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Design and integration of WAAM technology and in situ monitoring system in a gantry machine

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Abstract

Wire arc additive manufacturing, WAAM, is a popular wire-feed additive manufacturing technology that creates components through the deposition of material layer-by-layer. WAAM has become a promising alternative to conventional machining due to its high deposition rate, environmental friendliness and cost-competitiveness. In this research work, an adaptation of a gantry machine with in-situ monitoring and a control system has been carried out, in order to expose the ability of the WAAM technology to fabricate complex-shaped parts. The retrofitting of the machine has been done in several layers called respectively hardware, control and software layers. For the validation of the implemented system, a stainless steel 316L demonstrator has been manufactured, and the required stages have been employed, including part design (CAD), process parameters selection, tool-path definition (CAM) and part manufacturing. This study has shown the feasibility of the adapted machine for additive manufacturing as a controlled process.

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Keywords: WAAM; monitoring; control system; laser scanner

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1. Introduction

Wire Arc Additive Manufacturing (WAAM), is a very promising technology that enables complex shaped big part manufacturing of high added value materials. This technology is part of the additive layer manufacturing processes which uses metallic wires as raw material and a plasma arc as energy source. WAAM process has important advantages over other conventional machining processes, such as high resource efficiency, high productivity and low equipment cost. The recent focus is in fabricating complex-shaped metal components including titanium and nickel alloys [1].

Although the feasibility to manufacture titanium parts with WAAM has been demonstrated [2], this technology has not been totally industrialized yet due to the lack of machine manufacturers offering a holistic solution. In [2], the mechanical properties for Ti-6Al-4V were investigated and though the process produced acceptable parts, an improvement of the related mechanical properties was proposed by cold working processes. In [3], a review of mechanical properties of Ti-6Al-4V, when using different additive manufacturing technologies, such as, selective laser melting (SLS), selective laser sintering (SLS) and WAAM was carried out. The fatigue, porosity and surface roughness were studied and for WAAM fabricated titanium parts a large anisotropy was observed.

The essence of WAAM process was described in the 1920s; nonetheless, the use of an electric arc to generate 3D objects with titanium alloys was not examined until 2007 by the Cranfield University [4]. Thus, all developments related to this process are solutions for laboratory-scale, based both on robotic solutions and Gantry-type machine solutions. However, WAAM technology is considered a novel manufacturing process, which is expected to bring great changes in the aircraft industry. Nevertheless, more studies are needed regarding its commercialization in the aircraft industry [5].

The major progress in this aspect has come from the Norsk Titanium company (Norway), which reached TRL8 (Technology Readiness Level) maturity level for aerospace industry, which means that actual system is completed and flight qualified through test and demonstration (ground or flight) [6]. Recently, some other machine manufacturers launched commercially new solutions for WAAM manufacturing: Addilan (Spain); Mazak Corporation (Japan) launched the new machine model VARIAXIS j-600AM, consisting on a vertical machining center which features an innovative Wire Arc-type metal deposition system; and Mutoh Industries (Japan) has unveiled a new metal arc welding 3D printer, the Value Arc MA5000-S1.

One of the greatest challenges of WAAM systems is the control algorithms needed to assure that the deposited geometry fits the required geometry with the required structural integrity. Thus, specific monitoring systems are needed to control both process parameters and deposited geometry, in order to avoid defects during processing, e.g. due to the difference between programmed tool path using theoretical models and the real geometry [7]. In [8], a relationship was established between the welding process parameters and bead geometry for WAAM technology. Bead modeling enabled, to control the path planning, determining the optimum weld settings and subsequently defining the deposition path together with the selected process parameters.

On the other hand, one of the major constraints of additive manufacturing process is the significant amount of time to fabricate parts [9]. For further enhancement of the effectiveness and efficiency of the process, in-situ monitoring plays an important role.

Although monitoring systems have been studied for other additive manufacturing methods, such as powder bed [10] Laser metal deposition [11] or Electron Beam Melting [12], little literature have been found for WAAM process.

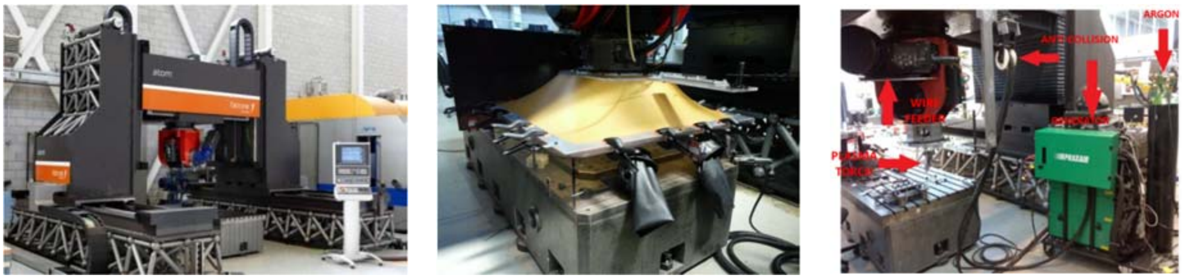
This work presents the integration of a plasma wire arc system in a gantry machine for additive manufacturing purpose, for which several components has been designed, specific protocols for communication have been developed and an in-situ monitoring and control system have been implemented. In addition, the manufacturing process of a stainless steel 316L part is described as a demonstration of the developed technology.

2. Retrofitting of a gantry machine for WAAM purpose

2.1. Hardware layer

The developed WAAM hardware is composed by the following parts:

- 5-axis machine: In the present work, an own designed and manufactured gantry machine, shown in Fig. 1. (a), have been employed.
- Plasma generator: A plasma generator is used to create reactive plasma in an argon chamber. The vacuum is placed inside of an aluminum box and radio frequency signal is applied to excite ions and create plasma. The employed plasma equipment has been a EWM Tetrix 400 device.
- Plasma torch: This device generates a direct flow of plasma. An Abiplas Weld 250 MT has been employed as can be seen in Fig. 1. (c).
- Protective chamber: A special closure (Fig. 1. (b)) has been used for manufacturing reactive parts such as Titanium.



a b c

Fig. 1. (a) General view of the machine; (b) Protective chamber; (c) Plasma equipment.

2.2. Control layer

The control layer has been broken out into two tranches: open- loop control for process monitoring, and closed-loop control for height adaptive control. The first step to a process control module for the prevention of different kind of errors that can occur (i.e. lack of fusion, pores, part deformation) is the development of a process monitoring system [13]. For the process monitoring, a pyrometer, welding camera, a laser scanner, a PC and an oxygen meter have been installed:

- Pyrometer: The pyrometer is a type of sensing thermometer used to measure the temperature of the surface. It is located in some distance from the plasma torch. The employed device has been OPTRIS CT Laser 1M.
- Welding camera: The welding camera is used to control the material deposition process by the operator. The employed camera has been Redman MC500 weld video camera.
- Laser scanner: This device continuously acquires 3-dimensional information of the bead. It can be used to create a point cloud of geometric samples on the surface of the piece. OPTRIS CT Laser XL 3MH3 has been used.
- PC application: This device is used for running the master application for monitoring the process. It processes the information in real time coordinating and synchronizing the rest of the devices.
- Oxygen meter: A Rapidox R2100 Oxygen Analyser has been used to measure the oxygen level. The oxygen level that specifies AMS 4999A, for additive manufacturing, is below to 1200 ppm for titanium alloys [14], although the maximum limit employed in the experiments has been 500 ppm.

A closed loop control system has been also developed for assuring constant distance between the plasma torch and the substrate, thus, the commanded z value is corrected every layer, according the height of the last measured layer. The monitoring of the process has been carried out with external mentioned sensors and internal signals (voltage, intensity, feed rate and machine positions in the axis (x, y, z, a, b, c)). Several communication protocols have been implemented between the devices of the system.

- PC application - machine: The communication between the PC application and machine serves to monitoring the process. Also, the application sends corrections to the machine in real time.

- PC application – laser scanner: The communication between the PC application and laser scanner is to control the laser (on/off). This connection also provides to the PC application the measurements of the laser scanner.
- Laser scanner – machine: This communication protocol guaranties the linking between the measurements of the laser scanner and machine positions.
- Machine – plasma: This communication serves to control the torch (on/off). Through the communication protocol, the machine reads the signals provided by the plasma machine to send to the PC application.

2.3. Software layer

Powermill® CAD/CAM software is employed for designing parts and programming the tool-paths. A number of CAD packages provide automatic torch path sequencing, but there are a lot of constraints that are complicated and not feasible to be linked in WAAM technology. For that reason, a fully automated CAD has still not been developed. The missing connection is to generate robotic welding paths directly from CAD models based on various process models [15].

In our case, in order to create adequate tool paths, firstly, a single layer has been programmed. The consecutive layers are programmed using 1.5 mm theoretical height, whilst the control system is employed to correct the theoretical programmed distance in real time. This is carried out with the implemented communication protocol of the system, as the PC application, with the data obtained from the laser scanner, sends corrections to the machine in real time.

3. Validation of the system through part manufacturing

3.1. Part design

The first step in fabricating an over-dimensioned solid block is to design the piece using CAD software. Additive manufacturing opens the opportunity of producing parts with complex geometry that are difficult to obtain using material removal processes [16]. Therefore, when fabricating parts using additive manufacturing, it is an advantage to make complex parts to enhance performance or create visual appeal [17].

For that reason, the geometry of the piece, shown in Fig. 5. (a), has been specially designed for these experiments due to its high quantity of beads. Hence, the feasibility to fabricate a high complexity demonstrator can be exposed. The geometry consists of a vertical wall with unions in T.

3.2. Experimental tests for process parameter definition

After the part's design and its adaptation to the WAAM process, several decisions are taken into account. As such, suitable process parameters selection (intensity, feed rate and wire feed rate) and fabrication strategy (material adding order) need to be detailed. Weld parameter selection is an important step in process planning for WAAM technology [8]. There are different studies that investigate both, experimentally and based on statistical approaches the adequate process parameter selection. In order to find suitable process parameters that best fit to our experimental framework, a total of 83 single beads were deposited in a plate of 10 mm using different combination of levels of process parameters stated in Table 1.

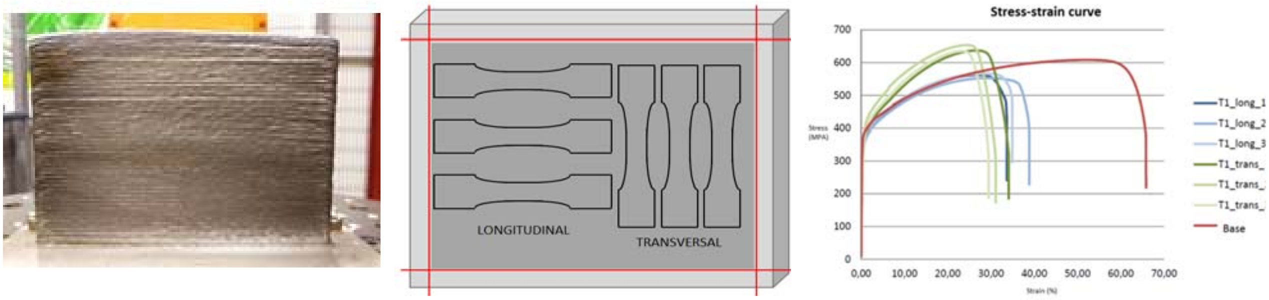
Table 1. Process parameters used in the experiments.

Feed Rate [mm/min]	Intensity [A]	Wire Feed Rate [m/min]
From 120 to 360	From 100 to 250	From 1 to 6

Some of the parts presented defects, such as holes, lack of fusion and unmelted wire (Fig. 2.). Based on these criteria, the parts were classified into two groups: acceptable part quality and unacceptable part quality. This study revealed that suitable values for process parameters to assure part quality were: $150 \leq Intensity \leq 250$; $200 \leq Feed\ Rate \leq 350$ and $1 \leq Wire\ Feed\ Rate \leq 4.5$

Fig. 2. Effects of the process parameters on the material.

To select specific process parameters that are within the stated ranges, tensile tests of a vertical wall of stainless steel 316L have been done. Some horizontal and transversal test-pieces were taken to compute the stress-strain curve (Fig. 3. (a), (b)). As can be seen, similar acceptable results are obtained for all the performed tests, although there are significant differences in the substrate as might be expected. In the base material, a tensile strength of 608 MPa and a strain of 67% have been obtained, while in the added material an average tensile strength of 642 MPa and 561 MPa for longitudinal and transversal directions respectively, and an average strain of 43.2% and 38%, for longitudinal and transversal directions respectively. The differences obtained between these two directions are related to grain size difference in these two directions: the grains are larger in transversal direction than in longitudinal direction. Taking into account the mentioned criteria, the selected process parameters for part manufacturing has been: 180 A, 224 mm/min and 3m/min.



a b c

Fig. 3. (a) Manufactured vertical wall; (b) Test-pieces extracted from the wall; (c) Performed stress-strain curve.

3.3. CAM programming for tool-path definition

A tool-path planning is important to improve surface integrity of the WAAM process [18] and to enhance the efficiency of the process [19].

The manufactured part's tool-path definition has been carried out using the Powermill® CAD/CAM software. Fig. 4 shows, the programmed piece design and tool-path definition for a single layer. Some extra beads have been manufactured in the joints of the beads in order to ensure higher thickness when machining.

The fabricated demonstrator part is composed by 21 beads and 200 layers and the employed material has been stainless steel 316 L. The part is fabricated above the same material plate called substrate.

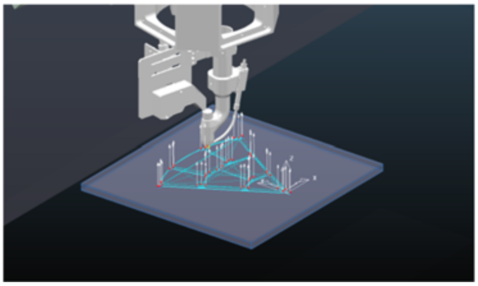


Fig. 4. Tool-path planning definition using Powermill® CAD/CAM software.

3.4. Part manufacturing

A stainless steel 316 L part, the dimensions of the piece were shown in section 3.3, has been manufactured using the previously introduced WAAM machine. The process parameters have been selected based on the criteria of section 3.2. As can be seen in Fig. 5. (a), the geometry of the piece consisted on vertical walls with unions in T.

The final part obtained from the WAAM technology, is shown in Fig. 5. (b). The monitoring of the process has allowed plotting the manufactured part's 3-dimensional geometry using the machine positions *(x,y,z)* when the machine was adding.

In Fig. 5. (c), the machine positions during the material deposition process are shown. In the axis z, there are some visible deviations caused by the corrections sent to the machine.

a **b** **c**

Fig. 5. (a) Part design using CAD software; (b) Final manufactured piece; (c) Manufactured 3-dimensional geometry, where the machine corrections in axis Z are visible.

3.5. Results of the monitoring process

The signals acquired by both, external and internal devices, have enabled us to be aware of the process characteristics. As can be seen in Fig. 6. (a), some higher voltage values were found in the analyzed signals. Those values correspond to some of the starting and final points of the beads, precisely where the joints of the beads are given. The location of the high values of voltage is shown with red dots in Fig. 6. (b).

The mentioned phenomenon occurs owing to the fact that the material is accumulated in the extreme of the piece. That is why the voltage takes higher values in the mentioned location as the distance between the torch and the part is different from the rest of the bead.

In Fig. 7., the temperature measured by the pyrometer and its location in the piece are shown. As can be seen, in the large beads the achieved temperature is higher than in the shorter beads. This information can allow relating the parameters involved in the adding process to some parameters related to mechanical properties of the piece. As the location of the signals in the piece is known, due to the machine positions are saved, specific test-pieces can be selected for future tensile tests. The analysis of these figures has served to demonstrate the utility of monitoring the process and the achieved good performance of the control system.

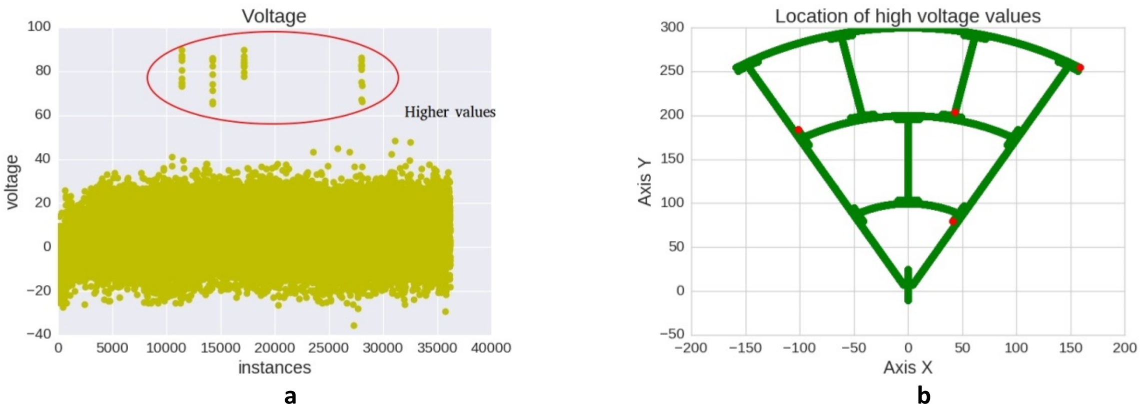


Fig. 6. (a) Voltage during the adding process of the manufactured part, where the achieved higher values are circled in red; (b) The location of higher values of voltage in the manufactured part.

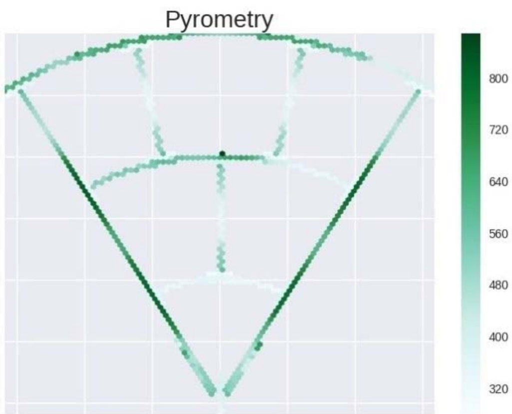


Fig. 7. The reached temperature and its location in the piece during the adding process, measured by the pyrometer.

4. Conclusions and future work

All this work done in adapting such a machine, for an additive manufacturing process would allow manufacturing series of parts in a controlled environment assuring identical properties.

Data obtained from the plasma machine itself and from the external devices installed is stored and available for its analysis so that any deviation can be detected to determine whether the manufactured part is correct or not.

The contributions presented in this work have led to some new research directions. For example, an analysis of the acquired signals will serve to relate the bead geometry with the process parameters to guarantee part accuracy. That also will serve to select optimum process parameters to achieve specific bead geometry.

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