CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

ICAM2022

ASTM INTERNATIONAL
Helping our world work better

Inconel 625 L-PBF part categorization by process parameters using resonant ultrasound spectroscopy

Anne-Françoise Obaton, Gregory Weaver, Lucas Fournet Fayard, Charles Cayron, Florian Montagner, Olivier Burnet, and Alex Van den Bossche

October 31- November 4, 2022

www.amcoe.org

Baker Hughes GrindoSonic THE IMPULSE EXCITATION TECHNIQUE WeaverNDT Non-Destructive Testing & Consulting LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS LNE

Biography

Anne-Françoise Obaton

Dr. habil. **Anne-Françoise Obaton** is involved in research in metrology at the Laboratoire National de Métrologie et d'Essais (LNE) in Paris (French National Metrology Institute (NMI)). Her research focused on metrology for additive manufacturing (AM). Since 2014, she is **conducting research on the investigation and qualification of volumetric non-destructive testing (NDT) methods for quality insurance of AM parts** and particularly on **X-ray tomography (XCT)** and **resonant ultrasound spectroscopy (RUS)** methods. Related to this topic, she has been staying abroad, as guest researcher, in several countries:

- two months in 2016 at BAM in Berlin (German Designated Metrology Institute) working on XCT inspection of AM parts in the frame of the Joint Research Project (JRP) MetAMMI (see below);
- fifteen days in 2017 at PTB in Braunschweig (German NMI) working on the characterisation of XCT in the frame of the JRP MetAMMI;
- one year in 2018 at NIST in Gaithersburg (US NMI) working on various NDT methods for quality insurance of AM parts;
- three months in 2020 at DTU in Lyngby (Danish Technical University) working on the design and fabrication of standards for the characterisation of XCT in the frame of the JRP AdvanCT (see below);

Since 2014, she is involved in standardization on AM (national group: UNM 920, international group: ISO/TC261-ASTM/F42, joint group JG59 on “NDT for AM parts” and more recently in JG52 on "Standard test artifacts"). Since 2022, she is involved in ASTM E07.01 Radiology (X and Gamma) Method including XCT and E 07.06 Ultrasonic Method including RUS. She is also strongly involved in the XCT working group of the French Confederation for Non-Destructive Testing (COFREND) in which she is presently conducting 2 round robins: one on image quality and one on dimensional measurements. Finally, she is a CIRP corporate member.
She has set up and was involved in two national projects with industrial partners on quality insurance of AM parts (FUI I AM SURE 11/2015-05/2020, FA-CanalSafe® 07/2019-06/2021) and was involved in the JRP “Advanced Computed Tomography for dimensional and surface measurements in industry” (AdvanCT, 17IND08 06/2018-05/2021, https://www.ptb.de/empir2018/advanct/).

From 06/2016 until 05/2019, she has set up and coordinated the JRP “Metrology for Additively manufactured medical implants” (MetAMMI, 15HLT09, http://projects.lne.eu/jrp-metammi/) which received funding from the EMPIR programme.

Overview

- Resonant ultrasound spectroscopy (RUS)
- Investigated parts
- RUS examination of the parts
- X-ray computed tomography (XCT) examination of some parts
- Summary and conclusions

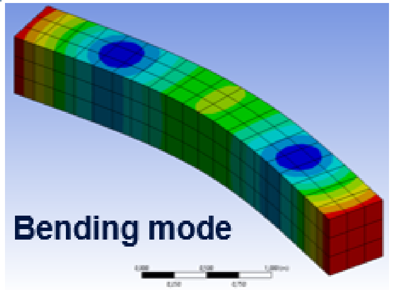
Principle and benefits of RUS

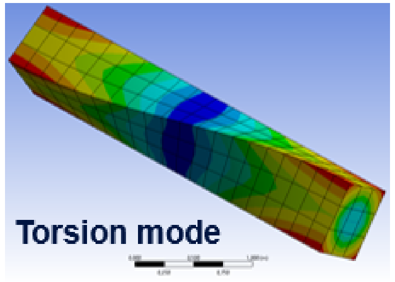
Resonant Ultrasound Spectroscopy (RUS) methods

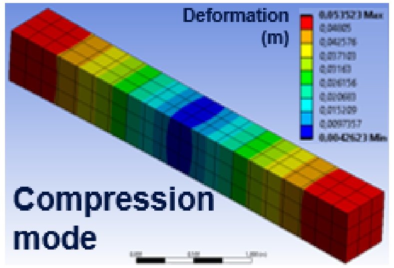
ICAM2021

Principle of RUS methods

1. Mechanical impulse of the sample under test to generate its natural resonant frequencies
2. Monitoring of the vibrational response of the sample under test ⇒ frequency spectrum (resonant peaks of the vibrational modes of the sample under test)
3. Comparison of the spectrum of the sample under test to the spectra of an established acceptable resonant frequency pattern (reference parts or parts from the same family or simulations)
4. Analysis of the frequency shifts between the peaks of the sample under test and the peaks of the pattern: shifts ⇒ Difference in the intrinsic properties of the sample





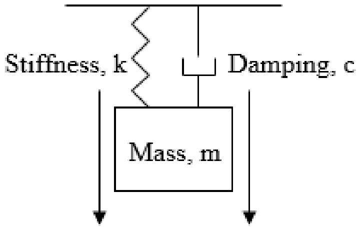


2 types of RUS methods according to E2001-18

1. "Swept sine method" with a piezoelectric sensor
2. "Impulse excitation technique" (IET) with a hammer tip

Resonant frequencies are related to:

1. The geometry of the part
2. The density of the part
3. The elasticity of the part
4. The external and internal structural integrity of the part (e.g. crack)



Benefits of the methods

- ➢ **deals with complex shapes and rough surfaces**
- ➢ **deals with large parts**
- ➢ **fast and easy to use**

Drawbacks of the methods

- ➢ **global or full body methods**
- ➢ **comparison methods**

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

Draft, in progress, of a standard practice for IEM

ICAM 2022

E07
Nondestructive Testing

E07.06
Ultrasonic Method

Skeleton Draft

Standard Practice for Resonance Testing Using the Impulse Excitation Method

1. Scope

1.1 This practice describes a general procedure for using Impulse Excitation Method (IEM) to measure natural frequencies and detect defects and material variations in metallic and non-metallic parts. This test method is also known as Impulse Excitation Technique (IET), Acoustic Resonance Testing (ART), Resonant Acoustic Method (RAM), ping testing, tap testing, and other names. IEM is a type of Resonance Ultrasound Spectroscopy (RUS) method. The method applies an impulse load to excite and then record resonance frequencies of a part. These recorded resonance frequencies are compared to a reference population or within subgroups/families of examples of the same part and/or modeled frequencies.

RUS systems investigated in collaboration

A-F. Obaton, A. Van den Bossche, O. Burnet, B. Butsch, I. Zouggarh, F. Soulard , and W. Johnson, "Novel or Improved NDE Inspection Capabilities for Additively Manufactured Parts", in Progress in Additive Manufacturing 2020, ed. N. Shamsaei and M. Seifi (West Conshohocken, PA: ASTM International, STP1637, 2022).

Overview

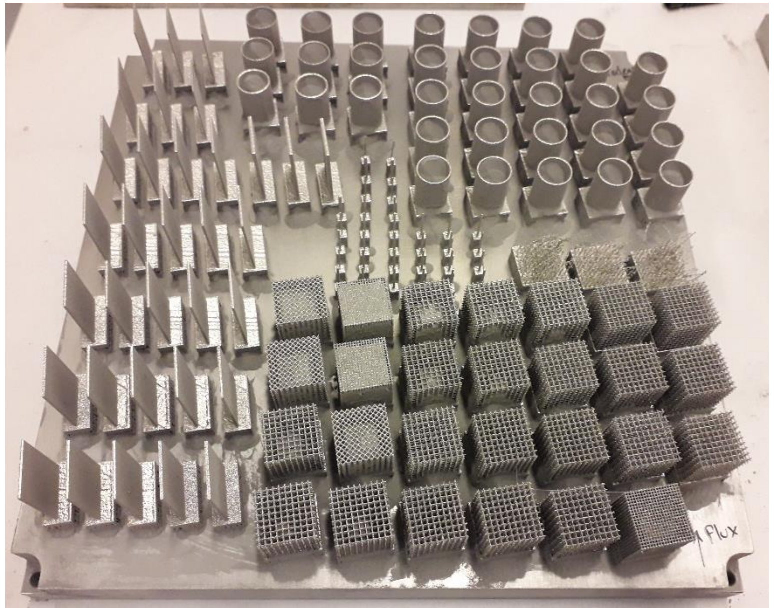
ICAM 2022

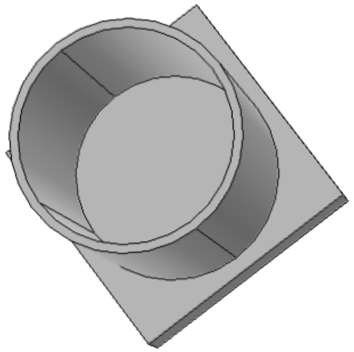
- Resonant ultrasound spectroscopy (RUS)
- **Investigated parts**
- RUS examination of the parts
- X-ray computed tomography (XCT) examination of some parts
- Summary and conclusions

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

Parts with different process parameters or wall thickness

3DSystems ProX DMP320 PBF-LB machine



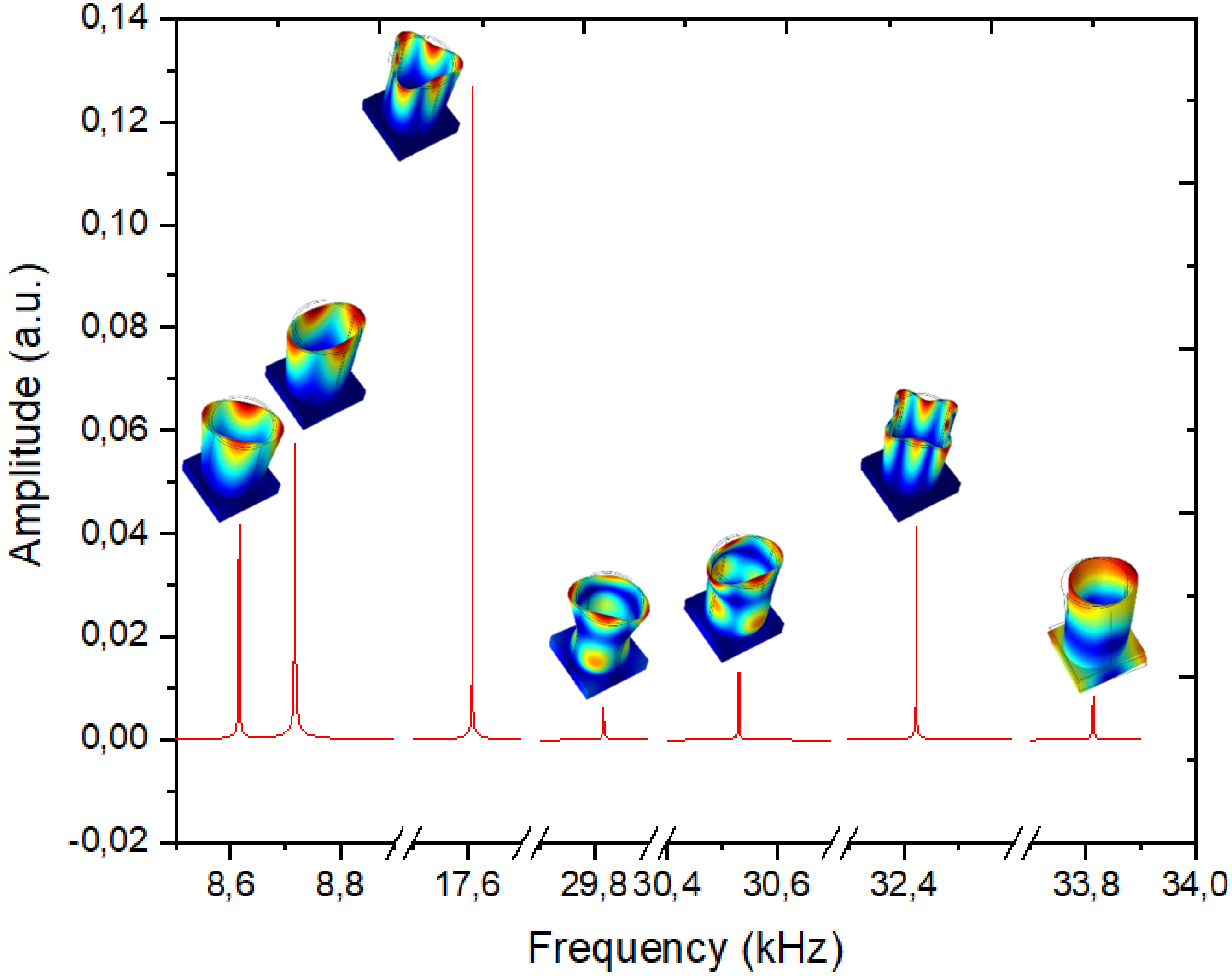


Inconel 625 parts

Parameter	Wall thickness (mm)	Laser power (W)	Scanning speed (mm/s)	Laser power for contour (W)	Scanning speed for contour (mm/s)
Variation range	0.25 to 0.75	253 to 400	900 to 1875	180 to 253	900 to 1500

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

Part’s vibrational modes

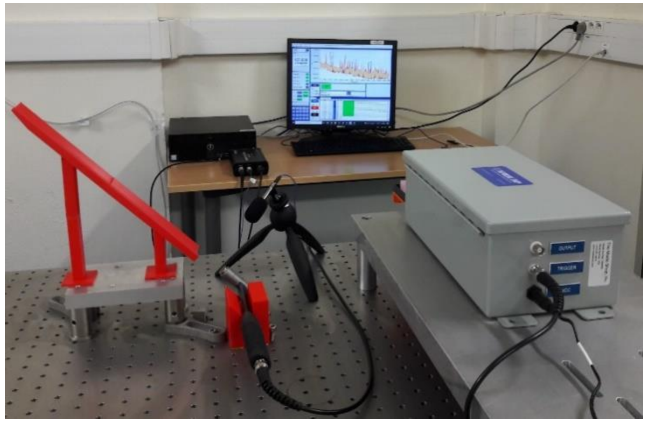


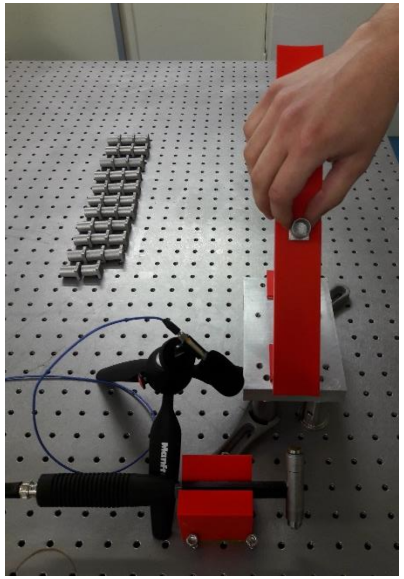
Mode number	Simulation (Hz)	Experience (Hz)
Mode 1	8615	8596
Mode 2	8718	8874
Mode 3	17609	16542
Mode 4	29817	29801
Mode 5	30531	30072
Mode 6	32423	32901
Mode 7	33817	34299

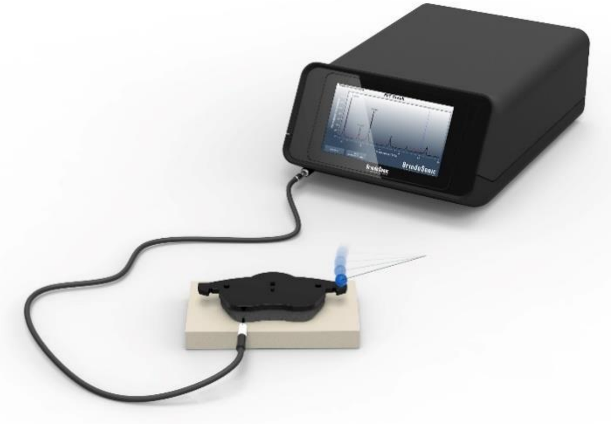
Overview

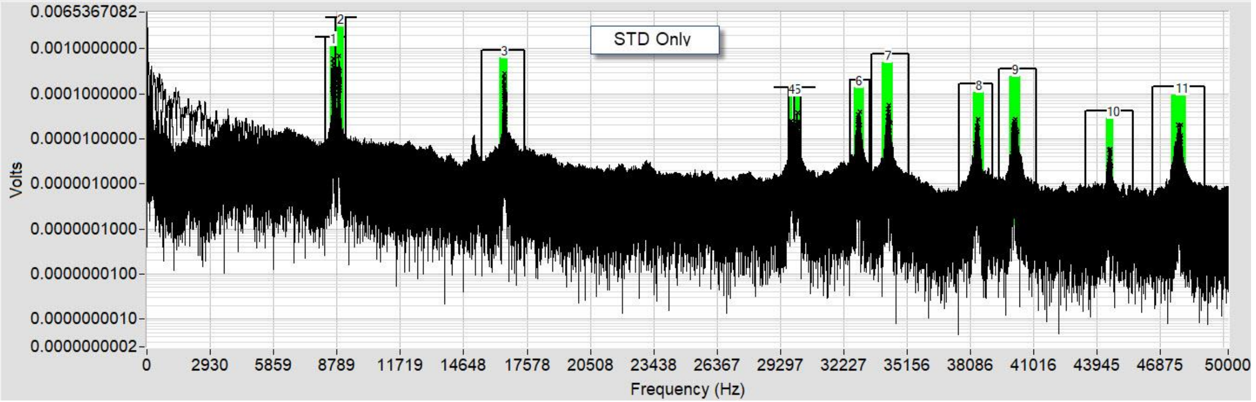
- Resonant ultrasound spectroscopy (RUS)
- Investigated parts
- **RUS examination of the parts**
- X-ray computed tomography (XCT) examination of some parts
- Summary and conclusions

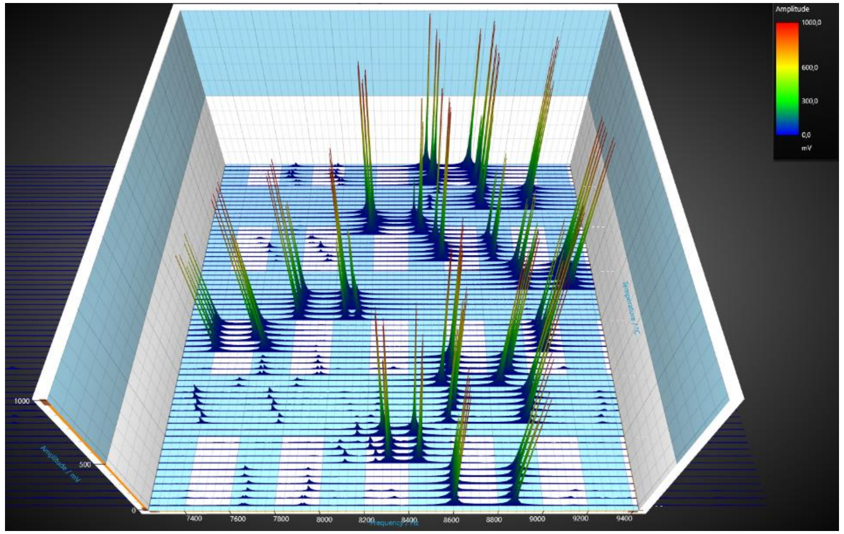
RUS examination of the parts











Z-score analysis

ICAM 2022

Z-score offers a physical interpretation of the data :

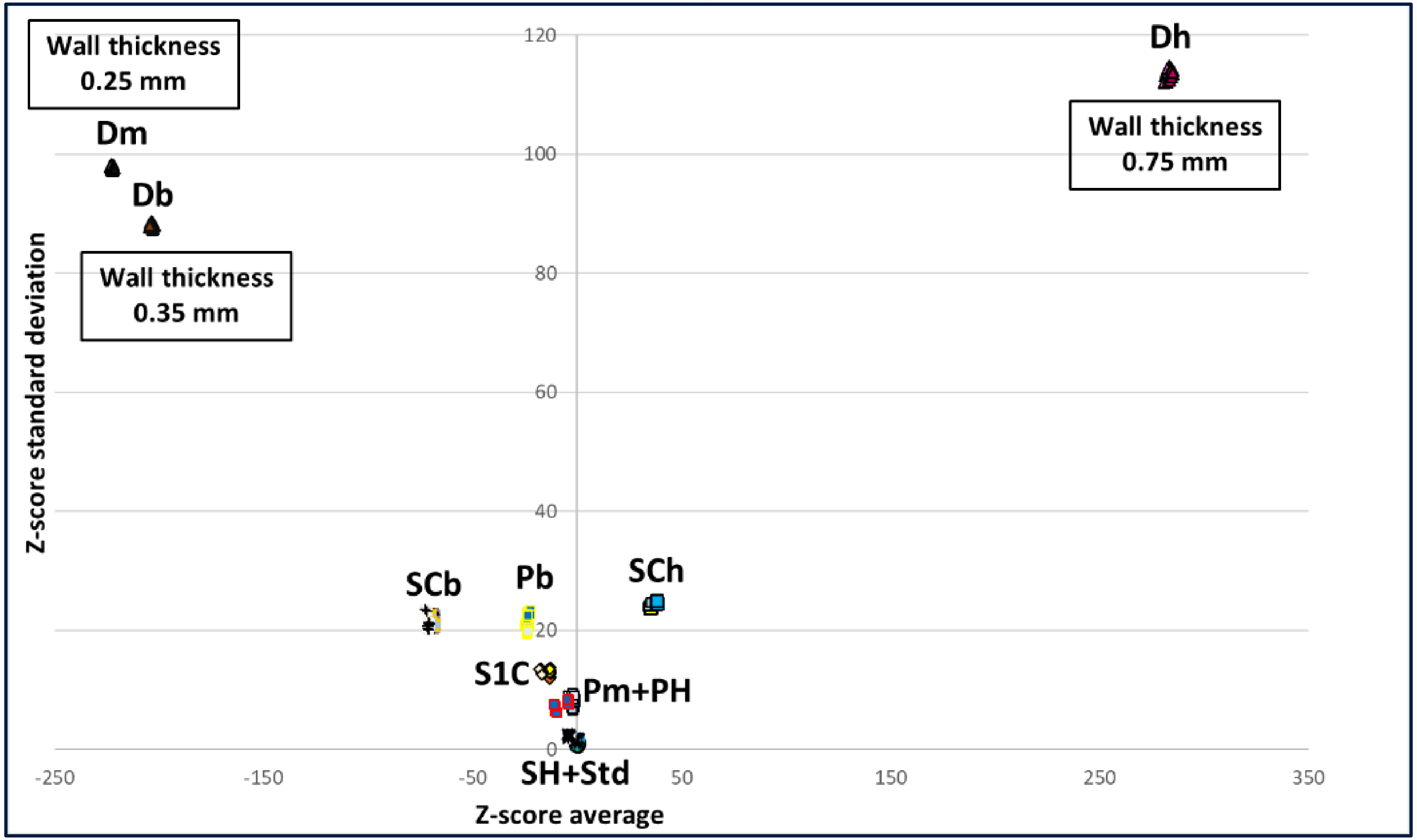
- used to compare a sample's location within a population of reference samples,
- expresses the deviation of the sample from the mean value of the reference samples' population in term of standard deviation on the population taken as reference.

$$Z\ score = \frac{peak\ frequency\ of\ a\ sample - mean\ of\ the\ peak\ frequencies\ of\ a\ reference\ samples'\ population}{standard\ deviation\ of\ the\ peak\ frequencies\ of\ the\ reference\ samples'\ population}$$

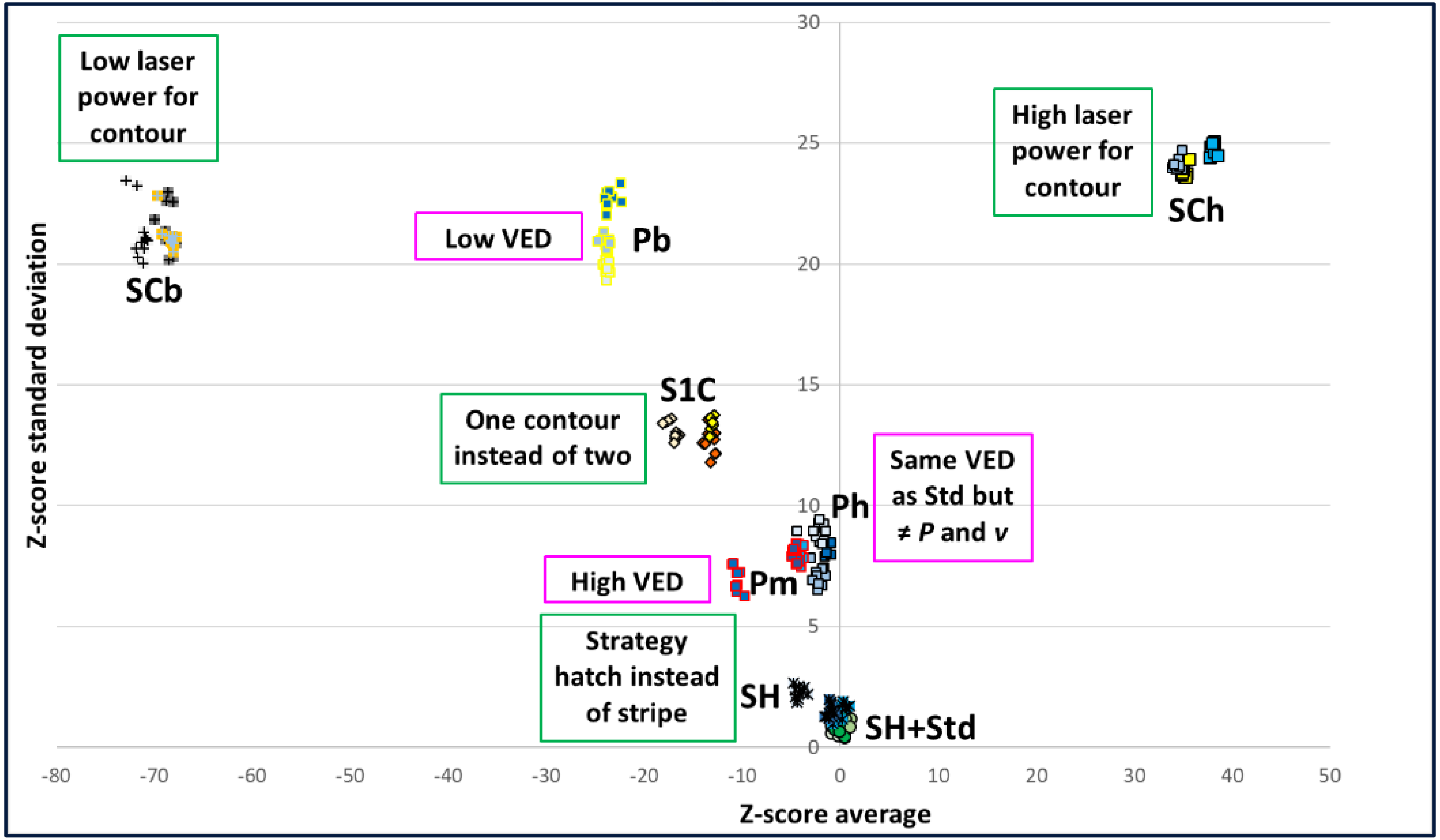
WeaverNDT Non-Destructive Testing & Consulting

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

Z-score analysis of the RUS data

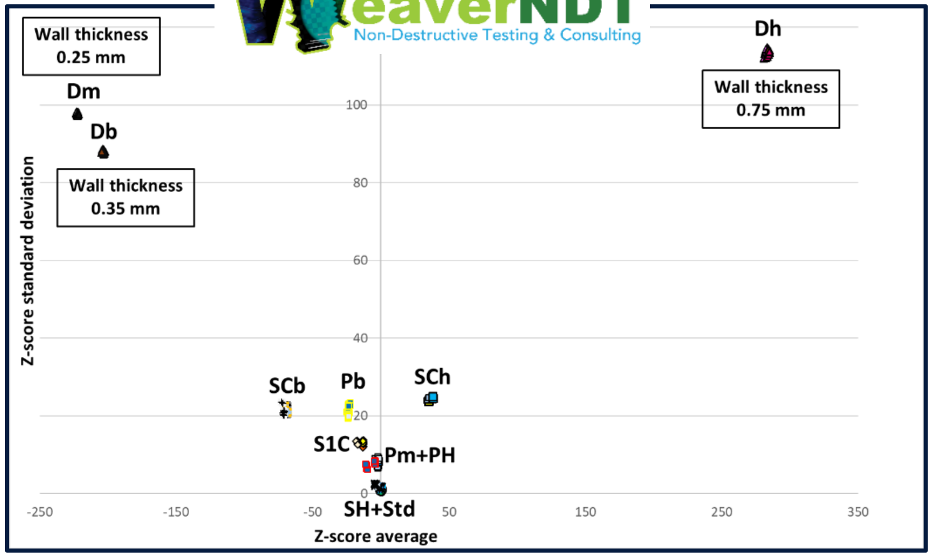


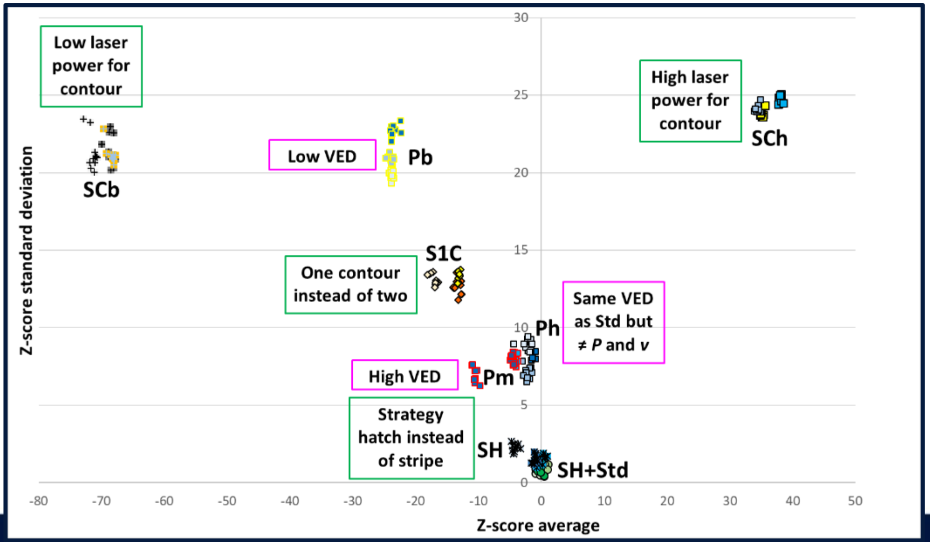
Z-score analysis of the RUS data

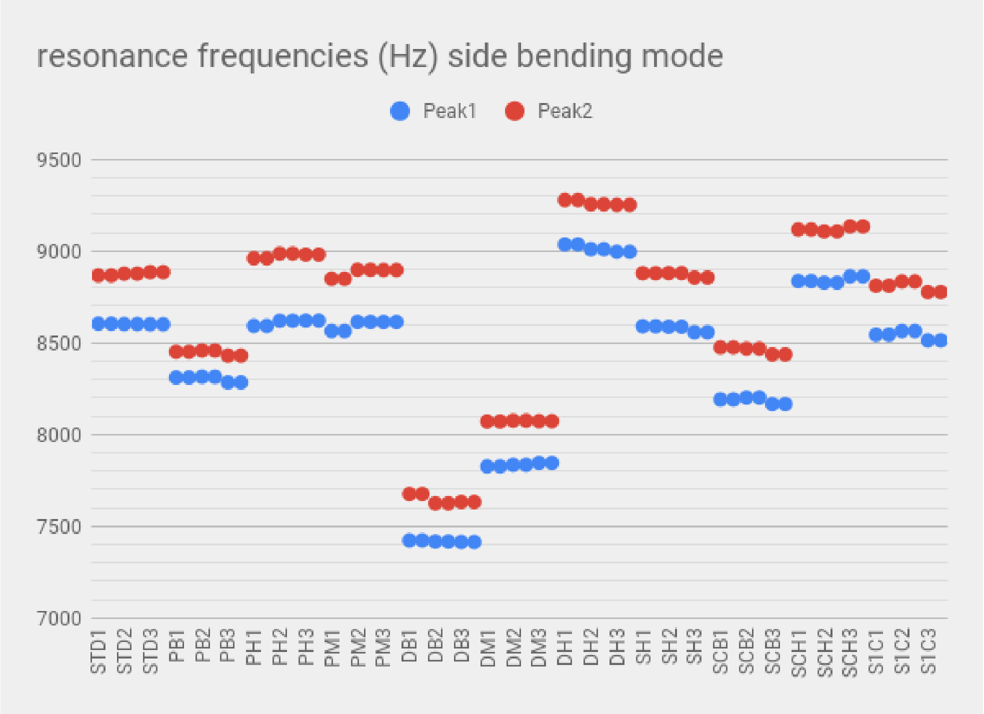


Z-score analysis of the RUS data

ICAM 2022

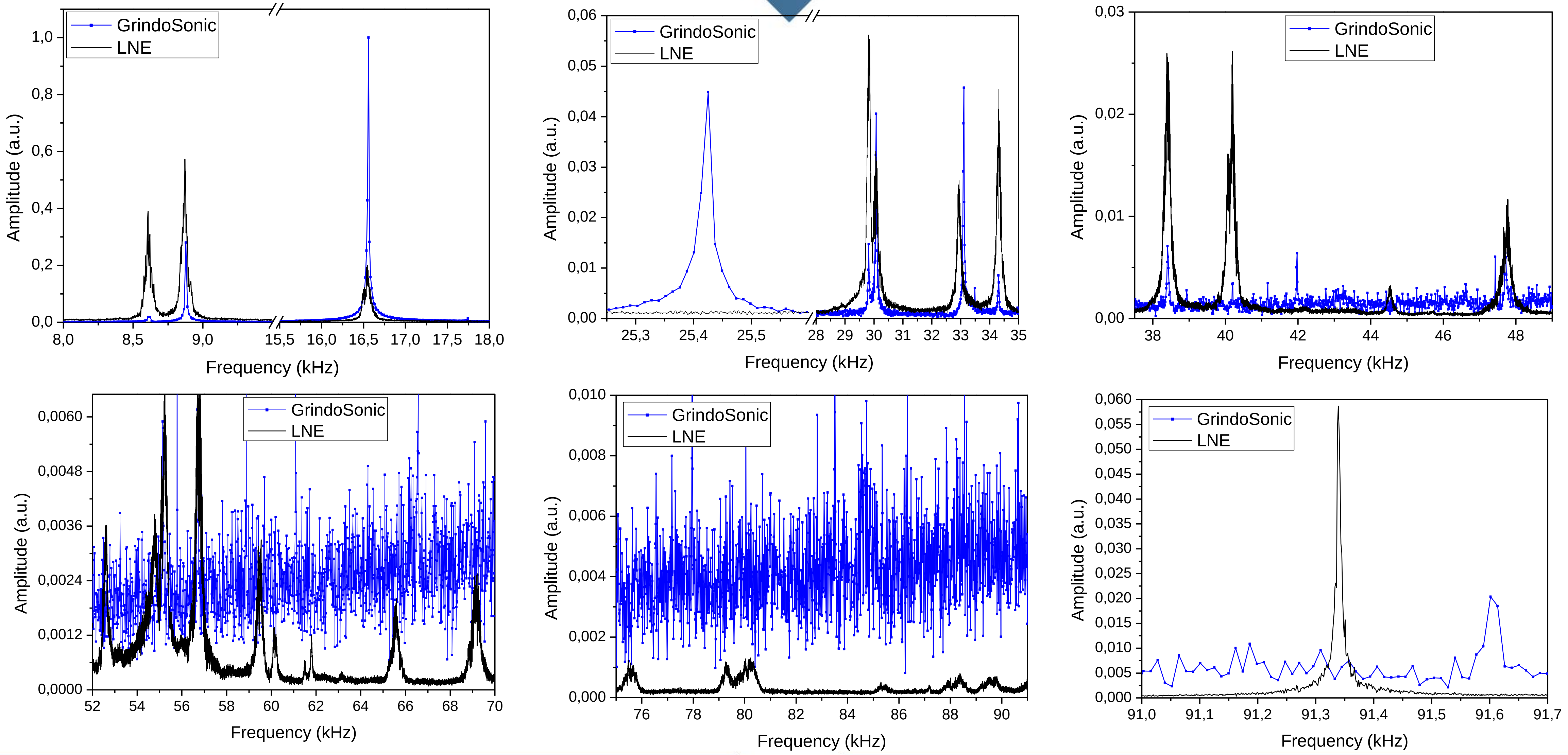




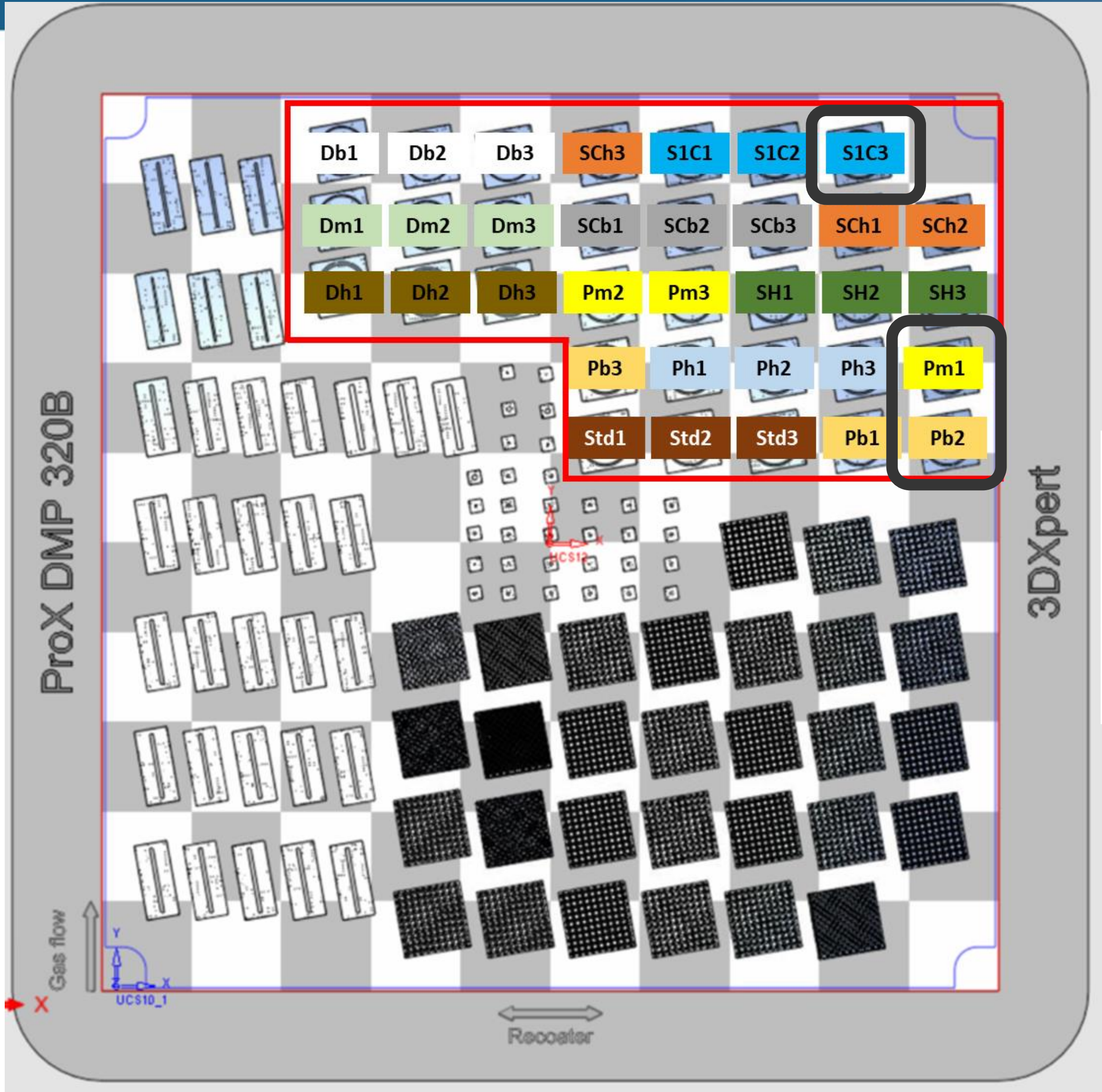


⇒ The analysis of the data acquired with the RUS system from GrindoSonic confirms the data acquired with the RUS system from LNE.

Comparison of RUS spectra, GrindoSonic/LNE



Analysis of the RUS data



Outlier in a set of 3 cylinders

Outlier in a set of 3 cylinders	Position on the AM platform	Cylinders that should be XCT scanned
Pm1	Isolated from Pm2/3 and on the edge	Pm1and Pm2 or Pm3
SH3	On the edge	SH3 and SH1 or SH2
S1C3	On the edge	S1C3 and S1C1 or S1C2

⇒ These outliers, as well as one part from the same set, were scan by X-ray computed tomography (XCT).

Overview

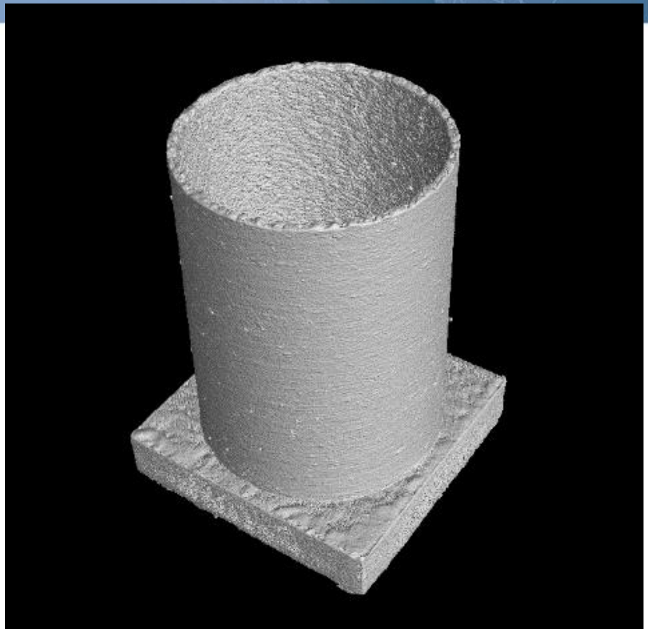
ICAM 2022

- Resonant ultrasound spectroscopy (RUS)
- Investigated parts
- RUS examination of the parts
- **X-ray computed tomography (XCT) examination of some parts**
- Summary and conclusions

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

XCT examination of some parts (outliers)

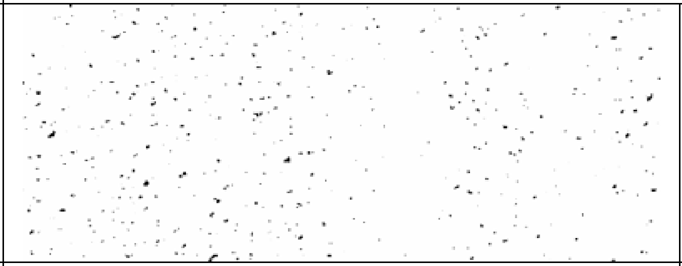
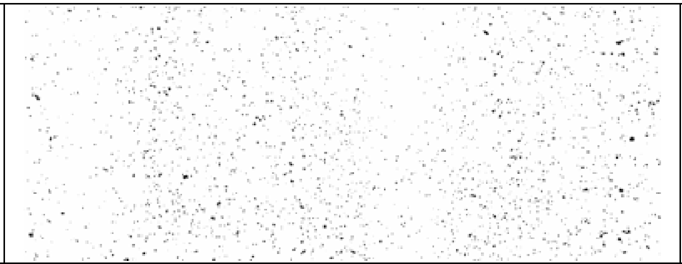
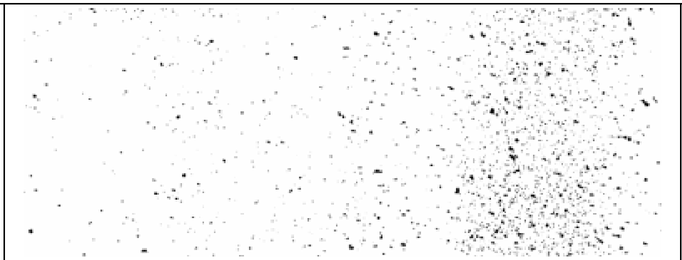
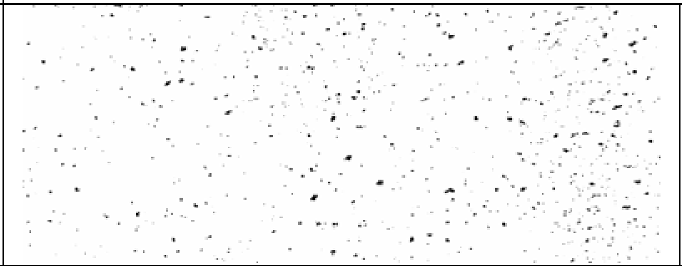
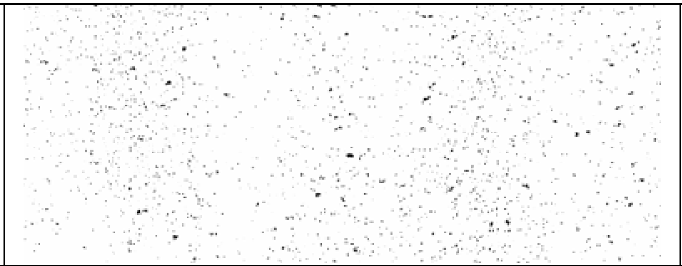
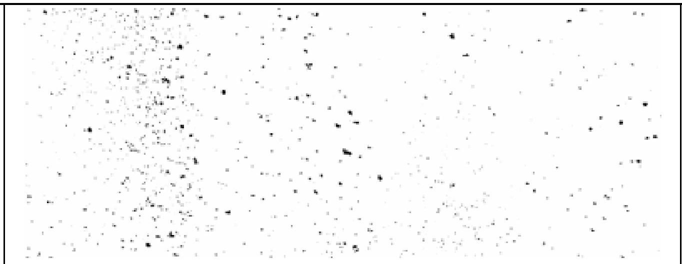
Waygate Technologies
v|tome|x m 300/180 XCT system



XCT parameters	Voltage (kV)	Current (µA)	Exposure time (ms)	Filter	Number of projections	Frame per projections	Reconstructed voxel size (µmxµmxµm)
	180	100	334	none	2200	3	18x18x18

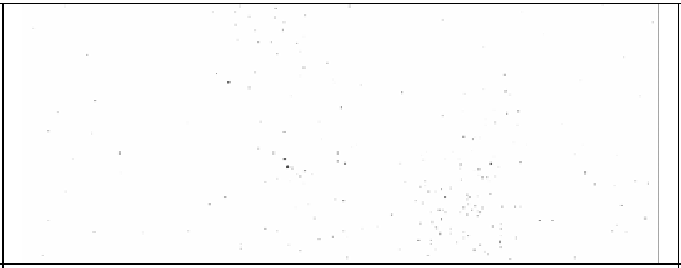
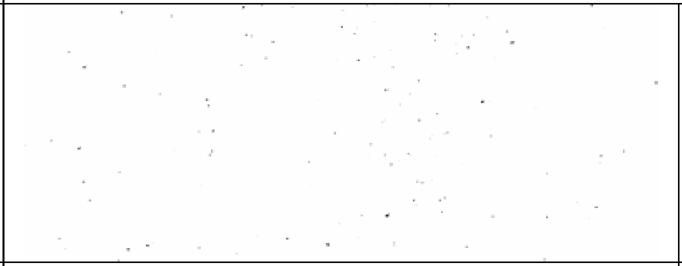
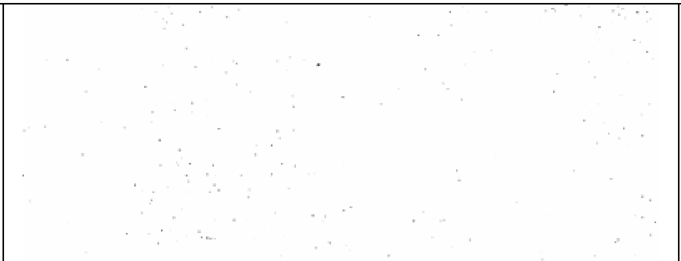
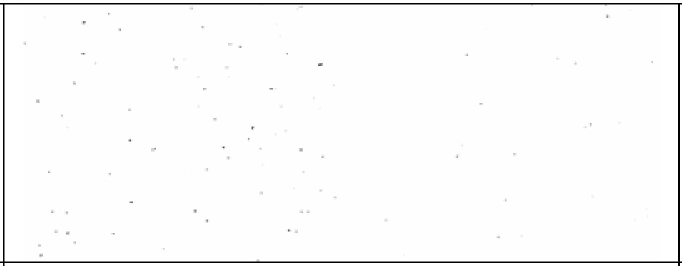
XCT unrolled images for Pm1/Pm2

ICAM 2022

Position (mm)	-0.15	0	+0.15	avg	std
Part's reference	Pm1 outlier				
Image					
Porosity (%)	0.809	1.537	1.942	1.43	0.47
Part's reference	Pm2				
Image					
Porosity (%)	1.260	1.413	1.012	1.23	0.17

3 different layers on the cylinder element: in the center (defined as position 0 mm) and then on both borders (defined as position -0.15 mm and +0.15 mm from the center)

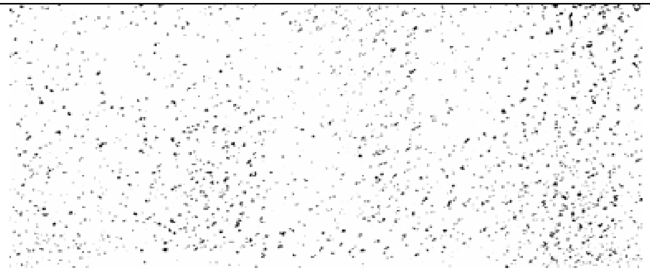
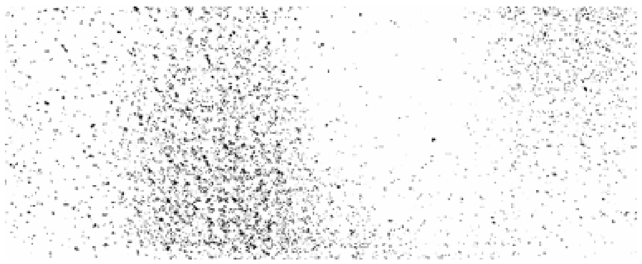
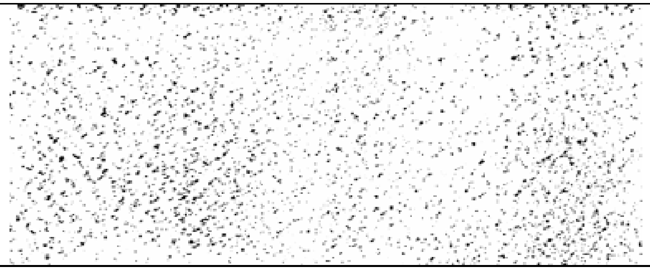
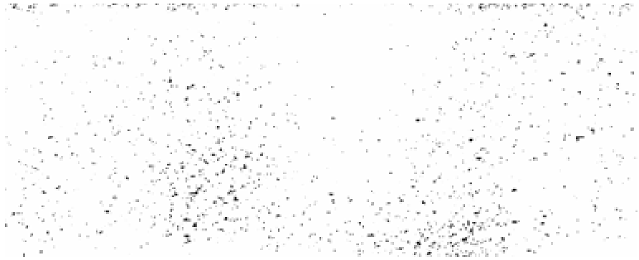
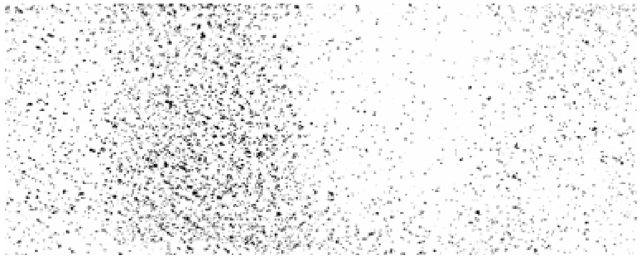
XCT unrolled images for SH3/SH1

Position (mm)	-0.15	0	+0.15	avg	std
Part's reference	SH3 outlier				
Image					
Porosity (%)	0.264	0.081	0.152	0.166	0.075
Part's reference	SH1				
Image					
Porosity (%)	0.085	0.087	0.069	0.0803	0.0080

3 different layers on the cylinder element: in the center (defined as position 0 mm) and then on both borders (defined as position -0.15 mm and +0.15 mm from the center)

XCT unrolled images for S1C3/S1C2

ICAM 2022

Position (mm)	-0.15	0	+0.15	avg	std
Part's reference	S1C3 outlier				
Image					
Porosity (%)	2.570	0.971	4.376	2.6	1.4
Part's reference	S1C2				
Image					
Porosity (%)	4.455	1.293	5.095	3.6	1.7

⇒ The differences between the parts, produced with the same parameters, can be assigned to a difference in porosity levels and/or the uneven distribution of the porosity and therefore a difference in overall material modulus.

Overview

ICAM 2022

- Resonant ultrasound spectroscopy (RUS)
- Investigated parts
- RUS examination of the parts
- X-ray computed tomography (XCT) examination of some parts
- **Summary and conclusions**

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

Summary and conclusions

ICAM 2022

Summary

- We investigate the feasibility of resonant ultrasound spectroscopy (RUS) methods to classify metal laser-powder bed fusion (PBF-LB) additively manufactured (AM) parts, according to their machine process parameters (wall thicknesses, laser powers, scanning speeds and scanning strategies).
- These parts were tested with two different RUS systems, and then analyzed using the Z-score statistical method by comparison to a set of parts fabricated using default parameters.
- To validate the RUS results, XCT inspections were also performed.

Conclusions

- The AM process parameter changes clearly influenced the resonance responses of the parts, and thus the method is able to classify the different groups of parts according to their process parameters.
- Hence, the RUS methods can provide industries convenient tools: simple to operate, fast and efficient global comparative volumetric NDT alternative methods to XCT to check the integrity of their parts before use in identifying defective parts, but also in configuring AM machine parameters according to the expected and desired material properties.

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

ICAM 2022

ASTM INTERNATIONAL
Helping our world work better

Thank you.

Anne-Françoise Obaton
anne-francoise.obaton@lne.fr

October 31- November 4, 2022

www.amcoe.org

GrindoSonic
THE IMPULSE EXCITATION TECHNIQUE

Gregory Weaver

Olivier Burnet

Alex Van den Bossche

LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

Charles Cayron

Florian Montagner

Baker Hughes

Lucas Fournet Fayard
PhD student "Metrological study of the influence of PBF-LB process parameters on geometrical and dimensional accuracy of AM parts”