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In-process non-destructive ultrasonic testing application during wire plus arc additive manufacturing

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A B S T R A C T

Additive manufacturing is a technique which builds structures by depositing material in a layer-by-layer manner. Wire plus arc additive manufacturing technology also belongs into this group of manufacturing processes. It has been investigated in the last twenty-five years, although the first patent dates from 1925. Wire plus arc additive manufacturing uses existing welding equipment, an electric arc as the heat source, and wire as the feedstock. In this paper, we explain some basic process planning and implementation techniques, as well as the main advantages and disadvantages of the process. In addition, we discuss the potential of in-process non-destructive ultrasonic testing application to this process, in order to inspect the quality of the part while it is being produced, and to enable eventual repairs in-situ. Some authors have already presented the idea of non-destructive testing for AM products, and stated that ultrasonic testing could provide the most reliable results for detecting the lack of fusion, porosity, and other possible flaws. While researches so far were limited to post-process testing, this paper proposes the idea of in-process testing, which could provide a chance to find the flaws and the defects earlier in order to change the parameters in-situ, and avoid production of the whole part if it is already recognised as unacceptable. Despite some constraints, we believe the proposed method has great potential and represents a challenge worth investigating in more detail in the future.

A R T I C L E I N F O

Keywords:
Additive manufacturing;
Wire plus arc additive manufacturing;
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Ultrasonic testing;
Repairs in-situ

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1. Introduction

Thanks to the development of modern industries, there is always a continuous need for investigating and developing new technologies. One of the examples is the Aerospace industry, which will need about 20 million tonnes of raw material in the next 20 years [1]. Due to high safety standards, and considering the fact that this industry requires distinctive materials like titanium and other special alloys, which are expensive to produce and often not so suitable for machining [2], it is clear that production solutions need to assure minimum failures. Additive Manufacturing (AM) technologies are applied increasingly. A basic AM system consists of a combination of a motion system, heat source and feedstock. Unfortunately, most of the conventional AM technologies use only polymer materials or metal in powder form, resulting usually in porous structures [3], which is often not good enough to make fully functional products [4]. On the other hand, Wire plus Arc Additive Manufacturing (WAAM) offers a solution to solve the structural functionality issues related to most other AM technologies.

WAAM has been investigated in the last 25 years, despite the fact that the first patent dates from almost 100 years ago, from 1925 [5]. The heat source used in WAAM is electric arc, and the additional material is welding wire, which makes it a combination of welding and AM technology. In addition, WAAM uses ordinary welding equipment (power source, torch, shielding gases, etc.), but combines it with robotic systems or CNC machines, which move the torch and wire feeder. It should surpass present technologies for producing fully functional metal products (especially aerospace components), which can be very big in size. A high deposition rate (usually 50-130 g/min, depends on method), low cost and safer operation makes it desirable [6]. However, there are still challenges to be resolved, like the residual stresses and deformations due to enormous heat input, relatively low part accuracy and rough surface (post-processing is needed) [7]. Some of these problems have already been reduced. Yet, there are still some challenges that need to be investigated further. In this paper, we present a possibility to apply in-process Non-Destructive Testing (NDT) within the WAAM in order to inspect the quality of the part while it is being produced, and to enable eventual repairs in-situ.

2. WAAM process planning and implementation

Firstly, just like in any other AM technology, a 3D CAD model of desired part has to be made. These models can be designed in appropriate software or using reverse engineering (3D scanning). The designed part is then saved in standard convenient format, usually ".stl" (Standard Tessellation Language), and it serves as a link between the software (CAD model) and machine for processing, providing the basis for slicing part into layers [6]. Software „slices" the part on more layers per height and a layer's 2D contour is used for generating a tool (torch) path. For the parts which have the same cross-section per entire height, the first contour is the same as the last one, and as every one between them. Problems usually appear for the parts where the cross-section is changing with height; the process is more complex and difficult, due to the need for generating more tool paths. The next step in the process is choosing suitable welding parameters (wire-feed speed, welding speed, amperage and voltage of welding current, etc.) and bead modelling. Using the generated tool path and chosen welding parameters, the product is then made in layer-upon-layer fashion (the first layer is deposited on the base plate, the torch goes up and deposits the second layer onto it, and the process continues until the whole part is made). Additionally, a post-process machining path can be generated, or post-processing can be done independently [8]. Heat treatment is also usually done after the process itself. The schematic diagram of the complete WAAM based process is shown in Fig. 1 (on the left) [8, 9], and an example of a WAAM system with its main features is shown in the same Figure on the right-hand side.

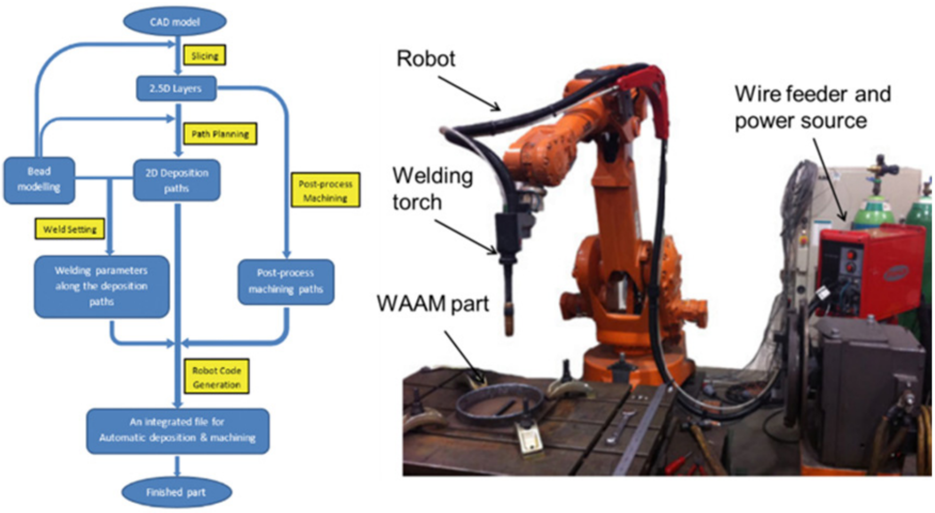

Fig. 1 Scheme of WAAM process (left) and example of WAAM system (right) [8, 9]

Even if the process seems to be quite easy and simple, it must be clear that all of the main steps contain smaller and numerous sub-steps, which have to be calculated and implemented carefully in order to get the part as good as possible. Slicing algorithms have been developed to provide layers of better quality [10]. Different path patterns [11] or bead modelling methods [12] were investigated for the same reason. Also, there has been a lot of research conducted regarding optimisation of welding parameters [13, 14]. All these investigations led to a conclusion – this is a complex process, and every mistake in any of the steps can cause major mistakes, affecting the part's surface finish, microstructure, mechanical properties and overall quality. If everything is done correctly, parts can be made like the one shown in Fig. 2 [6].

MIG (Metal Inert Gas) is the welding method, which is mostly used in WAAM technology. The wire is coaxial with the welding torch, which leads to an easily generated tool path. CMT (Cold Metal Transfer), a special metal transfer process in MIG welding, is used often. Using CMT means it is necessary to control welding parameters more strictly, but it can provide excellent quality of the layers, with lower heat input and almost without spatter. It is convenient for materials like steel and aluminium, but when it comes to titanium, this process is affected by arc wandering, so it produces a very rough surface. Due to that, TIG (Tungsten Inert Gas) welding is used more often for producing titanium parts. These processes need external wire feeding, and to obtain a product of good quality, the wire has to be delivered always from the same direction. It means additional torch rotation is necessary, which complicates robot programming and tool path generation [5].

Fig. 2 Producing WAAM part (left) and partially post-processed part (right) [6]

3. Advantages and disadvantages of WAAM

WAAM advantages are numerous. Investment and material costs are low because there is no need for buying special machines or systems. If a robotic hand or CNC machine are already available, they just need to be combined with the welding system, and material can be bought as welding wire. The choice of materials is wide. Deposition rates are much higher compared to other AM technologies (depends on the method, but goes up to 130 g/min, and it can reach even 10 kg/h, but then it compromises part accuracy). There is less waste, and that is important, especially in the Aerospace industry, where the cost is evaluated by the Buy-To-Fly (BTF) ratio, which is the ratio of the initial work piece mass to the finished component mass (it can be expressed in volume). Using WAAM, it can be reduced below 2, while, when using traditional manufacturing methods, it can go up to 20. This means it is possible to make a part which weighs 10 kg by buying 20 kg of raw material (feedstock) using WAAM, and for traditional methods 200 kg of raw material could be necessary for the same part. For some materials, this means huge cost savings. WAAM also enables short lead-time production and near-net-shape processing, which makes the whole manufacturing process faster and shorter. Additionally, part size is almost unlimited (it is limited only by the possible base plate size, or by the size of the chamber used to create the protective gas atmosphere, if it is needed) [5, 15].

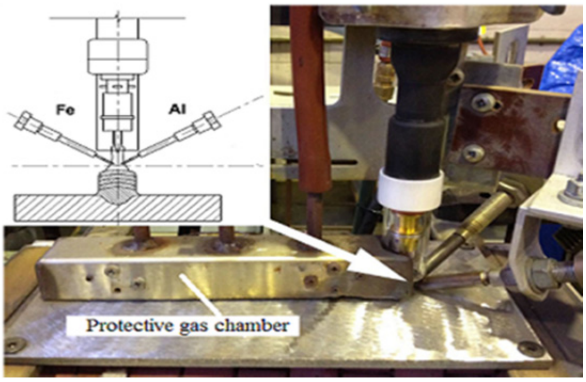

Fig. 3 Producing Fe_3Al using WAAM technology [16]

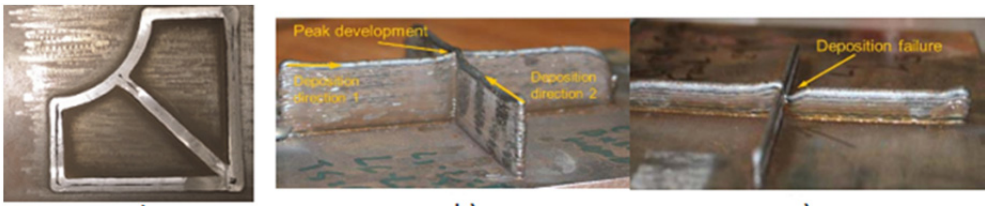

Fig. 4 Cavities (a), excessive camber (b) and sag (c) [1, 11]

It can offer a solution for producing functionally graded materials – they are characterised by the change in their composition and structure progressively over volume, which results in corresponding modifications in the properties of the material. Materials like these are usually produced for particular applications due to their specific properties, and one of the most used is iron aluminide, Fe_3Al. The process of producing that kind of material is shown in Fig. 3 [16]. Also, some researches showed that particular mechanical properties of WAAM material match, or even exceed, properties for the same cast or wrought material. Strength and ductility can reach these properties [17], and fatigue resistance can be even better [18]. All of these advantages are already well-known, and they make WAAM a desirable replacement for traditional manufacturing methods.

Unfortunately, there are still some disadvantages and constraints which cause problems, and there have been many conducted researches to reduce or avoid these problems.

Firstly, WAAM is more suitable to make large and less complex parts, rather than smaller parts with complex geometry, and this is a constraint which clearly defines its application. [5] Many researchers concluded that the parts produced by using WAAM have anisotropic properties, with higher strength and lower ductility in a horizontal (deposition) direction [18, 19]. Some issues related to bead modelling can also occur. Bead modelling controls the path planning variables, and it is used to define optimum welding parameters which can produce appropriate bead geometry. To manufacture parts with good surface quality, low roughness and geometrical precision, it is inevitable to develop both carefully and precisely – single weld bead geometry and multi-bead overlapping model [12]. If it is not done correctly, issues like excessive bead overlapping, or vice-versa, insufficient bonding, can occur. Some papers offered a solution to this problem, like the mathematical model TOM (Tangent Overlapping Model), which provides the necessary overlapping for obtaining desirable accuracy and quality [12, 20]. A generating tool path is inclined to defects like porosity, cavities, excessive camber (peak development) and sag (deposition failure). Porosity and cavities can occur in thick parts, which have to be filled inside (Fig. 4a), while camber and sag usually occur in crossing features (Figs. 4b and c) [1, 11].

Issues with porosity and cavities usually occur using the traditional contour pattern, which fills 2D geometry from external boundaries towards the inside. If step-over distance "d" (it is the distance between the two parallel tool-paths for depositing two adjacent layers) is not calculated properly (as the function of weld bead width "w"), then the torch may not melt enough wire and adjacent layers will not bond to each other, leaving cavities inside. The solution for this problem is an innovative technique of using the Medial Axis Transformation (MAT) of the geometry, where the torch starts from the inside and works towards the outside. Using this strategy, it is possible to fill the internal area of the geometry completely, and it has been investigated and explained in detail in some other papers, including [11, 12]. The peak at the layers' intersection appears when the weld beads are overlapping, while deposition failure occurs when too much heat is lost through the base plate and there is a lack of deposited material (accumulated) on one side of the crossing. Instead of depositing cross-like features, layers can be deposited as two „L" shapes which are touching each other at an intersection. This approach was investigated in [1].

Other types of problems that can occur are residual stresses, distortions and deformations, which are typical welding issues. Fig. 5 shows examples of these problems and a possible solution.

Usually, the part is made on one side of the base plate. Due to great heat input, deformation tends to „pull" the base plate in the building direction. The base plate bends, which may also bend the deposited wall and deform it (Fig. 5, a). The base plate can be clamped trying to reduce this, but Fig. 5 (b) shows software simulation for that situation. Residual stresses are released after unclamping the base plate, and no significant progress is made. However, Fig. 5 (c) offers a solution, called symmetrical building, or balanced building strategy [5, 15]. It is required to find the most appropriate plane of symmetry for the component, and the base plate should be set to coincide with that plane. Layers are then deposited on both sides of the plate, and stresses produced on one side are balanced with those produced on the other side. Sometimes two parts are needed anyway, so this is an additional benefit, but sometimes redesign is necessary.

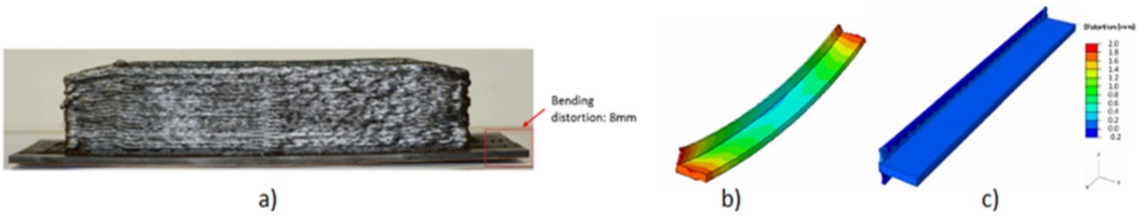

Fig. 5 Deformations (a, b) and solution through balanced building strategy (c) [5, 15]

4. Future trends

Researches on WAAM are interdisciplinary, and there is still plenty of space for improving and introducing new ideas. Some researchers suggest non-destructive testing of produced parts to be included in the process [5]. We elaborate on this idea more thoroughly in the next section. Issues with anisotropic properties can be solved using interpass rolling, which is also a subject of investigations [21]. It is even possible to integrate machining simultaneously with the layer deposition process, which would reduce the need for post-processing [22]. Some researches introduce new materials (besides steel, titanium and aluminium), like magnesium, to this process [23]. Also, there is a chance for complete process automatization, where human interaction would virtually be necessary only to start the process [8]. Further investigations should include work on these ideas and researches, alongside improvement of parameters' optimization, part design, heat treatment, monitoring and process control, which will, altogether, lead to better understanding and implementation of WAAM technology.

5. In-process non-destructive testing

The idea about Non-Destructive testing (NDT) that would be included in the process seems very interesting, but it has to be elaborated in detail. NDT is the common name for an extensive group of testing methodologies and techniques used in engineering, science and industry to assess the properties of a product, part or assembly without destroying it. NDT does not bend, break or affect the part being tested in any way. It is a highly valuable technique that can provide great savings during product and prototypes' design, inspection and testing, or troubleshooting and research. Methods that are used mostly are: Visual testing, liquid penetrant testing, magnetic particle testing, ultrasonic testing, radiographic testing, acoustic emission testing, along with some other, less conventional methods such as, for example, impedance-based monitoring [24]. Each of these methods have their own characteristics, advantages and constraints. Liquid penetrant and magnetic particle testing are cheaper and easier to carry out, but can only show defects on a part's surface and a few millimeters below. Ultrasonic and radiographic testing are more expensive and require more time for training, but can show defects in the entire part [25]. Considering problems, needs, requirements and defects which can occur in WAAM produced parts, ultrasonic testing seems to be the most appropriate method to improve the development of this process and the part being produced in this manner.

Ultrasonic testing (UT) is based on the same principle as, for example, ultrasound fish finders on boats, or ultrasound examination of the foetus during pregnancy. Ultra-high frequency sound is released inside the tested material, and if the beam strikes a material with a different acoustic impedance (density and acoustic velocity), part of the beam returns back to the probe and can be shown on the display of a UT machine. Material with a different acoustic impedance is usually some flaw in the part which is being inspected (gas particle, cavity, porosion, etc.). the position and size of the defect can be determined by knowing the speed of sound in the part and amplitude of the sound source. An ultrasonic transducer (probe) is used to introduce the sound into the part. It converts electrical impulses from the UT machine into sound waves. When these waves reflect back, it converts them back so they can be presented as sf visual signals on the display. If the machine is tuned and balanced (a special process called calibration), a qualified Inspector can calculate the distance from the probe to the indication. If the Inspector is experienced, he should also be able to define the type of defect (inclusion, cavities, slag, porosity or cracks in a material) that caused the indication. Ultrasound cannot travel through air, and use of a couplant is necessary. The couplant could be some liquid (water, oil) or a gel. It is used to transmit ultrasound from the probe to the material, and it is put on the surface of the tested part. The most common sound frequencies used in UT are between 1 and 10 MHz, which are too high for human ears to hear. The lower frequencies have greater penetrating power, and can detect the flaws at greater depths, but their sensitivity (the ability to detect small indications) is lesser, while the higher frequencies do not reach greater depths, but can detect smaller indications. The two types of sound waves which are used mostly in common inspections are the compression (longitudinal) wave and the shear (transverse) wave. Longitudinal waves are used in straight-beam probes, and shear waves are used in angle-beam probes.

The basic principle of UT can be seen in Fig 6, where an initial pulse (sound introduced to a part) and back surface echo (sound reflected from the back wall of the part) can be seen. They are always seen on the screen of the UT device. Everything else that appears between these two signals is some indication. Of course, it is not so easy to carry out these inspections, and that is why UT requires a well-trained and skilful operator, who can distinguish false signals from real flaws in the material.

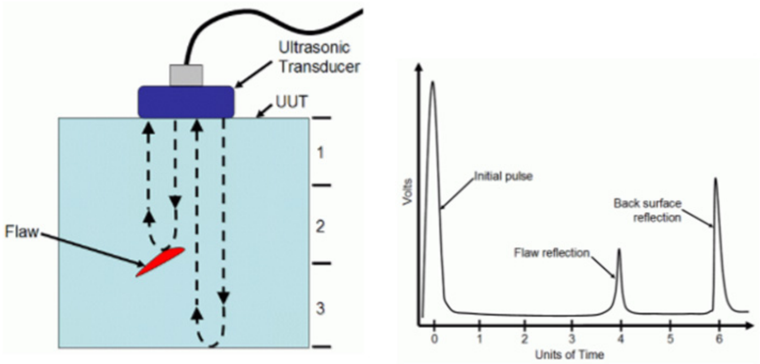

Fig. 6 Ultrasonic testing principle [26]

An important part of UT is preparation for inspection, which includes calibration of the equipment. A UT system is very sensitive, and calibration has to be carried out before each inspection. Sound speeds are different in different materials, and those speeds affect the accuracy and precision of the obtained results. Probes have to be calibrated on the same material as that which will be inspected. Etalons used for calibration are standardised, their composition and dimensions are known, and so probes can be adjusted correctly. Some of the advantages are: Depth of penetration and reach for defect detection or measurement easily surpasses possibilities of other methods; it is usually enough for an operator to test only one side of the product; it can characterise defects in detail, giving information about size and distance from the probe; etc. Main disadvantages are: Surface must be accessible to the probe and couplant, as clean and flat as is possible; operators have to be very skilful and well-trained (more effort is necessary than for other NDT methods); thin parts may be difficult to inspect; etc. [27].

The question is how UT can be combined with WAAM technology, and what benefits can it bring? First of all, it is important to mention that, to the authors' best knowledge, no one has ever tried to integrate UT directly in the WAAM process. Some authors, like [5], just mentioned the idea of it like a suggestion for future researches. So far, the only contribution to UT application in WAAM is reported in [28], where the authors tried to evaluate the results of three different NDT methods used to inspect WAAM products. The biggest difference between their approach compared to our idea is the place of UT in the whole process – they tested WAAM parts once after they had been made. It is almost like ordinary ultrasonic testing, because when a part is finished, it can be treated just like any other part made using any conventional method. There are also numerous papers regarding NDT of AM parts, but with regards to online process monitoring, all of those papers are irrelevant, because they did not make any contribution to the theory that UT can be included directly in the process. However, on the other hand, paper [28] confirmed the fact about the biggest problem for application of UT in WAAM technology – an irregular surface. UT probes are very sensitive and they require as flat a surface as possible. It could be hard to achieve implementation of UT during the deposition process, but some ideas, which include machining during the process (Fig. 7), are introduced in [22], and they can make further innovations possible.

In [22], the researchers introduced a new idea for WAAM technology, adding a new tool for the CNC machine which moves the welding torch, and they managed to achieve in-process milling, which makes the surface finer and more appropriate for UT. That would fulfil the first requirement for inspection. In addition, another "tool" designed just to hold the probe, which will go after the surface milling tool and look for flaws in the produced layers (Fig. 8a), should be added to the same CNC machine. The probe does not have to follow the milling tool after every pass, but it can go after a particular number of deposition passes, for example. The simple straight-beam probe will be good enough to provide the necessary results. If the part is not thick or high enough (there was not a sufficient number of passes), then a double straight beam-probe can be used. Its principle is the same as of the ordinary straight-beam probe, but it can detect flaws which are closer to the surface. Some solutions could also include two probes (one would be a transmitter of the signal, and the other one would be a receiver). This solution has to be combined with side milling, and probes would not slide across the part's surface, but across two lateral sides (Fig. 8b). The tool holder should be designed differently than in the first two cases, but the results should be the same. Some manufacturers also produce special probes for a particular application, which may reduce the need for milling (special probes could overcome the problems regarding surface roughness), but they are much more expensive than ordinary probes, so they should be used only if machining is not possible for some reason.

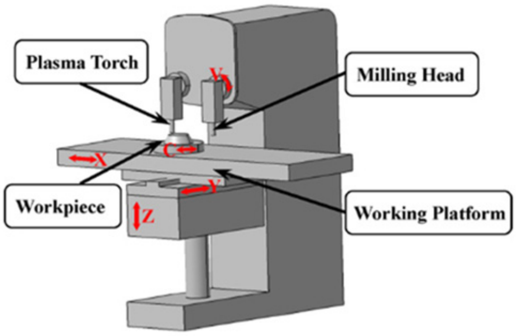

Fig. 7 CNC machine with welding torch and additional tool for milling [22]

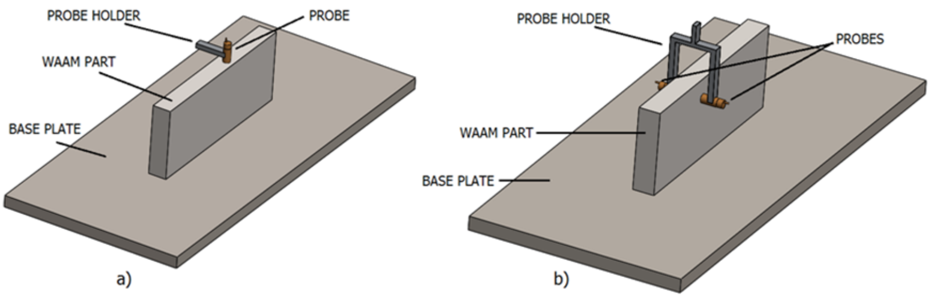

Fig. 8 Simplified preview of possible solutions for ultrasonic testing of WAAM parts

Another possible solution could be the idea proposed in [28], where the UT probe is applied from the bottom of the base plate, which is shown in Fig. 9. A problem that can occur with this method is when the materials of the base plate and wire are not the same, which is not rare in WAAM processes. In that case, signals appearing on the boundary of the two materials have to be taken into consideration.

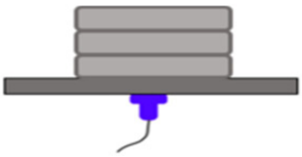

Fig. 9 Ultrasonic testing with probe on the bottom of the base plate

Regarding all of these ideas, what benefits for WAAM are possible by applying in-process UT?

- *Online monitoring*. By applying in-process UT there would be no more need to wait until the whole part is finished before inspection, as the proposed method provides the possibility to inspect the part while it is being produced, which means that most of the defects can be seen virtually at the moment when they appear.
- *Repairs in situ*. The proposed in-process testing application enables the operator to stop the process due to the appearance of defects, and resolve the problem immediately.
- *Detection of numerous flaws at a whole cross-section of a part* – UT enables detection of different kinds of defects (porosities, cavity, unwanted gas or solid particles) in the WAAM part. As UT is a Non-Destructive Testing method, the part remains undamaged, and can be used after inspection.
- *Detection of microstructural changes*. UT does not only find the flaws, but it can even indicate microstructural changes that can cause anisotropic mechanical properties. When the grains are bigger and coarser, there will be more attenuation (the ultrasound will lose more power going through the material). That will be seen on the screen as weaker signals, which is a sign for an operator to adjust some manufacturing parameters.

- *Money and material savings*. Probably the most important advantage of this approach. Using UT after the part is made usually means the whole part has to be thrown away if defects could not be repaired. However, if defects could be seen during the process, the process could be stopped at the moment the defects occurred, and that could save further material wasting. After detailed testing (if it is needed), additional work should be done to remove the defect if it is possible, and to ensure it does not occur anymore.

Of course, the idea proposed in this paper also has some constraints which need to be taken into account before real-life application.

- *Longer and slower process*. Probes should not be exposed to high temperature differences from the etalon to the material in order to work properly. The part temperature should not differ too much from the temperature of the etalon used for probe calibration. This means the part has to be allowed to cool for a while after deposition, which would make the entire process slower and longer.
- *Machining is necessary*. The only solution to avoid machining (at least some part) is to look for specially designed probes. They are more expensive, more difficult to be designed and produced, and cannot always guarantee correct results if they are not used on the part which they are intended for. Ordinary probes are a better solution, but, in this case, machining is inevitable.
- *A new tool path has to be generated*. A new tool path for the UT probe has to be generated just like for the additional machining.
- *Anew tool holder is necessary*. Another requirement is anew tool holder. Generally, it should not be a problem to make it, due to its simplicity. It would only require a modern CNC machine or robotic hand which is capable of holding and exchanging more tools.
- *More expensive process*. Ultrasonic testing is not cheap. Operators have to be well educated and trained, and modern equipment is expensive, which makes paying for the service or developing own human and equipment resources very demanding.

Despite all the constraints just mentioned, we believe the application of UT in the WAAM process has a great potential, and represents a challenge worth investigating in more detail in the future. All potential problems and constraints can be solved, while the benefits of the proposed in-process UT application are certainly interesting enough to put more effort into its realisation. This is one-step forward in entire WAAM process automation, despite the fact that it is still not totally possible. No matter how modern equipment is, human interaction in calibrating and monitoring the inspection process is still necessary.

6. Conclusion

WAAM technology is the future for researching and commercial use, regarding all of its advantages and disadvantages. Good process speed, wide choice of materials, the acceptable price of equipment and feedstock, along with good mechanical properties, are some of the reasons why some specialists predict that WAAM technology will be more and more present in some industries, especially in the Aerospace industry. Although it is not suitable for making parts with complex geometry, the possibility of making large metal parts is more important. Conventional AM technologies use mostly polymers, and even if there have been more polymer parts in recent years, which are fully functional products, for some industries metal parts are still required. In addition, there is no need for some special equipment, as only some knowledge about how to connect computer software to existing welding systems is necessary. Disadvantages like porosity, cavities, residual stresses and deformations have already been avoided with some methods, or at least there is a way to reduce their influence. Post-processing still remains a disadvantage, and for now it has to be accepted as a necessary setback, but other technologies have things like that as well. This technology is a combination of welding (which is one of the most popular and most widespread technologies) and additive manufacturing (which is already present, but it is also the future), and it is clear why it is so interesting in research and also from a commercial