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Procedia CIRP 37 (2015) 48 – 53

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CIRPe 2015 - Understanding the life cycle implications of manufacturing

"Designing a WAAM Based Manufacturing System for Defence Applications"

Alessandro Busachi[a]*, John Erkoyuncu[a], Paul Colegrove[b], Filomeno Martina[b], Jialuo Ding[b]

[a]*Through Life Engineering Services Centre, Cranfield University, Cranfield, United Kingdom*
[b]*Operations Excellence Institute, Cranfield University, Cranfield, United Kingdom*
[c]*Welding Engineering and Laser Processing Centre, Cranfield University, Cranfield, United Kingdom*

* Corresponding author. Tel.:+447790779432; *E-mail address:* a.busachi@cranfield.ac.uk

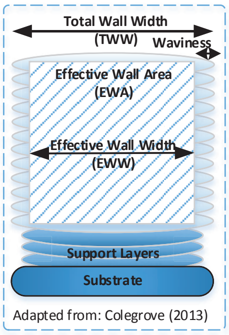
Abstract

Current developments in "Wire+Arc Additive Manufacturing" (WAAM) have demonstrated the suitability of the technology for rapid, delocalized and flexible manufacturing. Providing a defence platform with the ability of on-board WAAM capability, would give the platform unique advantages such as improved availability of its systems and ability to recover its capability after being subject to shock. This paper aims to investigate WAAM technology and define a WAAM based manufacturing system for In-platform applications.

Keywords: Wire +Arc Additive Manufacturing, Manufacturing Systems, Defence Platforms

1. Introduction

According to Martina et al. [4] "Wire+Arc Additive Manufacturing" (WAAM) is a novel "Additive Manufacturing" (AM) technology which provides significant strategic advantages. The technology combines arc welding with wire feeding and is able to benefit from design freedom, buy-to-fly ratios as low as 1.2, potentially no constraints in size, and low cycle times. These aspects make WAAM particularly suitable for custom made, large functional components made of high value materials [1]. As described by Ding et al.[2] WAAM consists in building 3D metallic components, by depositing weld beads one above the other in a layer by layer fashion. The result is a straight metallic wall with a minimum width of 1-2 mm, including the "waviness". This is the material which must be removed in post-processing to eliminate surface irregularities, defined as the difference between the Total wall width and the Effective wall width (Figure 1) [3]. As outlined by Martina et al. [4] when WAAM is compared with traditional subtractive manufacturing the reduction of waste decreases dramatically from a typical 90% to 10%. WAAM technology has various benefits over other AM technologies and traditional manufacturing. It allows near net shape or net shape manufacturing enabling strong savings in high value materials such as titanium. The deposition rates of titanium reaches up to 1 kg/h, which is considerably higher than the 0.2 kg/h achieved with powder bed technologies.



Adapted from: Colegrove (2013)

Fig. 1. - WAAM Wall

The manufacturing system is fairly simple and compact,

doi:10.1016/j.procir.2015.08.085

therefore suitable for applications where space is limited such as ships. The equipment required is readily available on the market and requires a low investment (circa £200k) [5] .

WAAM Systems can be configured in different ways; different heat sources such as “Tungsten Inert Gas” (TIG), “Metal Inert Gas” (MIG) and Plasma torches are employed for different materials. WAAM configuration for Ti-6Al-4V depositions is based on plasma and requires a tent for shielding the deposition. Configuration for Stainless Steel and Aluminum do not require a tent providing the benefit of unlimited build volume, and the elimination of the set-up activities for the tent and the waiting time for purging it.

WAAM systems are made of a torch to deliver the heat input and deposit the wire, a robot or CNC to follow the paths of the geometry, a control board to control the robot, a wire feeder to control the deposition of the material and a roller which is applied between layers to improve the microstructural properties.

The purpose of this paper is to investigate and define exhaustively a WAAM based manufacturing system. The paper starts by investigating WAAM process and system aspects, outlining key information on the technology and defining all the necessary elements of the system which are necessary to accomplish its aim. Then, the operating environment within a platform is investigated. This will be used to define which key requirements need to be considered when designing the system for In-Platform applications.

2. WAAM Process Aspects

Due to high heat input, components deposited through WAAM are affected by:

- Residual stress: which reduces mechanical performance of the component
- Distortion: which leads to difficulties in achieving the required tolerances

To improve these aspects, extensive experimental research has been carried out by Colegrove et al. [6], Ding [1] and Qiu [7]. The result is a set of mitigation strategies which can be categorised as pre-process, online process and post-process strategies. According to Ding et al. [2] pre-process strategies are optimisation of the parameters, clamping and optimisation of building strategy. While clamping and building strategies have a strong impact on the reduction of distortion, the optimisation of parameters affects it only slightly. Online strategies refer to the ones that occur during the deposition process and are the most effective. Balanced building refers to depositing same geometry on one side of the substrate and the opposite side. Balanced building has a strong impact on the reduction of distortion but has no effect on residual stress. Optimisation of cooling time refers to the limitation of time in order to use the existing heat to pre-heat the following layer achieving a reduction of residual stress [1]. Drawback is excessive heating of the piece; therefore optimisation of cooling time has to be carried out. Moreover, to improve the cycle time of the deposition, parallel deposition may be carried out with a reduction of waiting time [3].

The most promising process with strong impact on residual stress is online rolling.

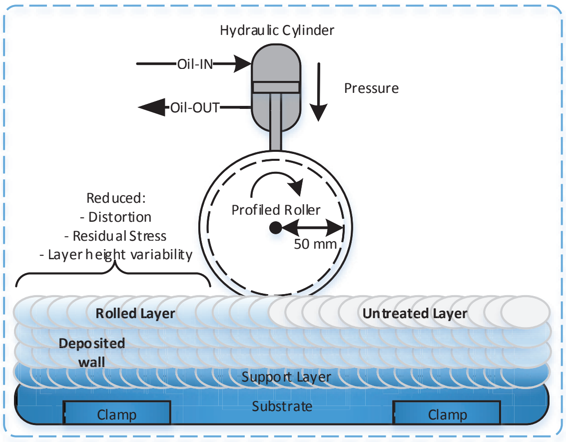


Fig. 2. - WAAM Online Rolling

As it is outlined in Fig. 2. - WAAM Online Rolling, online rolling occurs after the deposition of a layer and consists in applying pressure to the wall through a hydraulic cylinder which pushes a roller. Colegrove et al. [6], Qiu [7] and Martina [8] outlined various benefits such as strong impact on microstructural refinement and improvements on residual stress.

- Reduction from 600 MPa to 250 MPa of residual stress
- Reduced layer height variability and lateral deformation (waviness)
- Improved microstructure properties, through refinement of grain size.

Conclusions of their studies indicate that rolling has impact on residual stress reduction, improved fatigue crack growth rate, improved mechanical properties such as tensile strength by 19% and yield strength by 26% [7] [8]. Post processing strategies refer to traditional heat treatments and post-deposition rolling which has the major disadvantage of allowing only rolling on the last layer.

A detailed Quality Assurance (QA) procedure is missing in international standards such as “American Society of Mechanical Engineers” (ASME). According to Martina [8] current “Quality Assurance” (QA) tests on WAAM are neutron diffraction and contour method to measure residual stress and X-ray and ultrasound for defects.

Differently from powder based processes, in WAAM the wire is entirely molten at the point of deposition and the occurrence of defects is unlikely. Appropriate selection of process parameters is not done based upon modelling results, rather by relying on experimentally gathered knowledge through build and characterisation of WAAM samples.

3. WAAM System Aspects

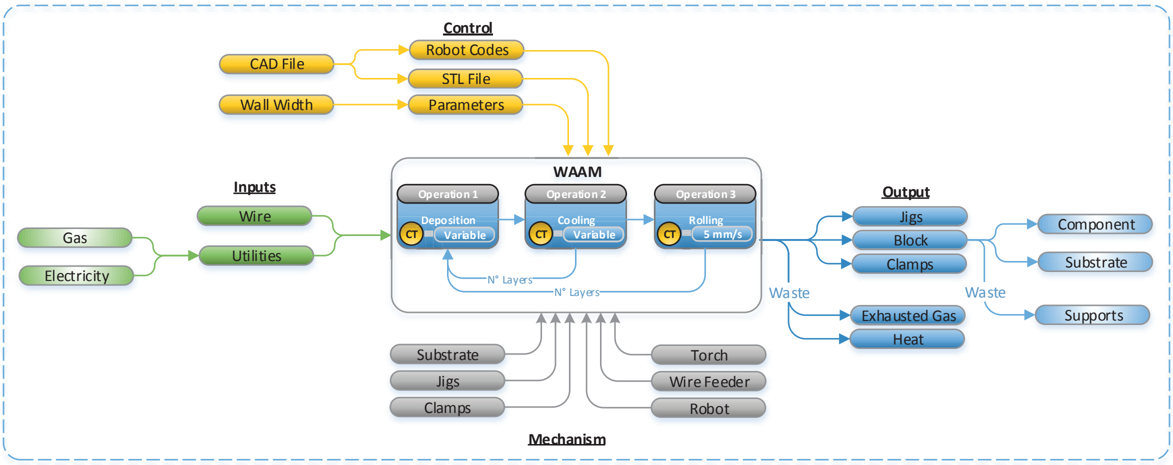


Fig. 3. - WAAM IDEF0

Fig. 3. - WAAM IDEF0 outlines an "Integration Definition of Function Modelling" (IDEF0) of WAAM which has been developed to gather a deeper understanding on what are the operations, inputs, outputs, controls and mechanism of the system. In order to develop the IDEF0, an interview has been carried out with a researcher of the "Welding Engineering and Laser Processing Centre" of Cranfield University. The aim of the IDEF0 is firstly to provide a basic understanding on WAAM and secondly to provide the reader the logic to investigate further the deposition process, what it involves and which resources are consumed.

The inputs of WAAM are mainly: standard wire which ranges from 0.8 mm to 1.2 mm; and utilities such as gas to shield the deposition and ensure an oxygen free environment, and electricity to power all the elements of the system and to provide heat input for melting the wire. In some configurations there might be also cooling water which flows within the substrate to extract the excess heat from the component.

On the operations side it is outlined that WAAM is broken down into three main phases: the deposition where the wire is melted to the desired shape, the cooling stage to reach optimal temperature and the rolling phase to ensure microstructural refinement. In order to calculate duration of WAAM's cycle time, Zhai [9] and Guo et al. [8] developed equations to perform estimations.

The following equation is employed to outline the time of the deposition phase:

$$t_w = \frac{V_{dm}}{\frac{(\pi * D^2 * WFS)}{4} * E_p} \qquad (1)$$

Table 1- List of Variables

t_w	Time of welding
V_{dm}	Volume of deposition
D^2	Diameter of wire
WFS	Wire Feed Speed
ρ_m	Density of material
E_p	Part built efficiency

The following equation is employed to outline the time of the cooling phase[11]:

$$t_c = \frac{\left(\frac{Q}{(Hm - H_{O}) * v * b}\right)^{*2}}{4 * a * \left(erf^{-1} * \left(\frac{T - T_0}{T_m - T_o}\right)\right)^{*2}} \qquad (2)$$

Table 2- List of Variables

t_c	Time of cooling
Q	Power input to weld
$H_m - H_o$	Enthalpy to heat
T_m	Melting temperature
a	Thermal diffusity
v	Travel speed
erf^{-1}	Error Function
T_m	Melting temperature

The mechanism of WAAM are the previously described torch, wire feeder and robot and the substrate which is the main building platform on which the deposition occurs, the jigs which are used to fix the substrate to the WAAM system and the clamps which are used to limit the distortion of the deposited material. The substrate, jigs and clamps need to be designed and customized based on the geometry of the deposition and they are utilizable for more depositions therefore they are represented also as outputs. Moreover, jigs and substrate are in a trade-off situation and they are part of the building strategy phase. Their design is a critical decision and some rules need to be established to engineer these mechanism.

Outputs of WAAM are represented by a block made of the deposited component, the supports which are deposited on the substrate and finally the substrate itself. This aspect outlines that a subsequent manufacturing process is essential in order to divide component from substrate. Finally the waste of the WAAM system is the support which can be recyclable, exhausted gas which is recyclable and heat. As depositions may last for long hours, gas consumption may become high, therefore it is recommended to consider ways to collect and recycle argon in order to improve the autonomy of the system.

The control side is featured by the CAD file which contains the geometry and the process parameters file which controls some aspects of the generator, the robot and the wire feeder. Process parameters are extensive and are strongly linked with the quality of the material deposited. Main parameters are wire feed speed, travel speed, wall width, current, torch angle and trim. Controls are the most important and complex part of the WAAM system. To support the decision making on controls, various models, optimization studies, algorithm and support software have been developed in the “Welding Engineering and Laser Processing Centre” of Cranfield. Moreover Ding, [1] automated the file processing activities through the development of “RUAMROB” a software with a GUI that performs automatically most of the files conversions.

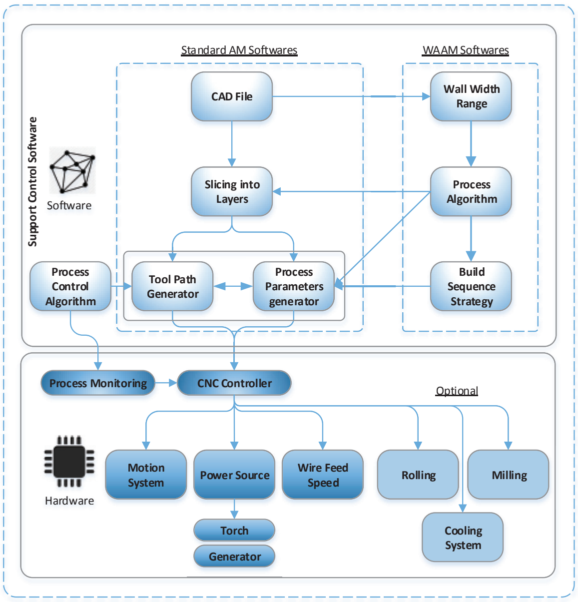


Fig. 4. - WAAM System Architecture

Fig. 4. - WAAM System Architecture outlines the System Architecture of WAAM which is made by a software module and a hardware module [1]. The software module is divided in standard software commercially available and custom made software to support the WAAM process. As indicated in Fig. 4. - WAAM System Architecture these software are numerous and need to interact with each other in order to deliver the files to control the CNC controller which guides the WAAM process: wire feed, torch and robot. The combination of these modules interacting between each other allows the WAAM system to be fully automated and autonomous without the need of supervision and may continuously deposit without interruption.

Currently research focus is on process control algorithm and online monitoring processes to govern the deposition and improve WAAM robustness and repeatability. Process monitoring may lead the WAAM system to higher reliability and ability to reproduce constantly high quality products. This is supported by [12] which outlines that *“the development of accurate process control models capable of determining the weld bead geometry and plate fusion characteristics from the welding process parameters is one of the crucial software components for WAAM technological and commercial development”*

3.1 Data Processing Activities

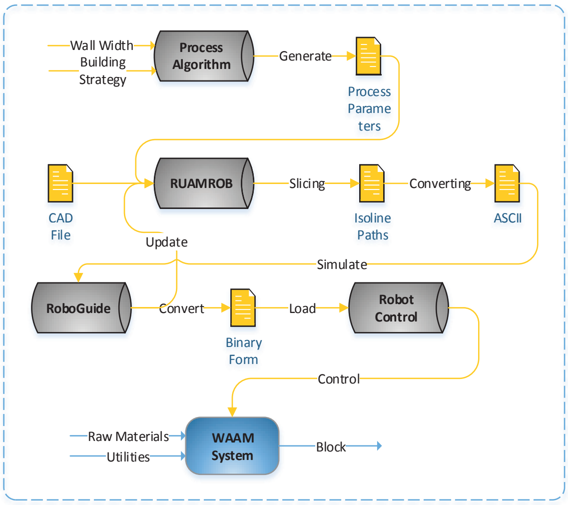


Fig. 5. – Data Processing Activities

Data processing activities allows converting CAD file containing the geometry, process parameters and building strategy into a readable robot program which controls the WAAM system. Fig. 5. outlines the process map of a complete data processing activity for WAAM.

The first phase of the software is slicing the CAD file into Isoline paths which needs to be converted into ASCII format in order to be processed by the Robot Control. Concurrently a Process Algorithm generates a process parameters file which is developed based on wall width and building strategy information. This algorithm has been optimized to identify correct process parameters to avoid three main defects shown in Fig. 6.

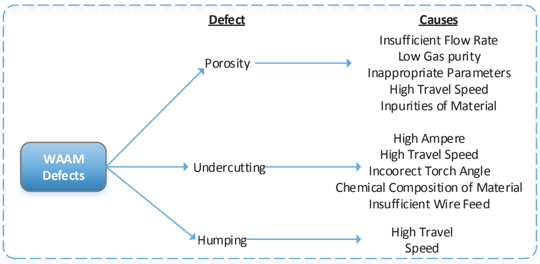


Fig. 6. - WAAM Defects

Porosity refers to cavities within the weld bead and is considered a defect as it affects the performance of the weld. Undercutting refers to concavity of the weld bead which compromises the tolerances requirements. Humping refers to an uneven material deposition.

The aim of the Process Algorithm is to maximize the deposition rate in order to reduce as possible the building time. As explained by Martina et al. [4] “wire feed speed, to which the deposition rate depends on, should be maximised to build the walls as fast as possible, whenever productivity is a key factor”. Therefore the rules of the algorithm are to maximize travel speed, wire feed speed. Process model optimization charts have been developed by Adebayo [13] to outline and examine the interactions of wall width, wire feed speed/travel speed ratio and wire feed speed and set rules for process parameters to respect quality aspects. In the following phase the ASCII file will be tested within RoboGuide, a robot simulation software. This allows testing the robot path, updating it to avoid collisions and correct errors. As the robot program is tested in early phase it allows the elimination of waste during the actual deposition.

3.2 Deposition Process

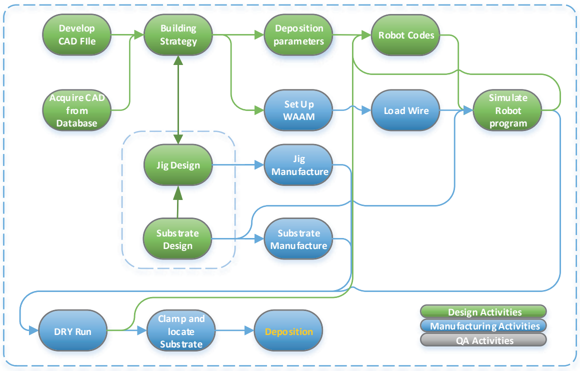


Fig. 7. - WAAM Defects

In order to outline all the necessary activities required to perform a deposition, a process map outlined in Fig. 7. has been developed with the experts of the “Laser Engineering and Welding Processing Centre” of Cranfield University. The process map outlines the sequence and concurrency of activities. These have been divided into design activities performed by design engineers, manufacturing activities performed by technician and finally quality assurance activity performed by a quality inspector.

The process starts with the development of the geometry of the component to be printed. This might be already available and stored in a database. Afterwards the geometry is analyzed and the building strategy is developed. Concurrently the jigs and substrate design is performed. These are part of the building strategy and in trade-off, therefore increasing substrate size result in a reduction in jigs size.

The following phase consists in developing the deposition parameters perform setup activities, which generally takes up to 1.5 hour and manufacture jigs and substrate. Substrate manufacturing is a standardized process as is based on cutting and de-burring standard metal sheets with different thickness. Jigs manufactures require a high level of customization and therefore needs to be manufactured tailor made. Lead times of both activities are difficult to estimate as they are not standard. In order to guide the robot to perform the designed path, a robot code needs to be generated and in parallel the wire needs to be loaded on the machine. Afterwards the robot code has to be simulated with the design of the substrate to check if conflicts occur. Moreover a dry run with actual substrate and jigs is considered necessary to perform a second check for conflicts. During the deposition, conflicts might compromise the entire build, the substrate and damages to the torch may occur.

Once the dry run has been performed and the process has been cleared the deposition can start. The deposition process is featured by various operations. This depends on the WAAM System configurations. As reported in Figure 6 the classic configuration is made by three operations: deposition, cooling through waiting and rolling. Integrated WAAM allows a strong reduction in setup time as this occurs just once and milling after deposition allows improving dramatically the accuracy of the wall and reducing also the waviness. After the deposition a cooling phase is required in order to cool down the component to avoid damages to instruments for measurement. This phase may take some minutes depending on the volume of the part and the cooling times adopted during the deposition process.

3.3 Defining the Operating Environment

Defence Platforms operate in safety, mission critical and potentially hostile environments. As follow a list of aspects which needs to be considered when designing the WAAM manufacturing system outlined in Table 3. Appropriate mitigation strategies needs to be developed in order to meet the strict requirements of the platforms.

Table 3- List of Aspects

Aspect	Description
Vibration (Input)	The Platform may be subject to strong vibrations
Vibration and Noise (Output)	The installed equipment may deliver vibrations or noise which can increase the likelihood of detection of the platform
Shock	The Platform might be subject to explosive-based shock events
Controlled Atmosphere	In some Platforms atmosphere is controlled therefore aspects such as oxygen consumption, heat, humidity, exhaust gas outputs needs to be controlled
Oscillations	Some Platforms may be subject to oscillations and unstable situations
Autonomy	Some Platforms can require operation for up to 3 months without external replenishment of consumables
Utilities	Utilities in Platforms are limited
Volume and Weight	Platforms have limited tolerance for any additional changes in volume and weight from the design baseline
Corrosion	Equipment might be subject to corrosive agents such as water and salt
Safety	Equipment’s materials need to satisfy the regulations
Mission Critical Environment	Equipment needs to be highly reliable and robust in order to perform when required to do so
Waste Management	Waste has to be minimized and recycling aspects needs to be investigated

4. Discussion

Fig. 8. outlines a process map of a complete WAAM System; it outlines the sequence of processes and the minimum number of equipment in order to convert geometry into a functional component. Moreover, the process map outlines the flow of the product and the inputs of equipment such as electricity, gas, compressed air and cooling solutions. The outputs have been divided in critical and non-critical. Critical outputs might be noises and vibrations while non-critical are waste such as the waviness which is removed from the component and the heat which occurs during each process. Another important aspect is the revitalization loop for the substrate, which consists in removing the supports.

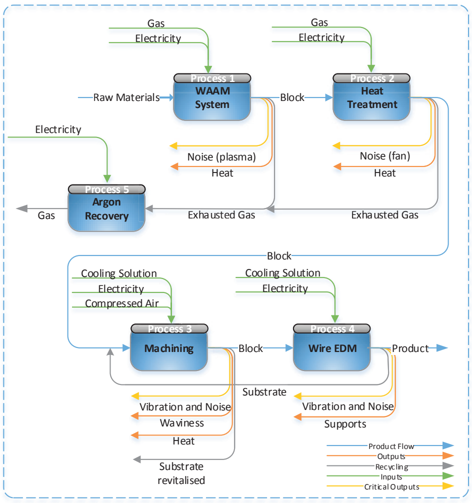


Fig. 8. - WAAM Manufacturing System

In order to reduce the stocks of gas and prolong the autonomy of the system, plasma torch with localized shielding should be employed to eliminate the need for tent purging. Moreover argon recovery equipment has been included. This is due to high consumption of argon during the whole deposition process which may take more days and the heat treatment which needs to be performed in inert atmosphere in order to avoid oxidation of the material. Moreover a fixed gas distribution system should be included in order to minimize gas cylinder handling which is time consuming and requires lifting equipment. In order to reduce vibration in input and output and to compensate potential blasts and reduce noise levels on the WAAM System, equipment needs to be installed on anti-vibrating bushings. Aspects such as potential load, stiffness of structures, working life, operating temperature and weight need to be considered to perform the design of the bushings which consists in an elastomer study, selection of materials and technology. Aspects such as potential load, stiffness of structures, working life, operating temperature and weight need to be considered to perform the design of the bushings. Platforms which operate in sea may be subject to oscillation due to waves. This aspect may influence negatively the WAAM deposition as the weld bead core is partially in a liquid state which may lead to increased waviness. Nevertheless this aspect is limited in WAAM as it is a wire fed process. Technologies based on powder beds require a high accuracy in powder spreading over the substrate.

5. Conclusions

This research aimed to investigate WAAM technology in order to define an early design of a WAAM based Manufacturing System for In-Platform applications. The secondary research on WAAM allowed gathering data and information on the technology. This helped to outline a performance envelope, what are the defects, how to reduce them and outline some financial data. The System Aspect section outlined the actual IDEF0 of WAAM providing information on what are the inputs, outputs controls and mechanism. Moreover the Systems Architecture has been outlined to understand what are the software and hardware which are necessary for the technology to operate. Aspects of data processing activities have been investigated providing a realistic representation of the complexity of the process. Deposition process outlined what are all the key activities necessary in order to produce and actual build. The Operating Environment definition allowed defining the critical factors that need to be considered when implementing a system within a Platform. This section puts in context WAAM technology. Finally the discussion allowed assessing the suitability of the technology providing some early mitigation strategies in order to reduce the negative factors of the system. Moreover a draft of a WAAM based Manufacturing System has been outlined providing knowledge on what are the Post-Processes necessary to produce a part which can be qualified.

6. Acknowledgement

The Authors thank Dr. Richard Drake and Dr. Peter Kay of Babcock International for their contribution. This research is performed within the EPSRC Centre for Innovative Manufacturing in Through-Life Engineering Services, grant number EP/1033246/1.

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2015-10-09

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Busachi, Alessandro

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Busachi A, Erkoyuncu J, Colegrove P, Martina F, Ding J. (2015) Designing a WAAM Based Manufacturing System for Defence Applications. Procedia CIRP, Volume 37, 2015, pp. 48-53

http://dx.doi.org/10.1016/j.procir.2015.08.085