Recent developments at NRC Canada for Steel Microstructure Characterization and Weld Inspection

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Recent developments at NRC Canada for

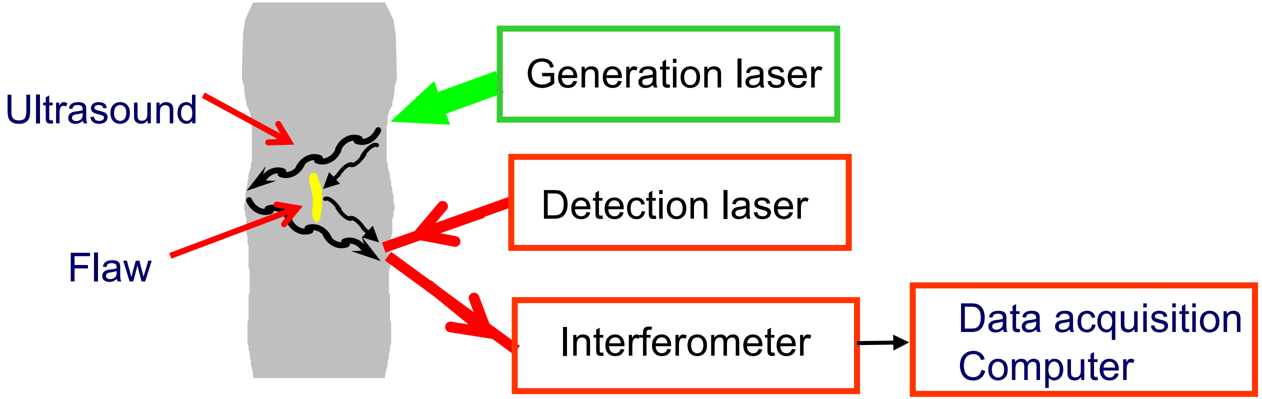
Characterization of steel microstructure

- Austenite grain size using LUS attenuation
- Grain size evolution during rapid deformation
- Austenite fraction during phase transformation

Inspection of metallic welds and metal additive materials

- Weld inspection (EB space application, laser, arc welding, friction stir welding)
- Additive Manufacturing (EB, Laser, Cold Spray, cladding)

Laser Ultrasonic Inspection

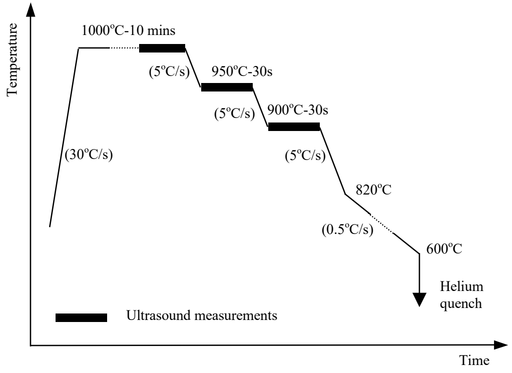


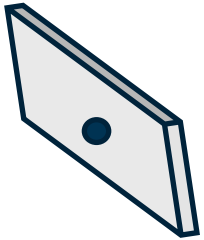
- Generation and detection spots can be superimposed
- Parts can be optically scanned with contours of complex geometry
- Non-contact: inspect during manufacturing, no coupling medium (water)
- Broad frequency bandwidth: good spatial resolution, small flaws

RECENT DEVELOPMENTS AT NRC CANADA FOR MICROSTRUCTURE

Gleeble-LUS setup

Laser-ultrasonic system coupled to a Gleeble





Ultrasound measurement, PE

Thermal cycle

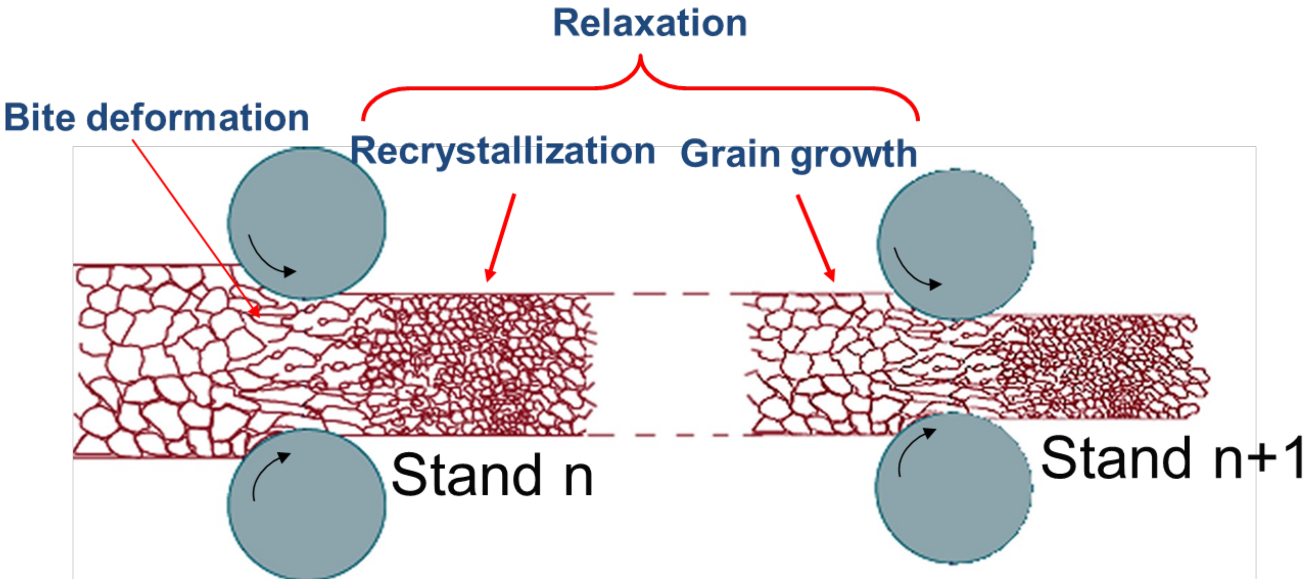
Ultrasound measurement, TTU

Rapid Deformation

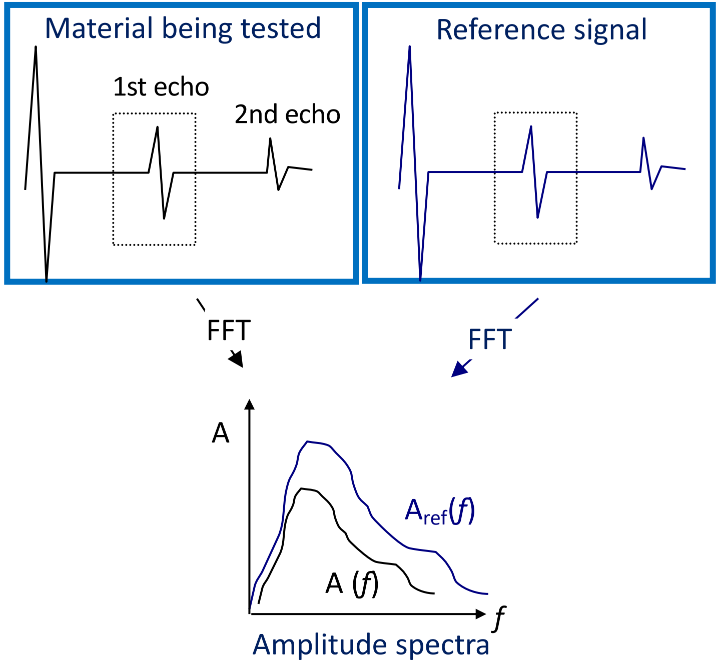
STRESS RELAXATION

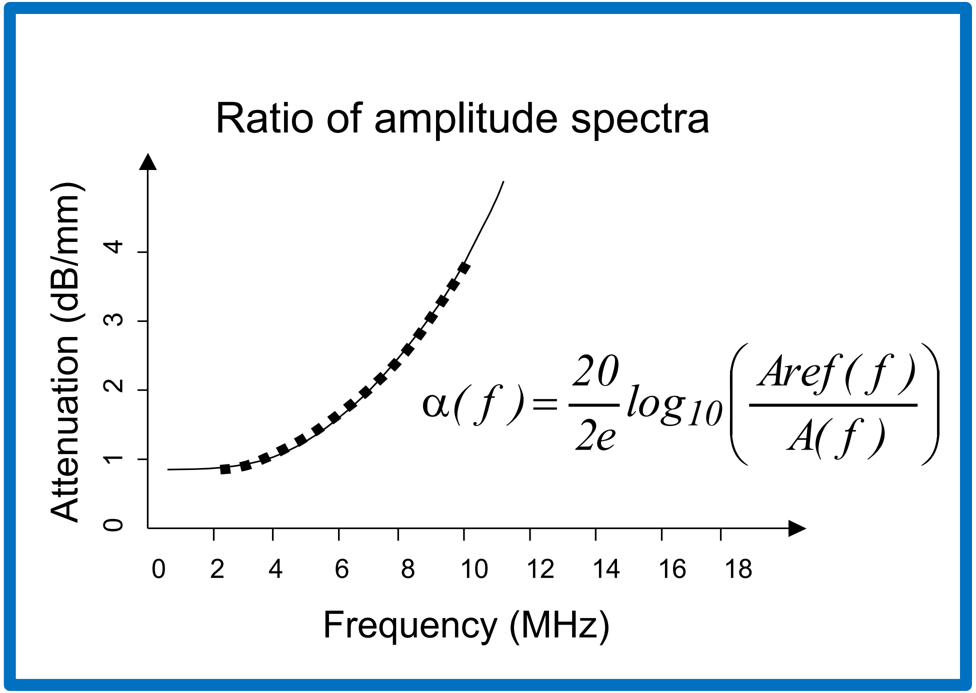
Austenite grain size after deformation (single hit, double hit)

Recrystallization and grain growth after hot deformation



Austenite grain size using LUS
Attenuation spectrum: single echo

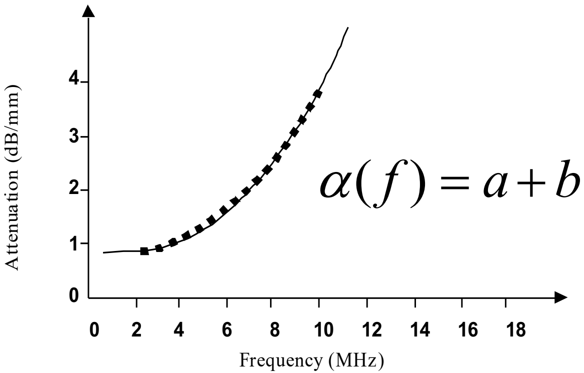




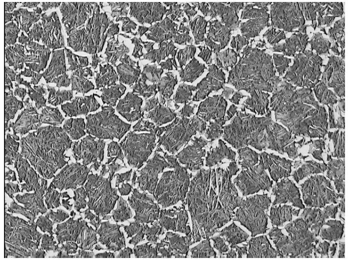
$$\alpha(f) = \frac{20}{2e} \log_{10}\left(\frac{Aref(f)}{A(f)}\right)$$

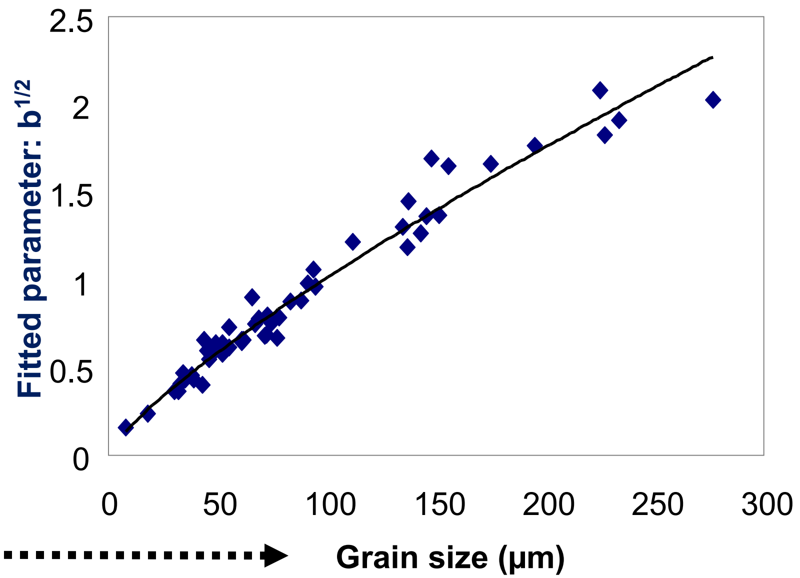
Austenite grain size using LUS

Austenite grain size: calibration



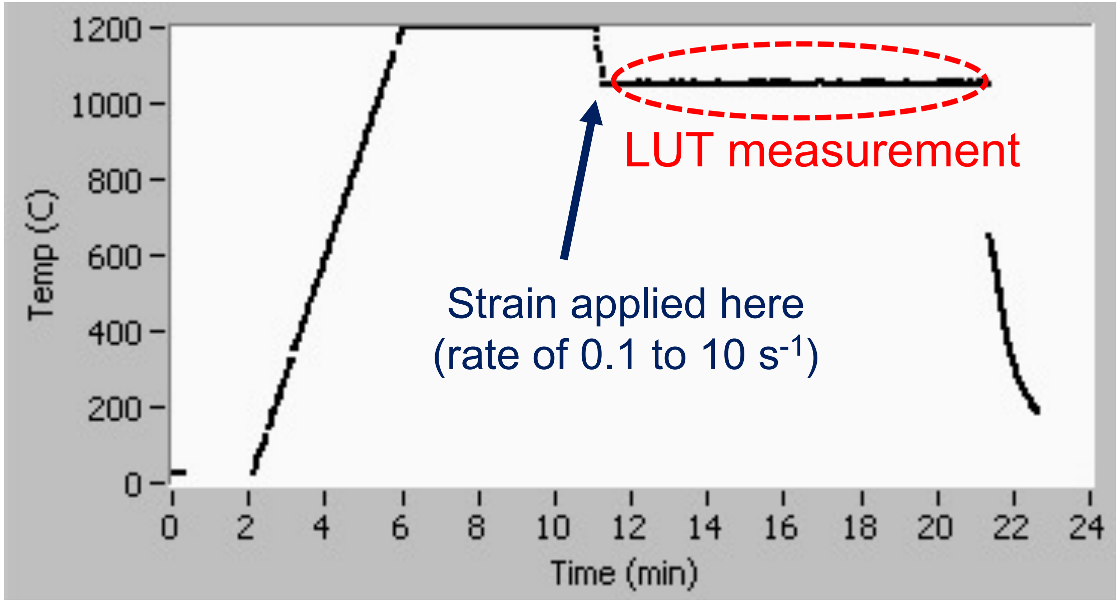
$$\alpha(f) = a + b\, f^3$$





Austenite grain size after deformation, Single hit

Test conditions: Temperature vs time



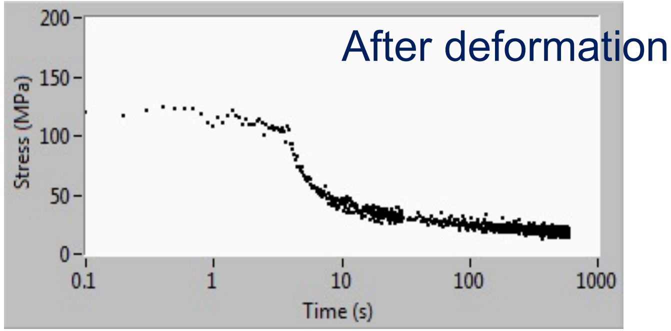
Hot compressive strain applied
to cylindrical samples
Dimensions: 10 mm dia, 15 mm long

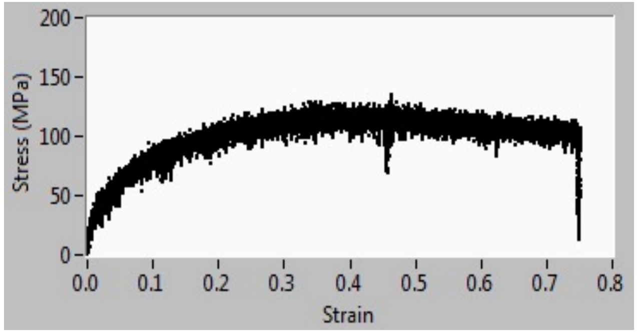
Austenite grain size after deformation, Single hit

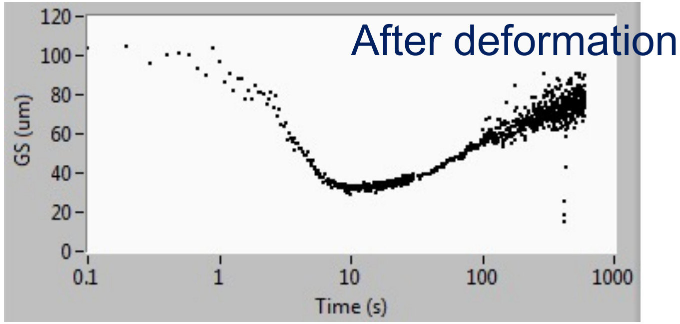
DP780: Slow rate

Plateaus 1200-950 C

Strain=0.75 (actual 0.77), Rate=0.1 s^{-1}

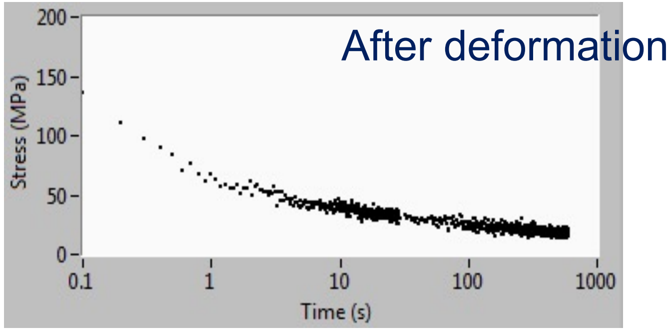


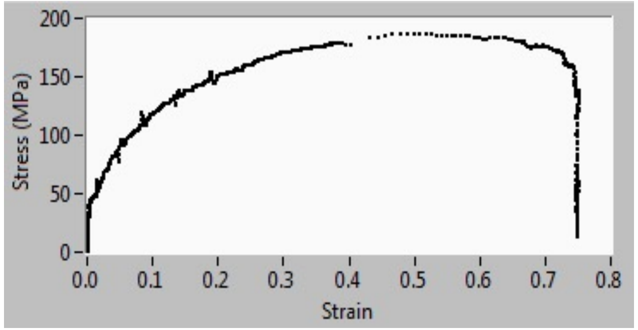


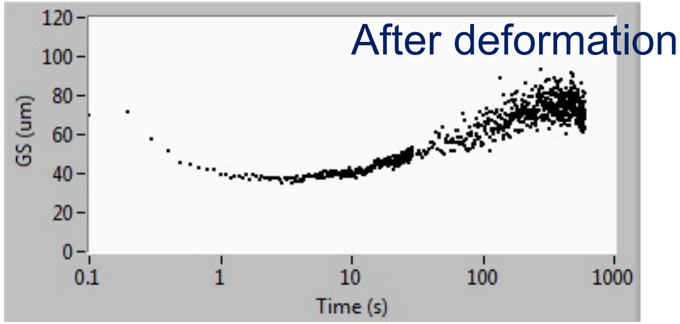


Austenite grain size after deformation, Single hit
DP780: Fast rate

Plateaus 1200-950 C
Strain=0.75 (actual 0.79), Rate=10 s-1





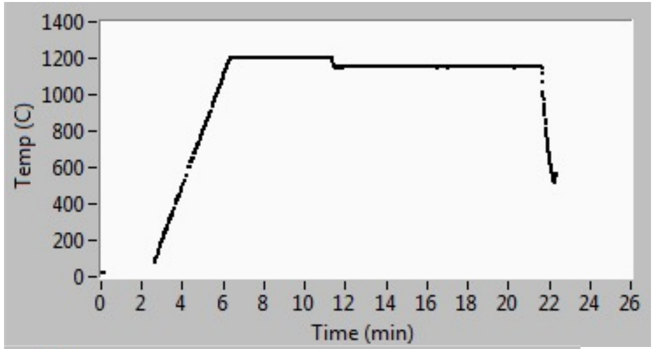


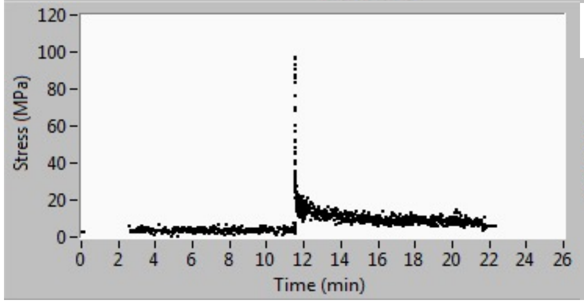
Austenite grain size after deformation, Double hit

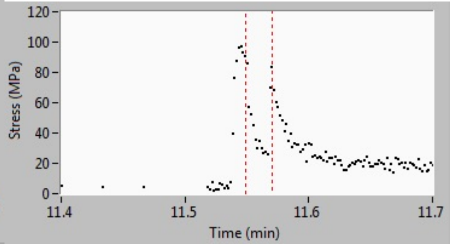
X70: Interpass of 1 s

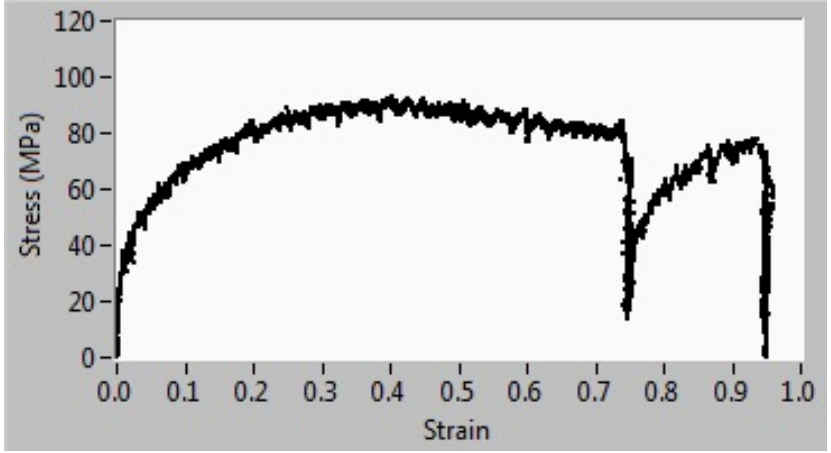
Plateaus 1200-1150 C

Strain=0.75+0.20 (actual 0.89)







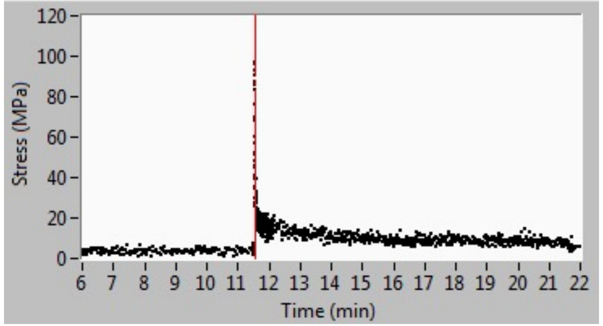


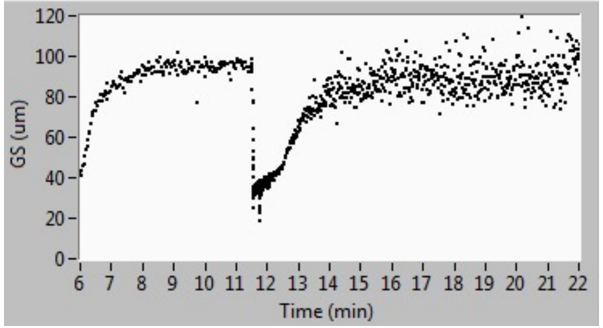
Austenite grain size after deformation, Double hit

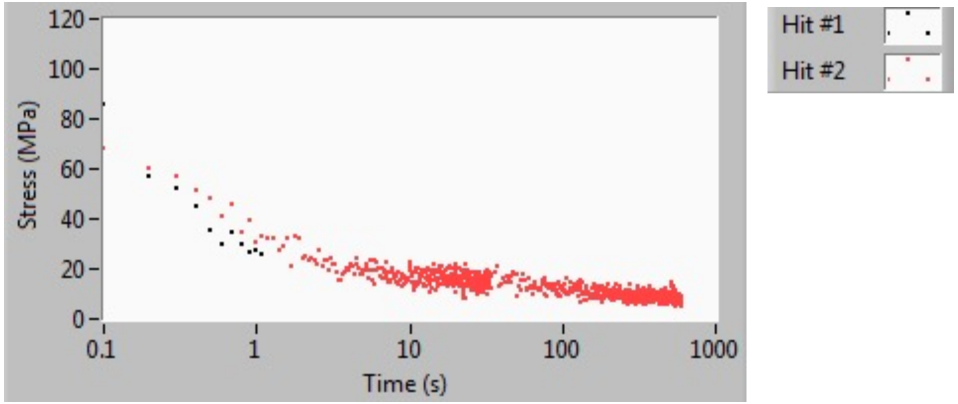
X70: Interpass of 1 s

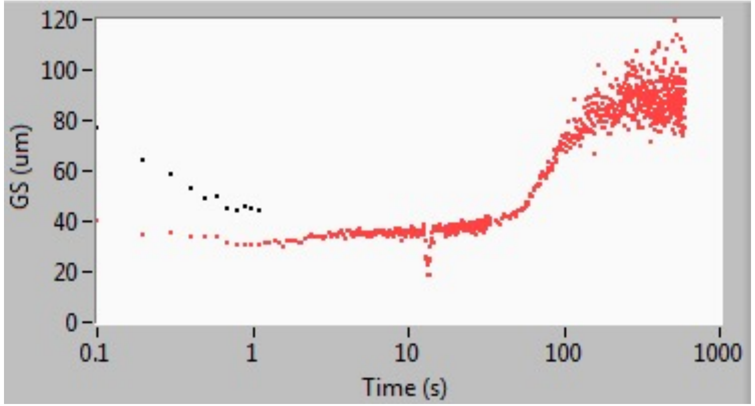
Plateaus 1200-1150 C

Strain=0.75+0.20 (actual 0.89)







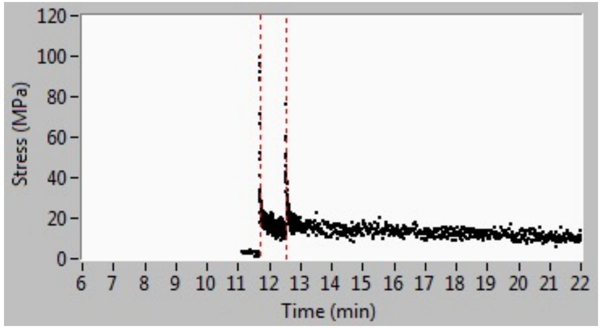


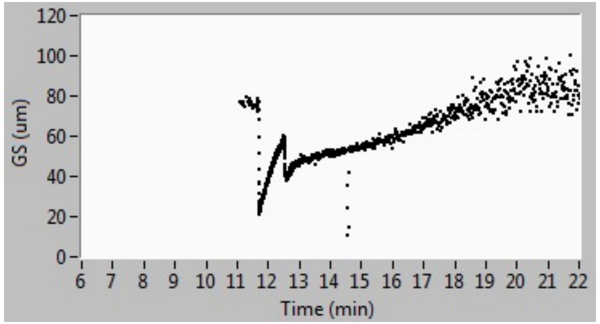
Austenite grain size after deformation, Double hit

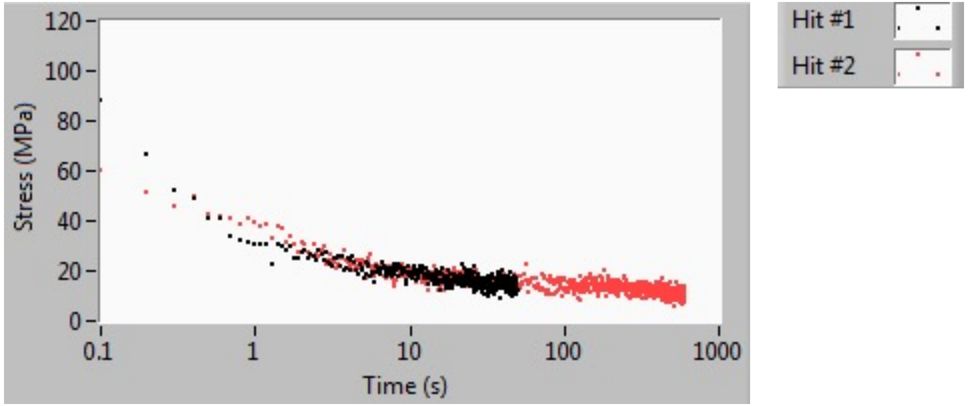
X70: Interpass of 50 s

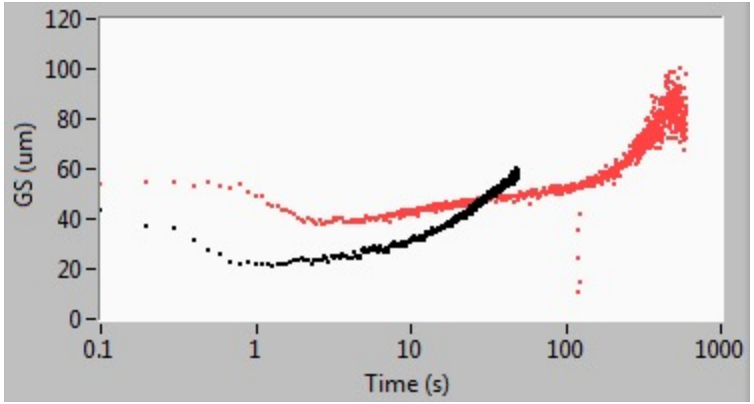
Plateaus 1200-1150 C

Strain=0.75+0.20 (actual 0.92)





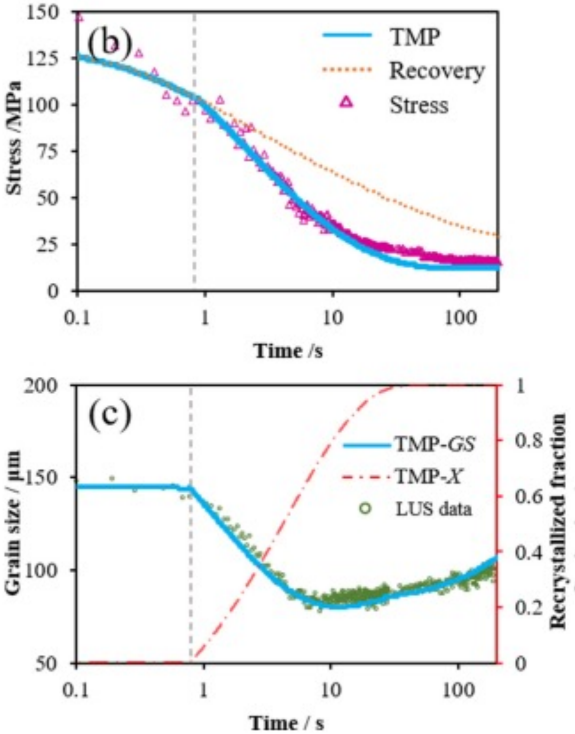




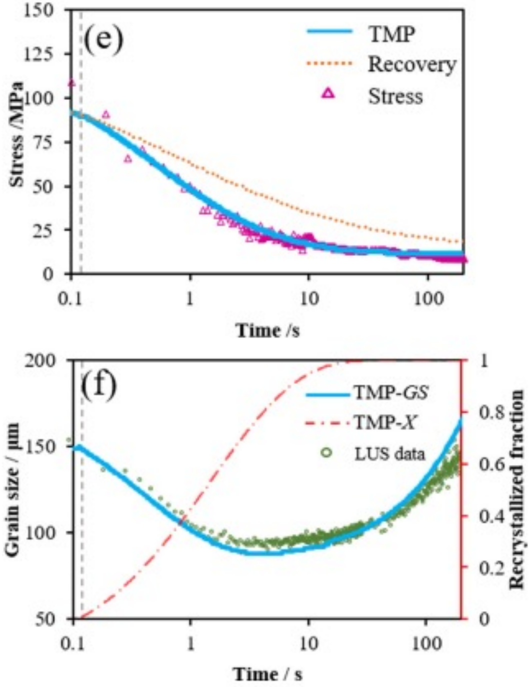
Austenite grain size after deformation,

Comparison with model of thermomechanical processing (TMP)

Plateaus 1200-**950** C
Strain=0.35, Rate=1 s^{-1}



Plateaus 1200-**1050** C
Strain=0.35, Rate=1 s^{-1}



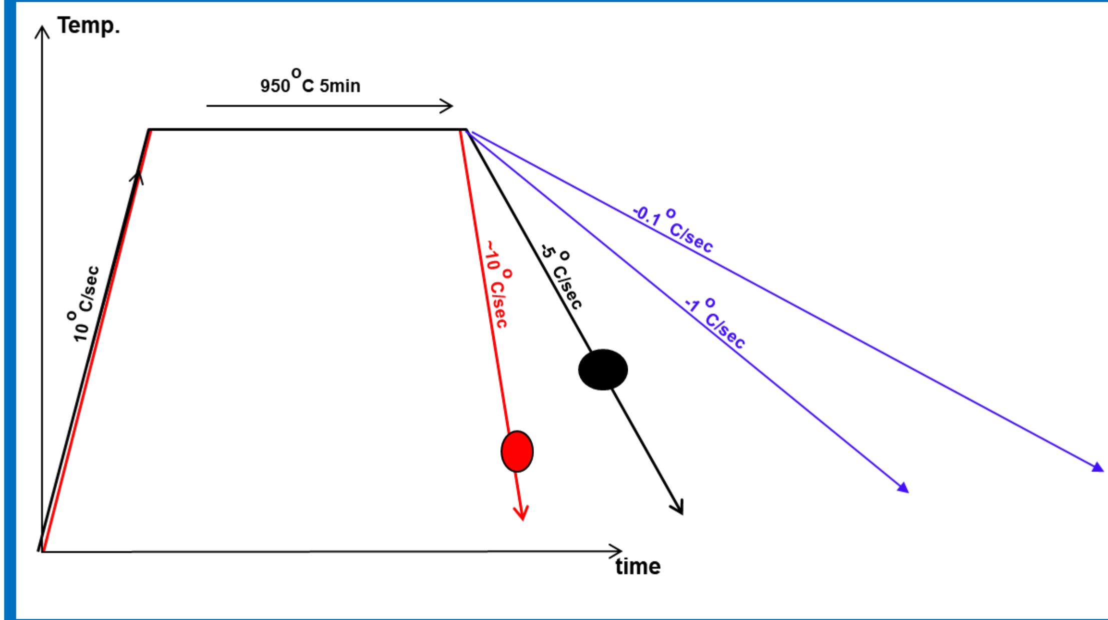
Ref: S. Liang, D. Levesque, N. Legrand, H.S. Zurob, Materialia 12, 100812 (2020)

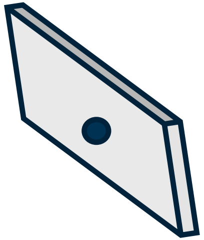
PHASE TRANSFORMATION

Austenite fraction during phase transformation

Phase Transformation

Test conditions: Temperature vs time





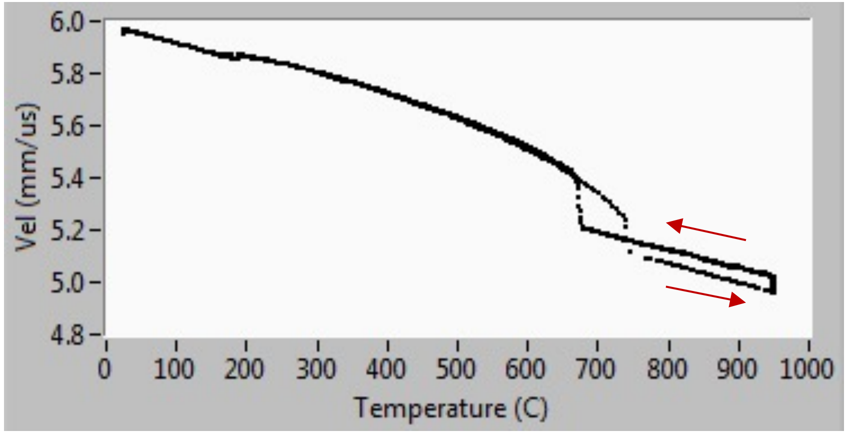
Ultrasound measurement, PE

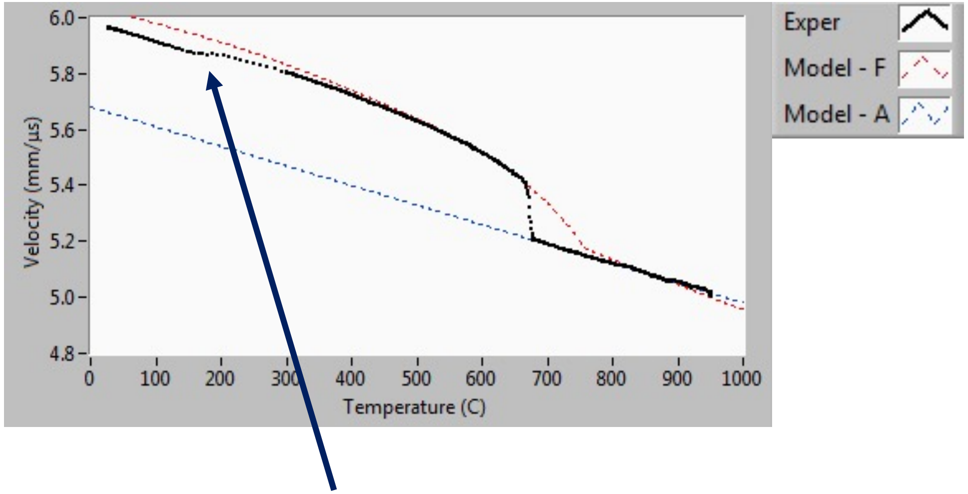
Plate dimensions: 150 mm x 15 mm x 3 mm

Phase Transformation

Laser ultrasonics on cooling: Grade 1080 @ -0.1 C/s

Heating - Cooling



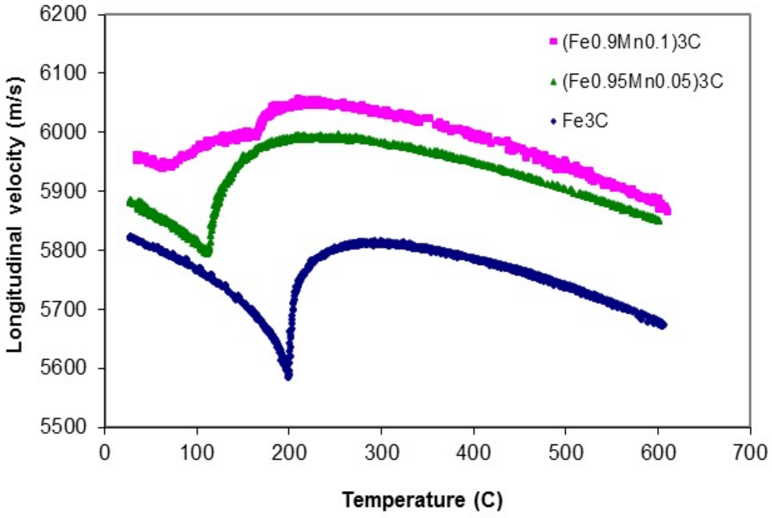


Pure pearlite is: 89 wt% ferrite, 11 wt% cementite

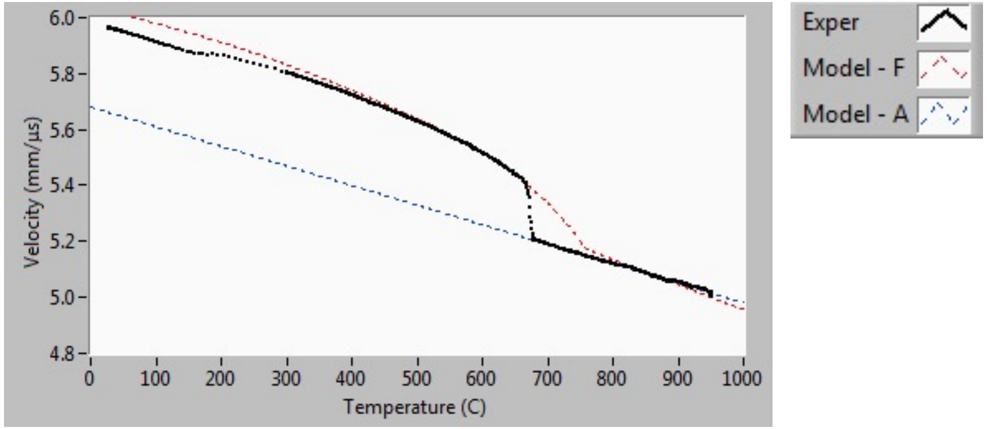
Phase Transformation

Laser ultrasonics on cooling: Grade 1080 @ -0.1 C/s

Temperature dependence in bulk cementite



Magnetic transition observed



Model for pearlite should include bulk cementite behavior

$$\min_{x}\left\{\sum_{T}\left[V^{meas}(T)-V^{calc}(T,V_{cementite},V_{ferrite},x)\right]^2\right\}$$

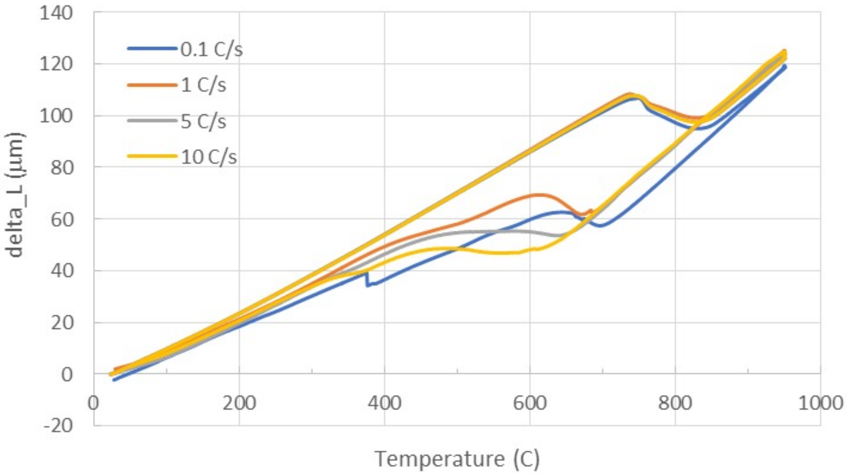
$$with \quad V^{calc}=xV_{cementite}+(1-x)V_{ferrite}$$

Ref: M. Umemoto, S.E. Kruger, H. Ohtsuka, Mat. Sci. & Eng. A 742, pp. 162-168 (2019)

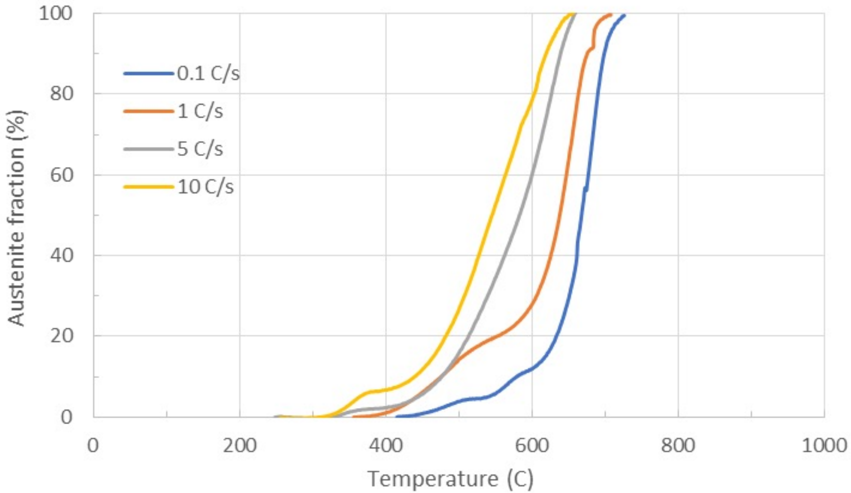
PHASE TRANSFORMATION

Phase transformation: Industrial grades

Phase Transformation
Dilatometer results on cooling: Grade DP780



Use of lever rule method

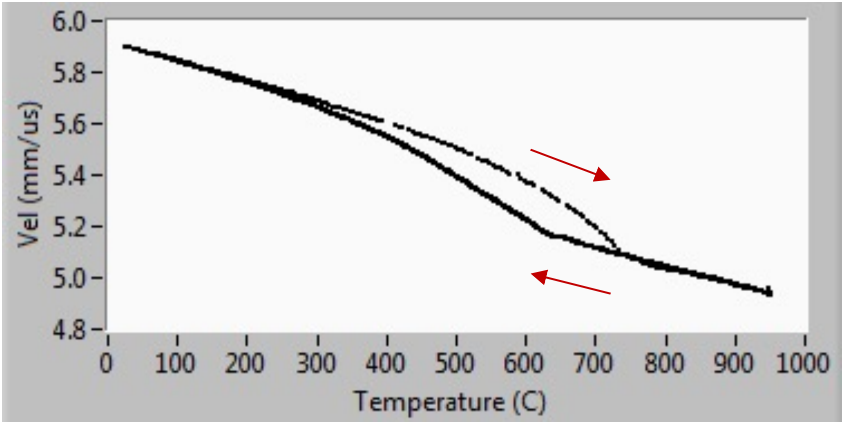


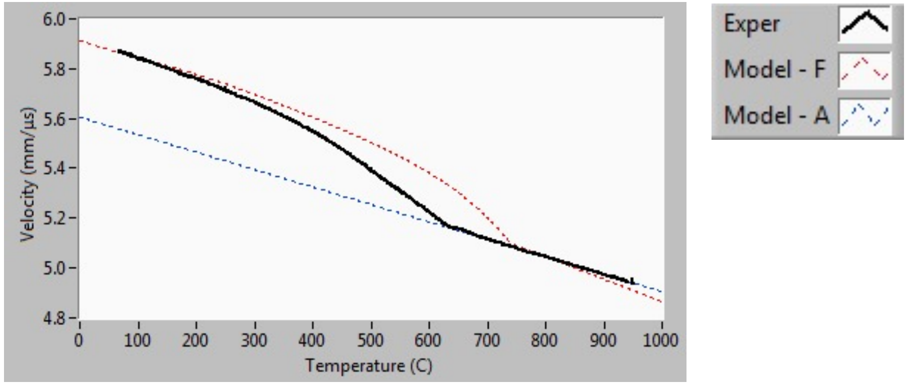
Length change: 20 μm
0.02/10 = **0.2 %**

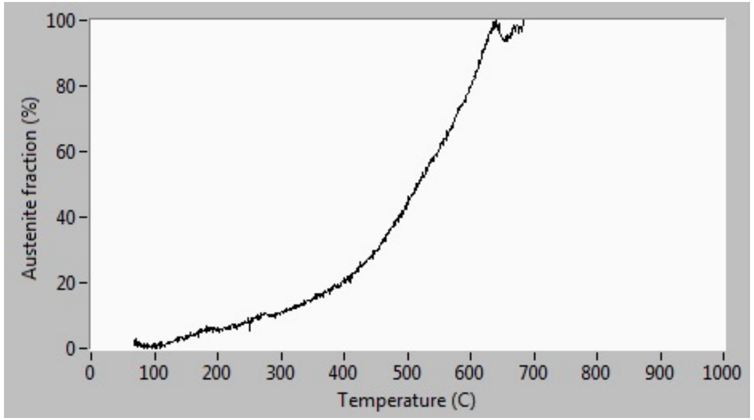
Phase Transformation

Laser ultrasonics on cooling: Grade DP780 @ -5 C/s

Heating - Cooling





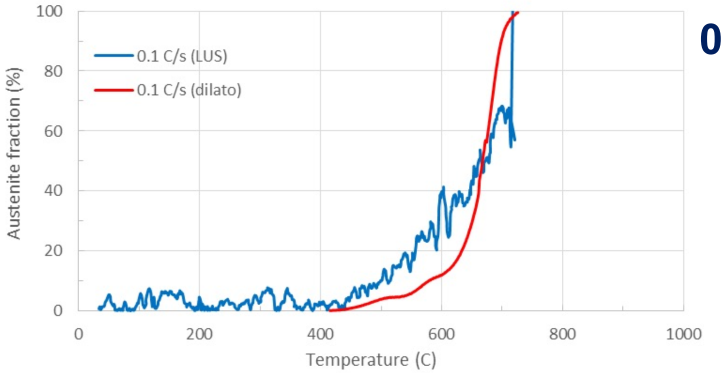


Velocity change:
0.3/5.4 = **5.5 %**

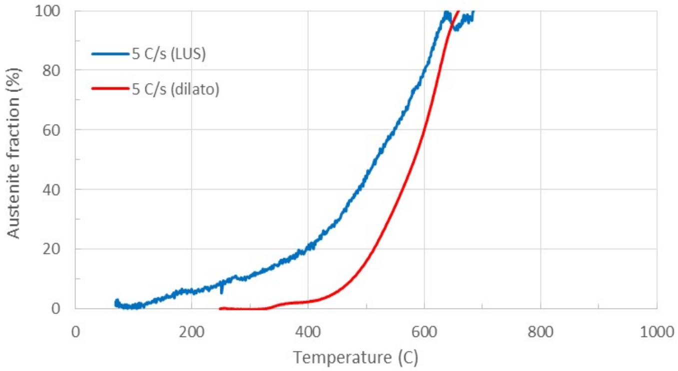
Phase Transformation

Comparison LUS vs Dilato (1): Grade DP780

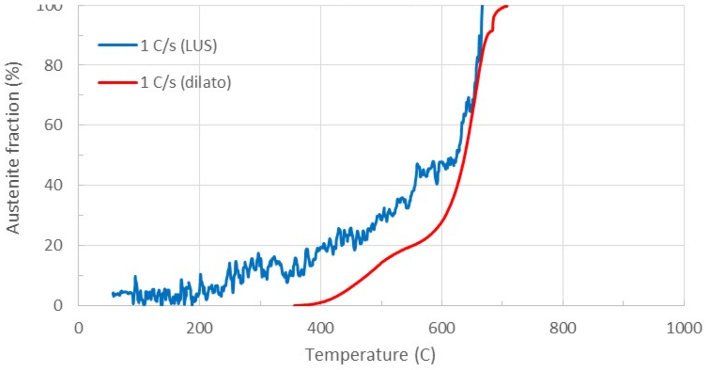
0.1 C/s



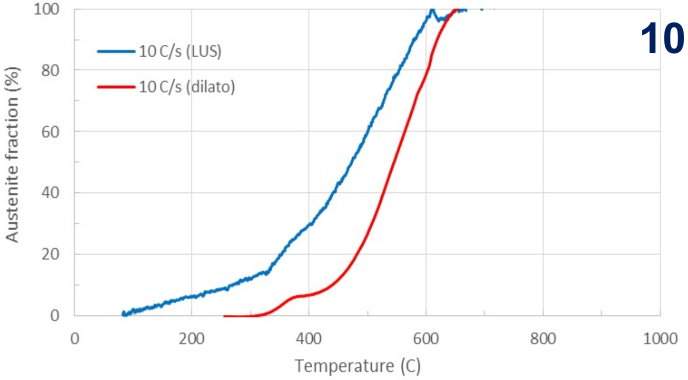
5 C/s



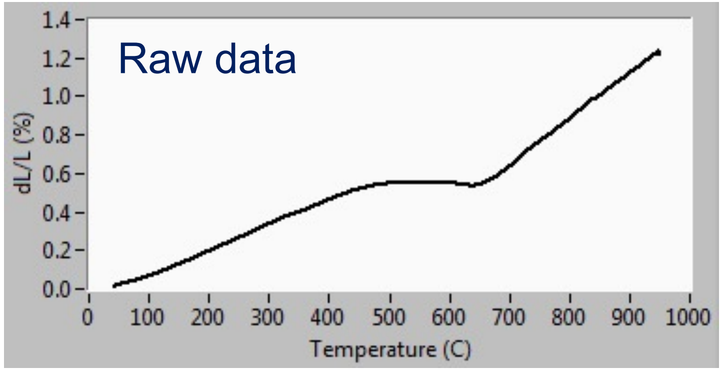
1 C/s

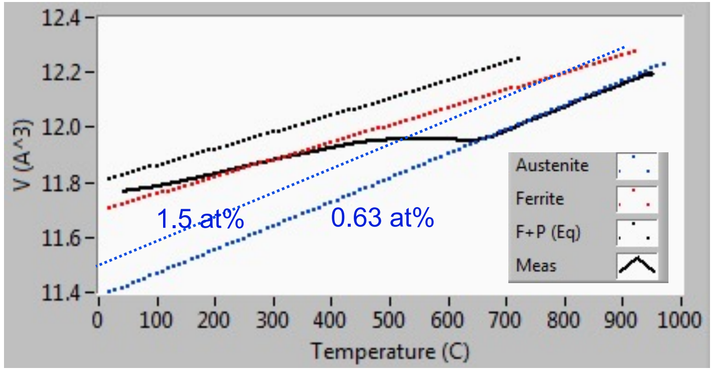


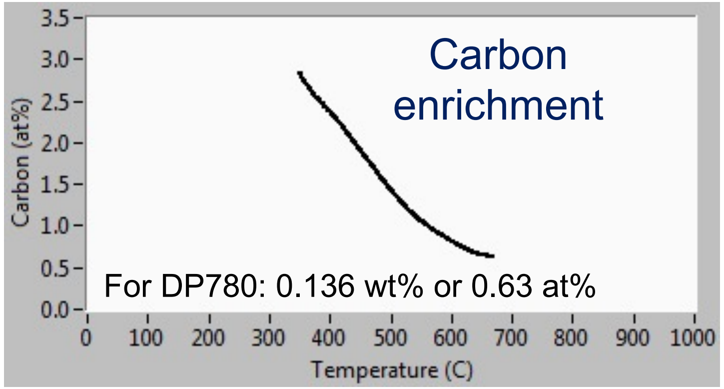
10 C/s

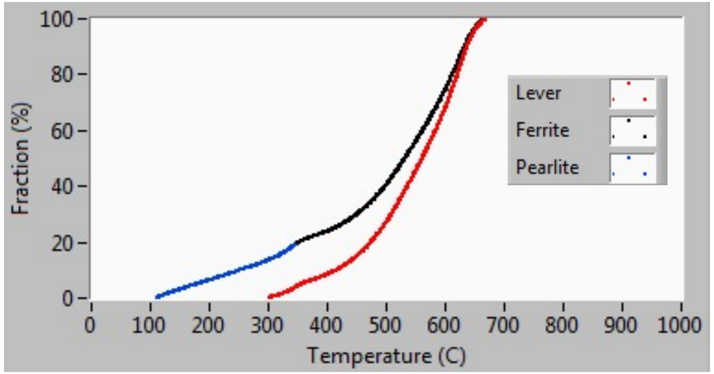


Phase Transformation
Dilatometry with correction: Grade DP780 @ -5 C/s





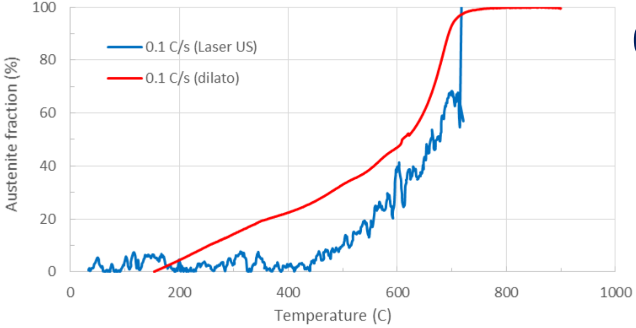




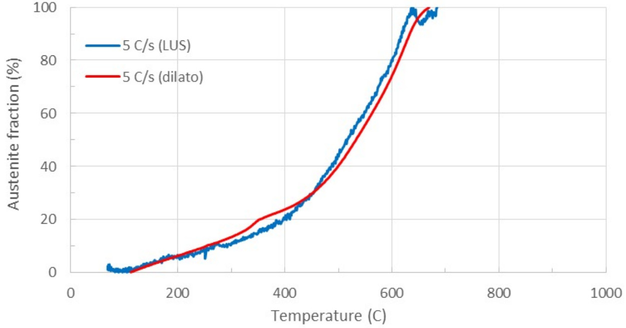
End of stage 1: Ts= 350^{o}C, C=2.82 at%
End of transfo : P=20%, F=80% (as expected)

Ref: T.A. Kop et al., J. Mater. Sci. 36, pp. 519-526 (2001)

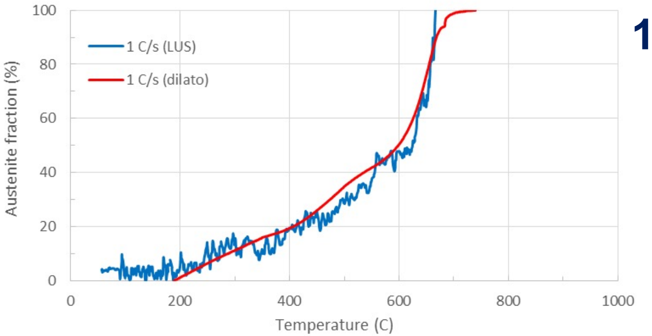
Phase Transformation
Comparison LUS vs Dilato with correction: Grade DP780



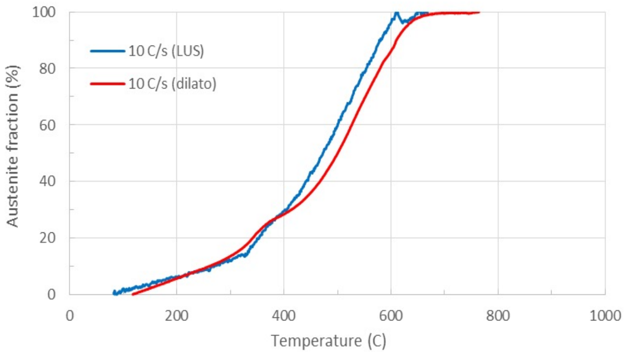
0.1 C/s



5 C/s



1 C/s



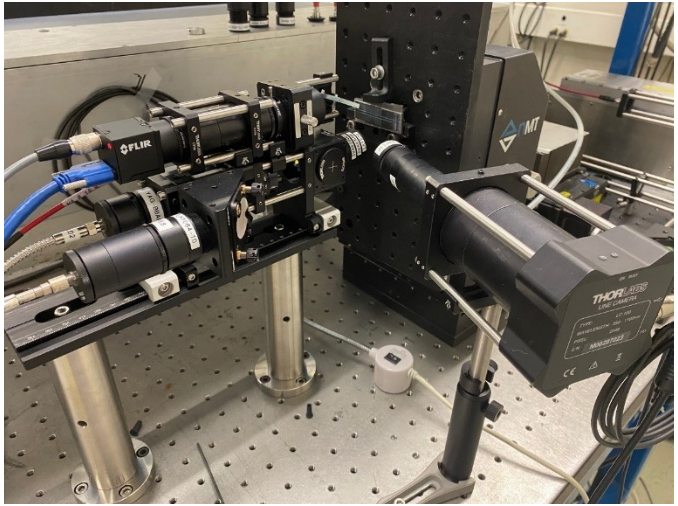
10 C/s

Microstructure
Conclusion

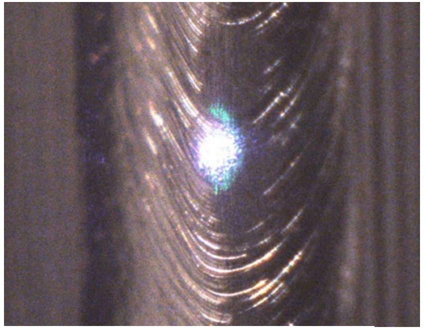
- Single hit tests were performed at different temperature deformation and strain rates. Depending on the conditions, recrystallization and grain growth are observed.
- Double hit tests were performed for different interpass times. Depending on the deformation temperature, measured grain growth behavior between successive stages of deformation can be quite different.
- Empirical models for the temperature dependence of LUS velocity in austenite, ferrite and cementite are given. Using a mixing rule, a model for pearlite is obtained.
- Comparison of dilatometry and LUS for phase transformation of DP780 are found in good agreement after a proper correction of dilatometric data for carbon enrichment of the remaining austenite during transformation.

RECENT DEVELOPMENTS AT NRC CANADA FOR WELD INSPECTION

Laser Ultrasonic Weld Inspection

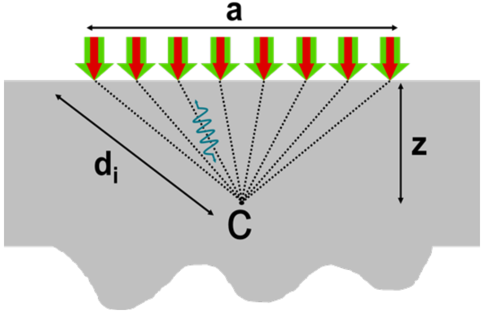


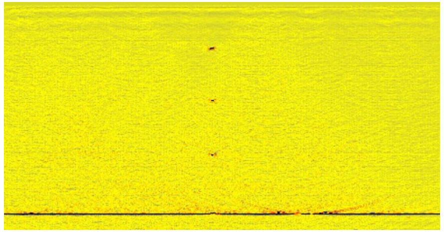
All optical fiber Laser ultrasonic head
With surface profile measurement



Superimposed
Generation (∅500μm) &
Detection (∅200μm)
Lasers

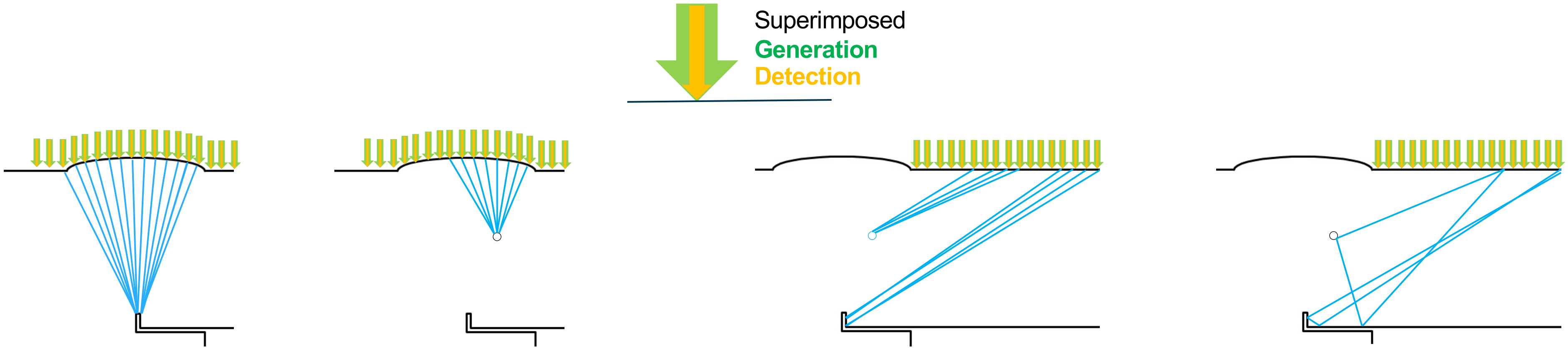
SAFT imaging





SAFT processed data (B-Scan)

Weld Inspection
Flaw detection and SAFT imaging



SAFT with longitudinal (L) waves ~ normal incidence
- Suitable for weld imaging
- Efficient for porosity sizing
- Can detect top of large LOP
- Requires inspection on weld bead
- Requires weld bead profile acquisition

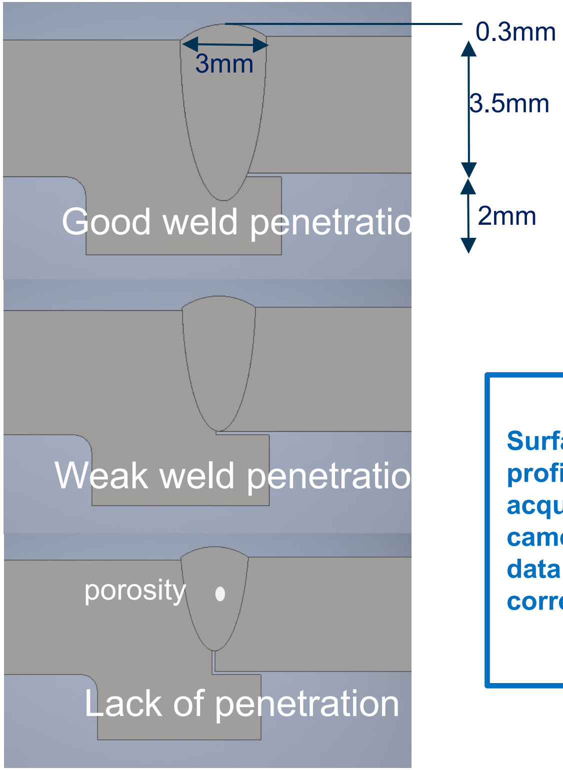
SAFT with shear (S) waves ~ oblique incidence
- Suitable for void detection from aside
- Height of indication difficult to assess
- Should detect thin LOP
- Should detect thin Cracks
- Do not require inspection on weld bead (better surface for detection, no profile acquisition)

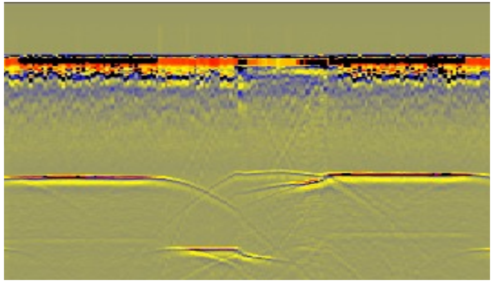
WELD INSPECTION

EB Weld inspection, Space Shuttle Pressure Vessels

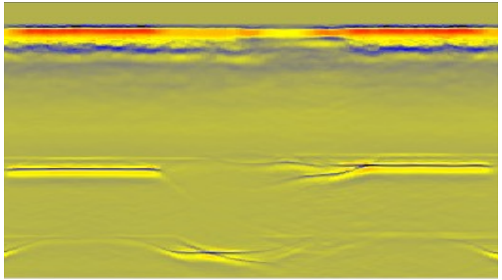
Weld Inspection - Reference Standard

EB weld, Space Shuttle Pressure Vessels



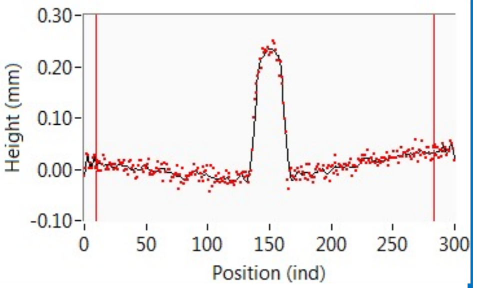


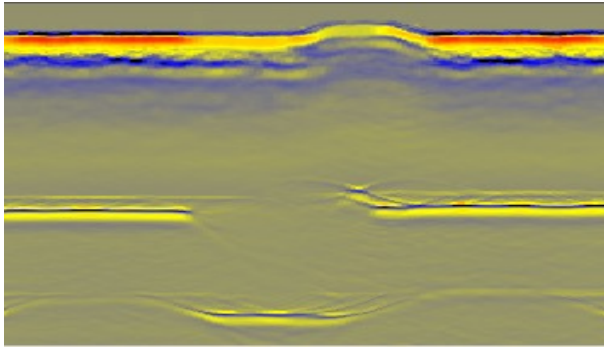
B-scan/Section view/Raw data



B-scan, L-Wave SAFT image

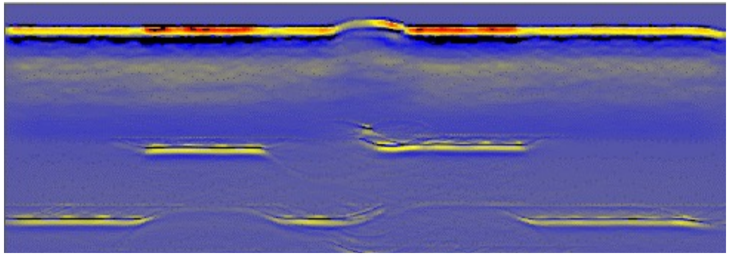
Surface profile acquired by camera for data correction



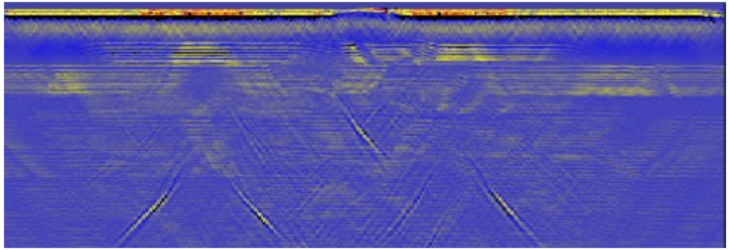


B-scan, L-Wave SAFT image with correction

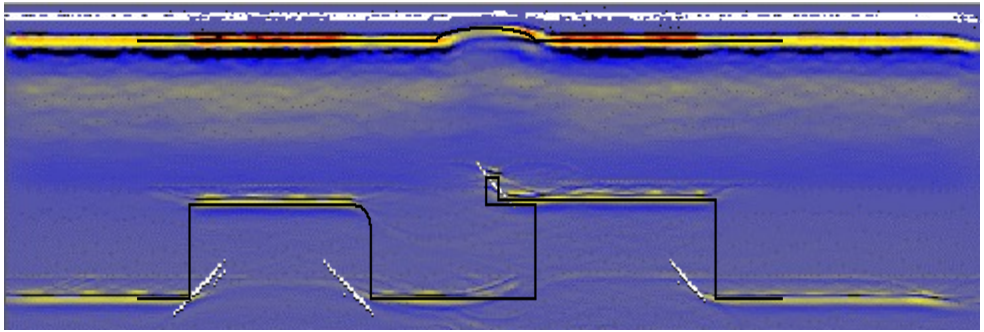
Weld Inspection - Reference Standard
EB weld, Space Shuttle Pressure Vessels



SAFT with Longitudinal (L) Waves



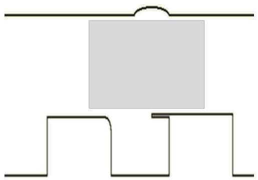
SAFT with Shear (S) Waves ~ Oblique Incidence



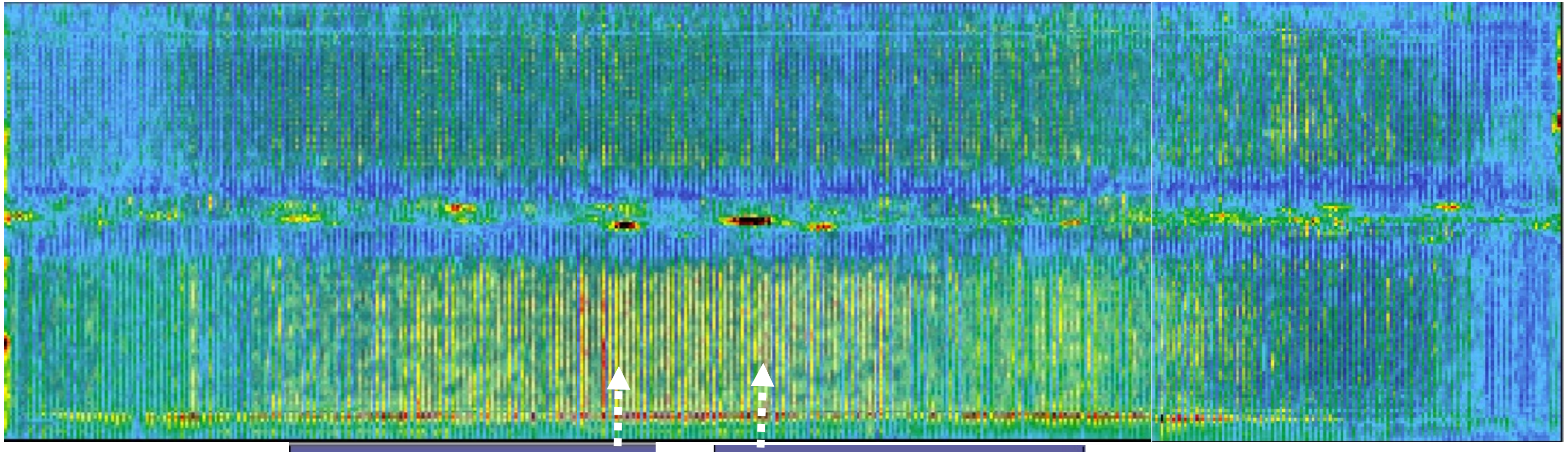
Superposition SAFT with L and S waves Wave

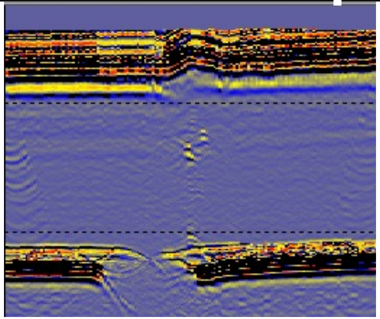
Weld Inspection – Real Part
EB weld, Space Shuttle Pressure Vessels

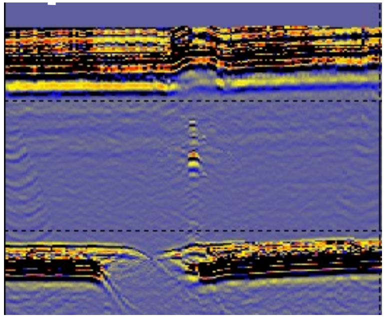
SAFT CScan



Area of void investigation





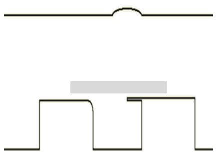


Bulk indications detected

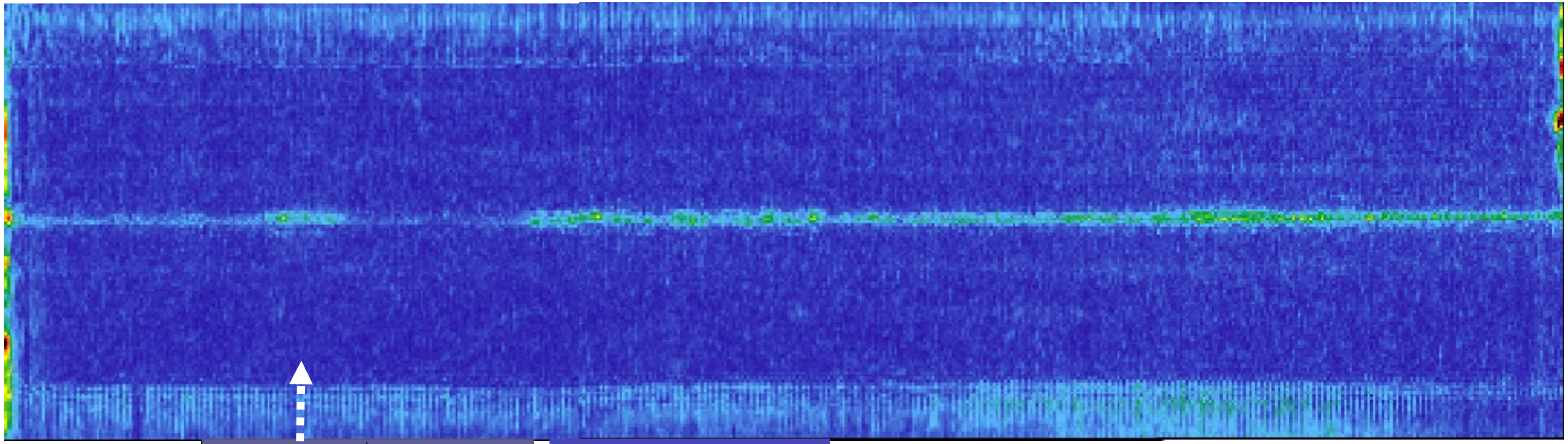
Weld Inspection – Real Part

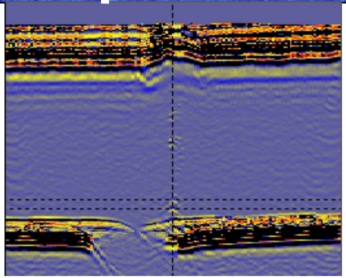
EB weld, Space Shuttle Pressure Vessels

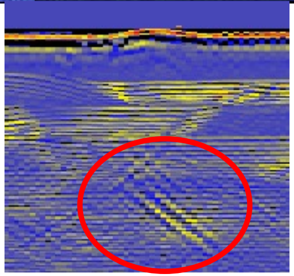
SAFT CScan



Area of void investigation







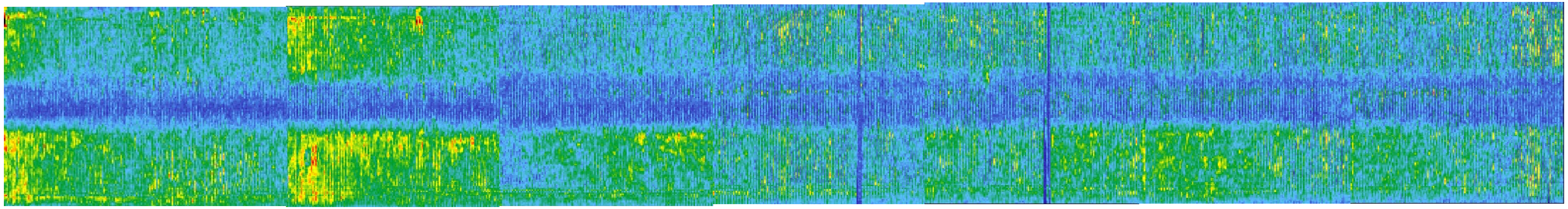
S-Wave Oblique Incidence

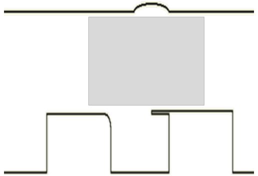
Indications close to the Weld root detected

Real part with indications

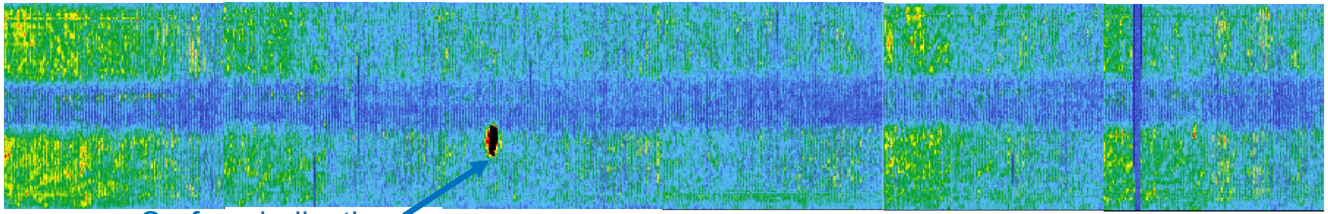
Weld Inspection – Real Part
EB weld, Space Shuttle Pressure Vessels

SAFT CScan



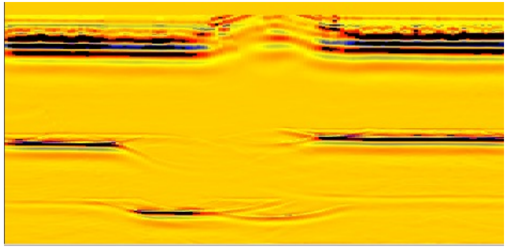


Area of void investigation

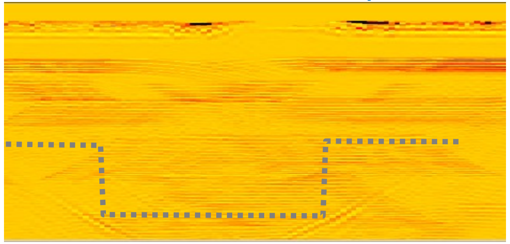


Surface indication

L-Wave Normal Incidence



S-Wave Oblique Incidence



No bulk indications detected

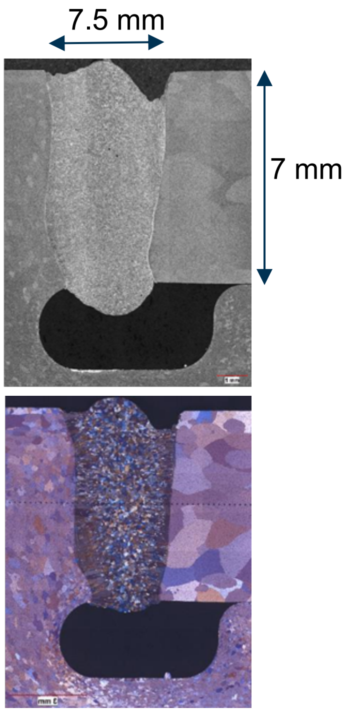
No indication close to the Weld root detected

WELD INSPECTION

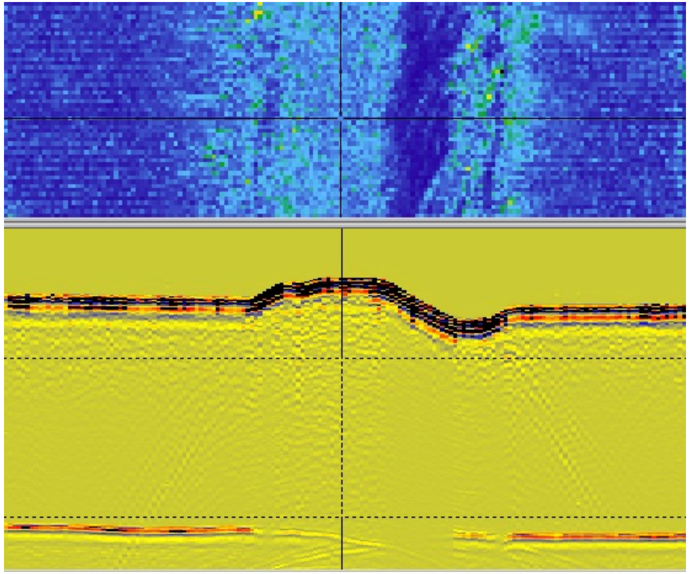
Various Welds

Weld Inspection

Weld inspection of large train structure, Robotic laser fusion

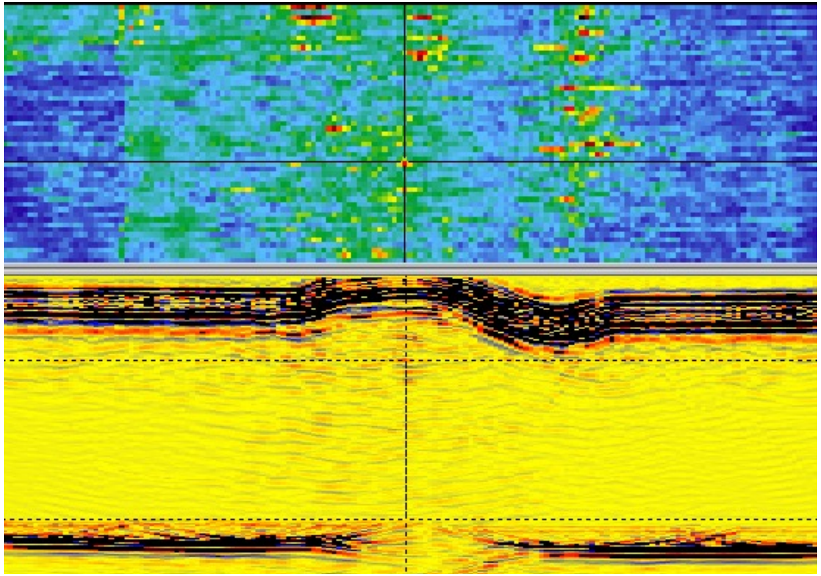


C-Scan (Raw data)



Raw B-Scan - Weld bead profile correction

SAFT C-Scan

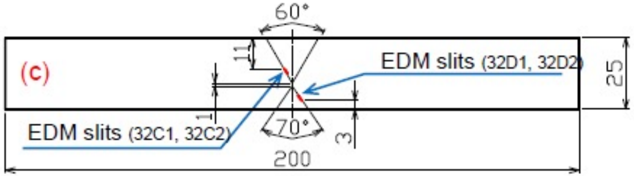


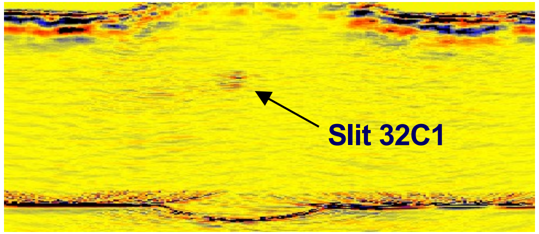
SAFT B-Scan - Weld bead profile correction

Weld Inspection

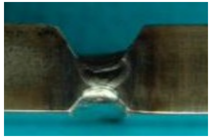
Multi-Pass Arc Welding - Thick Weld Inspection

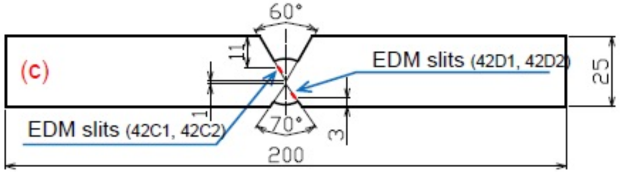
Complete Weld

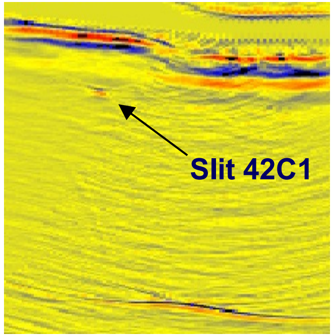




Underway Weld







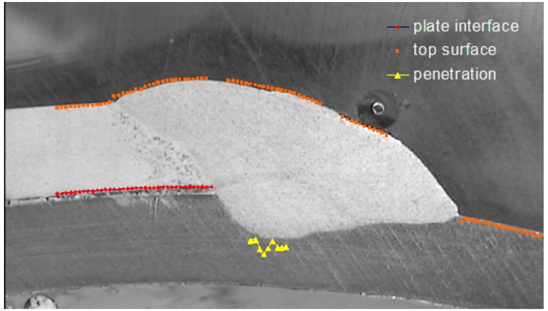
Inspection of thick welded joints using laser-ultrasonic SAFT

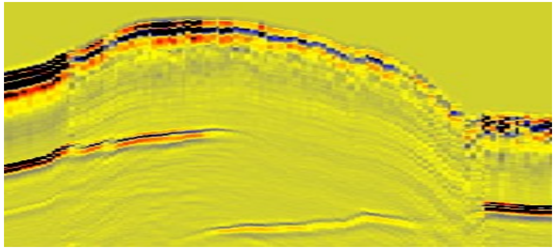
D. Lévesque, Y. Asaumi, M. Lord, C. Bescond, H. Hatanaka, M. Tagami, J.-P. Monchalin

Ultrasonics 69, pp. 236–242, (2016)

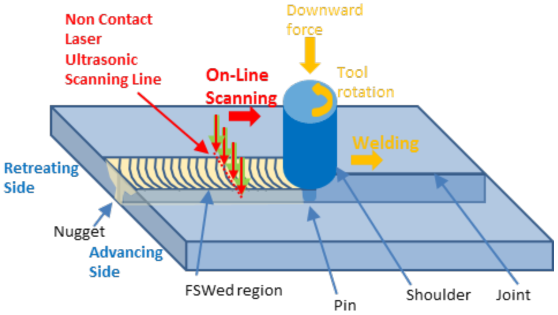
Weld Inspection

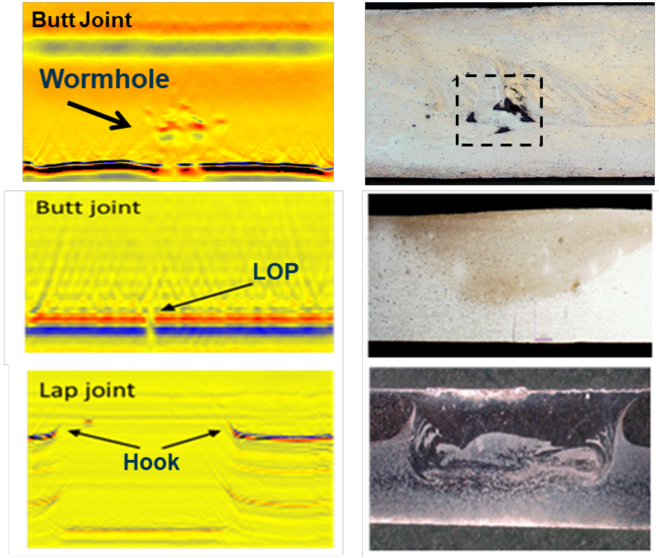
Robotic Laser Arc Welding





Friction Stir Welding



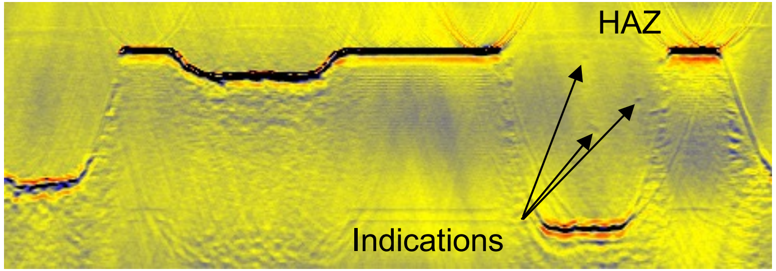


ADDITIVE MANUFACTURING INSPECTION

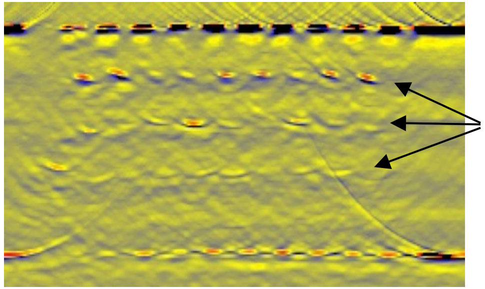
EB fusion, laser fusion, Cold spray, … powder & wire deposition

Additive Manufacturing Inspection
EB and laser fusion, powder and wire deposition

Inconel, powder deposition, laser fusion

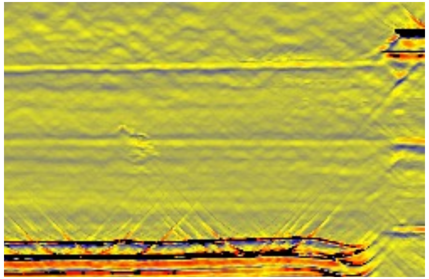


Inconel, wire deposition, laser fusion



Incomplete fusion between wires

Ti-6Al-4V, wire deposition, EB fusion



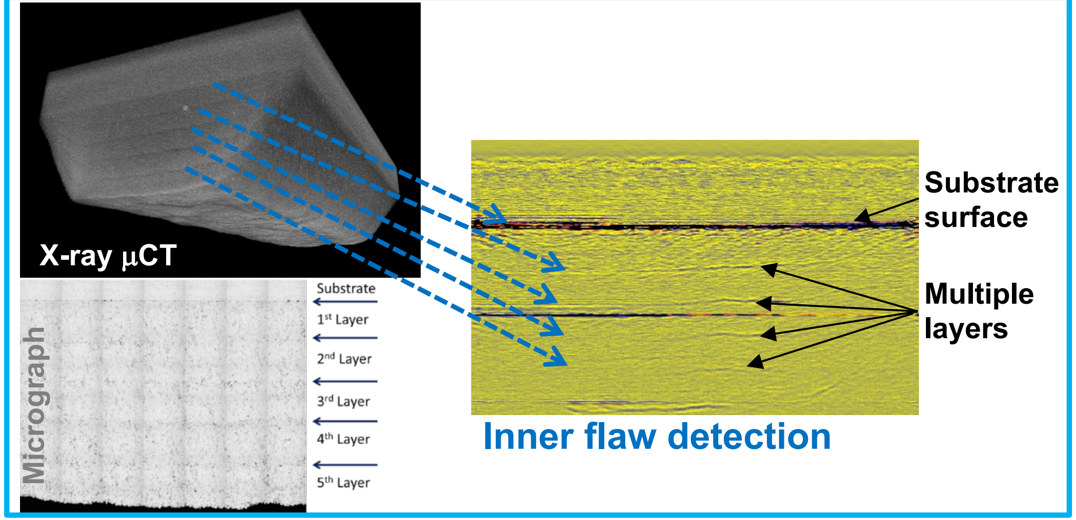
Complete fusion between wires

Inspection of additive manufactured parts using laser ultrasonics
D. Lévesque, C. Bescond, M. Lord, X. Cao, P. Wanjara, and J.-P. Monchalin
AIP Conf. Proc. 1706, pp. 130003-1–130003-9 (2016)

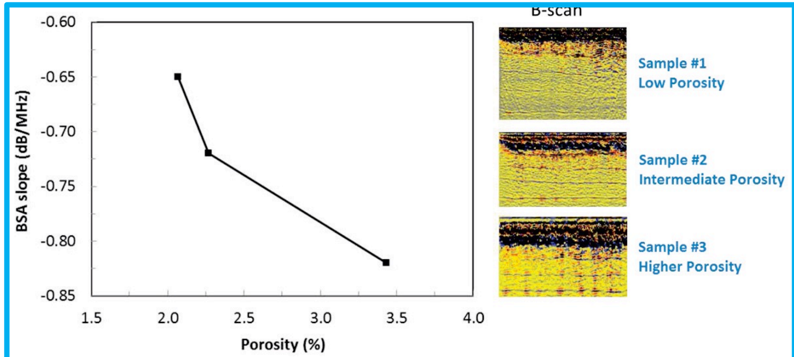
Additive Manufacturing Inspection

Cold Spray Additive Manufacturing (powder spray)

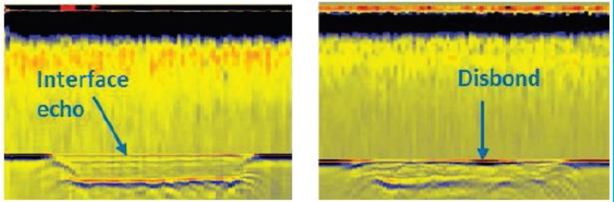
Cold Spray Additive Manufacturing



Inner flaw detection



Porosity assessment

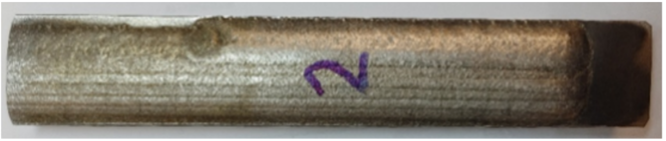


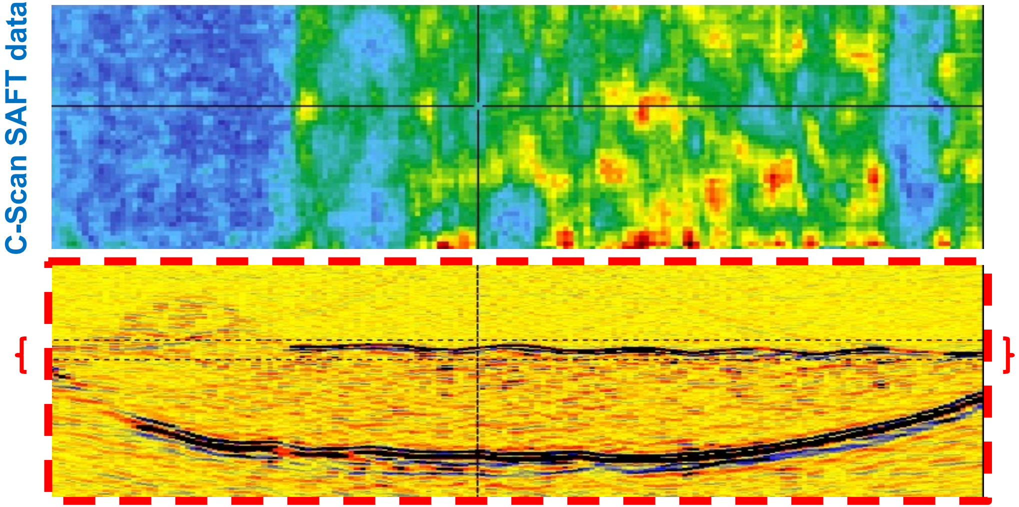
Bond integrity & bond strength

Laser-ultrasonic inspection of cold spray additive manufacturing components
D. Lévesque, C. Bescond and C. Cojocaru
AIP Conf. Proc. 2102, pp. 020026-1–020026-10 (2019)

Additive Manufacturing Inspection

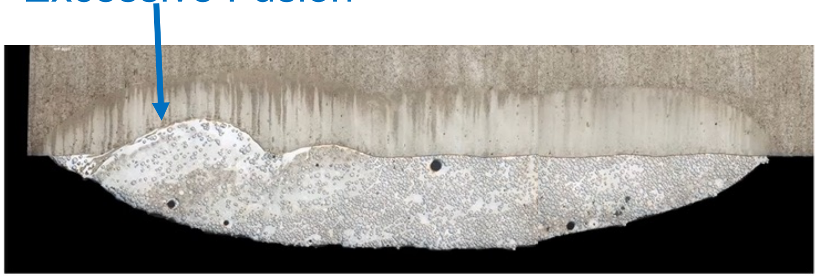
Hard coating laser cladding (Canada - Germany collaboration)





B-Scan SAFT data

Excessive Fusion



CONCLUSION

Conclusions

- Weld inspection and additive manufacturing results have been presented with SAFT imaging.
- S-wave Oblique incidence SAFT Imaging provides signature of corner indication → validation of a lack of penetration.
- Inspection of EB weld for Space pressure vessel is on-going with online implementation. Laser ultrasonic can be performed in the chamber with or without vacuum, without moving the part, what will enable weld repair and re-inspection.
- On-line Inspection of large structure with robotic laser fusion is on-going.
- Additive Manufacturing inspection is on going for laser Cladding.

THANK YOU

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