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Non-destructive testing application of radiography and ultrasound for wire and arc additive manufacturing

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ABSTRACT

The present work addressed the challenges of identifying applicable Non-Destructive Testing (NDT) techniques suitable for inspection and materials characterization techniques for Wire and Arc Additive Manufacturing (WAAM) parts. With the view of transferring WAAM to the industry and qualifying the manufacturing process for applications such as structural components, the quality of the produced parts needs to be assured. Thus, the main objective of this paper is to review the main NDT techniques and assess the capability of detecting WAAM defects, for inspection either in a monitoring, in-process or post-process scenario. Radiography and ultrasonic testing were experimentally tested on reference specimens in order to compare the techniques capabilities. Metallographic, hardness and electrical conductivity analysis were also applied to the same specimens for material characterization. Experimental outcomes prove that typical WAAM defects can be detected by the referred techniques. The electrical conductivity measurement may complement or substitute some destructive methods used in AM processing.

1. Introduction

Additive Manufacturing (AM) is increasingly gaining a relevant place in the manufacturing industry, in a very large range of available materials. However, the potential of AM processes to produce large parts is still requiring significant research to reach a reliable industrial implementation.

Wire and Arc Additive Manufacturing (WAAM) recently proved to have the potential for the production of large scale engineering structures [1]. This manufacturing technique combines an electric arc as heat source and wire as feedstock to produce components, adopting the same technologies and equipment as in welding. These arc-based AM technologies are receiving considerable attention from the manufacturing industry due to the capability of producing customized large parts, with a high deposition rate, at lower cost, in comparison with other additive manufacturing processes [20]. In fact, the term “wire arc additive manufacturing” was mentioned in 536 documents in the 2017 Scopus database [2]

However, significant research and further understanding of the process are required in several fields. An important aspect where research needs to be focused is to develop or adapt methods to ensure the components’ structural integrity. The main challenge WAAM is the lack of Quality Assurance (QA) standards and methods to guarantee that the parts manufactured are suitable for the operation scenario they will be put through.

Non-Destructive Testing (NDT) allows detecting and evaluating flaws in materials or differences in its characteristics, without destroying the serviceability. The integration of NDT with AM faces many challenges, such as the complex geometry of the part, high surface roughness or deep defects location. In addition, the implementation of NDT during the process (in-line inspection), as opposed to post-operation, is a key aspect when selecting the correct NDT techniques. For instance, if an in-line inspection is required, some NDT techniques can not be used, due to the high temperature of the material. On the other hand, this inspection condition can be used with advantage in thermography inspection.

The urgent need for AM standards has seen an unprecedented co-operation between two of the most established standards organizations, International Organization for Standardization (ISO) and ASTM, forming two joint groups for development of AM standards in the areas, including terminology and NDT for AM parts (ISO, 2011).

In summary, in terms of industrial manufacturing of large scale engineering structures, WAAM manufacturing technique has already proven to be successful and its application is expected to grow over the

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Table 1
Main available Non-Destructive Testing Techniques for Wire and Arc Additive Manufacturing.

	NDT Technique	Physical Phenomena	Fundamentals	Applications
Imaging	Radiographic Testing	Electromagnetic radiation (ionizing)	Requires the incidence and penetration of radiation energy on and through an inspected material, which is absorbed homogeneously by the material, except in the regions where thickness, density variations or defects arise. The radiation that passes through material impinges an image in a sensing medium revealing the defects.	Detect deep or embedded defects (virtually no limits); Poor sensibility for defects perpendicular to the radiation direction; Poor sensibility for small defects compared to the sample dimension; Not suitable for on-line inspection. Human health concerns.
	X-ray Backscatter	Electromagnetic radiation (ionizing)	Backscatter X-ray detects the radiation that reflects from the target as opposed to conventional X-rays.	Detect deep or embedded defects (virtually no limits); It can operate even if only one side of the target is available; Inspecting times can be unacceptably long.
	Computed Tomography	Electromagnetic radiation (ionizing)	Method of forming reliable three-dimensional (3D) representations of an object by taking many x-ray images around an axis of rotation and using algorithms to reconstruct a 3D model.	Detect deep or embedded defects (virtually no limits); Not suitable for online inspections. Time-consuming and size limitations.
Ultrasonic	Conventional Pulse-echo Ultrasonic Testing	Mechanical vibration	A beam of high-frequency sound waves is introduced into a material, travel through it and are reflected at interfaces or defects. The reflected sound is analyzed to identify the presence and location of defects.	Can be used for flaw detection, location and measurement; It cannot be used for high-temperature inspection (typically > 300 °C); Surface treatment dependent. Not adequate for locally non-planar surfaces.
	Phased Array Testing	Mechanical vibration	PA systems utilize multi-element probes, which are individually excited under computer control. By exciting each element in a controlled manner, a focused beam of ultrasound can be generated. Software enables the beam to be steered. Two and three-dimensional views can be generated.	Can be used for flaw detection, location and measurement; Fast inspection times; Able to penetrate thick sections; Cannot work at high temperatures; Requires coupling; May require several probes.
	Immersion Ultrasonic Testing	Mechanical vibration	Immersion or water-column (squirt) US techniques allow a more efficient coupling between the US probe and the inspected material. It facilitates the automation of the inspection process providing C-scan images of the test pieces.	Improved probability of detection of the smallest defects; More accurate sizing and location of subsurface flaws; Good results independents of the geometry complexity; Cannot be used on-line and under high temperature; Requires immersion of the part.
	Electromagnetic Acoustic Transducer (EMAT)	Mechanical vibration and Electromagnetic induction	This inspection method uses an electromagnetic acoustic (EMA) way of ultrasound excitation and reception.	Can be used for flaw detection, location and dimensional measurements. Contactless and couplant independent but requires proximity; Suitable for high temperatures; Geometry constrained. Low sensibility for small defects.
	Laser Ultrasonic Testing	Thermal expansion and optical measurement	A laser pulse is directed to the surface, heating it and inducing an ultrasonic pulse that propagates into the sample. This ultrasonic pulse may interact with a defect and then returns to the surface. A separate laser receiver detects the displacement that is generated when the pulse reaches the surface.	Can be used for flaw detection, location and measurement; Capable of detecting very small flaws (virtually no limits); Contactless and couplant independent; Can be used on complex geometries, curved or difficult to access areas; Can be used at very high temperatures.
Electromagnetic Based	Potential Drop	Electrical current	Measurement of the potential drop by an increase in the electric resistant between two measurement electrodes in a presence of a discontinuity.	Very good at estimating surface cracks depth; Penetration depth of few mm; Surface roughness reduces the accuracy of the sized cracks. Can be used at high temperature.
	Eddy Currents	Electromagnetic induction	A coil (probe) is excited with an alternating electrical current, producing an alternating magnetic field around a conductive test piece. Eddy currents are induced in the materials, but defects cause a change in eddy current, corresponding to a change in the impedance coil, allowing the identification of the defects.	Can be used for surface and subsurface flaw detection; Penetration depth of few mm (1/2 mm); Very sensitive to small defects. Contactless but requires proximity; Limited to conductivity materials.
	Magnetic Particle Testing	Magnetic field	The inspected material is magnetized. The presence of a surface or subsurface defect allows the magnetic flux to leak. Then magnetic (ferrous) particles are applied on material surface and attracted to the flux leak zone, indicating the presence of a defect.	Limited to ferromagnetic materials; Can detect subsurface defects. Not adequate for online inspection.

(*continued on next page*)

Table 1 (*continued*)

	NDT Technique	Physical Phenomena	Fundamentals	Applications
Thermography	Infrared Thermography	Electromagnetic radiation	Infrared thermography aims at the detection of subsurface features, owing to temperature differences (DT) observed on the investigated surface during monitoring by an infrared camera.	Can detect subsurface defects; Risk-free (no radiation); Suitable for online monitoring; Requires heated working material; Large areas can be scanned fast.
	Laser Thermography	Electromagnetic radiation	A high-power laser source is used for external heat delivery and the energy will diffuse in the specimens' surface making discontinuities detectable with the analysis of the temperature distribution near the laser spot.	Can detect subsurface defects; Suitable for online monitoring; Contactless and requiring no surface finishing;
	Vibro Thermography	Electromagnetic radiation and mechanical vibrations	An ultrasonic transducer generates elastic waves within the test specimen. These waves will interact with the irregularities present in the object and due to the friction, energy will be dissipated in heat form and later detected by an IR camera.	Can detect subsurface defects; Requires contact; Very short measurement time (seconds). Difficult to apply in heated surfaces.
	Eddy Current Thermography	Electromagnetic induction and radiation	Use of induced EC to heat the sample and defect detection is based on the changes of the induced eddy currents flows revealed by thermal visualization captured by an infrared camera.	Can detect subsurface defects. May require time to deposit enough energy in the material; Suitable for online monitoring.
Others	Penetrant Testing	Capillary action	Components are wetted with a fluorescent penetrant and penetrant soak into a surface defect. The penetrant excess is removed, and a developer is applied to the surface, drawing penetrant from defects out, forming a visible indication of the defect.	Cannot detect interior defects; Cannot be implemented on-line; It is time-consuming (> 20 min).
	Acoustic Emission	Mechanical vibration	Elastic waves that are emitted in a medium due to crack can be captured by suitable piezoelectric sensors on the surface of a specimen.	Can be used for flaw detection and location; Perfect for parts in operation; Not suitable for post-manufacture inspection (prior to service). Not adequate for online inspection.

next decades. However, significant research needs to be developed in order to transfer WAAM to the industry. One of the aspects to address is the evaluation of the potential of the existing non-destructive testing techniques to ensure the quality of the parts produced, which is the focus of the present paper.

2. Mapping of non-destructive testing techniques

As referred, Wire and Arc Additive Manufacturing (WAAM) uses the same technologies and equipment as in welding. Thus, the expected challenges in arc-based AM are similar to the ones associated with traditional welding [3], which means that porosity, lack of fusion and inclusions must be measured.

To establish the Non-Destructive Testing (NDT) suitable for WAAM a revision of currently available techniques is presented in Table 1.

By analysing the characteristics of the techniques referred in Table 1 a first approach to the ones with potential for inspection of parts produced by WAAM can be derived.

In terms of techniques already tested in AM specimens, recent studies have shown optimal X-ray backscatter technology (XBT) results in subsurface crack detection, without requiring surface treatment and/or preparation but requiring a significant amount of time to perform detection. [4] showed experimentally that XBT can detect an artificial crack of 0.02 mm width located in steel at 3 mm depth of near-surface cracks under weld-deposited cladding (Fig. 1). The result should make XBT suitable for defect detection in AM although the operation time will require technologic advances to make it applicable to production. To tackle this issue (S. [5]) is studying a XBT using uncollimated X-ray irradiation (XBU), which enables to inspect a large area of an object surface at once by wider X-ray irradiation and X-ray 2D detection.

Also, in a study made by [6] Ti–6Al–4V parts were fabricated using an Electron Beam Melting (EBM) system for analysis by computed tomography (CT) scanning. After analysis, CT has proven to be capable of detecting defects of sizes above 600 µm. Nevertheless, the application of microCT to AM has been studied in order to detect imperfect melting [7] and recent investigations using this technique have already reported porosity ranging of 10–60 µm [8].

In the field of ultrasonic techniques, [9] focused on the ultrasonic technique using a pulsed laser to generate acoustic waves on reference samples manufactured by Laser Melt Deposition (LMD) and a laser interferometric system to detect them. The use of scanning laser transmitter and receiver and the interaction of the incident ultrasonic wave with sub-surface and surface defects have also been widely investigated [10]. The reference samples were analyzed and defects with sizes ranging from 100 µm and depth up to 700 µm have been successfully detected.

In cases of powder feed (PF) deposition, the probability of detection (POD) of sub-surface flaws of a single Inconel layer examined by laser ultrasonic (based on reference samples and two PF samples) found a 90% POD for surface defects of 0.1 mm diameter and 0.9 mm at 1 mm depth.

In the same study, Eddy Current (EC) testing showed promising results for detecting smaller subsurface flaws than laser ultrasonic (90%

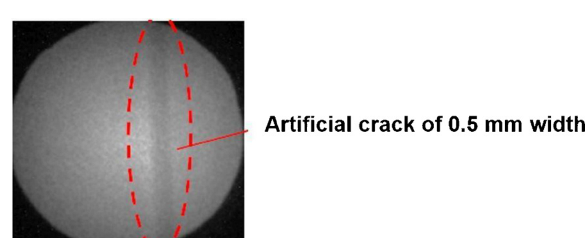

Fig. 1. Image (11 mm x 11 mm) of XBT when using the pinhole of 1.0 mm diameter [5].

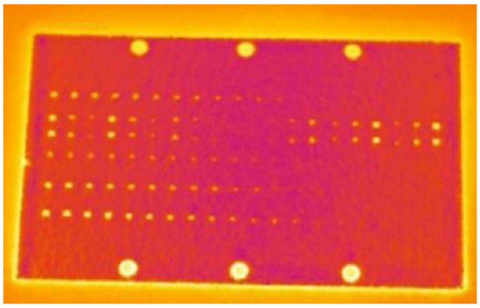

Fig. 2. IR image for the part designed with intentional defects. Source: [6].

POD 0.2 mm at the surface and 0.6 mm at 1 mm depth) [11]. The main adversity for the application of EC to AM parts is related to the overall surface roughness, since it is difficult to distinguish signals from cracked or scratched areas from signals of smooth surface where the noise was significant. EC tests done by [12] on a Selective Laser Melting (SLM) valve showed just that, the scratched areas were not able to be distinguished from the areas with cracks.

Regarding Thermography, it has been one of the most studied NDT techniques for AM. It has the advantage to monitor the process during manufacturing from a certain distance, allowing for fast results, through the correction of defects on the spot. [6] also evaluated IR imaging in his study (referenced on the XCT section). Fig. 2 shows an IR image of the part with the designed defects that are evidenced by the spots within the rectangular melt area. Defects smaller than approximately 600 μm were either not detected by the IR camera or not properly fabricated by the EBM system.

Although defects smaller than approximately 600 μm were either not detected by the IR camera (or not properly fabricated by the EBM system), the thermography analysis provided a good indication of defects present within a fabricated part.

From the reviewed literature, imaging, ultrasonic, electromagnetic based techniques and thermography methods were already applied to AM parts. In fact, regarding PF, visual and camera-based methods are the ones showing more potential. However, despite the existence of a considerable number of publications related to NDT, there is almost no data available concerning its potential for use in WAAM components nor on the potential for implementation of these techniques during the manufacturing process. In this paper an experimental analysis of Radiographic Testing (X-ray) and Ultrasonic Testing (UT) for inspection of aluminium and steel parts produced by WAAM is presented.

3. Materials and methods

For evaluation of the different NDT techniques blocks of two different materials were made on the top of a substrate plate. These geometries were produced by Wire and Arc Additive Manufacturing (WAAM), with Cold Metal Transfer (CMT) arc welding process, and the motion was provided by a six-axis Kuka Robot.

The blocks were deposited to form a structure of approximately 30 mm high, as shown in Fig. 3. An example of aluminium block is presented in Fig. 3b. Deposition parameters and manufacturing strategies were selected in order to ensure that different defects (lack of fusion, inclusions and porosity) would be present in the components.

Two different materials were used as welding wire consumable, an Aluminium alloy (AA5083) and a Mild-steel (ER70S). These materials were selected because they are representative of the most commonly used in WAAM and they present different characteristics, namely with respect to magnetic and electric properties, which allows for a more comprehensive study of the non-destructive testing techniques.

3.1. Non-destructive testing techniques

In order to detect the defects present in the blocks, Radiographic Testing (X-ray), Liquid Penetrant Inspection (LPI) and Ultrasonic Testing were applied. For the X-ray testing, the procedure consisted of adjusting the parameters needed for the test. Voltage, current and time of exposure had to be adjusted for each part as thickness and material have a major role in obtaining a good radiography. The equipment used for radiography was the SMART 583–1007, YXLON International AS. For penetrant liquids, the fluorescent or color contrast (dye) penetrant was applied followed by a developer, applying the recommended exposure times for each material, and then the respective appropriate method of cleaning. In this study, FLUXO P125 was applied as red dye penetrant, FLUXO P175 as a developer and FLUXO S190 as a solvent cleaner. In case of ultrasonic testing, the equipment used consisted of different transmitting probes, coupling gel and a conventional UT equipment OLYMPUS, OMNISCAN MX. Regarding conventional probes, the specimens were inspected by a MB 4 S (from GE), with 4 MHz and 10 mm element size, suitable for larger parts with simple geometry. Another probe was used to inspect smaller thicknesses, a DA 301, also from GE, with 5 MHz.

3.2. Materials characterization techniques

Apart from non-destructive evaluation, destructive testing was used in order to evaluate the characteristics of the deposited material. Macrostructure and microstructure analysis were performed, by destroying the AM blocks to produce samples from the sections. Both tasks required the same four steps which were cutting the samples from the blocks, grinding and polishing, etching, and finally inspection under optical microscopy. Also, in order to analyze the hardness of each sample, Vickers hardness tests were made on a transversal section of the blocks. Electrical conductivity measurements were performed using customized circular helicoidal eddy current probes with ferrite cores of

a) b)

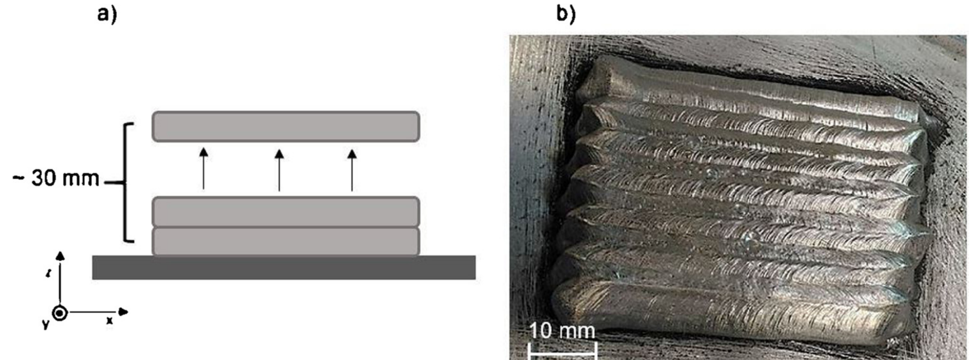

Fig. 3. WAAM samples produced for NDT inspection. (a) Scheme of the production method of blocks. (b) Example of aluminium block.

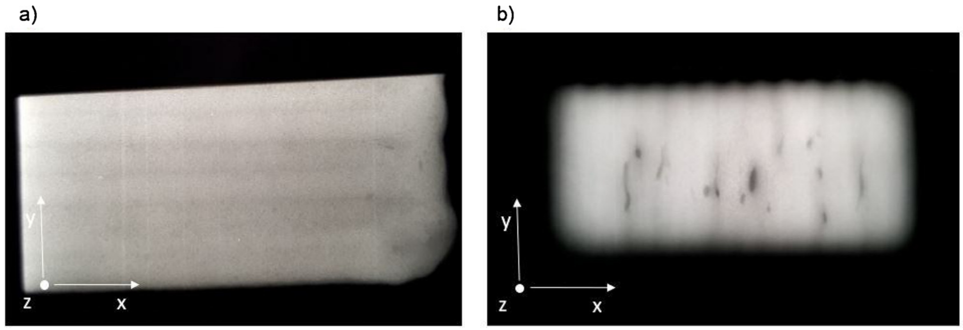

Fig. 4. X-ray results. (a) Aluminum and (b) Mild-steel.

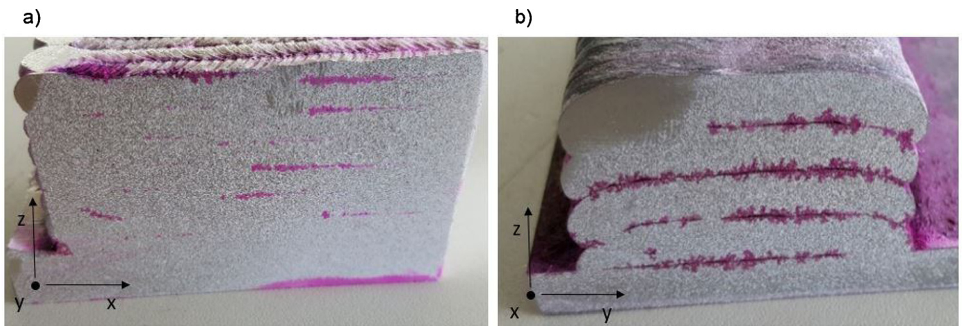

Fig. 5. Cutting sections to confirm the X-ray NDT test results with dye penetrant to make defects more evident. (a) Aluminum and (b) Mild-steel.

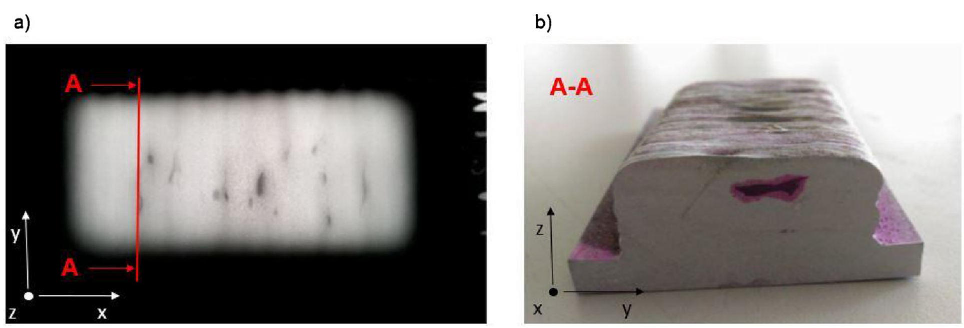

Fig. 6. Comparison between X-ray and LP with the purpose of confirming inclusion flaws. (a) X-ray results and (b) LP results.

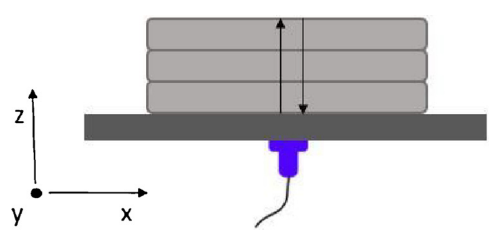

Fig. 7. Scheme of UT testing.

about 0.7 mm diameter in order to increase the spatial resolution. The inspection frequency was 500 kHz.

4. Experimental evaluation of the inspection techniques

As shown in Fig. 4, porosity, inclusions and lack of fusion were detected by radiographic testing. It is known that X-ray is a reliable test for detecting 3D defects, however it is not able to show planar (2D) defects and small defects in the perpendicular direction of the radiation incidence. Thus, the detection of the lack of fusion between layers will depend on the radiation orientation. Moreover, the technique allows to reliably scale the defects, however it does not fully locate them (in this case of incidence, the depth of inclusions is unknown).

In order to confirm the NDT results from X-ray a destructive testing was performed, consisting on analysing two cutting sections (Fig. 5). To help the visualization of the defects a dye penetrant was used in the cut surfaces. It must be noticed that dye penetrant was used not as an NDT technique, but just to make the defects more evident in the cut sections. The pink areas are coincident with the interface between the different deposits which indicate that no effective bonding between each layer, confirming the X-ray results.

Apart from lack of fusion, and in order to confirm the flaws detected through X-ray, Sample b was sectioned at A-A. In Fig. 6, the A-A section can be seen and the elongated inclusion is confirmed.

Ultrasonic testing was performed in order to compare the previous results and achieve conclusions about the capability of this technique. Considering that the ultrasonic NDT process cannot be applied to an irregular surface, the analysis and scan were made through the back of the plate (Fig. 7). Using the A Scan (Figs. 8 and 10) the echo amplitude and transit time are plotted on a simple grid, showing the travel distance (DA) made by the emitted and reflected wave. Thus, if the peaks appear before the total thickness of the part, this means that there is an interface that reflects the echo back to the probe, which is a defect.

Results shown in Fig. 8 represent zones that were the most relevant for the inspection of the parts.

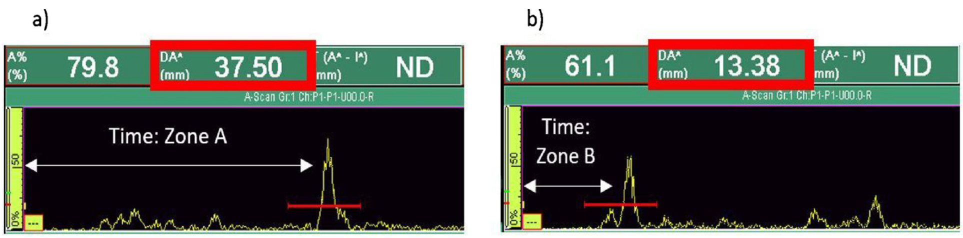

Fig. 8. Conventional UT analysis of aluminium sample. (a) Zone A and (b) zone B.

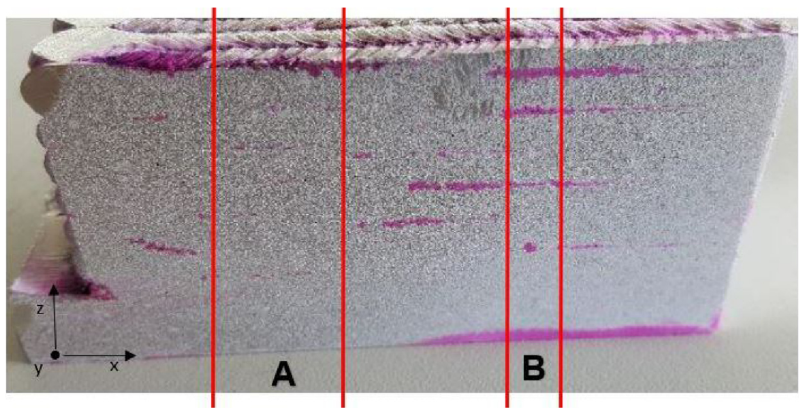

Fig. 9. Visualization of the application of the ultrasonic testing method by analysing a part through LP (aluminium sample).

Results obtained from the aluminium sample show two distinguished zones with two different UT specters (Fig. 8). The first specter presents a no defect region (zone A) and the second one reveals a defect in a distance of 13.38 mm from the substrate plate surface (zone B).

Through Fig. 9 it is easily visualized that the defect in spectre B is lack of fusion with a round shape. This spectre represents a partial lack of fusion between layers, partial because otherwise if it were the entire width of the part no sound would go through and no peak would exist at the 37.5 mm mark.

Mild-steel specters only present one defect, a lack of fusion between the tested part and the substrate plate, showed by the first echo at approximately 6 mm (Fig. 10), which is the substrate thickness. This sample was tested with different UT probes (changing the contact diameters and frequencies), but the results were the same.

The LP testing shows the severity of the flaws detected (Fig. 5b). As opposed to the lack of fusions detected in aluminium sample, the ones found here do not allow the sound to travel, making this method not even suitable to detect the total thickness of the part.

In summary, the defects were easily detected by X-ray, although multiple radiographic imaging with different orientation will be needed to fully detect them. Regarding UT, tests confirm that it is a reliable technique for detecting and scaling the WAAM defects, in both materials. However, the software data analyzed provided allows to locate the defect but does not reveal the type of defect. The three techniques can thus be complementarily used to evaluate the defects in WAAM structures.

5. Materials characterization

To fully characterize AM specimens several techniques are required, mainly destructive, as hardness or metallographic testing. However, as stated above, the overall manufacturing process productivity will be increased by using non-destructive methods for materials characterization, preferably in-process. Electrical conductivity measurements, based on the eddy-currents physical principle, has already proven a good correlation with the microstructure and hardness observed for Friction Stir Welding [13]. This method was tested in the reference samples in order to correlate the electrical conductivity field and the microstructure and hardness observed for the WAAM process.

5.1. Macrostructure & microstructure

From the micrographic analysis, it is possible to observe that the WAAM samples have defects. Specially, poor fusion between layers is presented in each sample and significant amount of porosity can be seen in aluminum. Fig. 12 reveals the presence of a considerable number of pores on aluminium sample and a clear example of lack of fusion between each layer on the mild-steel.

Microstructure analysis was used to better understand the defects. A

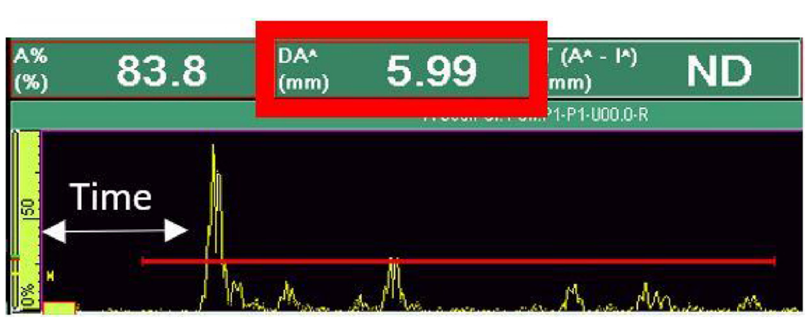

Fig. 10. Conventional UT analysis of mild-steel sample.

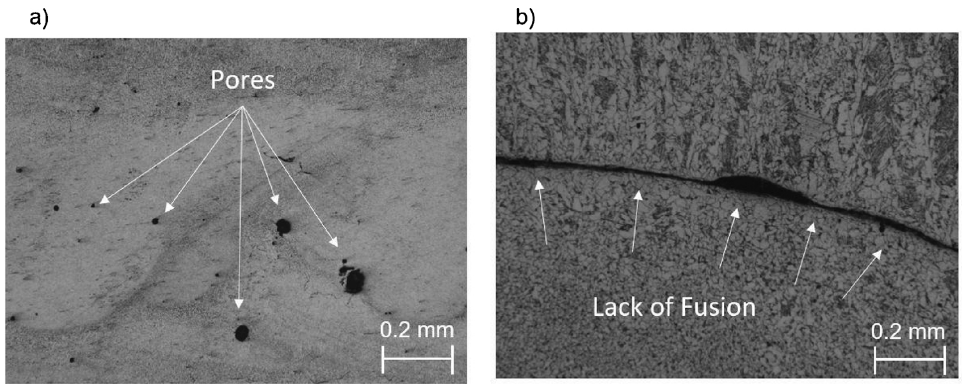

Fig. 11. Examples of defects from the microstructure analysis. (a) Pores on aluminium sample of about 50 μm dimension. (b) Lack of fusion on mild-steel sample (between layers) of about 20–30 μm.

detailed look at the microstructure images (Fig. 11) shows that the main defect observed is, in fact, the lack of fusion between layers. However, in the aluminium sample, in addition to the referred pores, some small cracks can also be seen.

5.2. Hardness

Fig. 12 shows the indentation mark made during the hardness test. In the two samples a small deviation from the average hardness is observed, however, the difference between the highest value and the lowest value is not significant, allowing to conclude that the mechanical properties are homogeneous over each layer, despite variations of the involved temperatures.

From the results obtained it can be seen that generally, the layers present lower hardness than the substrate material, as expected. In case of mild-steel, the difference of the hardness profile can be seen in Fig. 12. Aluminium results are below the usual hardness results for its alloy, according to Aerospace Specification Metals (ASM).

5.3. Electrical conductivity

Measurements of the electrical conductivity field of the surface samples were performed by eddy currents to characterize and complement existing techniques as hardness measurements and micrographic analysis. Electrical conductivity of materials depends on the electronic mobility, on the crystalline structure of existing phases, as well as, on the crystal defect content, namely point defects such as voids and interstitials, linear (dislocations) and surface defects (twins and grain boundaries) [14].

Additionally, information related to the electrical conductivity field is crucial when NDT based on eddy currents is to be applied, since defects are detected based on a local change of the electrical conductivity of the material. Previous knowledge of the electrical conductivity field variation due to processing is required, in order to distinguish background material from eventual defects [14].

In order to identify porosities and other heterogeneities, a characterization of both samples was made using bi-dimensional analysis, as showed in Figs. 13 and 14.

Figures show that the measured values of electrical conductivity

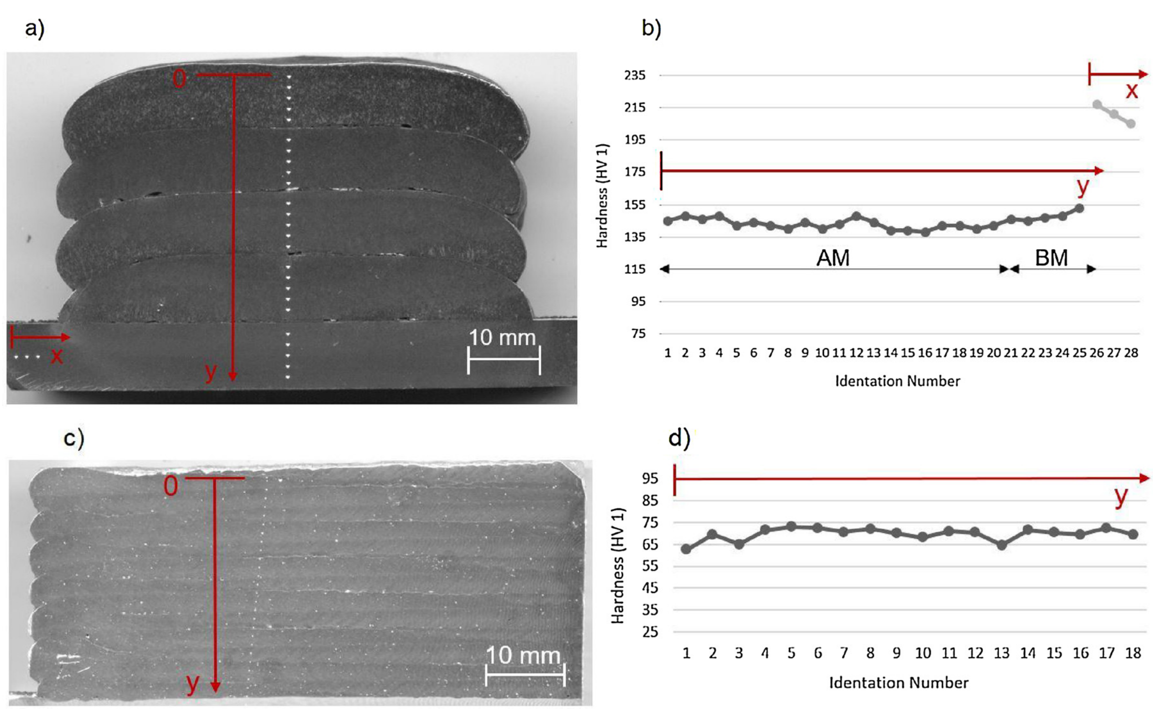

Fig. 12. Results for aluminium (above) and mild-steel (below). (a and c) Indentation marks on samples on the right and (b and d) Vickers hardness tests result with 1 kg of indentation load.

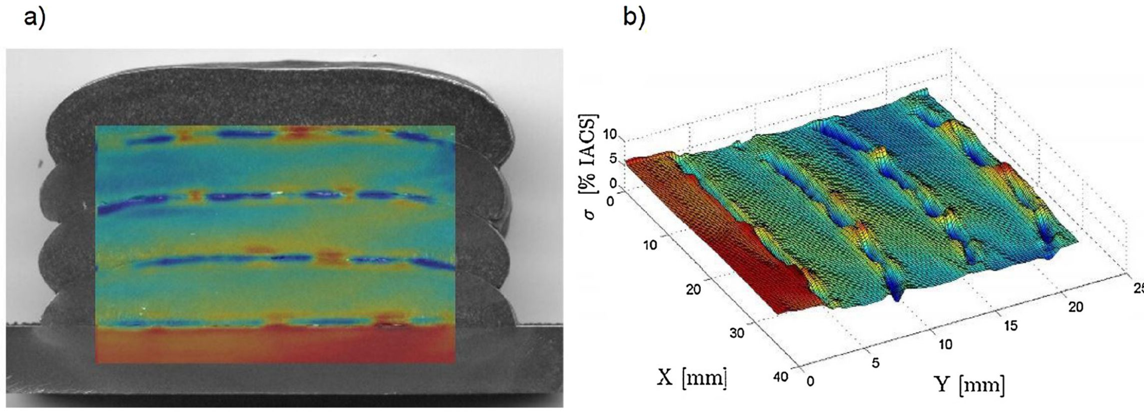

Fig. 13. Analysis of the electrical conductivity of the mild-steel. (a) Bi-dimensional and (b) tridimensional representation.

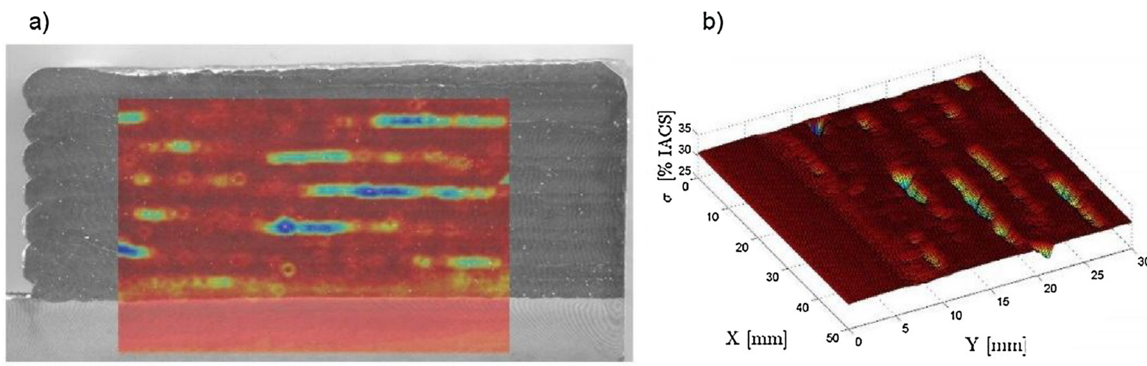

Fig. 14. Analysis of the electrical conductivity of the aluminum. (a) Bi-dimensional and (b) tridimensional representation.

allow identifying the sections where significant variations can be observed. First, for both samples, a considerable difference of homogeneity from the substrate to the deposited material can be seen. This is in agreement with the hardness results, as these also reveal inconsistencies along each layer. Moreover, these inconsistencies revealed by the electrical conductivity measurements are coincident with the LP and X-ray results, which indicate that the heterogeneities can be identified. Comparing Fig. 13a) and Fig. 5b) it can be concluded that electrical conductivity measurements can identify defects of about 20–30 μm between layers, according to the microstructure analysis presented on Fig. 11b).

Also, in Fig. 13a significant decrease of the conductivity can be seen between each layer, which may be explained by the lack of fusion effect. It is clear from the previous studies that no effective bonding between the layers has been achieved in the mild-steel sample, which represents greater resistance to the electronic mobility. Electrical conductivity results show great sensitivity to this fact.

The aluminium results (Fig. 14) are not so clear as the mild-steel, however, the heterogeneities detected in both hardness and microanalysis can also be seen by the electrical conductivity. In the heterogeneities zones, an increase in hardness and decrease in electrical conductivity is observed.

These results show that the electrical conductivity can be seen as a complementary technique to hardness measurements, because of the different physical phenomena involved. This technique also achieves higher test speed and requires less surface preparation requirements. Essentially, this technique revealed to be able to successfully identify the existence of defects, heterogeneities and lack of bonding between layers, in both samples.

6. Conclusions

The objective of this work was to contribute to the evaluation of parts produced by WAAM using non-destructive techniques. Knowing the goal of an inspection and how geometries influence the ability to deploy non-destructive techniques, a broad review of different NDT methods was made, showing the pros and cons of each technique.

For in-process inspection Eddy Current (EC), ultrasonic (UT) and thermography are the most suitable candidates. However, within UT techniques, conventional UT and PAUT need couplants and are susceptible to high temperatures, while EMAT or Laser UT have less limitation and can be a good approach. Regarding the electromagnetic based methods, EC might be applied but it is suitable for detecting defects at small depth. Also, the influence of the surface finishing in the process needs to be considered for the techniques referred above, which requires customised probes to overcome rough surface finishes.

For the off-line approach a broader set of NDT techniques can be applied. XCT and X-ray or UT, PAUT and EC (after surface machining) can be applied. In this case, costs, time for inspection and part size are the main factors to consider.

Based on the results of the review, applicable NDT techniques were selected, and their potential was analysed in WAAM reference specimens for comparison of results. This study demonstrated that radiographic testing and ultrasonic can give correct information on the location of the defects, despite the limitations of each one of them. Ultrasonic inspection proved the capability to detect and scale WAAM defects, with limitations relatively to the need for good surface finishing. A wide range of defects was easily detected by X-ray. However, it presents stringent safety limitations, in addition to the difficulties in defects detection that are associated with the angle between the crack and the radiation.

Regarding materials characterization, the measurement of electrical conductivity field has proven to be a reliable and expedite technique. Allowing to characterize WAAM samples, on the surface and in depth. This technique complements hardness evaluation with further advantage of being faster and of not requiring surface polishing.

To tackle WAAM inspection there will not be a "one size fits all" solution. Limitations as geometric complexities and more critically roughness have to be considered. The biggest challenges are the implementation of NDT techniques in-process. For off-line inspection there is a range of techniques that can detect WAAM defects. Nevertheless, this work shows that existing NDT techniques clearly demonstrate potential for in process and off-line inspection of WAAM parts.

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