

Implementation of Non Destructive Testing and in-line monitoring techniques on extra-large structures printed with WAAM technology

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Abstract

Grade2XL is a European project funded by the H2020 program that gathers 21 academic and industrial partners. Started in March 2020 for 4 years, the principal objective is to print extra-large structures using the WAAM (Wire Arc Additive Manufacturing) method with a complete control of the fabrication process. Since WAAM is a relatively new technology for printing large specimens, it is important to develop quality assurance methods that can be used during the fabrication and once the structure has been built, which is the focus of CEA List in the project. Regarding methods applied built structures, CEA List has investigated Resonant Ultrasound Spectroscopy (RUS) for the material characterization and more specifically the evaluation of the elastic constants or more conventional ones for the inspection with phased-array ultrasonic techniques (PAUT) or eddy current (EC) for the detection of indications are implemented and optimised them for the inspection of the final structures. Concerning the development of in-line monitoring methods, CEA List has been working on laser Doppler vibrometry (LDV) and X-ray fluorescence (XRF) spectrometry, in order to get structural information during the printing but also detect the appearance of abnormal events and correlate them to the appearance of defects generated during the WAAM process.

This proceeding presents the advantages of those methods for the inspection of extra-large structures made by WAAM and discusses the first results obtained in the framework of the project.

Keywords: Additive Manufacturing, NDT, Imaging techniques, Eddy current, In-line monitoring, laser vibrometry, X-ray fluorescence spectrometry, Resonant Ultrasound Spectroscopy.

1. Introduction

Additive Manufacturing (AM) is a technology that covers a large number of different processes and is as of 2023 often used to realize specimens with complex geometry by depositing material in a layer by layer fashion, based

on a numerical model of the object to be built [1]. The main objective of this technique is the manufacturing of complex designs while ensuring the reproducibility of the specimens and reaching chosen mechanical properties. The process of interest in the Grade2XL project is the Wire Arc Additive Manufacturing (WAAM), which has the specificity to produce fully dense metallic structures with virtually no porosity and a high productivity (compared to other currently available AM techniques). This article presents parts of the results from the on-going European Grade2XL project that focuses on functionally graded materials in extra-large structures. The research topics investigated at CEA List concern inspection techniques occurring at various steps of the fabrication process. The different non-destructive methods will be presented, with the obtained results. Finally, an outlook on the remaining steps of the work will be given.

2. Presentation of the Grade2XL project

2.1. Context

The Grade2XL project [1] is a European joint development collaboration funded by the Horizon H2020 programme. It brings together twenty-one partners involved at all stages of the WAAM manufacturing process of metallic structures. The motivation of this proposal came from multiple observations such as:

- a massive increase in material consumption in the last century (by a 34 factor),
- unsustainable large waste streams and unprecedented CO2 emissions,
- products thought and designed with a single material,
- the need to design a product by considering its function meaning giving it the right properties at the right location,
- the importance of optimizing a product and designing it for multiple functionalities.

In parallel, the development of Additive Manufacturing and more specifically Wire Arc Additive Manufacturing has illustrated the advantages of these new techniques in comparison to the conventional ones. Indeed, WAAM

proposes a wide range of design possibilities, with the possibility to control the local properties of the specimen but having the cost-intensive materials at specific relevant interfaces for example. This printing technique also allows the realization of a design with multiple materials that present shorter lead and production times.

2.2. Objectives of the project

In this context, the Grade2XL consortium proposed a project with the ambition of demonstrating the potential of multi-material WAAM products of superior quality and performance for large structures with complex geometries (from 1 to 10 m length). Three main objectives have been considered in this scientific programme through the development of high throughput WAAM systems.

The first one is the control of the two main factors that govern the material properties, which are the chemical composition and thermal cycle during the realization of the manufacturing process of functionally graded multi-materials specimens. The second focus is the increase of the productivity of the WAAM system by multiplying the wire deposition system from 2 kg/h to 5 kg/h. In addition, in-line contact-less inspections will be developed and implemented to ensure the first time right quality of the specimen and facilitate the qualification of the final specimen. Finally, the third objective is to demonstrate the lifecycle benefits of the WAAM multi-material devices and in-line process control with the challenging applications proposed by the industrial partners of the Grade2XL project.

A large number of industrial partners are involved in the project, offering the possibility to work on demonstrators (shown in Figure 1) from different industrial sectors such as the energy, maritime, sanitary ware, automotive, aerospace, white goods or heavy lifting sectors.

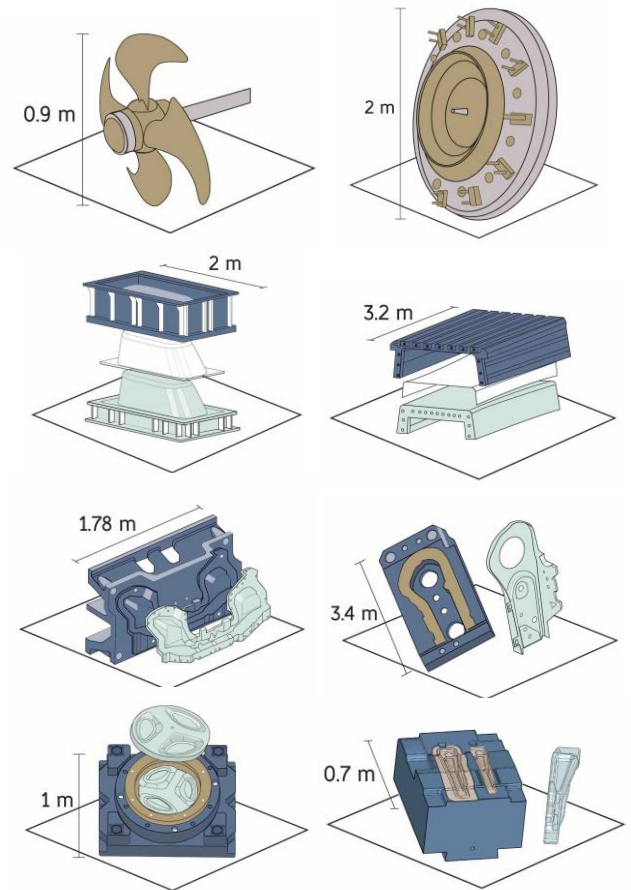


Figure 1: Illustration of the demonstrators considered in the Grade2XL project, as well as their scales.

2.3. CEA List involvement

CEA List is involved in the inspection of the demonstrators to be printed in the framework of the project and more specifically the WP3 named In-line inspection and control, which aims at developing in-line monitoring of the WAAM fabrication process and implementing Non Destructive Testing (NDT) techniques to ensure the quality control of the component during the fabrication process and the final demonstrator ready for use.

Many developments are on-going regarding the WAAM fabrication process and more specifically the monitoring of the fabrication process in terms of deposition rate and nozzle displacement. Indeed, during the realization of the component, the position of the nozzle is precisely known and a follow-up of the built geometry is done based on the numerical model of the specimen, used for the manufacturing. The main objectives of this work package are the evaluation of the in-line monitoring systems integrated on the pilot lines and the analysis and correlation of the monitored data and the process parameters with NDT on post-processed specimens.

As will be presented in the following sections, CEA List is working on these two objectives. We are using multiple in-

line monitoring, NDT and characterization techniques as no single one can address all the needs required to certify the complete fabrication process from the raw material properties to the final demonstrators properties, integrity and functionality.

3. Specimens inspections during the fabrication

One of the objectives of the project is to properly master the fabrication process and adapt it by stopping the printing to modify the parameters and avoid the generation of defects within the WAAM specimen. The development of in-line monitoring systems is realized with this in mind.

3.1. X-ray fluorescence technique

The first technique developed aims at evaluating the chemical composition of the printed specimen during its fabrication using X-ray fluorescence spectrometry. This technique is mostly used for post-process analysis (recent work can be found in [2]), but in-process measurement is also targeted here.

A first system was developed and tested on coupons already printed with different grades of steel. It is composed of a low power collimated X-Ray tube, an XRF semi-conductor based detector (Silicon drift detector) and a laser profilometer to measure the geometry of the bead shape (Figure 2).

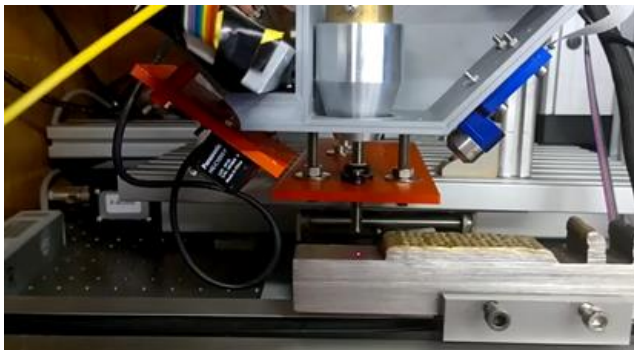


Figure 2: X-ray system developed at CEA List.

The system was tested on coupons printed at TU Delft by a 2-D raster scan trajectory. The spectra of the different elements in the specimen were measured (see Figure 3) and a quantitative analysis is on-going to estimate their proportion as well as the uncertainties due to tube fluctuation, surface state, etc.

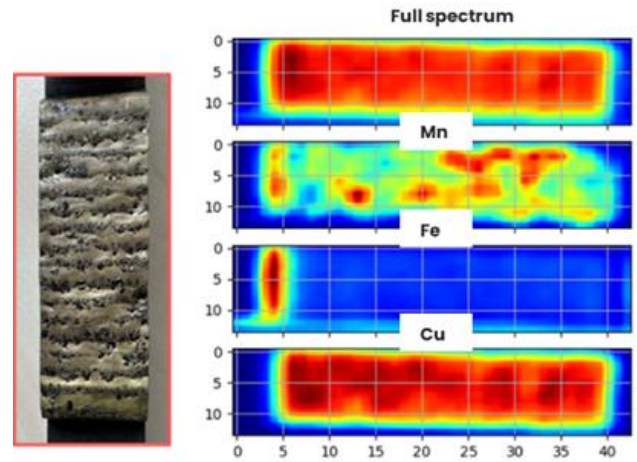


Figure 3: Spectra of the chemical elements detected within a WAAM printed coupon.

The system has been optimized and tested during printing. It was positioned a few centimetres after the welding torch to acquire the chemical composition a few seconds after the printing. The complete analysis is on-going but the first results show a clear element composition modification of the wires during the printing through the detection of the nickel element, which is the main constituent of Inconel 625 but much less present in the initial 316L layer (Figure 4).



Figure 4: Picture of a two wires coupon (top) and the associated variation in the count of the Nickel ray of fluorescence (bottom).

3.2. Contactless acoustic emission

Another work performed at CEA List is the use of a Laser Doppler Vibrometer instrument to measure the vibrations on the specimen surface during the fabrication in a contactless manner. A monochromatic light source (laser) and an interferometer (Mach-Zehnder interferometer) allow the measurement of the Doppler Effect due to the phase difference between the transmitted signal and the reflected signal. From the interference between the two signals, the frequency and amplitude of the displacement

of the sample surface can be deduced. A Scanning Laser Doppler Vibrometer, and driven by a functional and practical human machine interface developed with Python has been designed and put together. This system has been used in the project as a listening device in order to acquire the acoustic emission signal continuously [3] during the fabrication and then make a post-processing analysis to observe events that happened during the printing process. The system was first assessed at TU Delft on an automatic welding machine carrying a MAG welding torch. The measurement was made on the edge of the substrate as shown in Figure 5.

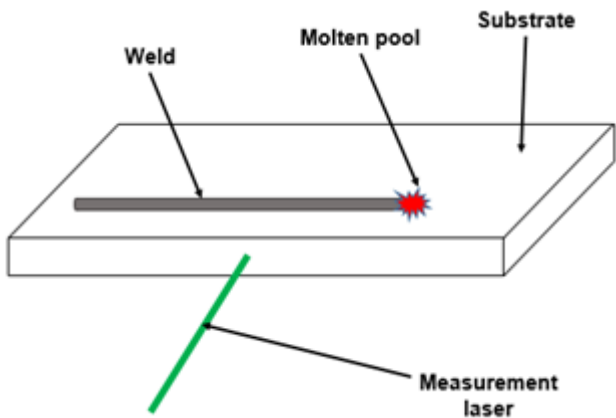


Figure 5: Schematic of the experimental setup.

A coupon (Figure 6) was printed with the following characteristics:

- Nozzle speed displacement 10 mm/s,
- Gas: 50% CO₂ and 50% Argon,
- Gas flow: 20 to 17 L/mm,
- Wire material: 316L,
- Substrate material: S690,
- Length of the weld bead: 250 mm.



Figure 6: Coupon printed for the SLDV experiment.

A time-frequency image was obtained by post-processing the acquired signal to remove the continuous environment noise, and highlight the welding component at a specific frequency and the events detected during the fabrication (Figure 7).

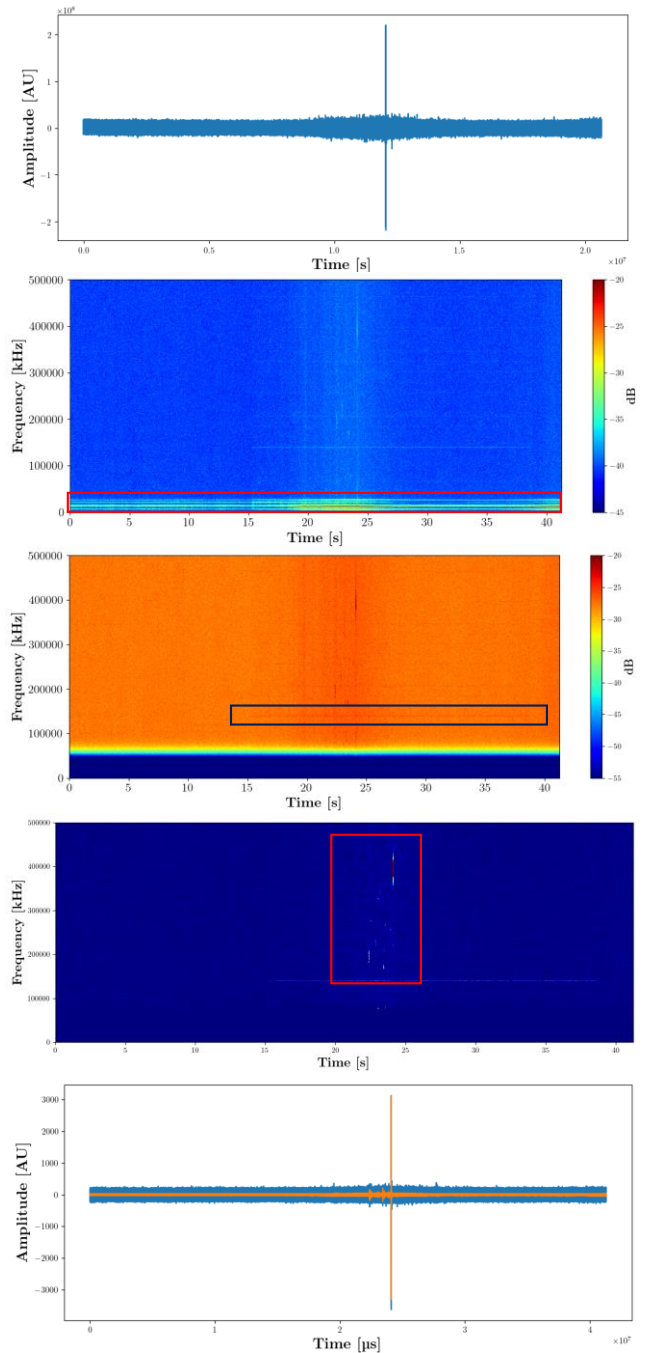


Figure 7: From top to bottom: raw acoustic signal, continuous noise environment, welding component, events observation, time-domain signal associated to the events.

From this first experiment it was possible to correlate the visual observation of defects with the information provided by the acoustic emission signal. The system was then optimized to ensure the same acquisition parameters by using a head fiber clamped to the WAAM torch (Figure 8).

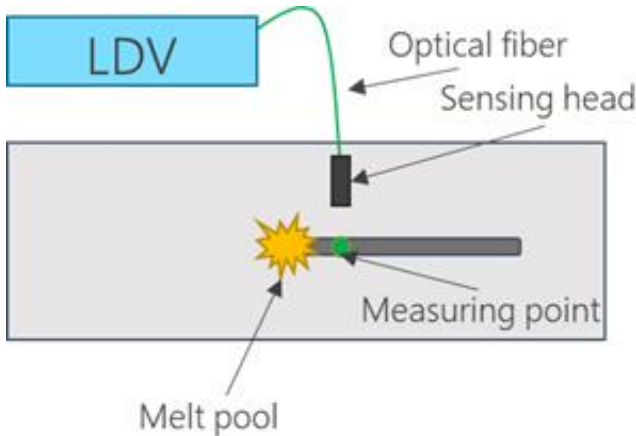


Figure 8: Schematic of the optimised SLDV system.

This new version was tested with the XRF system and the analyses of the acquired signals are on-going. The final objective would be to connect at least one of these systems to a WAAM machine at one of the partner’s facilities and monitor the printing of a more complex specimen.

4. Final demonstrators control

A second work axis within the project is the inspection of the extra-large structures after the entire fabrication process has finished. To this aim, different inspection techniques have been tested on specimens printed by the partners in charge of the fabrication of the demonstrators in order to assess the capabilities of conventional techniques. The coupons provided had dimensions equivalent to the final specimen, were made with the material selected following the material studies and the surface state was polished and or finished according to the industrial partners requirements.

4.1. Eddy current techniques

The majority of non-destructive testing of forged/casted or welded specimens is primarily performed by dye penetrant testing in order to detect imperfections at the surface of the material. In order to comply with the necessity to inspect the surface of the specimen and cover the first millimetres below the surface, eddy current testing methods were evaluated [4].

For one of the demonstrators, the coupon provided is a bi-material 60 mm thick with a mirror-type polished surface (Figure 9). The probe used is composed of a head with kapton film and an engraved sensor composed of two coils in transmit/receive (T/R) mode. The coils have an internal radius of 3.54 mm, an external radius of 5.06 mm and a number of turns N of 10.



Figure 9: Mirror-type polished coupon printed by Ramlab.

To achieve surface and sub-surface control, the inspection was carried out at different frequencies. As shown in Figure 10, different signatures were observed for different defects detected within the specimen.

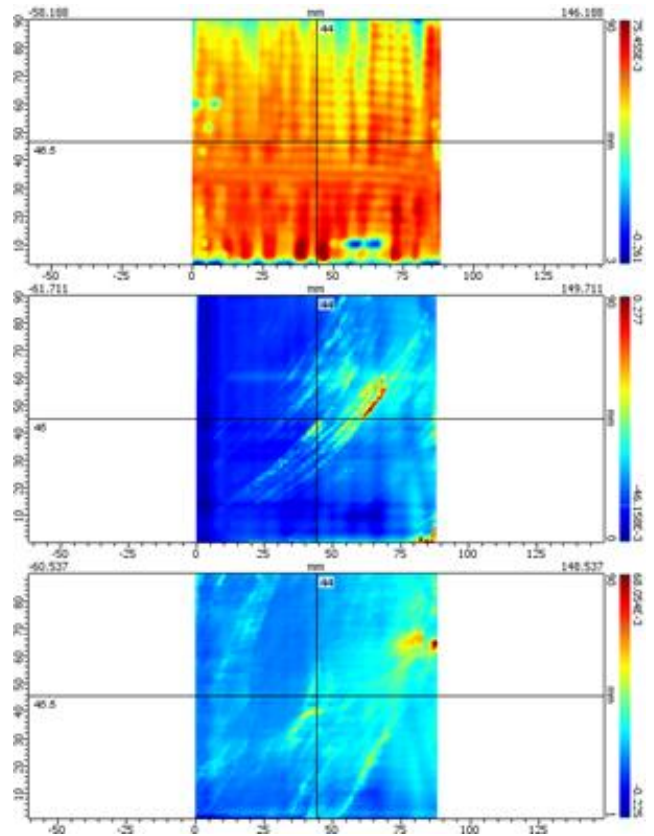


Figure 10: Cscans performed with EC technique at three frequencies. From top to bottom: 520, 100 and 70 kHz.

4.2. Imaging methods

In order to inspect the entire volume of the specimen, the ultrasonic imaging technique PWI (Plane Wave Imaging) [5] was evaluated in immersion with a 10 MHz linear phased array probe. The coupon provided is a monomaterial specimen presenting two steps (Figure 11).

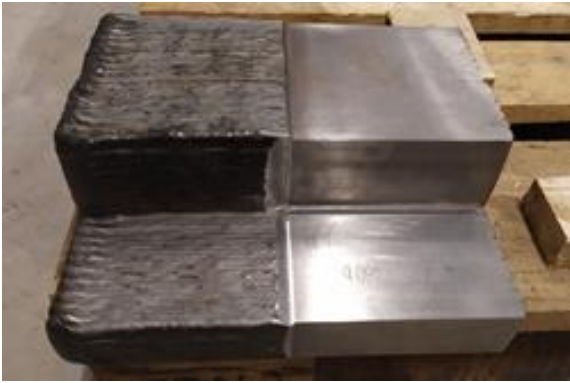


Figure 11: Two-steps specimen printed by Naval Group.

The entire volume of the specimen was inspected and the reconstructions made for each step showed indications within the specimen (Figure 12).

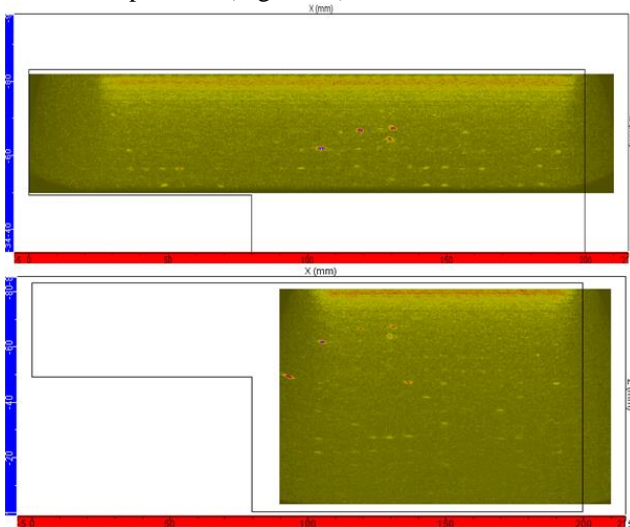


Figure 12: PWI reconstructions within the monomaterial coupon inspected at 10 MHz.

Correlation with work made by partners from the project has been made to confirm the presence and the size of the indications detected. The coupon was cut and macrographs were realized (see Figure 13). These macrographs confirmed the localization of the indications detected in the PWI images.

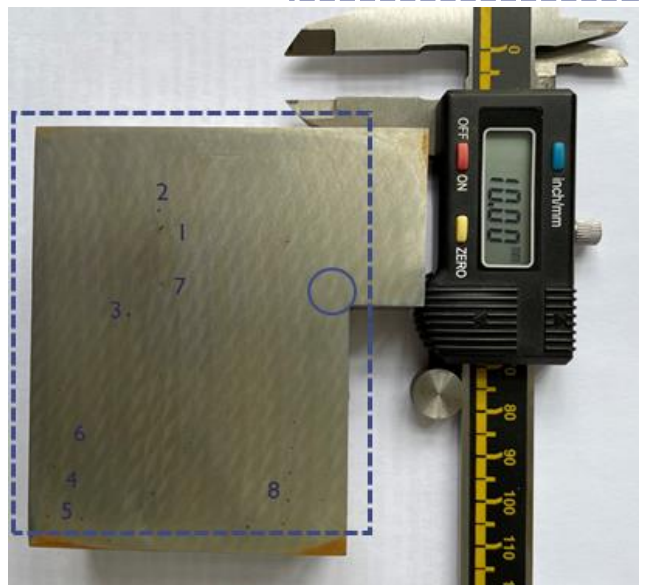
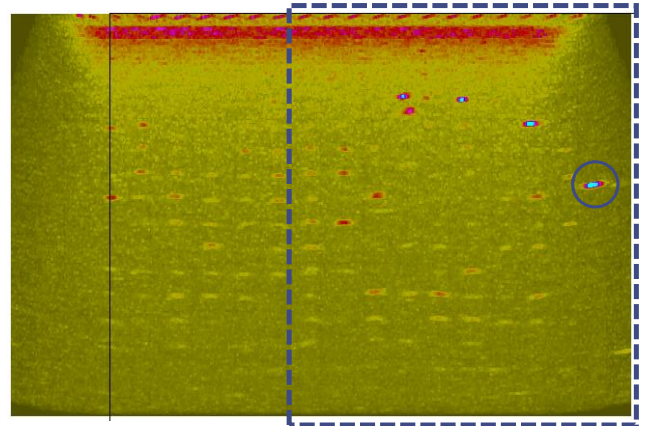


Figure 13: Coupon cut by TU Delft to realize macrographs.

The feasibility studies were performed on various coupons made of different materials to evaluate conventional inspection techniques that could be used to control the final demonstrators considered in the framework of the project. Furthermore, the methods tested are based on the current standards for forged/casted and welded specimens in order to evaluate techniques well known in the industry and which could be proposed for standardization on WAAM specimens in the near future.

5. Material characterization by Resonant Ultrasound Spectroscopy

The last axis of work is the characterization of the material selected for the printing of the specimen. Indeed this aspect is quite important for the realization of NDT inspections, as the material printed by WAAM might have characteristics slightly different from material used for conventional fabrication process. A RUS [6] experimental setup developed at CEA List has been used for this purpose [7], as shown in Figure 14.

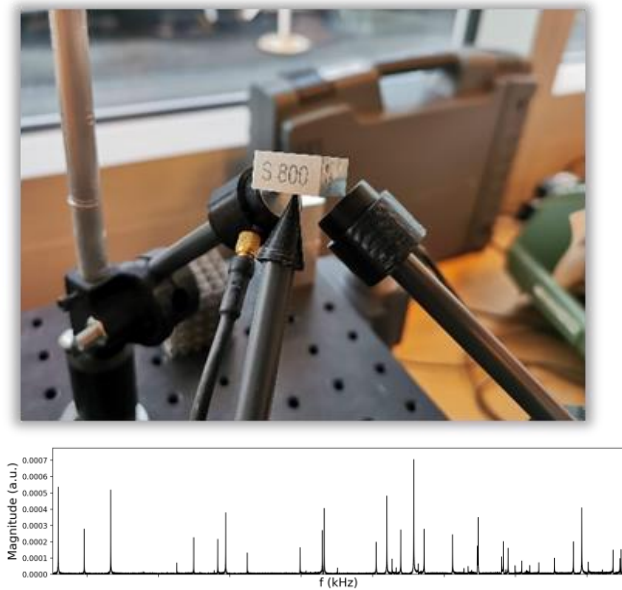


Figure 14: RUS setup used at CEA List (top). A S800 sample is suspended over emitting and receiving transducers while a frequency sweep is carried out. Bottom: typical spectrum obtained from this measurement.

The obtained spectra are post-processed and elastic inversion is performed to recover elastic constants (C_{ij}) that characterize the material. 10 coupons made out of 5 different wires were tested. 4 wires lead to coupons that exhibited isotropic effective behaviour and produced good fits. The 316L wire produced samples that were macroscopically well fitted by an orthotropic model. Results are shown in **Erreur! Source du renvoi introuvable.**

Table 1 : Elastic constants (C_{ij}) obtained by the RUS method on WAAM printed samples.

sample	c11	c22	c33	c44	c55	c66	c23	c31	c12
isotropic cubes	267,1	267,1	267,1	81,0	81,0	81,0	105,0	105,0	105,0
316L #02 (gradient)	214,7	216,3	247,4	69,8	112,7	118,6	108,6	139,5	121,7
316L #02 (Bayesian)	212,0	215,3	246,4	67,1	113,0	116,5	102,7	136,1	118,3
316L #01 (gradient)	215,1	210,8	255,8	65,9	109,8	118,8	103,5	139,4	115,4
316L #01 (Bayesian)	225,8	215,9	270,3	67,4	108,7	109,2	113,1	151,2	122,6
relative difference 316 #2 vs isotropic	-20%	-19%	-8%	-16%	39%	45%	1%	31%	14%
relative difference 316 #1 vs isotropic	-17%	-20%	-2%	-18%	35%	41%	3%	38%	13%
relative difference 316 #1 vs #2	-3%	1%	-6%	3%	3%	3%	-2%	-5%	1%

The orthotropic effective elastic properties of the 316L samples led to further investigations, since we wanted to confirm the RUS result that showed that the sample was indeed strongly anisotropic.

Ultrasonic phase velocity measurements could not be carried out properly on the 316L samples due to strong attenuation. Therefore, partners at UGent applied EBSD analysis to one of the samples. The resulting orientation map shows strong anisotropy with grains elongated in the build direction (Figure 15).

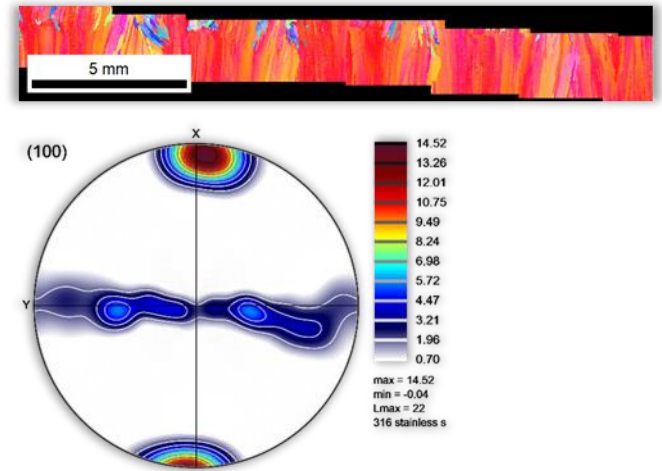


Figure 15: 316L grain structure as measured by EBSD (top) and 100 pole figure showing the fiber-like texture of the 316L sample.

Using the Voigt, Reuss and Hill schemes and assuming cubic single crystal elasticity for the 316L, the EBSD data was averaged to obtain a C_{ij} tensor that can be compared to RUS results, see **Erreur! Source du renvoi introuvable.** Since both tensors are quite close, we conclude that the RUS method is successful in estimating the anisotropy effect due to texture. In particular, both methods agree on a softening along the build direction.

Table 2. Comparison of C_{ij} estimated using RUS and EBSD.

	c11	c22	c33	c44	c55	c66	c23	c31	c12
RUS	265,0	225,9	221,9	119,9	66,0	109,4	127,5	113,2	150,0
Voigt	275,8	243,2	273,3	111,7	79,1	109,3	130,1	97,4	127,6
Reuss	259,6	237,9	257,8	107,4	65,9	102,4	132,3	110,7	130,5
Hill	267,7	240,5	265,5	109,5	72,5	105,8	131,2	104,1	129,1

Further investigations will concentrate on how these results can be correlated to other available data from partners at UGent and TU Delft, where tensile tests have allowed to estimate Young moduli that could be compared to the elastic constants already obtained.

6. Conclusions

This paper has presented the results obtained by CEA List in the Grade2XL project. Available non-destructive techniques have been optimised for in-situ monitoring of the WAAM process. Preliminary results suggest that laser vibrometry and X-Ray fluorescence spectrometry are sensitive enough to help designers of the process. A second part of our work concerned the inspection of the demonstration parts of the project. Eddy currents and ultrasound imaging have shown good potential for detection of manufacturing defects. A final aspect concerns material characterization of WAAM

microstructures. The resonant ultrasound spectroscopy technique has shown promise in its capability to identify anisotropic microstructures elaborated with WAAM.

Acknowledgements

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References

- [1] Grade2XL, [Online]. Available: <https://www.grade2xl.eu/>.
- [2] C. Vanhoof, J. R. Bacon, U. E. Fittschen, L. Vincze, 2020 atomic spectrometry update – a review of advances in x-ray fluorescence spectrometry and its special applications, *J. Anal. At. Spectrom.*, 2020,35, 1704-1719. <https://doi.org/10.1039/DOJA90051F>.
- [3] A. García de la Yedra, M. Pflieger, B. Aramendi, M. Cabeza, F. Zubiri, T. Mitter, B. Reitingner, E. Scherleitner, "Online cracking detection by means of optical techniques in laser-cladding process", *Struct Control Health Monit.* 2019; 26:e2291. <https://doi.org/10.1002/stc.2291>.
- [4] AFNOR, "Non-destructive testing – Eddy current testing – General principles and basic guidelines," NF-EN-ISO-15549, 2019.
- [5] L. Le Jeune, S. Robert, E. Lopez Villaverde and C. Prada, "Plane wave imaging for ultrasonic nondestructive testing: generalization to multimodal imaging," *Ultrasonics*, vol. 64, pp. 128-138, 2016. <https://doi.org/10.1016/j.ultras.2015.08.008>.
- [6] A. Migliori, J.L. Sarrao, William M. Visscher, T.M. Bell, Ming Lei, Z. Fisk, and R.G. Leisure. "Resonant Ultrasound Spectroscopic Techniques for Measurement of the Elastic Moduli of Solids." *Physica B: Condensed Matter* 183, no. 1–2 (January 1993): 1–24. [https://doi.org/10.1016/0921-4526\(93\)90048-B](https://doi.org/10.1016/0921-4526(93)90048-B).
- [7] Florian Le Bourdais, Jitendra Singh Rathore, Camille Ly, Michel Pellat, Caroline Vienne, Vincent Bonnefoy, Vincent Bergeaud, and Jean-Paul Garandet. "On the Potential of Resonant Ultrasound Spectroscopy Applied to the Non-Destructive Characterization of the Density of (LPBF) Additively Manufactured Materials." *Additive Manufacturing* 58 (October 1, 2022): 103037. <https://doi.org/10.1016/j.addma.2022.103037>.