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

Christophe Bescond, Daniel Lévesque, Silvio E. Kruger and Charles Brosseau
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
Laser-ultrasonic system coupled to a Gleeble

Thermal cycle

- 1000°C-10 mins
- 950°C-30s
- 900°C-30s
- 820°C
- 600°C

Ultrasound measurements

- Helium quench

- 600°C

- Ultrasound measurement, PE

- 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

Material being tested
1st echo
2nd echo

Reference signal

\[ \frac{A(\omega)}{A_{\text{ref}}(\omega)} = \frac{20}{2e} \log_{10} \left( \frac{A_{\text{ref}}(f)}{A(f)} \right) \]

Attenuation spectrum

\( f \) (MHz)

Amplitude spectra

Frequency (MHz)

Attenuation (dB/mm)
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

Strain applied here (rate of 0.1 to 10 s\(^{-1}\))

LUT measurement
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)

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

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

\[
\min_x \left\{ \sum_T \left[ V_{\text{meas}}(T) - V_{\text{calc}}(T, V_{\text{cementite}}, V_{\text{ferrite}}, x) \right]^2 \right\}
\]

with \( V_{\text{calc}} = x V_{\text{cementite}} + (1-x) V_{\text{ferrite}} \)

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

Velocity change:
0.3/5.4 = 5.5 %
Phase Transformation
Comparison LUS vs Dilato (1): Grade DP780
Phase Transformation
Dilatometry with correction: Grade DP780 @ -5 C/s

Raw data

Carbon enrichment

For DP780: 0.136 wt% or 0.63 at%


End of stage 1: Ts= 350°C, C=2.82 at%
End of transfo : P=20%, F=80% (as expected)
Phase Transformation
Comparison LUS vs Dilato with correction: Grade DP780

Graphs showing the comparison of austenite fraction with different cooling rates for Grade DP780.

- 0.1 C/s
- 1 C/s
- 5 C/s
- 10 C/s
• 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 (Ø500µm) & Detection (Ø200µm) 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

Good weld penetration

Weak weld penetration

Lack of penetration

Surface profile acquired by camera for data correction

B-scan/Section view/Raw data

B-scan, L-Wave SAFT image

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

Area of void investigation

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

SAFT CScan

Area of void investigation

Indications close to the Weld root detected
Real part with indications

S-Wave Oblique Incidence

NATIONAL RESEARCH COUNCIL CANADA
Weld Inspection – Real Part
EB weld, Space Shuttle Pressure Vessels

SAFT CScan

Area of void investigation

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

7.5 mm

7 mm
Weld Inspection
Multi-Pass Arc Welding - Thick Weld Inspection

**Complete Weld**

**Underway Weld**

**Inspection of thick welded joints using laser-ultrasonic SAFT**
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

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

Inspection of additive manufactured parts using laser ultrasonics
D. Lévesque, C. Bescond, M. Lord, X. Cao, P. Wanjara, and J.-P. Monchalin
Additive Manufacturing Inspection
Cold Spray Additive Manufacturing (powder spray)

Cold Spray Additive Manufacturing

Laser-ultrasonic inspection of cold spray additive manufacturing components
D. Lévesque, C. Bescond and C. Cojocaru
Additive Manufacturing Inspection
Hard coating laser cladding (Canada - Germany collaboration)

C-Scan SAFT data

B-Scan SAFT data

Excessive Fusion
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

Christophe Bescond

Agent de recherche Sénior | Chef d’Équipe Technologies ultrasonores | Diagnostics de procédés
Portefeuille Énergie, mines et environnement du CNRC
Conseil national de recherches Canada
75, de Mortagne, Boucherville, Québec J4B 6Y4
Christophe.Bescond@cnrc-nrc.gc.ca | Tél : 450-641-5230 | Cell : 438-342-7321

Senior Research Officer | Team Leader Ultrasonic Technology | Process diagnostics
NRC Energy, Mining and Environment Portfolio
National Research Council Canada
75, de Mortagne, Boucherville, Québec J4B 6Y4
Christophe.Bescond@cnrc-nrc.gc.ca | Tel: 450-641-5230 | Cell: 438-342-7321