ADDITIVE MANUFACTURE OF LARGE STRUCTURES: ROBOTIC OR CNC SYSTEMS?

Yashwanth K. Bandari*, Stewart W. Williams, Jialuo Ding, and Filomeno Martina

Welding Engineering and Laser Processing Centre (WELPC), Cranfield University, Cranfield
MK43 0AL, Bedford, United Kingdom
*y.k.bandari@cranfield.ac.uk

Abstract

Additive manufacture of metre scale parts requires direct feed processes such as blown powder or wire feed combined with lasers or arcs. The overall system can be configured using either a robotic or Computer Numerical Controlled (CNC) gantry system. There are many factors that determine which of these is best and this will be presented in this paper. Some factors are inherent to the specific process type such as accuracy/resolution and any requirement for reorientation of the feedstock and heat source. Other factors depend on the particular application including material type, shielding options, part size/complexity, required build strategies and management of distortion. Further considerations include the incorporation of ancillary processes such as cold work, machining or inspection. The relative influence of these factors will be discussed. Cost implications for the different approaches will be highlighted based upon the type of process being utilized. Examples are provided where both robotic and CNC options have been evaluated and the best solution found.

Keywords: *Additive Manufacture**,** Direct feed, Robotics, Cost*

1. Introduction

Additive Manufacturing (AM) has over 100 years of history - the first patent was filed in 1920 by Baker [1]. This technology is becoming an increasingly important in the manufacturing field for direct fabrication of structural components. The basic and common principle of these AM technologies involves the direct production of 3D objects from computer aided design (CAD) by adding materials in layers. Nowadays, modern manufacturing industries, such as automotive and aerospace, are continuously seeking applications and systems that enable direct production of large and relatively complex full density metal parts, with low production volumes, high structural integrity, accurate dimensions, and that can be directly used in operational systems.

AM is also known as rapid manufacturing [2] or rapid prototyping [3]. Unlike conventional manufacturing techniques such as machining and stamping that fabricate products by removing materials from a larger stock or sheet metal, AM creates the final shape by adding materials. It has the ability to make efficient use of raw materials and produce minimal waste while reaching satisfactory geometric accuracy. Using AM, a design in the form of a computerized 3D solid model can be directly transformed to a finished product without the use of additional fixtures and cutting tools. This opens up the possibility of producing parts with complex geometry that are difficult to obtain using material removal processes. Lastly, AM is a cost-competitive approach for fabricating components made of expensive materials such as titanium and nickel alloys in aerospace industries, where such components suffer an extremely low fly-to-buy ratio [4].

AM technologies are mainly classified into powder bead fusion, directed energy deposition, binder jetting and sheet lamination as provided in Table 1. Typical additive materials are metal powder and metal wire. With regard to how the additive material is supplied, currently popular AM technologies can be classified as either a powder-feed/-bed process or a wire-feed process The majorities of the research in AM have been focused on the powder-feed/-bed AM, where the laser or electron beam equipment is usually used as the power source. Powder-based AM technologies are mainly classified into powder bead fusion, directed energy deposition, binder jetting and sheet lamination as provided in Table 1. Typical additive materials are metal powder and metal wire. With regard to how the additive material is supplied, currently popular AM technologies can be classified as either a powder-feed/-bed process or a wire-feed process. The majorities of the research in AM have been focused on the powder-feed/-bed AM, where the laser or electron beam equipment is usually used as the power source. Powder-based AM techniques generally involve a complex non-equilibrium physical and chemical metallurgical process, which exhibits multiple modes of heat and mass transfer, and in some instances, chemical reactions. A comprehensive review on the materials design, process control, property characterisation and metallurgical theories for laser sintering, laser melting and laser metal deposition of a wide variety of metallic powders has been reported recently [4]. Table 2 provides a comparison of the basic features between powder-feed/-bed and wire-feed process.

Table 1 Classification of Additive Manufacturing [4]

Classification	**Terminologies**	**Ref. Material**
Powder bed fusion	Direct metal laser sintering (DMLS)	Metal powder
	Electron beam melting (EBM)	
	Selective laser sintering (SLS)	
	Selective laser melting (SLM)	
Directed energy deposition	Electron beam freeform fabrication (EBF3)	Metal powder,
	Laser engineered net shaping (LENS)	metal wire
	Laser consolidation (LC)	
	Directed light fabrication (DLF)	
	Wire and arc additive manufacturing (WAAM)	
Binder jetting	Powder bed and inkjet 3D printing (3DP)	Metal powder
Sheet lamination	Laminated object manufacturing (LOM)	Metal laminate
	Ultrasonic consolidation (UC)	metal foil

The powder-feed/-bed approach is better developed due to its capability of fabricating parts with high geometrical accuracy. The typical layer thickness in powder-feed/-bed technology is 20–100 µm, and the completed components can achieve a dimensional accuracy of ±0.05 mm and surface roughness of 9–16 µm. In addition, it is possible to produce parts with functionally graded materials (FGM). However, the deposition rate of the powder-feed/-bed technology is extremely low, typically around 10 g/min, which limits its application in fabricating median to large-sized components. In wire-feed AM, a metal wire is used as supply material instead of metal powder. Depending on the energy source used for metal deposition, wire-feed AM can be classified into three groups, namely: laser-based, arc welding-based and electron beam-based . Wire-feed AM has higher material usage efficiency with up to 100 % of the wire material deposited into the component. Therefore, it is a more environmental friendly process, which does not expose operators to the hazardous powder environment. Compared with the powder-feed process, it has a much higher deposition rate of up to 2500 cm^3/h (330 g/min for stainless steel)[4]. It reveals that there is a trade-off between high deposition rate and high resolution while selecting which type of AM process to use for a certain component.

Table 2 Comparisons of some AM processes [4]

Additive materials	Process	Layer thickness (µm)	Deposition rate (kg/hr)	Dimensional accuracy (mm)	Surface roughness (µm)
Powder	LC	N/A	0.06-18	±0.025–±0.069	1-2
	SLM	20-100	N/A	±0.04	9-10
	SLS	75	~0.006	±0.05	14-16
	DLF	200	0.06	±0.13	~20
Wire	WAAM	~1500	0.72- 4	±0.2	200
	EBF	N/A	Up to 19	Low	High

2. Means of fabricating AM parts

AM parts require direct feeding of blown powder or wire feeding combined with laser or arcs. They are generally manufactured using industrial robots or on Computer Numerical Control (CNC) gantry systems. Recent developments in AM reflect the requirements for flexibility to adapt to changes taking place in the market, in the society and in the global economic environment. Major objectives for producing AM parts today are evolving. Users' requirements indicate that emphasis should be given to low-volume and large variety, even in high volume production industry, to face global competition. Flexibility is also required to use the same facility for the minor or major model changes that come in effective life span of the equipment [5].

The synergic integration of deposition unit with the CNC machine is independent of its age and make. Generally, the integration is done in such a way that the deposition acts an additional feature without disturbing the other capabilities of CNC machine. The other issues which are generally sorted are mounting of the torch on the side of the spindle head so that weld deposition is controlled through the same CNC controller, ability to retract the torch during starting and end of the deposition, appropriate safeguards to protect the machine elements from occasional spatter. The retraction of the torch is demonstrated in the figure 1. The full set up of the CNC gantry system with the deposition unit is shown in the figure 2.

Figure 1: Retracting the torch between the limits

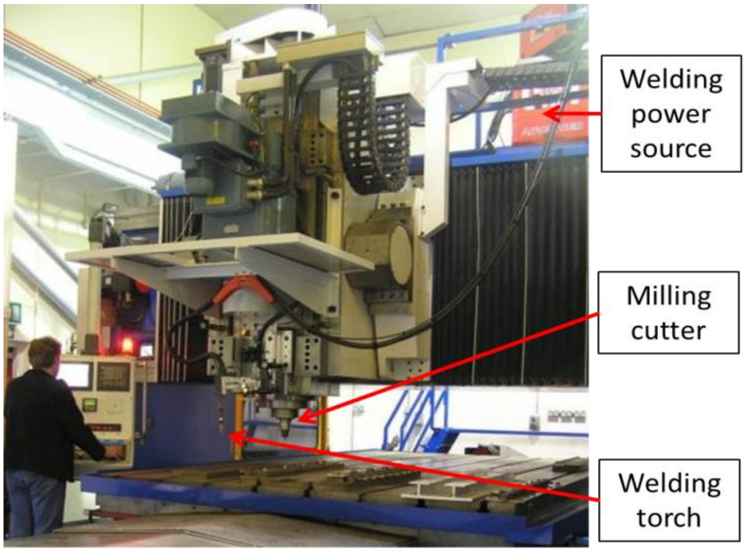


Figure 2: CNC gantry system with deposition power source

In case of robotic systems, the torch is attached to the wrist of the robot which has two or three axes of motion. The robot is programmed to move the torch along the path in a given orientation. The majority of the industrial robots are actuated by linear, pneumatic, or hydraulic actuators, and/or electric motors.

Table 3 shows the list of some universities/institutes where either of robotic system or CNC gantry system is used for deposition (not limited to), along with the deposition methodology.

Table 3 List of universities/institutes either robotic or CNC system is used

CNC gantry system	**Robotic system**
Los Alamos laboratory (DLF)	University of Nottingham (3D welding)
Southern Methodist University (DMD)	Cranfield University (WAAM)
Korean Institute of Science and Technology	TWI (DMD)
Indian Institute of Technology Bombay (WAAM)	Renishaw (DMLS)
Wuhan University (Hybrid Plasma Dep & milling)	Fronius, Lockheed Martin (WAAM)

There are many factors which determine which one is best and this will be presented in the paper. Some factors are inherent to the specific process type such as accuracy/resolution and any requirement for reorientation of the feedstock. Other factors depend on the particular application including material type, shielding options, part size, required build strategies and rotation of the part. Further considerations include the incorporation of ancillary processes such as cold work, machining or inspection. The relative influence of these factors will be discussed. Cost implications for the different approaches will be highlighted based upon the type of process being utilized. Examples are provided where both robotic and CNC options have been evaluated and the best solution found.

3. Factors influencing which is best

a) Accuracy: An industrial robot can fulfill the needs of todays and tomorrows industry for time and cost efficient, yet flexible mean of material processing. Most industrial robots are constructed as a cantilever, in which each of the arms is supported by motors, brakes and reduction gears, they struggle to achieve high positioning accuracy level, being limited to 0.5-2 mm [6] and at the same time are more prone to disturbances from the process forces. Thus, robot is not robust and accurate compared to the CNC system.

An investigation was done to measure the speed of the robot whilst moving along the sharp corners. The robotic movement was captured by a high speed camera with 100 frames per second. The video was analyzed by splitting into frames, and the robotic position in each frame was plotted on a graph sheet and the distance between successive positions was calculated. It was approximated to be a straight line between two successive positions because of large frame rate. If (x_1, y_1) and (x_2, y_2) represent 2 points in successive frames then the distance between them is given by the formula below:

$$\textbf{Distance}: \quad d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

From the distance calculated, it was seen that at the corners, the distance between points in successive frames decreased, when compared to the distance between points when the robot was moving in a straight line path, implying that the speed of the robot decreased. It was also dependent on the robotic speed set. It was seen that the change in speed increased with the increase in robotic speed. Figure 3 shows the graph between % change in travel speed of the robot at the corners and set travel speed of the robot.

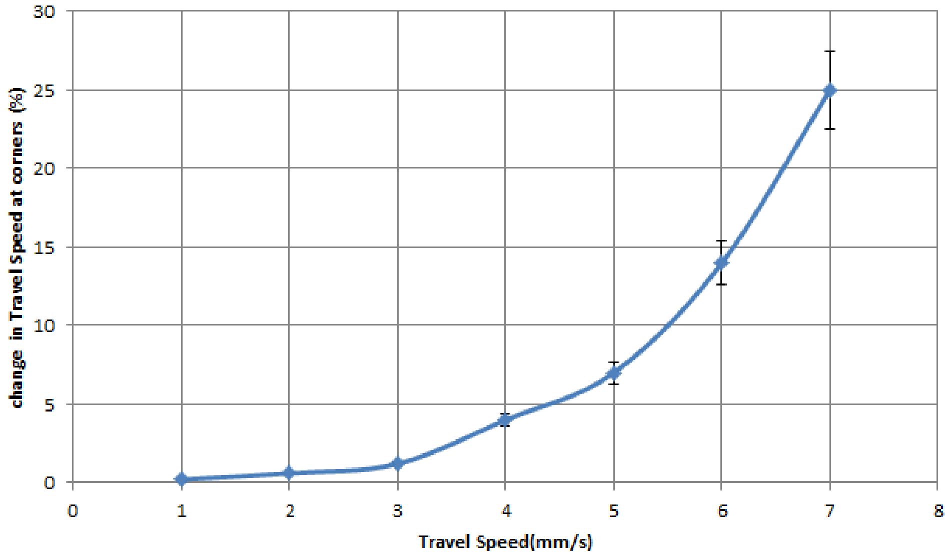
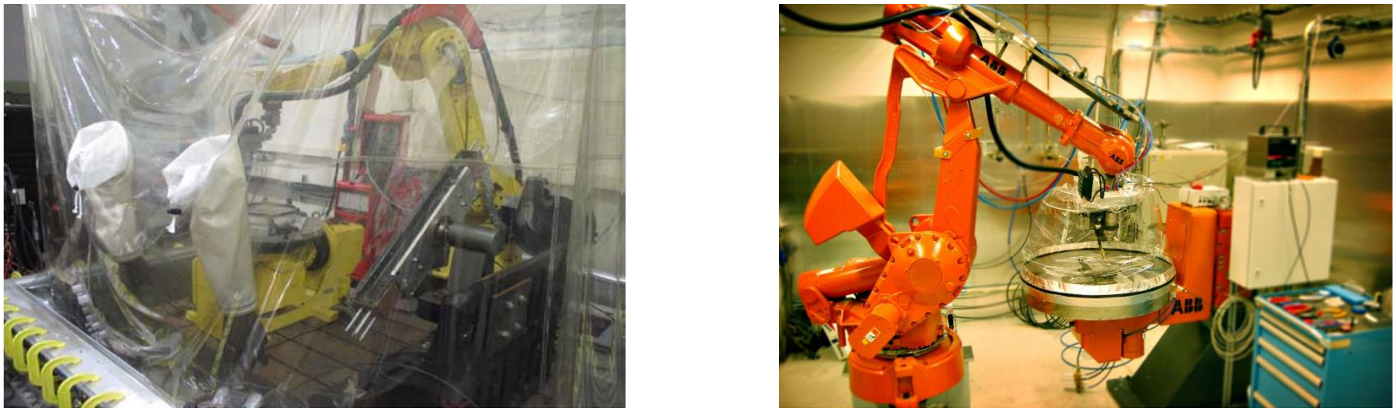


Figure 3 Graph between change in travel speed at corners and travel speed set

b) Shielding Vs material type: Shielding gases are of considerable significance in the protection of molten pool from atmospheric contamination during the deposition process. These gases play an important role in a number of aspects. Shielding gases in arc and laser processes have a remarkable effect on the overall performance of the welding system. It is also dependent on the process type and the material type. For the processes like GMAW, local shielding is required and for Plasma Arc Welding (PAW) with titanium, global inert atmosphere is needed. For the materials like mild steel, stainless steel, high strength steel, aluminum, Inconel, which are the commonly used ones; local shielding is required to avoid oxidation of molten pool, with varying combinations of Carbon-di-oxide and oxygen levels.

For process like PAW and materials like titanium, for global inert atmosphere, different options are tents, enclosures and local shielding. It is comparatively easy to set up the enclosures with a robot, compared to on a CNC system, because of the space occupied by the CNC and cost for setting up. Figure 4 shows some of the examples of the enclosures with robot.



Tent

Enclosure

Figure 4 Different enclosures to avoid oxidation

c) Process type: Part building is mainly done using GMAW, TIG and PAW. During the deposition process, wire feed orientation influences drop transfer and the quality of the deposit. In case of GMAW, wire is fed automatically through the torch (head), driving it through the conduit. Back feeding, side feeding, front feeding has all been tried in case of TIG and PAW. Thus, torch always needs to be rotated to guarantee the consistency of the bead geometry [7]. It is difficult to change the orientation of wire frequently in case of CNC system. However, with the robot, it is easy to rotate the torch, so that the wire can be fed in any orientation. Figure 5 shows the torch arrangement for a TIG set up.

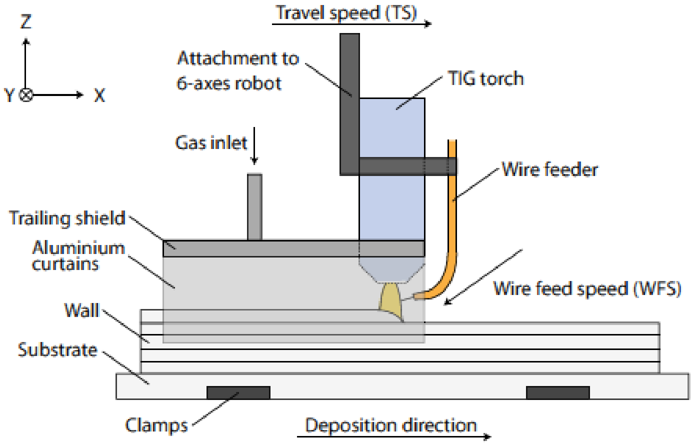


Figure 5 TIG torch with wire feeder

d) Deposition strategy: In order to obtain a geometrically stable deposited product, it is essential to deposit the metal using the strategies which results in a flat surface to be good base for the subsequent layer or nullify the amplification of distortion, residual stresses, dimensional inaccuracies, weld defects etc. It is generally found that as the number layers deposited are more, the geometric accuracy and precision as well as the thermal conditions within the object deteriorate. They cause major problems because they decrease the level of quality and subsequently the path design gets complicated [8].

Traditionally, wider walls are built by depositing metal next to each other in a parallel fashion, in a required number of passes. However, the arc needs to be turned off and on at the end of each pass, which results in higher fabrication time. Due to the considerable time between the adjacent passes, the metal becomes cold and thus, there is a high possibility of finding voids as defects. Therefore, to avoid these conditions, a new strategy proposed is called parallel linear square rounded strategy which would overcome all the drawbacks of parallel strategy. Figure 6 shows the parallel and parallel linear square rounded pattern.

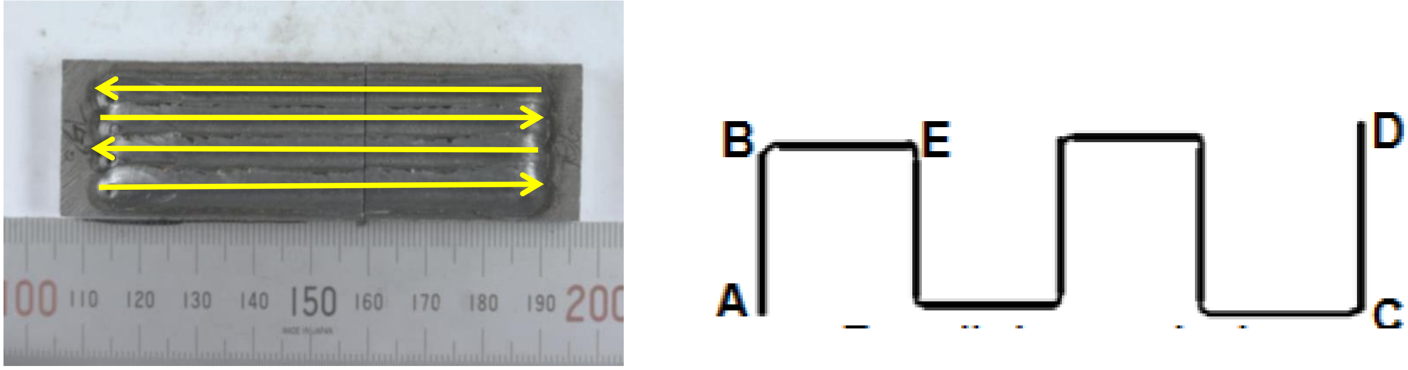


Figure 6 Parallel pattern (left), linear parallel square rounded pattern (right)

When walls are built using the parallel linear square rounded pattern on CNC and on robot, there was a difference in surface profile between the samples. Figure 7 shows the weld samples built using robot and on CNC, with same conditions.

Figure 7 Samples deposited using robot (left) and on CNC system (right)

From the deposited samples, it is clear that the surface profile is not the same. The one deposited on the CNC is more flat compared to the one built using robot. There is an extra material deposited at the corners when built using robot. This is due to the change of speed of robot at the corners. Travel speed of 7 mm/s was used to build the sample. Figure 3 shows that with 7 mm/sec travel speed, there is a decrease of 25 % in travel speed, which means there is a 25% extra material deposited. However, the movement of torch is governed by DC motors in case of CNC system and has a better control and thus, there is hardly any change in travel speed at the corners. Therefore, CNC is preferred to robotic system in this case.

e) Part rotation: Part rotation is one of the essential feature of part building, if part needs to be built double sided or part having overhang features which require 4/5 axis kinematics, counter distortion/residual stresses. In case of CNC, it is not possible to rotate the large bed. Some simple 4/5 axis CNC systems are capable but the cost of them are pretty high. However, with robot, part rotator can be incorporated, which would work independently or can have coordinate motion installed in it. Figure 8 demonstrates a U-shaped component where part rotation is necessary to build and also a part built double sided.

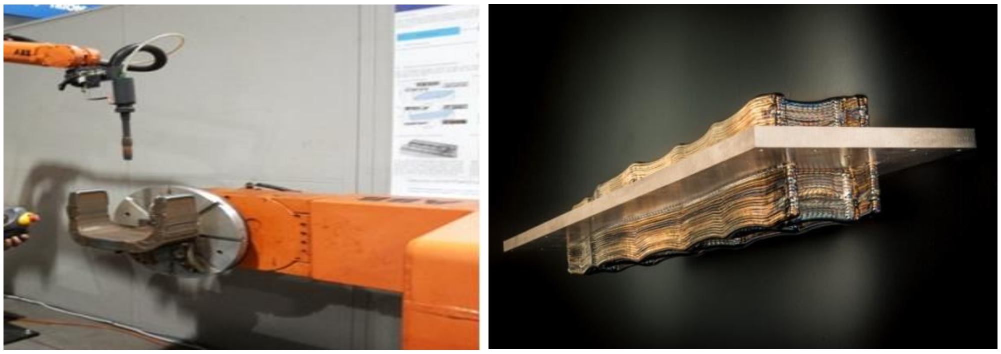


Figure 8 Part rotation examples

f) Cost comparison: The cost of a simple robot starts from 40,000 £ and with additional features like rotator, machining, so on and so forth the cost of it increases to 160,000 £. However, the cost of the simple 3 axis CNC machine starts from 100,000 £ and with additional features it increases to nearly 1,500,000 £, which is nearly 10 times higher than the cost of the robot. Table shows the various costs involved in building a rib with titanium, taking into consideration the higher end robotic and CNC systems. Thus, it can be concluded that cost of robotic system is less compared to cost of CNC gantry system.

Table 4 Cost comparison between robotic system and CNC system for Titanium rib

Feature	Cost of robotic system (£)	Cost of CNC gantry system (£)
Hardware	0.16 M	1.5 M
Software	90000	90000
Labor cost	45	45
Hourly cost of the cell	78	246
Cost of the part	5043	7382
Specific cost (£/kg)	249	364

g) Additional Processes: Incorporating additional processes like rolling, machining, NDT inspection are comparatively easier on a CNC system rather than on a robot. The robotic systems are not that rigid enough to absorb forces and pressure arising from the above listed additional processes. Figure 9 shows rolling process incorporated on a CNC machine.

Figure 9 Rolling rig added as an additional feature to CNC system

h) Scale: It is possible to build large parts on CNC gantry systems. It all depends upon the dimensions of the bed. Figure 10 shows a 5 m length wall deposited on a CNC system.

Figure 10 5 m long wall built on CNC gantry system

However, using robot as well, it is possible to build large structures using multiple robots or using robots on linear drives to facilitate the moving the robot as a whole to deposit at various places and increase its working envelope. Figure 11 shows multiple robots building an aluminum rib.

Figure 11 Multiple robots building a long Aluminum rib

4. Conclusion

From the factors listed above, it is clear that usage of either CNC gantry system or robotic system is purely dependent upon application. Robotic system is preferred when the part is to be built with lower cost, very long, involves rotating of the part, to be built in a global inert environment. On the other side, CNC gantry system is preferred when the part is to be built with high accuracy levels, involves additional processes like rolling, machining etc.

References

[1] Almeida, P. (2012), Process control and development in wire and arc additive manufacturing, PhD Thesis, Cranfield University. U. K

[2] Levy, G., Schindel, R., Kruth, J.P., (2003), Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies, State of The Art and Future Perspectives; CIRP Annals Vol. 52/2/2003; p. 589-609

[3] Kruth, JP., Leu, MC., Nakagawa, T., (1998), Progress in additive manufacturing and rapid prototyping. CIRP Ann-Manuf Techn 47:525-540

[4] Ding, D., Pan, Z., Cuiuri, D., Li, H., Wire-feed additive manufacturing of metal components: technologies, developments and future interests (2015) International Journal of Advanced Manufacturing Technology, 17 p. Article in Press.

[5] Pandremenos, J., Doukas, C., Stavropoulos, P., Chryssolouris, G., (2011), Machining with robots: a critical review. In: Proceedings of DET2011.

[6] Vergeest, J. S., & Tangelder, J. W. (1996), Robot machines rapid prototype. Industrial Robot, pp 17-20.

[7] Martina, F., Mehnen, J., Williams, S. W., Colegrove, P. and Wang, F. (2012), Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti–6Al–4V, Journal of Materials Processing Technology, vol. 212, no. 6, pp. 1377-1386.

[8] Siminski, M. (2003), Weld path optimization for rapid prototyping and wear replacement by robotic gas metal arc welding, Phd Thesis, University of Wollongong, Australia.