MAPPING OF NON-DESTRUCTIVE TECHNIQUES FOR INSPECTION OF WIRE AND ARC ADDITIVE MANUFACTURING

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ABSTRACT

The present work addresses the challenges of identifying applicable non-destructive-testing techniques suitable for inspection and materials characterization techniques for Wire and Arc Additive Manufacturing (WAAM) parts. The overall manufacturing process productivity will be increased by increasing the yield, driven by the reduction in scrap rate, enabled by in-process inspection and material characterization. Thus, the main objective of this paper is to evaluate the capability for detecting the potential defects that are associated with WAAM. During this study, radiography, liquid penetrant inspection and ultrasonic testing were applied on reference specimens in order to detect the defects and its location. Then, metallographic, hardness and electrical conductivity field analysis were applied on the same specimens for material characterization. Experimental outcomes prove that typical WAAM defects can be detected by the referred techniques. Also, the blocks characterization using the electrical conductivity technique shows that heterogeneities, porosities and interfaces between layers can be effectively identified, suggesting that the application of this physical principle to non-destructive-evaluation has the potential to complement or substitute the generally used destructive methods in AM processing.

Keywords: non-destructive techniques, materials characterization, additive manufacturing, wire and arc additive manufacturing.

INTRODUCTION

Additive Manufacturing (AM) is a manufacturing technique in which components are built by depositing materials layer by layer. This technique is increasingly gaining a relevant place in the manufacturing industry, in different areas and materials. So far, parts in plastic, metal and ceramics have been successfully manufactured by additive techniques. Regarding metals, laser based AM is already used in industry, particularly for small parts in high value materials like titanium and its alloys. However, the potential of AM processes to produce large parts is still requiring significant research to reach a reliable industrial implementation.

Recently, Wire and Arc Additive Manufacturing (WAAM) prove to have potential for the production of large scale engineering structures (Williams, 2016). This manufacturing technique involves the layered design of a component and subsequent welding deposition of the multilayer structure to produce parts, by using the same technologies and equipment as in welding.
WAAM technology is receiving considerable attention due to the capability of producing customized large parts at lower cost, in comparison with other additive manufacturing processes (Martina, April 2015). However, an important aspect where research needs to be focused in order to transfer WAAM to the industry is to develop or adapt methods to ensure the components’ structural integrity. This goal can be reached by allowing in-process non-destructive testing and repair of defects by layer machining. With the view of qualifying WAAM for applications such as structural components, Non-Destructive Testing (NDT) systems must be developed, in order to detect porosity levels and lack of fusion between layers (Clark, 2011).

In summary, WAAM manufacturing technique has already proven to be successful for the production of large scale engineering structures and its application is expected to grow over the next decades. However, research needs to be developed before the WAAM technologies become standard, and one of the aspects to address is non-destructive techniques to assure the quality of the parts produced. This last topic is the focus of the presented paper.

**LITERATURE REVIEW**

Non-Destructive Testing (NDT) can be referred to the techniques used to inspect parts for discontinuities and therefore evaluate their defects. These methods obtain information of the parts physical properties and imperfections in order to evaluate its condition and/or the fabrication process. Application of NDT must be conducted by specialized technicians to minimize errors such as failing to detect a defect or a result of a false positive, the incorrect use of this methods can lead to critical flaws and possibly structure failure, parts not meeting the standard criteria as well as unnecessary costs in part maintenance. NDT has seen a several developments over the years due to increasing rates of industrial requirements.

Integrating NDT with AM faces many challenges such as geometry of the part, surface finishing and others. Also, the need for implementation during manufacture as opposed to post operation, in order to save time, is a key aspect when selecting the correct NDT techniques.

Currently there are no standards regarding NDT for AM, the urgent need for them has put together cooperation between the International Organization for Standardization (ISO) and ASTM for the first time enabling the joint development of AM standards in the area (ISO, 2011). To establish the NDT suitable for AM a revision of current available technologies will be presented.

<table>
<thead>
<tr>
<th>NDT Method</th>
<th>Operation Principle</th>
<th>Pros</th>
<th>Cons</th>
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<tr>
<td>Radiographic Testing</td>
<td>Radiography requires the projection and penetration of radiation energy on and through an inspected material. The radiation energy is absorbed homogenously by the material, except in the regions where thickness or density variations arise. The energy that passes through is captured by a sensing medium (film) in the form of an image of the interior of the specimen.</td>
<td>-Reliability and no special specimen preparation is required prior to application</td>
<td>-Difficulties in detection may be associated with the angle between the crack and the radiation; -Not suitable for on-line procedure; -Safety limitations;</td>
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<td>Method</td>
<td>Details</td>
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<td>X-ray Backscatter</td>
<td>- Backscatter X-ray detects the radiation that reflects from the target as opposed to conventional X-rays. It has potential applications where less-destructive examination is required, and can operate even if only one side of the target is available for examination.</td>
<td>- Not susceptible to surface roughness; - Large structures are easily tested; - Limited availability of tailored X-ray sources; - Challenges in developing standards and procedures; - Inspecting times can be unacceptably long;</td>
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<td>Computed Tomography</td>
<td>- Method of forming 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.</td>
<td>- Detect deep or embedded defects; - Interrogate inaccessible features; - Confirm the effectiveness of post-process treatments often required to make usable parts made by AM; - Characterize and qualify as-manufactured parts made by AM; - Very precise; - Not susceptible to surface roughness; - Large structures are easily tested;</td>
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<td>Neutron Imaging</td>
<td>- Neutron imaging is similar to X-ray, a beam of neutrons passes through a sample and leaves an image on a film or detector.</td>
<td>- Neutrons have high penetration depth (suited for bulk samples), advantage over x-ray; - Absence of radiation damage; - Can produce images of components containing light elements; - Requirement for a nuclear reactor (although portable neutron sources do exist) work places may be limited; - Several constraints to implement on-line, suitable for off-line;</td>
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<td>Ultrasonic Testing</td>
<td>- UT uses high frequency sound energy travelling through the material to conduct examinations and make measurements that can be used for flaw detection, dimensional measurements and material characterization.</td>
<td>- High resolution among NDT Techniques; - Cannot function at temperatures higher than 500 K; - Surface treatment dependent (Surface parallelism is of utmost importance since even a few degrees of change can deflect important signal information away from the transducer);</td>
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<td>Phased Array Testing</td>
<td>- Phased array ultrasonic systems utilise 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 showing the sizes and locations of any flaws detected.</td>
<td>- Very precise; - No safety hazards; - Fast inspection times; - Able to penetrate thick sections; - Cannot work at high temperatures; - Requires coupling; - May require several probes;</td>
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<tr>
<td>Method</td>
<td>Description</td>
<td>Advantages</td>
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<td>Immersion Ultrasonic Testing</td>
<td>Immersion ultrasonic testing, is an advanced form of ultrasonic testing, and is a more effective method of inspecting than manual ultrasonic testing. It offers improved Probability of Detection (POD) of the smallest defects, and can provide you with accurate reporting of the size and location of sub-surface irregularities and flaws in material or products.</td>
<td>Good results independents of the geometry complexity; Improved accurate sizing; Cannot be used on-line; Requires immersion of the part;</td>
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<td>EMAT</td>
<td>This inspection method uses a electromagnetic acoustic (EMA) way of ultrasound excitation and reception.</td>
<td>Contactless and couplant independent; Suitable for very high temperatures; Contactless but requires close proximity; Geometry contained (hard to inspect very complex shapes);</td>
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<td>Laser Ultrasonic Testing</td>
<td>A laser pulse is directed to the surface and induces an ultrasonic pulse that propagates into the sample. This ultrasonic pulse interrogates a feature of interest and then returns to the surface. A separate laser receiver detects the small displacement that is generated when the pulse reaches the surface. The electronic signal from the receiver is then processed to provide the measurement of interest.</td>
<td>Contactless and couplant independent; Can be used on complex geometries, curved or difficult to access areas making it suitable for AM applications; Can be used at very high temperatures; Experimental results showed that knowledge of the internal geometry of the crack is required in order to obtain an accurate depth profile; More expensive than conventional UT; Optical detection techniques generally offer lower sensitivity than contact transducers;</td>
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<td>Potential Drop</td>
<td>Measurement of the potential drop by an increase in the electric resistant between two measurement electrodes in a presence of a discontinuity.</td>
<td>Very good at estimating surface cracks depth; Surface roughness reduces accuracy of the sized cracks; Penetration depth of few mm;</td>
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<td>Eddy Currents</td>
<td>Electromagnetic induction where the interaction between a magnetic source (produced by the probe) and the subject material is observed in order to detect a discontinuity or a defect.</td>
<td>No consumables used; Improved sensitivity; Surface finish and grain structure play a huge role in the success of the method in finding critical defects; Penetration depth of few mm;</td>
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<td>Magnetic Particle Testing</td>
<td>Magnetic particle examination (MT) is a very popular, low-cost method to perform nondestructive examination (NDE) of ferromagnetic material that checks for surface discontinuities and/or slightly below the surface, using a magnetic field and magnetic particles;</td>
<td>Low cost; Surface Preparation not as critical as to other NDT; Examination of large parts may require use of equipment with special power requirements; Limited subsurface discontinuity detection capabilities; Limited to ferromagnetic materials;</td>
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Penetrant Testing

- Components are wetted with a fluorescent penetrant and using a developer make even the smallest cracks visible under UVA light;
- Low Cost;
- Easy to implement;
- Cannot be implemented online;
- Cannot detect internal part defects;
- May not be a realistic method for inspection of porous or rough parts made by AM without special post-process machining and polishing;

Acoustic Emission

- Elastic waves that are emitted in a medium due to crack nucleation or propagation can be captured by suitable piezoelectric sensors on the surface of a specimen;
- Perfect for parts in operation (while defects are being formed);
- Not suitable for post manufacture inspection (prior to service);

Infrared Thermography

- Infrared thermography aims at the detection of subsurface features (i.e. subsurface defects, anomalies, etc.), owing to temperature differences (DT) observed on the investigated surface during monitoring by an infrared camera;
- Large areas can be scanned fast;
- Risk free (no radiation);
- Suitable for online monitoring;
- Not possible to penetrate in extended depths (can be used for few layers analysis);
- Environmental conditions may limit use if used outdoors;
- If the working material is not at an elevated temperature, requires external heating;

Laser Thermography

- 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;
- Suitable for online monitoring;
- Contactless and requiring no surface finishing;
- Deep scratches or indentations can perturb heat flow in a similar manner to a crack;

Vibro Thermography

- An ultrasonic transducer generates elastic waves within the test specimen. This elastic 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;
- Very short measurement time (seconds);
- Requires contact;

Eddy Current Thermography

- Use of induced eddy currents to heat the sample being tested and defect detection is based on the changes of the induced eddy currents flows revealed by thermal visualization captured by an infrared camera;
- For near-surface defects, direct interaction with eddy currents can improve detectability;
- Suitable for online monitoring;
- May require time to deposit enough energy in the material;

To provide more detailed information on several of the NDT techniques presented several studies have been conducted with potential applications to WAAM inspection. Recent studies have shown optimal XBT results in subsurface crack detection, without requiring surface treatment and/or preparation but requiring significant amount of time to
perform detection of micro cracks due to narrow pitch scanning of an object surface. (Babot D, 1994) 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. The result should make XBT suitable for defect detection in AM although the operation’s time will require technologic advances to make it applicable in production.

Fig. 1 - Image (11mm x 11mm) of XBT when using the pinhole of 1.0 mm diameter (S. Naito, 2009).

To tackle this issue (S. Naito, 2009) are studying a XBT using uncollimated X-ray irradiation (XBU), which enables to inspect a large area of an object surface at once by large area X-ray irradiation and X-ray 2D detection.

Fig. 2 - XBT Setup (S. Naito, 2009).

To evaluate manufactured AM parts in order to read tolerances and geometric standards and find defects here is not better method to evaluate then XCT due to its volumetric nature. XCT can be very useful to compare STL files and features such as pores are hard to measure with other NDT, as although detected the overall % of porosity is not achieved easily. Research has been able to calculate the ratio of the number of voxels representing pores to the number voxels representing solid material in an XCT scan (Taud H, 2005).

Fig. 3 - Part designed with internal defects source (Jorge Mireles, 2015).
In a study made by (Jorge Mireles, 2015) parts were fabricated using an EBM powder bed fusion system processed from Ti-6Al-4V. To analyse defects from the parts fabricated a CT scanning method, capable of detecting defects as small as \(\sim 40 \mu m\). To ensure CT results and evaluate its resolution, a part was manufactured by Electron Beam Melting (EBM) was designed with internal defects. Different geometries such as spheres, triangular prisms, cylinders and cubes were made simulating porosity sized from 100 to 2000 \(\mu m\). Defects with similar geometries were added occupying three and four layers in thickness to determine the effect from melting of subsequent layer.

For the CT analysis, a model was made using scan data of 60 \(\mu m\) slices of the part. After analysis, the defects found were no larger than 600 \(\mu m\) and the defects spanning three and four layers in thickness were still present. Defects smaller than 600 \(\mu m\) may not have been detected due to the accuracy of the EBM fabrication (\(\pm 200 \mu m\)) that make it difficult to fabricate defects of similar size.

In the field of ultrasonic techniques the most promising is Laser-ultrasonic due to its ability to be contactless (more than just a few mm as opposed to EMAT) allowing for it to be implemented during a manufacture process. (Monchalin, 1993) has proved this by showing that a laser-ultrasonic system can actually be used on-line in a steel mill and provide unique information, used to improve production control. (Donatella Cerniglia, 2013) focused on the ultrasonic technique, using a pulsed laser to generate acoustic waves on reference samples manufactured by LMD (Laser Melt Deposition) 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 (A K Kromine, 2000).

The reference samples manufactured by LMD and provided by TWI were analysed and defects with sizes ranging from 100 \(\mu m\) and depth up to 700 \(\mu m\) have been successfully detected with high sensitivity. The following proposed developments include noise reduction techniques, advancements in automatic selection of parameter values as well as additional analytical and statistical developments in automated defect detection.

In cases of powder feed 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) detection showed promise for detecting smaller subsurface flaws than laser ultrasonic (90% POD 0.2 mm at the surface and 0.6 mm at 1 mm depth). (Sharratt, 2015)

The main adversity for the application of EC to AM parts as to do with the overall surface roughness that has proven difficult to distinguish signals from cracked or scratched areas from signals of smooth surface where the noise was significant. Tests done by (Jess M. Waller, 2014) on a Selective Laser Melting (SLM) valve showed just that, the scratched areas were not able to be distinguished from the crack areas.

Regarding Thermography it has been one of the most studied NDT procedures for AM. It has the advantage to monitor the operation from a distance allowing for fast results therefore making possible the correction of defects on the spot.

(Jorge Mireles, 2015) also evaluated IR imaging in his study, Figure 5 shows an IR image of the part (Figure 3) with the designed defects that are evidenced by the spots within the rectangular melt area. Defects smaller than approximately 600 \(\mu m\) were either not detected by the IR camera or not properly fabricated by the EBM system.
Comparing the results of the IR camera with the ones from a CT analysis the measurement of the defected area varied by 60%, where the IR images gave evidence of greater flaws. The smaller defects of 600 µm were not detected either by the IR camera of the CT concluding that these may not have been fabricated.

These along with other studies has demonstrated that IR imaging can be used in situ to positively identify porosity or defects during AM fabrication, making it one of the most prominent methods of non-destructive evaluation of AM-fabricated parts.

Besides the existing of a significant number of publications related to NDT, there is almost no data available concerning its capabilities for use in WAAM components. In this context, this work presents a preliminary study of the NDT applications in WAAM specimens, being the main focus to test different non-destructive-techniques in order to analyze its potential for detecting WAAM defects.

**MATERIALS AND METHODS**

For evaluation of the different 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, with CMT (Cold Metal Transfer) arc welding process, and the motion was provided by a six-axis Kuka Robot.
The blocks were composed to form a structure of approximately 30 mm high. The deposition parameters and manufacturing strategies were selected in order to ensure that different defects would be present in the components. Figure 6 shows the scheme of the production procedure of the blocks produced.

Two different materials were used as welding wire consumable, an Aluminium alloy (AA5083) and a Mild-steel (ER70S). The materials selected presents different characteristics, namely with respect to magnetic properties, in order to make the study more comprehensive at the test level.

**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 in setting the parameters needed for the test, voltage, current and time of exposure, and adjust the test part and the X-Ray tube in order to guarantee a successful radiation absorption concerning the defects orientation. The equipment used for radiography was the SMART 583-1007, YXLON International AS. For the penetrants liquids, the fluorescent or colour contrast (dye) penetrant was applied followed by a developer and then a method of cleaning. For this study, the FLUXO P125 red dye penetrant, FLUXO P175 developer and FLUXO S190 solvent cleaner were applied. For the ultrasonic testing the equipment used consisted in: different transmitting probes, coupling gel and a conventional UT equipment OLYMPUS, OMNISCAN MX.

**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 analyse the hardness of each sample, Vickers hardness tests were made on transversal section of the blocks. The electrical conductivity measurements were performed using customized eddy current probes with ferrite cores of about 0.7 mm diameter in order to increase the spatial resolution.

**EXPERIMENTAL EVALUATION OF THE INSPECTION TECHNIQUES**

X-ray testing, liquid penetrant inspection and ultrasonic testing were applied in order to detect the samples defects. From the X-ray testing (Figure 8), only porosity was detected. It is known that X-ray is a reliable test for parts in volume inspection, however it is not able to
show the small defects in the same direction of the radiation incidence. Thus, the lack of fusion between layers is not possible to detect from these results. Moreover, the technique allows to reliably scale the defects, however it does not locate them (in this case of incidence, in depth).

Figure 9 shows that liquid penetrant inspection has the capability of detecting the lack of fusion between layers, after machining the surface of the samples, which means that X-ray and liquid penetrant inspection may be considered complementary tests. The pink areas are coincident with the interface between the different deposits which indicate that no effective bonding between each layer has been attained. This NDT method identifies superficial defects and can thus be used on the surfaces of the parts produced but the results observed do not indicate the presence of internal defects as X-ray does.

![Aluminium and Mild-steel X-ray results](image1)

**Fig. 8 - X-ray results. Left - Aluminum; right - Mild-steel.**

![Aluminium and Mild-steel Liquid penetrant results](image2)

**Fig. 9 - Liquid penetrant results. Left - Aluminum; right - Mild-steel.**

Ultrasonic tenting was then performed in order to compare the previous results and achieve conclusions about the capability of detecting the defects of WAAM.

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. The results collected show the travel distance 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.

![Scheme of UT testing](image3)

**Fig. 10 - Scheme of UT testing.**
The results shown in Figure 11 represent zones that were the most relevant for the inspection of the parts.

![UT results for Aluminium and Mild Steel](image)

The results obtained from the aluminium sample show three distinguished zones with three different UT spectres. The first spectre presents a no defect region, the second one reveals a defect in a distance of 13.38 mm from the substrate plate surface, and the third spectre shows the same defect, by the first echo at 13.41 mm, and a region immediately following without defects, showed by the second echo.

The mild-steel spectres 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, which is the substrate thickness. The sample was tested with different UT probes (changing the contact diameters and frequencies), but the results were the same, as it can be seen in Figure 11.

In summary, the tests confirm that UT is a reliable technique for detecting and scaling the WAAM defects, in both materials. However, the software data analysed 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.

**MATERIALS CHARACTERIZATION**

As stated above, destructive test was used in order to evaluate the characteristics of the deposited material. Through these analysis, it is also possible to observe the existent defects on the build blocks, like lack of fusion, porosity, inclusions and other metallurgical aspects.

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, based on the eddy-currents physical principle, has already proven a good correlation with the microstructure and hardness observed for Friction Stir Welding (Santos, 2011). The 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.
Macrostructure & Microstructure

From the macro analysis, it is possible to observe that the samples in study have defects. Specially, poor fusion between layers is presented in each sample and significant amount of porosity can be seen in aluminium, Figure 13 reveals the presence a significant number of pores on aluminium sample, and a clear example of lack of fusion between each layer on the mild-steel. Also, from Figure 13 it can perfectly be seen the number of layers that make up each block.

The microstructure analysis was used to better understand the defects. A detailed look at the microstructure images, 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.

Fig. 12 - Examples of defects from the microstructure analysis of the samples.

Hardness

Figure 13 shows the indentation mark made during the hardness test. In the two samples exists a small deviation from the average hardness, 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.

Mild-steel

Aluminium

Fig. 13 - Indentation marks on samples on the right and Vickers hardness tests results
From the results obtained it can be seen that generally the layers present average hardness than the substrate material, as expected. However, a significant difference of the hardness profile from the material to the deposited material can be seen. The hardness profiles allow to map the deposited layers since the variation of hardness in each layer follows the same trend. This is particularly clear in the case of mild-steel.

**Electrical Conductivity**

The measurement of the electrical conductivity field of the surface samples was performed by eddy currents to characterise and complement existing techniques as hardness measurements and micrographic analysis. The 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) (T.G. Santos, 2011).

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 in the material. Previous knowledge of the electrical conductivity field variation due to solid state processing is required in order to distinguish background material from eventual defects (T. G. Santos, 2011).

In order to identify porosities and other heterogeneities, a characterization of both samples was made using bi-dimensional analysis, as showed in Figures 14 and 15.

**Mild-steel**

![Fig. 14 - Bi-dimensional analysis of the electrical conductivity of the mild-steel.](image)

**Aluminium**

![Fig. 15 - Bi-dimensional analysis of the electrical conductivity of the aluminium.](image)

The figures show that the measured values of electrical conductivity allow to identify 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, in line with the hardness values for the substrate.

Also, in Figure 14 a 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. The electrical conductivity results show great sensitivity to this fact.

The aluminium results (Figure 15) are not so clear as the mild-steel, however the heterogeneities detected in both hardness and microanalysis can also be seen in by the electrical conductivity. In the heterogeneities zones, an increase in hardness and decrease in electrical conductivity is observed.

These results shown that the electrical conductivity can be seen as a complementary technique to hardness, under several aspects as the physical phenomena involved, higher test speed and less surface preparation requirements. Essentially, the technique revealed to be able to successfully identify the existence of defects, heterogeneities and lack of bonding between layers, in both samples.

CONCLUSIONS

The evaluation of the defects detection capability by NDT methods and materials characterization techniques for WAAM process was presented in this paper. Applicable non-destructive testing techniques were selected from the developed table showing the pros and cons of each technique. The reference specimens used were inspected by three different techniques, namely radiography, liquid penetrant (LP) and ultrasonic testing (UT). It was demonstrated that all three techniques can give correct information on the defects location, despite the limitations of each one of them. UT is the most flexible one regarding the relative position of the inspection equipment and the part, and proved the capability to detect and scale WAAM defects. X-ray presents stringent safety limitations and involves a more demanding procedure, in addition to the difficulties in defects detection that are associated with the angle between the crack and the radiation. LP is easy to perform but present the limitation of only detecting superficial defects. Regarding the materials characterization, the innovative method tested, evaluating the electrical conductivity by eddy currents in the samples, proved to be feasible to correlate the electrical conductivity with the existence of defects, heterogeneities and lack of fusions between layers. Measurement of electrical conductivity field thus suggests having potential to constitute a feasible, reliable and expedite technique to characterize WAAM samples, on the surface and in depth, complementing hardness evaluation with further advantage of being faster and do not require surface polishing.

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