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Study on Arc Welding processes for High Deposition Rate Additive Manufacturing

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Abstract

Although Additive Manufacturing implementation is rapidly growing, industrial sectors are demanding an increase of manufactured part size which most extended processes, such as Selective Laser Melting (SLM) or Laser Metal Deposition (LMD), are not able to offer. In this sense, Wire-Arc Additive Manufacturing (WAAM) offers high deposition rates and quality without size limits, becoming the best alternative for additive manufacturing of medium-large size parts with high mechanical requirements such as structural parts in the aeronautical industry.

WAAM technology adds material in form of wire using an arc welding process in order to melt both the wire and the substrate. There are three welding processes that are mainly used in WAAM: Plasma Arc Welding (PAW), Gas Tungsten Arc Welding (GTAW or TIG) and Gas Metal Arc Welding (GMAW or MIG). This paper studies these processes regarding on their capabilities for additive manufacturing and compares the mechanical properties obtained by the different welding technologies applied in WAAM. Obtained results show the applicability of the technology as an alternative of traditional metallic preforms manufacturing processes, such as casting or forging.

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1. Introduction

Wire Arc Additive Manufacturing (WAAM) combines arc-welding and wire feedstock material for additive manufacturing (AM) purposes. Although the original idea is not new, in the last years several research groups have been working on the use of arc welding processes on layer by layer manufacturing of 3D parts [1]. So, processes such as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) or plasma arc welding (PAW) have been applied for additive manufacturing of steel [2,3], aluminium [4,5], nickel superalloys [6,7] and Titanium alloys [8-12].

WAAM adds to the typical additive manufacturing processes' advantages such as, lower cost of welding equipment, wide availability of standard wires, virtual unlimited part size and higher deposition rates. In this sense, while for steels Selective Laser melting (SLM) reaches deposition rates of 0.1 kg/h or Laser Metal Deposition (LMD) is able to deposit

1kg/h, WAAM technology deposition rates increase up to 5-6 kg/h.

On the other hand, WAAM shows some disadvantages when comparing it to SLM or LMD. WAAM heat input is high, which induces to high residual stresses and distortion, therefore manufactured part accuracy and roughness is lower than in other AM technologies and consequently it always needs a finishing machining step. Moreover, the low accuracy makes difficult part redesign by using geometry optimization algorithms.

Therefore, WAAM process is adequate for manufacturing preforms of large size parts which are manufactures in high cost materials and require high volume of machining.

It is worth noting that many of the previous works have been completed in single bead multilayer configuration with or without torch waving or lateral oscillation. Single bead layers can produce wall thickness from 2.5 mm [13] to around 10

mm [10]. Manufacturing of thicker walls in some parts requires the overlapping of multiple adjoining weld beads. In this case, the overlapping distance or centre distance between adjacent beads greatly affects to the surface quality and layer flatness.

Previous investigations on multi-bead overlapping models have concluded that it is impossible to achieve an ideal flat overlapped surface [14]. Ding et al. [15] has recently developed a high accurate multi-bead overlapping model for the determination of optimal centre distance to ensure an stable overlapping process in GMAW-based WAAM of mild steels [15]. In WAAM applications, uneven deposition surfaces can lead quickly to cumulative errors along vertical direction which can result in unstable process. Despite the fact that this issue can be corrected by implementing real time monitoring to adjust and control arc length in real time, it impairs surface finishing and part accuracy leading to higher buy-to-fly ratios.

Up to now, GTAW and PAW based arc welding technologies have demonstrated to be more reliable processes for WAAM with fewer problems of sputtering, excessive heating, distortion or porosity in than GMAW. However, in these two technologies the wire is not fed coaxially and this leads to process variations when changing the welding direction and extreme sensibility to arc length. In fact, many robotic welding systems require a rotary axis to orient the wire feeding nozzle and keep it matched with welding direction which limits applicability.

In this work three arc welding technologies are studied: Plasma welding (PAW), Cold Metal Transfer (CMT) from Fronius and TopTIG from Air Liquide. PAW is a conventional welding technology, while CMT and TopTIG are evolutions of GMAW and GTAW welding processes, respectively. The first one reduces the heat input and distortions of traditional GMAW process and the second one is a coaxial GTAW which improves the typical deposition rates of this process. The presented results in this work include not only the capability of the different processes of generate high quality parts, but also the mechanical properties tested on two materials: an AISI 316L stainless steel and a Ti6Al4V Titanium alloy.

2. Experimental procedure

Tests were performed in the robotic cell situated in the IK4-Lortek facilities and in the two cartesian machines available at ADDILAN and TECNALIA (Fig. 1). Three different power sources were used:

- A Fronius Transplus Synergic 4000 CMT R power source connected to a Robacta drive torch from Fronius.
- A Top TIG 220 DC source and patented torch from Air Liquide.
- A Praxair-EWM TETRIX 400 Synergic Plasma source coupled to a Plasmatechnik PWM 350A torch.



Fig. 1. WAAM Facilities. Left) IK-4 Lortek (CMT&TopTIG). Centre) TECNALIA (PAW). Right) ADDILAN (CMT&PAW)

High purity Argon (99.999%) was used as pilot gas for both materials, Ti6Al4V and AISI 316L, and different shielding gasses have been investigated as local shielding gas, depending on welding process or material (Table 1). Finally, Ti6Al4V was performed in an Argon inert atmosphere with O₂ concentration below 50 ppm.

For AISI 316L tests, 1,5 kg/h deposition rate was maintained and, for the Ti6Al4V ones, the maximum value for each process was studied (Table 1). In both materials, standard welding wires with 1.2 mm diameter and 10 mm thickness substrates were used.

Table 1. Deposition Rates and Shielding gasses for each material

Material	Process	Shielding Gas	Deposition Rate
AISI 316L	CMT	25%CO ₂ /75%Ar	1.5 kg/h
	PAW	5%H ₂ /95%Ar	
	TopTIG	100%Ar	
Ti6Al4V	CMT	100% Ar	2.5 kg/h
		50%He/50%Ar	
	PAW	100% Ar	1.5 kg/h
		70%He/30%Ar	
TopTIG	70%He/30%Ar	1.0 kg/h	

Mechanical properties were evaluated by tensile test specimens which were extracted by electron discharge machining with a geometry according to ASTM E8-16 standard (Fig. 2). Two types of specimens were tested in order to study mechanical properties of the walls in two directions: bead generation direction (PL) and bead vertical overlapping direction (PT). AISI 316L specimens were tested as built condition and a standard stress relief treatment was performed on Ti6Al4V test parts

Tensile tests were performed in a model Z100 ZWICK/Roell at room temperature applying a displacement rate of 1.6 mm/min and using an extensometer with a gauge length of 25 mm.

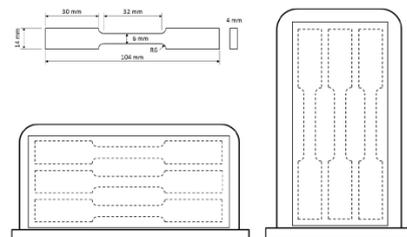


Fig. 2. Scheme of the tensile test specimens extracted from thick-walled WAAM samples.

3. Results

This section shows the main results obtained from the development of the three processes for Additive Manufacturing. Results include, not only mechanical properties values, but also the capability of each studied process to be applied in High Deposition Rate Additive Manufacturing.

Results are divided by WAAM technology (CMT, PAW and TopTIG) and materials (AISI 316L and Ti6Al4V).

3.1. CMT for WAAM

3.1.1 CMT - AISI 316L

CMT process is a welding process optimized for decreasing heat input into the substrate and is widely used on industrial welding of several steel alloys. So, although this work only shows the results obtained for 2,5 kg/h deposition rate in order to compare them with those obtained by other processes, CMT process has shown good results up to 5 kg/h deposition rates with AISI 316L.

However, CMT generates bead with relatively high aspect ratios (relationship between bead height and width) which could make difficult overlapping and could cause defects in the part like voids or pores.

Regarding mechanical properties, results show that properties depends clearly on the test direction (Fig.3). While longitudinal specimens (PL) are close to the minimum fixed by the standard, transversal ones (PT) do not reach these limits, showing lower yield strength and elongation at break which demonstrates a more rigid behaviour on traverse direction.

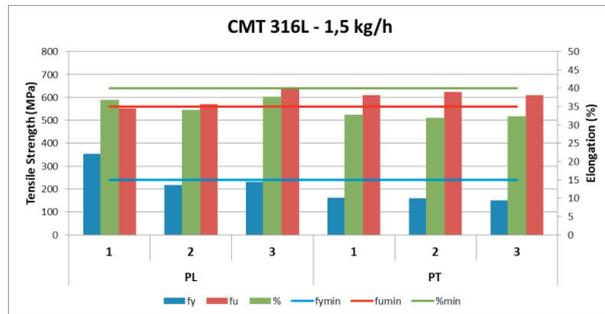


Fig. 3. CMT mechanical tests results for AISI 316L stainless steel

3.1.2 CMT- Ti6Al4V

In this case, Ti6Al4V needs more energy to be melted. Therefore, low heat input of CMT is not enough to melt substrate and obtained bead aspect ratio complicates overlapping (Fig. 4). This issue can be improved by using a shielding gas which increases overall energy of the welding. In this work, Ar/He mixtures have been tested in order to obtain suitable overlaps for Additive Manufacturing. In this sense, mixtures below 50% He, although allows single bead walls, do not show admissible results for horizontal overlapping (Fig.4).

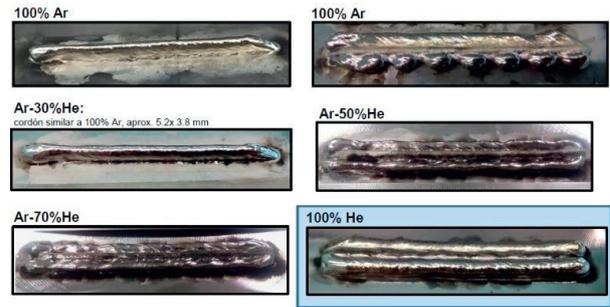


Fig. 4. Simple and overlapped beads for different shielding gases.

Therefore, for the tensile strength tests three types of gasses were selected: 100% Ar (single bead wall), 50%Ar/50%He and 100% He. It is worth noting that an increase of He percentage suppose an increase of the gas price.

Tests using 100% Ar show Ultimate and Yield strength close to the limit for both PL and PT specimens. On the contrary, Elongation at break is lower than minimum in both direction, showing a certain degree of anisotropy between them (Fig.5).

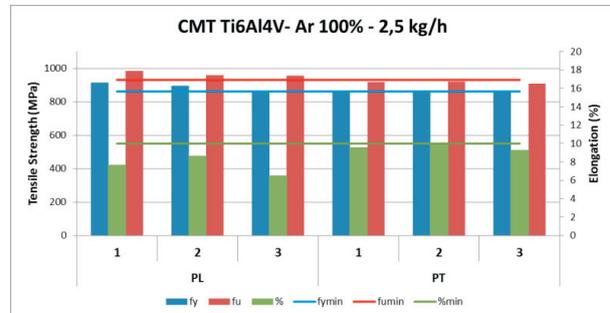


Fig. 5. CMT mechanical tests results for Ti6Al4V. 100% Ar shielding gas.

For the walls generated with 50%Ar/50%He shielding gas, the results are similar to those obtained for 100%Ar, but in this case, values of Yield and Ultimate strengths decrease to 97% and 98% of the limit, respectively (Fig. 6). Moreover, anisotropy decreases, obtaining more homogenous properties on the wall.

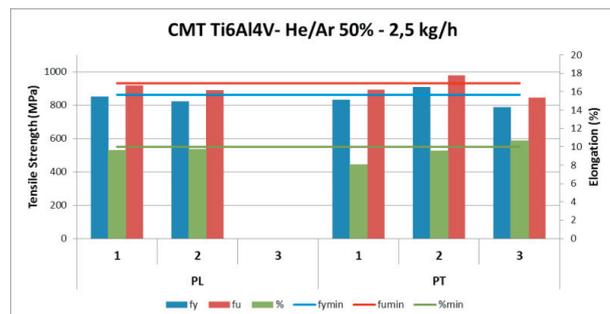


Fig. 6. CMT mechanical tests results for Ti6Al4V. He/Ar 50% shielding gas.

Finally, for the 100% He shielding gas Elongation at break drops to 38% and 89% of the limit on PL and PT specimens. On the contrary, Yield and Ultimate strengths continue above the established values (Fig. 7).

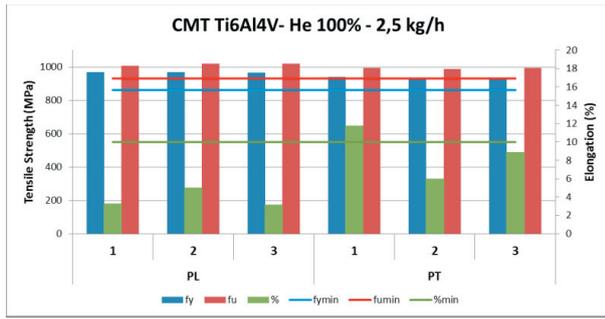


Fig. 7. CMT mechanical tests results for Ti6Al4V. 100% He shielding gas.

3.2. TopTIG for WAAM

3.2.1 TopTIG - AISI 316L

TopTIG is a TIG technology which allows coaxial feeding of wire increasing deposition rate and maintaining the high quality of TIG process. The main limitation of this technology is the low deposition rates comparing with CMT or PAW. The results establish this limit in 1.5 kg/h for AISI 316L and current equipment (Fig. 8). This limit results from the low heat input of the process which is not able to melt the wire when the feed increases. Furthermore, it is necessary to care about the aspect ratio which could make difficult horizontal overlapping.



Fig. 8. Beads obtained by TopTIG on AISI 316L. Left) 1 kg/h. Centre) 1.5kg/h. Right) 1.6 kg/h.

On the other hand, the mechanical results obtained for TopTIG are situated over the minimum required and show high homogeneity on both directions (Fig. 9).

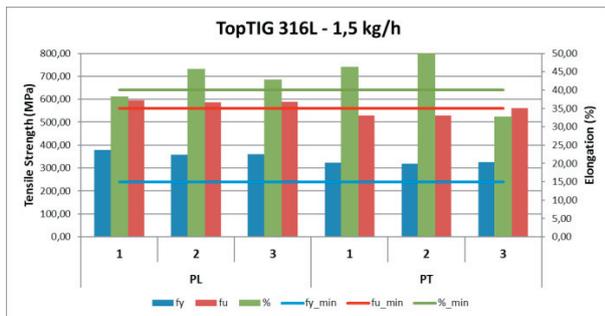


Fig. 9. TopTIG mechanical tests results for AISI 316L stainless steel.

3.2.2. TopTIG – Ti6Al4V

Low heat input issues increase for Ti6Al4V and, as occurred in CMT process, it is necessary to use a shielding gas mixture in order to increase overall energy and obtain an acceptable bead aspect ratio for horizontal overlapping. In this case, using a 30%He/70%Ar allows to obtain walls for a 1.1 kg/h deposition rate.

The tensile strength tests show that anisotropy appears again in terms of Elongation at break, being this below the limit in traverse direction (PT). However, Yield and Ultimate strengths exceed this limit and show a homogeneity between both directions (Fig. 10).

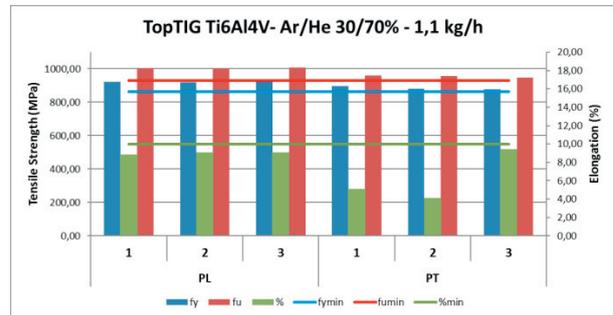


Fig. 10. TopTIG mechanical tests results for Ti6Al4V alloy.

3.3. Plasma Arc Welding for WAAM

3.3.1. PAW - AISI 316L

PAW constricts the arc within the pilot arc increasing the energy density so, beads generated by this process are wider and shorter, i.e. they have a lower aspect ratio. This fact eases the horizontal overlapping, avoiding voids and pores. Mechanical tests were accomplished on wall generates at 1.5 kg/h deposition rate, although 3.5 kg/h values can reach with suitable quality.

Test results (Fig. 11) show high anisotropy between directions. PL specimens cross both Yield and Ultimate strength limits, while the PT ones reach the limit only for Ultimate strength. In both cases, values of Elongation at break are below limit value.

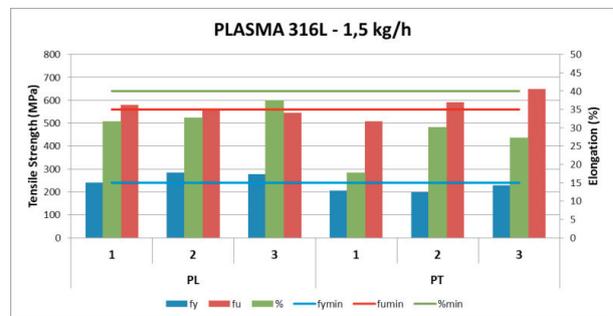


Fig. 11. PAW mechanical tests results for AISI 316L stainless steel.

3.3.1. PAW – Ti6Al4V

In contrast to CMT and TopTIG, PAW does not need shielding gas mixtures for generating optimal aspect ratios for horizontal overlapping up to 2 kg/h deposition rates. Moreover, the use of high purity Ar for both pilot and shielding gas helps to reduce undesirable contamination and oxidation of walls.

Regarding mechanical properties, although anisotropy is clearly shown, all the values are very close to established limits (Fig. 12). Main issue can be found for PT specimens

where Yield strength and Ultimate strength are about 94-95% of the limit. In this case, heat or mechanical treatments, such as rolling proposed by [16], could be interesting in order to reduce the elongation at break and improve strength properties.

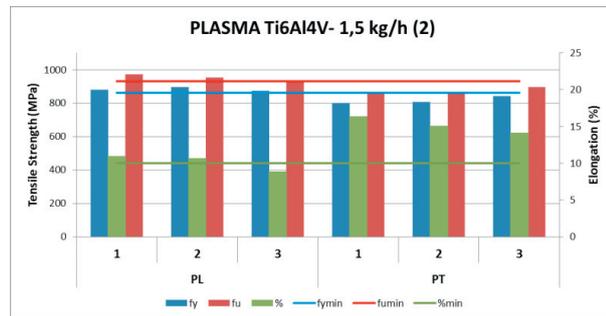


Fig. 12. PAW mechanical tests results for Ti6Al4V alloy.

4. Conclusions

This work studies three welding processes (Plasma Arc Welding, Fronius CMT and Air Liquide TopTIG) for Wire Arc Additive Manufacturing (WAAM) in terms of suitability and obtained mechanical properties. Two materials have been studied: an AISI 316L stainless steel and Ti6Al4V alloy.

From the results obtained following conclusions can be appointed:

- WAAM technology, regardless of welding technology used, achieves high quality parts with deposition rates up to 5 kg/h in stainless steel or 2.5 kg/h in Ti6Al4V alloy.
- The results show that, although WAAM technology is able to achieve the mechanical requirements, it is necessary to choose the correct welding process depending on the material and application required.
- CMT obtains the highest deposition rates in stainless steel but shows remarkable anisotropy in the mechanical properties. Moreover, for Ti6Al4V, low heat input inherent to the process makes necessary the use of gas mixtures for the shielding gas in order to get suitable aspect ratios for overlapping. In this sense, it could be concluded that CMT is suitable for large size Stainless steel parts with low/medium mechanical requirements.
- TopTIG obtains the best properties for stainless steel and shows a homogenous behaviour regardless of direction. On the contrary, its lower energy efficiency does not allow high deposition rates (1.5 kg/h maximum) and makes necessary the use of an active shielding gas mixture for Ti6Al4V alloy successful deposition. Therefore, TopTIG process could be used for small/medium size Titanium and Stainless steel parts which have medium/high mechanical requirements.
- PAW obtains intermediate deposition rates for stainless steel (3,5 kg/h) with relatively good properties in both directions. However, for Ti6Al4V, PAW shows the best deposition rate-mechanical properties ratio, reaching a 2 kg/h deposition rate and average values of Yield

Strength, Ultimate Strength and Elongation at Break of 97%, 98 % and 120% of minimum limits, respectively.

Thus, PAW process is recommended for medium/large size Titanium and Stainless steel parts which have medium/high mechanical requirements.

- Regardless the welding process, parts manufactured by WAAM have shown an anisotropy in the mechanical properties which must be taken into account during design step or be heat/mechanically treated during production step.

References

- [1] Ding D, Pan Z, Cuiuri D, Li H. Wire-feed additive manufacturing of metal components: technologies, developments and future interests. *Int. J. Adv. Manuf. Technol.*, vol. 81, no. 1–4, pp. 465–481, 2015.
- [2] Youheng F, Guilan W, Haiou Z, Liye L. Optimization of surface appearance for wire and arc additive manufacturing of Bainite steel. *Int. J. Adv. Manuf. Technol.*, pp. 1–13, 2016.
- [3] Kapil S, Legesse F, Kulkarni P, Joshi P, Desai A, Karunakaran KP. Hybrid-layered manufacturing using tungsten inert gas cladding. *Prog. Addit. Manuf.*, vol. 1, no. 1, pp. 79–91, 2016
- [4] Gu J, Cong B, Ding J, Williams SW, Zhai Y. Wire+Arc Additive Manufacturing of Aluminium. *SFF Symp. Austin Texas*, pp. 451–458, 2014.
- [5] Cong B, Ding J, Williams S. Effect of arc mode in cold metal transfer process on porosity of additively manufactured Al-6.3%Cu alloy. *Int. J. Adv. Manuf. Technol.*, vol. 76, no. 9, pp. 1593–1606, 2015.
- [6] Cooper DE. The High Deposition Rate Additive Manufacture of Nickel Superalloys and Metal Matrix Composites. Thesis Doctoral, University of Warwick, 2016.
- [7] Xu F, Lu Y, Liu Y, Shu F, He P, Xu B. Microstructural Evolution and Mechanical Properties of Inconel 625 Alloy during Pulsed Plasma Arc Deposition Process. *J. Mater. Sci. Technol.*, vol. 29, no. 5, pp. 480–488, 2013.
- [8] Addison A, Ding J, Martina F, Lockett H, Williams S, Zhang X. Manufacture of Complex Titanium Parts using Wire+Arc Additive Manufacture. *Int. Titanium Association*, May 2015.
- [9] Harris ID. New Developments in Welding and Metal Additive Manufacturing Using Directed Energy Deposition (DED). *Titanium Europe 2015 Conference*, Birmingham (UK), 2015..
- [10] Baufeld B, Van der Biest O, Gault R. Additive manufacturing of Ti-6Al-4V components by shaped metal deposition: Microstructure and mechanical properties. *Mater. Des.*, vol. 31, Supple, pp. S106–S111, Jun. 2010.
- [11] Colegrove P. High deposition rate high quality metal additive manufacture using wire + arc technology. *Cranfield University*, Internal Report 2013.
- [12] Hoyer NP, Appel EC, Cuiuri D, Li H. Characterisation of metal deposition during Additive Manufacturing of Ti-6Al-4V by Arc-Wire Methods. *SFF Symp. Austin Texas*, pp. 1015–1023, 2013.
- [13] Williams SW, Martina F, Addison AC, Ding J, Pardal G, Colegrove P. Wire + arc additive manufacturing. *Mater. Sci. Technol.*, vol. 836, no. March, p. 1743284715Y.000, 2015.
- [14] Suryakumar S, Karunakaran KP, Bernard A, Chandrasekhar U, Raghavender N, Sharma D. Weld Bead Modeling and Process Optimization in Hybrid Layered Manufacturing. *Comput. Aided Des.*, vol. 43, no. 4, pp. 331–344, 2011.
- [15] Ding D, Pan Z, Cuiuri D, Li H. Process planning for robotic wire and arc additive manufacturing. *Proc. 2015 10th IEEE Conf. Ind. Electron. Appl. ICIEA 2015*, pp. 2000–2003, 2015.
- [16] Donoghue J, Antonyamy AA, Martina F, Colegrove PA, Williams SW, Prangnell PB. The effectiveness of combining rolling deformation with Wire-Arc Additive Manufacture on β -grain refinement and texture modification in Ti-6Al-4V. *Mat. Ch.* vol 114, pp. 103–114, 2016.