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Effect of atmosphere conditions on additive manufacturing of Ti4Al6V by coaxial W-DED-LB process

Eva Vaamonde[a,*], Pilar Rey[a], Rosa M Arias[a], Iago Troncoso[a]

[a]*AIMEN Technology Centre, E36418 - O Porriño – Pontevedra – Spain*

Abstract

Additive Manufacturing is being a strategic tool for industrial applications even for large size structural parts where high deposition rates, as achieved by Directed Energy Deposition (DED) techniques based on wire deposition, are required. However, manufacturing of large components on reactive materials as titanium alloys requires specific atmosphere conditions to reach the specified properties on the deposited material. In this paper coaxial laser wire deposition (W-DED-LB) of titanium grade 5 alloy has been studied to achieve the highest deposition rate and process stability and the effect of protective conditions has been assessed. Three different configurations (local, inert chamber, local + inert chamber) were tested in order to bring a deep understanding of the influence of protective conditions on process stability, surface quality, metallurgy, hardness and oxygen content of deposited material.

Keywords: laser additive manufacturing; coaxial wire; titanium alloy; oxigen content

1. Introduction

Significant advances in the additive manufacturing (AM) technologies during last years have enabled the production of fully functional parts using titanium and its alloys. In this sense, directed energy-based technologies (DED) offer higher deposition rates that can lead to considerable savings through considerably reduced buy-to-fly ratios, overall weight reduction, and scrap reduction [1], especially for large size structural parts.

* Corresponding author.
E-mail address: evaamonde@aimen.es.

DED technologies allow parts manufacturing by melting metal material (powder or wire form) as it is being deposited to build up three-dimensional components. The multi-axis deposition capability of DED processes enable the manufacture of complex parts, such as thin-walled structures. Although initially developed for powder feed, wire DED processes are now attracting the interest of the industry, particularly from aeronautic sector. Common wire DED processes are based on electron beam (EBAM)[2], plasma(Rapid Plasma Deposition)[3] or arc energy sources. Laser based wire DED (W-DED-LB) is becoming a feasible alternative to these processes, considering the main advantages for the manufacturing of large size components as: good adhesion between substrate and deposited layer of material, wide range of metal materials and alloys, low level of dilution, high deposition rates, high reproducibility of the process, low impact of substrate properties or high flexibility on part size. Deposition rates up to 12kg/h [4]and the coaxial wire configuration [5], which makes the process independent from any orientation, have increased the potential of the W-DED-LB, process making the process more profitable compared to machining techniques.

As it was mentioned above, a wide range of metal materials and alloys can be processed by W-DED-LB process, including titanium alloys. However, high reactivity of titanium is a critical issue that must be considered to avoid oxidation or oxygen enrichment of the deposited material. The maximum oxygen content in the deposited material is restricted to 0.2%, according to the AMS4999[6]. Besides, process inerting combined with DED advantages result in titanium alloys with higher strength and lower ductility values concerning the conventionally processed one [7]. In consequence titanium alloys must be processed under protective atmosphere, usually Ar inert gas, although according to the literature the conditions of this inert atmosphere, regarding oxygen content, are variable. The AMS 4999 standard establish a limit of 1200ppm for oxygen concentration, but values under 50ppm or 100ppm are found in the literature [7-10].

The aim of this work, besides to optimize the process parameters for laser wire DED process of Ti6Al4V, is to evaluate three different atmosphere conditions for laser base wire DED deposition process of Ti6Al4V alloy: Local shielding with Ar gas, Ar inert chamber, and Ar inert chamber + Ar local shielding. The main goal is to evaluate the influence on microstructure, hardness, and oxygen content of deposited material to assess the viability of each working condition according to required quality.

2. Experimental set up, materials and methods

2.1. Experimental set-up

The robotic DED industrial work cell and main equipment used is shown in Fig. 1. It consists of a 6-AXIS industrial robot ABB4400 as positioning system that is holding and displacing DED process head along the built part.

Fig. 1. Robotic laser metal deposition workstation and process equipment of the experimental setup

Main process equipment is a disk laser Trudisk, 16kW maximum power, coupled by 600µm optical fiber to a laser process head. In this case a coaxial solution provided by Precitec (CoaxPrinter) is used to manufacture structures by W-DED-LB process. This laser process head allows completely direction-independent laser wire deposition. Based on the unique ring-shaped beam shape and the coaxial feeding of the additional filler material, the wire is fused homogeneously from all directions and well connected with the local melt pool. Fig. 2 shows the process head set up and the laser beam shape measured by a laser beam analyzer. The TS5000 system from Fronius was used as wire feeder device.

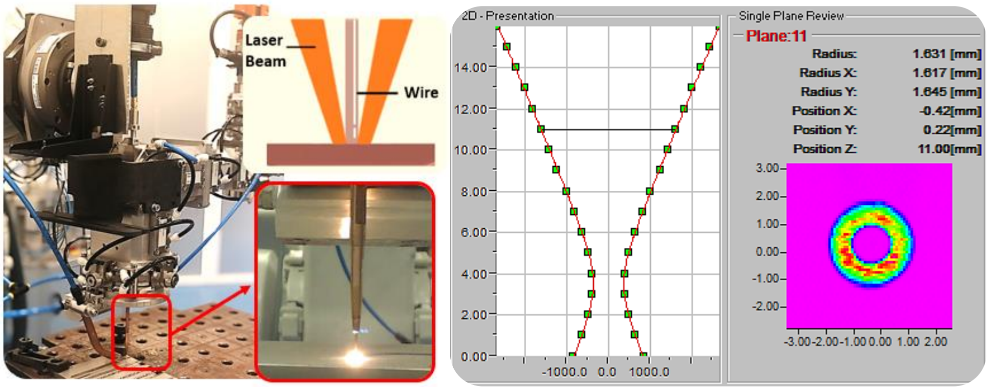


Fig. 2. Integration of the coaxial wire processing head and laser beam analysis at the working plane

2.2. Materials

The case of study is mainly focused on deposition on Ti grade 5 alloy by W-DED-LB process. The filler wire material used for these trials is titanium alloy Ti6Al4V with 1,14mm diameter, provided by VBC group, under specification AMS4954K, which is the specified material for aeronautic applications. Table 1 shows the detailed composition of this filler wire.

Table 1. Chemical analysis of Ti grade 5

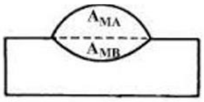
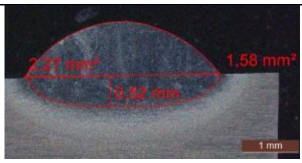
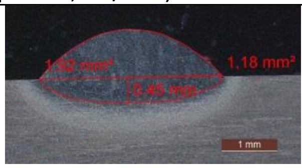
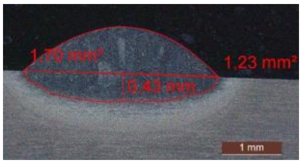
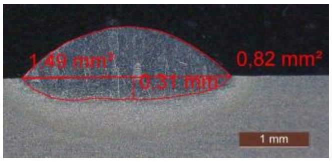
Element	Al	V	Fe	O2	C	N	H	Ti
%	6.27	3.89	0.18	0.15	0.021	0.007	0.002	Bal.

The base material to be used as substrate is hot rolled Ti6Al4V plate in annealed condition and 10mm thickness (provided by CONECBAND). The base material fulfills the specification ABS5125A.

2.3. Process parametrization

The process development was started with single tracks, followed by overlapping tracks and the development of buildup strategies for thin walls. During process set up and parametrization, main key process different wire speed, laser power and process speed have been tested using a design of experiments (DoE). Process window has been defined according to best ratio between dilution, geometry, and process stability. The metallographic evaluation of different experimental trials was performed in order to measure the area of the deposited material. Table 2 shows the cross sections of different single tracks performed with 1,3m/min wire speed. It is clearly shown that the penetration depth in the substrate is higher as laser power density is increased. However, in terms of dilution, calculated according to the equation shown in Table 2, there is not a linear correlation between the dilution and the laser power density. For 1,3m/min wire speed the dilution at high power density (150W s/mm) is similar or even lower than the dilution at medium power density (107W s/mm).

Table 2. Cross sections of wire DED deposited tracks out of Ti6Al4V deposited with a different power density.

Dilution formula	Cross sections (wire speed 1,3m/min)	
 Dilution (%) = $\frac{A_{MB}}{A_{MA} + A_{MB}}$	 Power density: 150 W s/mm Dilution: 41%	 Power density: 125 W s/mm Dilution: 38%
	 Power density: 107 W s/mm Dilution: 42%	 Power density: 90 W s/mm Dilution: 36%

Dilution calculation for the different trials performed in the DoE are plotted in fig. 3. According to these results, the lower dilution on a single track (26%) is achieved with 1,6m/min of filler wire and 90 W s/mm of power density. But it is remarkable that close similar dilution is obtained for this wire speed at higher power densities as 125 W s/mm (28%) or 150 W s/mm (29%). This behaviour is observed at different wire speeds tested.

In the other hand, considering geometrical homogeneity of the track and process stability on single tracks and overlap multi tracks the following parameter set was selected: 1,3m/min wire speed and 125W s/mm of power density (dilution=38%).

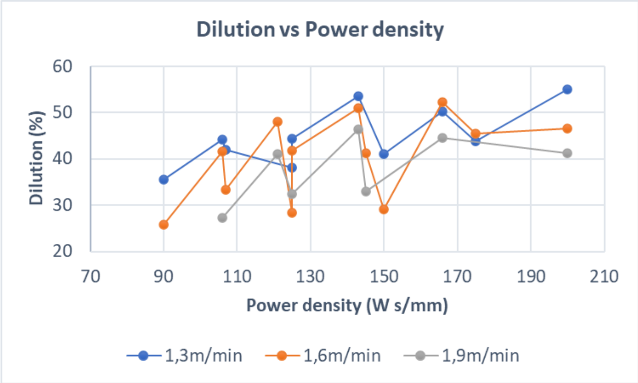


Fig. 3. Graphical representation of the dilution for different wire speed and laser power density

The track width after process optimization is: 3.28mm. Additional process development tests as 1-layer multi track and several layers deposition were conducted to finally estimate other path planning configuration parameters such as overlap and layer height. Two overlap tracks with a final overlap of 12.5% of the track width and layer height of 0.9mm were selected to manufacture the wall structures for final analysis.

2.4. Build up procedure.

In order to evaluate the influence of the atmosphere conditions on the manufacturing of Ti6Al4V structures by wire DED laser process, three different cases of study were studied using Ar gas as protective atmosphere: local shielding gas, inert chamber and local shielding + inert chamber. In these three cases, structures with two overlap tracks and up to 70 layers have been manufactured with the same process parameters and same process sequence (stop each 5 layers to avoid overheating and better molten pool stability). Ar flow and O_2 concentration inside the inert chamber are summarized in table 3. To control the O_2 content an OXI-3 oximeter from Orbitec is used.

Table 3. Main conditions for the three cases of study

Local	Inert chamber	Local + inert chamber
Two nozzles with 15l/min Ar flow	O_2<200ppm	One nozzle with 10l/min, O_2< 200ppm

With the local shielding the top surface of the deposited Ti wire seems to be quite protected from oxidation and the aspect is shiny, especially in the first deposited tracks. However, the lateral surface of the wall shows high level of oxidation. By using the inert chamber, the top and lateral surfaces of the wall keep a shiny aspect, but the oxidation of the lateral surfaces has been increasing as the height of the wall is increased. Multiple bands with different colouring appear on the lateral surface of walls manufactured under inert chamber and inert chamber + local nozzle configuration. It should be noticed that this colouring is easily removed by machining 0,2mm, Fig. 4.

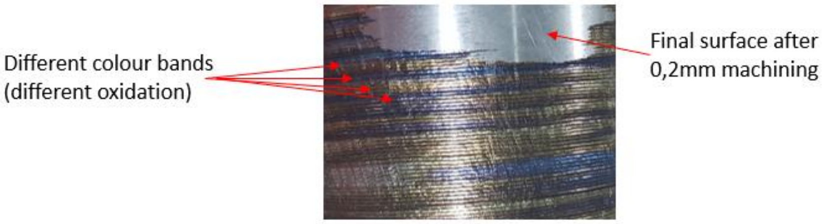


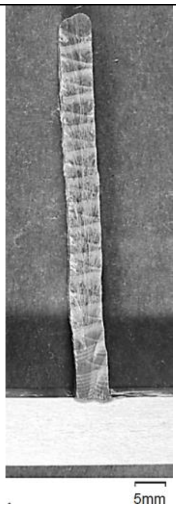
Fig. 4. Different oxidation levels in the wall structures manufactured in Ar inert chamber.

3. Results and discussion

3.1. Microstructure analysis

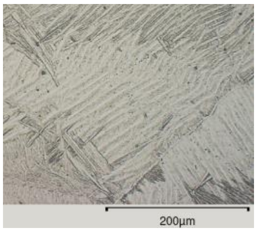
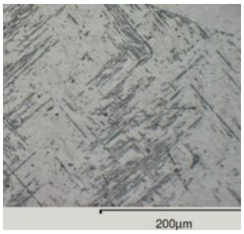
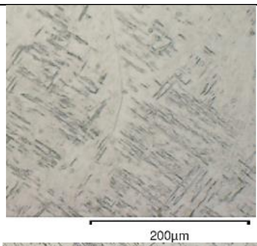
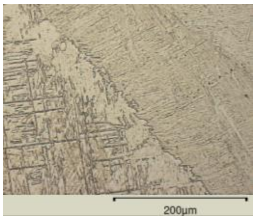
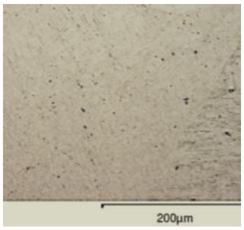
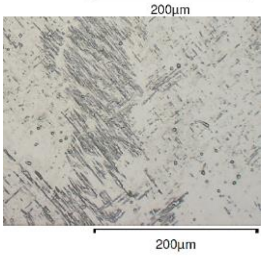
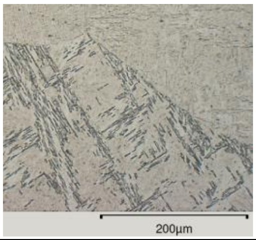
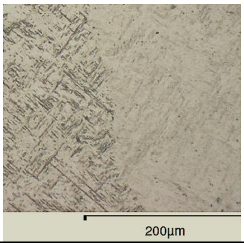
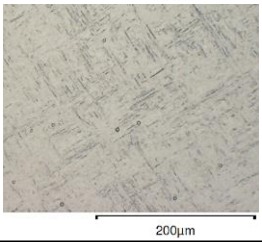
Cross sections of the different structures were per performed in order to evaluate the microstructure and the hardness of the deposited material. Table 4 shows the macrographs of the three wall structures manufactured under different atmosphere conditions. Layered bands are clearly observed in wall structures manufactured under inert chamber conditions showing that Ar atmosphere modifies the thermal cycle of the deposited material.

Table 4. Macrostructure of the three cases showing columnar prior-β grains along the build direction.

Local	Inert chamber	Local + inert chamber
		

The as-built microstructure observed on the wall structures shows mainly α lath colonies from β phase transformation, table 5. Slightly difference is observed on microstructure of the wall structure manufactured with local shielding Ar, where martensitic structure is predominant in some regions (top). Those colonies have been formed inside the prior-β grains. It was observed that the prior-β grains in the deposit are columnar and oriented nearly perpendicular to the substrate along the build direction (z-direction), and slightly tilted in the direction of laser motion in the x-z plane.

Table 5. Microstructure of the three cases at different heigh position of the walls.

	Local	Inert chamber	Local + inert chamber
Top			
Medium			
Bottom			

3.2. Hardness

Additional Vickers hardness HV10 tests were performed on the lateral and the center of each wall structure according to UNE-EN ISO 6507-1: 2018. Fig. 5 shows the hardness values plotted against the position of the wall where are measured. Hardness of wall structure manufactured with Ar local shielding Ar is significantly higher than hardness measured on wall structures manufactured under inert chamber conditions, especially in the top region with values above 400HV10. Those values are in accordance with the martensitic structure observed in different regions of this wall structure. The hardness profiles on walls manufactured under inert chamber conditions show no significant trend in hardness vs. location in the build, which differs from some results from the literature where hardness values increase when stepping from bottom to the top.

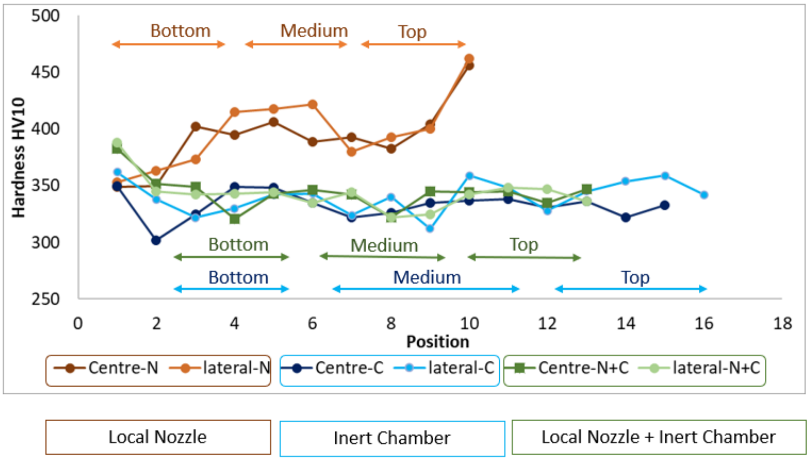


Fig. 5. Hardness on the center and lateral regions of wall structures.

3.3. *Oxygen content*

A semi-quantitative chemical analysis was performed by Energy-dispersive X-ray spectroscopy (EDS), on the external surface and into the transversal sections of the builds. As it is expected, oxygen content on laterals surface of the wall manufactured with Ar local shielding is extremely high, over 40%. Major difference is observed between both wall structures manufactured under Ar inert chamber and Ar inert chamber + local shielding. As it is shown in fig. 6 oxygen content on lateral surfaces of wall manufactured under Ar inert chamber + local shielding condition is significantly lower than Ar inert chamber condition.

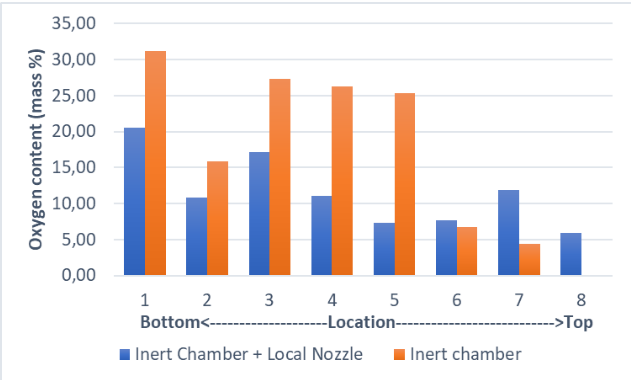
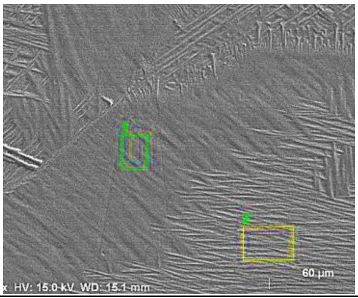
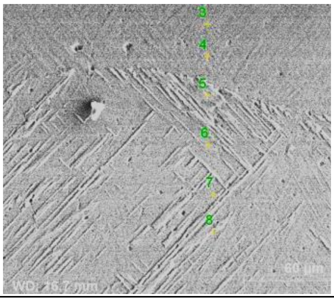
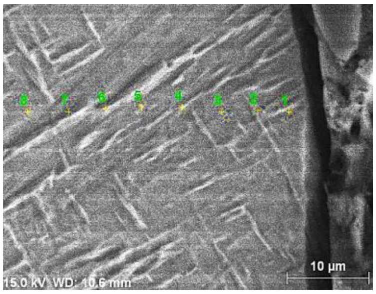


Fig. 6. Oxygen content from bottom to top on external surfaces of walls manufactured under inert chamber conditions.

The analysis on transversal section of the builds mainly reveals no oxygen content or very low contents in the three cases under evaluation. Table 6 shows the mean values of oxygen content measured by EDS and the images from SEM analysis for the three manufacturing conditions. However, as EDS provides a semi-quantitative analysis additional test as inert gas fusion is required to evaluate de oxygen content with higher precision.

Table 6. Mean values of oxygen content measured on transversal section of wall structures and images from SEM analysis for the three different conditions local shielding(a), inert chamber(b) and inert chamber + local shielding(c).

Oxygen content measured by EDS (mass %)		
Local (a)	Inert chamber (b)	Local + inert chamber (c)
Mean value in sections 1 and 2: 0,00%	Mean value (points 4-8): 0,00%	Mean value (points 1-8): 0,08%
		

4. Conclusions and Future work

In this work the laser wire DED process was set up and optimized for titanium alloy Ti6Al4V. As result of the DoE performed the process parameters has been optimized in terms of dilution, homogeneity of deposited material and process stability (considering single track and multi-track conditions). Wall structures were finally manufactured with selected process parameters and different atmosphere conditions. From the undergone analysis following conclusions are reached:

- Macrostructure analysis reveals columnar growth of prior-β grains in all wall structures. Layered bands are clearly observed in wall structures manufactured under inert chamber conditions suggesting differences on thermal cycles compared with local shielding build structure.
- Build structures under inert chamber conditions (with or without local shielding) show similar microstructure with α lath colonies formed inside the prior-β grains. Martensitic microstructure is observed in some regions of the build structure under local shielding conditions.
- Build structure manufactured under local shielding conditions show higher hardness values (up to 460HV10 in the top region of the wall) which is in consonance with the martensitic structure found in this build structure.
- Main difference on build structures manufactured under inert chamber conditions relies on different oxygen content on external surface, being significantly lower on build structure manufactured under inert chamber + local shielding conditions.
- On transversal sections very low oxygen content has been detected by EDS analysis. However further tests should be performed to consolidate those results.

Next steps planned to continue this work will mainly comprise performing mechanical tests, deeper analysis of oxygen content and analysis of influence of heat treatment on hardness and microstructure on deposited material.

Acknowledgements

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