mn-0.2Si-0.047Nb-0.038Al-0.0094N

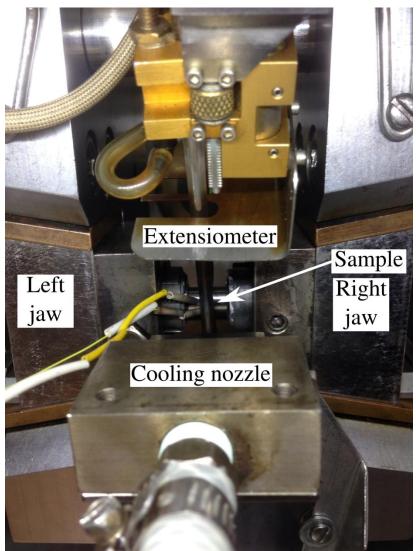
Rule of mixture between parent and product phase



Hot deformation experiments

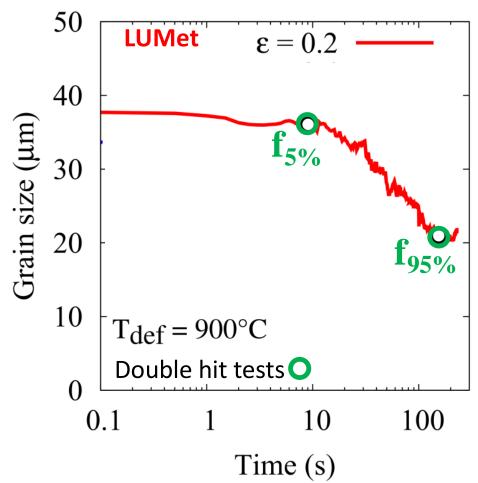
- Mo-TRIP, forged bar
- Composition (wt %) C0.19, Mn1.5, Si1.6,Mo0.2
- Uniaxial compression tests

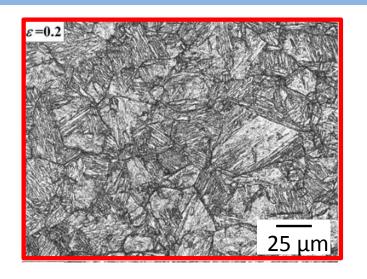




Evolution of the average grain size

Grain refinement during recrystallization

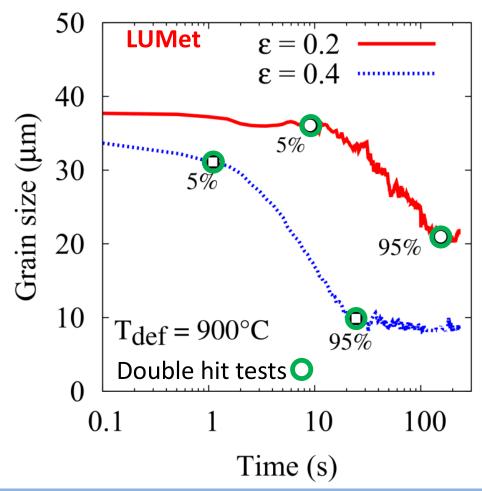


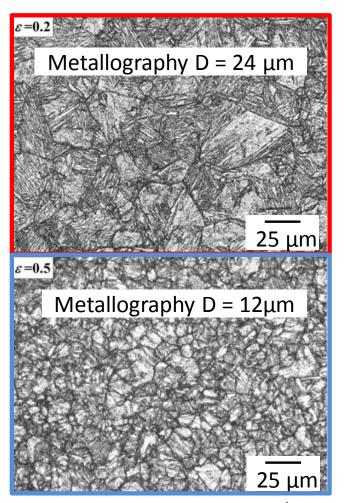


Liu.D et al., 894 Sarkar.S et al., 897

Evolution of the average grain size

Larger grain refinement at higher deformation strain

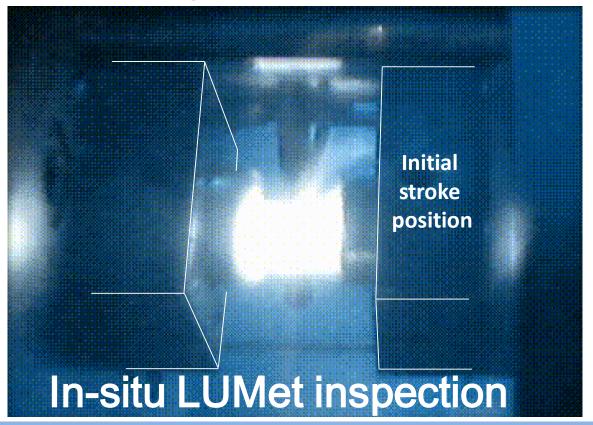


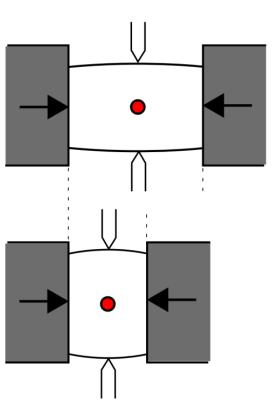


Liu.D et al., 894

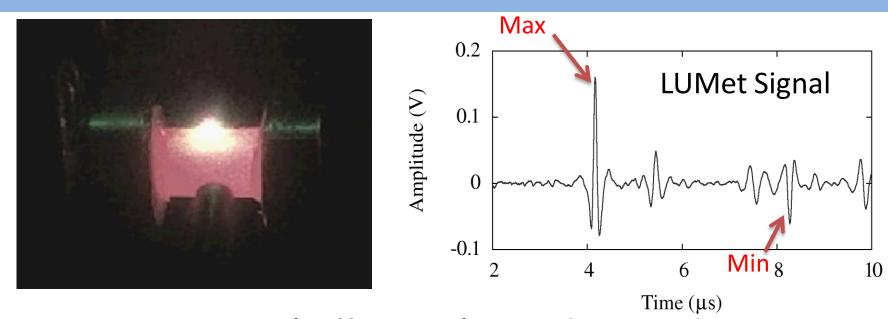
Measurement during deformation?

- ✓ Max Stroke displacement 1mm/s⁻¹ (strain rate of 0.1 s⁻¹ for 10x15 mm cylinder
- ✓ Max length to diameter ratio 0.6 (Max Strain ≈ 0.4)





Wave reflection on curved surface



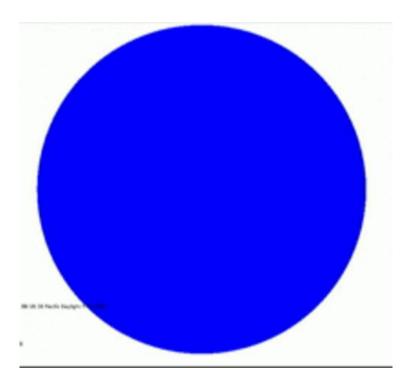
Geometry (Diffraction) is evolving with time

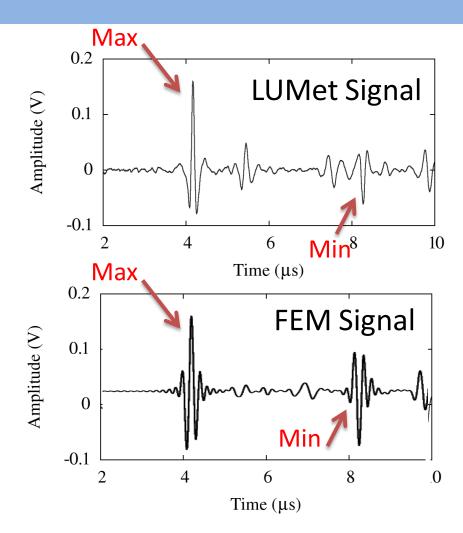
→ Must use two echoes of the same waveform

Inversion of polarity of the echoes in cylinder geometry

Wave reflection on curved surface

FEM Single Crystal, Isotropic Diffraction in a cylinder

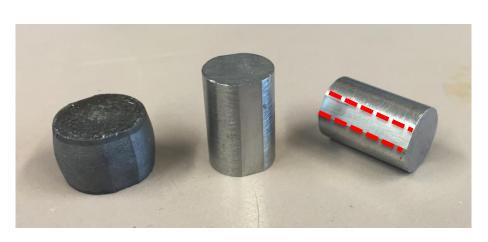




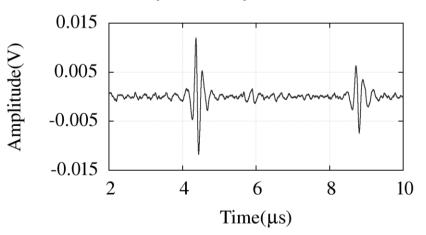
How to prevent polarity change between echoes?

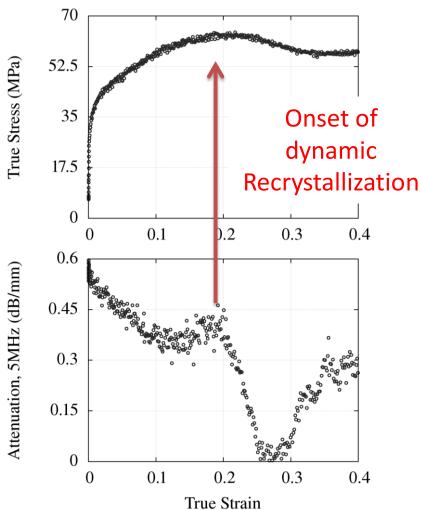
Improved geometry for compression tests

Faceted cylinders for propagation between flat surfaces



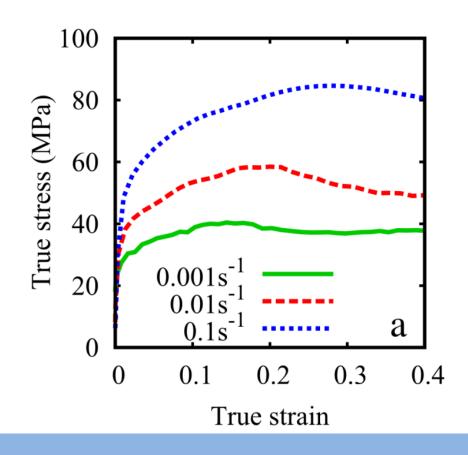


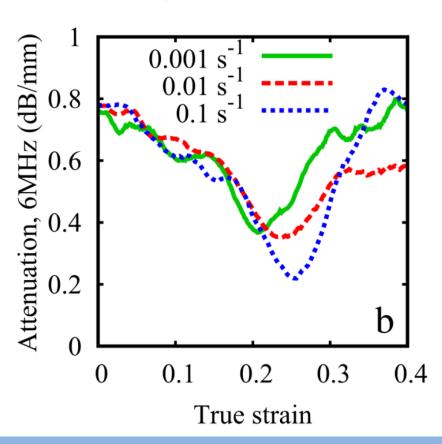




Effect of strain rate on attenuation

- ✓ Delays the onset of dynamic recrystallization.
- ✓ Decrease in attenuation related to diminution of the average grain size in the material during recrystallization

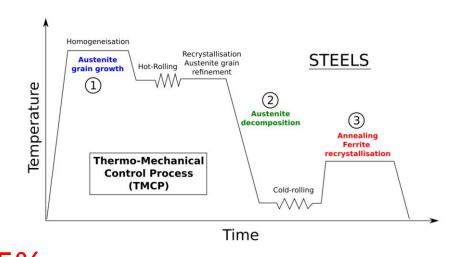




Guidelines and conclusions

Range of applications of LUMet

1 mm < thickness < 13 mm
Temperature up to 1300°C
Grain size up to 300 μ m
Strain up to 0.4
Strain rate up to 0.1 s⁻¹
Precision in Bulk Modulus 0.05%



LUMet – disruptive sensor technique for Research and Development, process modelling and process control: Innovative microstructure design for better steels