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Additive manufacturing of a titanium flap track by coaxial laser Wire Directed Energy Deposition process

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Abstract

Wire Directed Energy Deposition (W-DED) process is becoming a key manufacturing process in aerospace industry, mainly due to higher deposition rate, ability to build larger structures and high efficiency in material compared with other usual AM technologies, as PBF, or powder-based DED processes (p-DED). Manufacturing of medium-/large-sized metal components is still challenging, especially by laser-based W-DED process, due to a complex heat management along with the requirement of specific atmosphere conditions to reach the specified properties on the deposited material. In this paper coaxial laser wire deposition (W-DED-LB) of Ti6Al4V alloy has been studied to manufacture a large component for the aeronautic industry. Process parameters and different manufacturing strategies have been developed and optimized to reduce the distortion of the final component. Selection of the manufacturing strategy for the manufacturing of the final demonstrator was also supported by simulation. Metallurgy and mechanical behaviour of deposited material was also analysed.

Keywords: laser additive manufacturing; coaxial wire; titanium alloy; distortion; mechanical behaviour

1. Introduction

Directed Energy Deposition (DED) processes are getting bigger relevance within Additive Manufacturing (AM) for titanium parts, due to key advantages as flexibility and high deposition rates, particularly in the manufacturing of large metal components in the aeronautic sector. Besides DED process enables considerable savings by dropping buy-to-fly ratios, weight saving, and scrap reduction [1].

The DED process is defined as “additive manufacturing process in which focused thermal energy (laser, electron beam, or plasma arc) is used to fuse materials by melting as they are being deposited” by ISO/ASTM 52900 standard [2]. Initially developed to deposit material in powder format, wire DED processes are now drawing attention of the industry, mainly due to higher efficiency of the material being deposited, high part quality (lower porosity) and safer process than powder base process (lower pollution). Besides common wire DED processes as wire electron beam, rapid plasma deposition or WAAM (Wire Arc Additive Manufacturing), laser based wire DED process (W-DED-LB) is becoming a feasible alternative, specially due to advantages 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 [3]. Potential of the W-DED-LB process at industrial level has been raising in the last years supported by deposition rates up to 12kg/h (even higher with multi-wire systems) and laser processing heads with coaxial wire configuration, enabling a direction-independent processing, have increased the potential of the W-DED-LB process at industrial level.

Manufacturing of medium-/large-sized titanium components by W-DED-LB process is still challenging due to the specific processing requirements: inert atmosphere is required to avoid oxidation or oxygen enrichment of the deposited material and drawbacks linked to a complex heat management. The implementation of inappropriate building strategies would result in significant distortions and residual stresses in the final built component. In this sense numerical modelling methodologies play an important role on adoption of DED processes and its implementation at industrial level.

This study aims to stablish the manufacturing methodology based on W-DED-LB process able of ensuring the manufacturability of a large Ti6Al4V part (1300x350x100mm approximately), a flap track demonstrator. The paper shows the results of the work developed in order to:

- Establish the process parameters for the deposition of Ti6Al4V wire by laser DED process.
- Evaluate the properties of the deposited material.
- Define the manufacturing sequence (supported by experimental and simulation results) which will reduce the distortion of the manufacturing of a Ti6Al4V flap track by W-DED-LB process, considering its dimensions and final geometry (plane of symmetry).

2. Experimental set up

2.1. Experimental set-up

This experimental work was performed at the robotic DED working cell available at AIMEN facilities. It consists of a 6-axis industrial robot ABB4400 with an integrated coaxial laser wire head (Precitec CoaxPrinter). This laser process head allows completely direction-independent laser wire deposition. For those trials, a flexible inert chamber has been coupled between the robot and the two-axis positioner and filled with Ar to reduce the oxygen content below 400ppm. Main process equipment is a disk laser Trudisk, 16kW maximum power, coupled by 600µm optical fiber to the laser process head. Dinse system is used for wire feeding. Fig. 1 shows the process set-up.

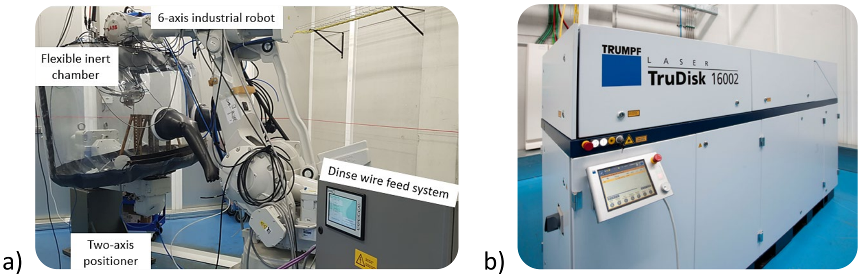

Fig. 1. Experimental set-up: (a) Robotic laser metal deposition workstation; (b) Laser source.

In order to cover the manufacturing of the flap track component, an upgraded version of the inert chamber was required in accordance with its dimensions. Considering the required volume of the inert chamber a recirculating system has been used to keep the oxygen and moisture levels under the correct limits (under 400ppm in both cases, fulfilling the AMS 4999 standard limit of 1200ppm for oxygen concentration) and reducing the Argon consumption.

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 under specification AMS4954K, which is the specified material for aeronautic applications. The base material used as substrate is a hot rolled Ti6Al4V plate in annealed condition with thickness between 10-12mm. The base material fulfills the specification ABS5125A. Table 1 shows the detailed composition of filler wire and the base material used as substrate.

Table 1. Chemical analysis of Ti grade 5 (filler wire and base material).

Element %	Al	V	Fe	O2	C	N	H	Ti
Wire	6.27	3.89	0.18	0.15	0.021	0.007	0.002	Bal.
Base material	6.13	4.00	0.16	0.16	0.02	0.01	0.0077	Bal

3. Experimental work and results

3.1. Process parametrization and characterization

Process parametrization has been carried out with the analysis of single tracks, where main key process as wire speed, laser power and process speed has been modified to reach the best ratio between dilution, geometry, and process stability. The metallographic evaluation of different experimental trials was performed to measure the size of the track and the dilution area and process parameters have been established; wire speed: 1,3m/min, laser power: 1,5kW and process speed: 12mm/s. In a second step, overlapped tracks has been carried out to determine the right overlap distance and to stablish a correlation between the number of overlapped tracks and the final width.

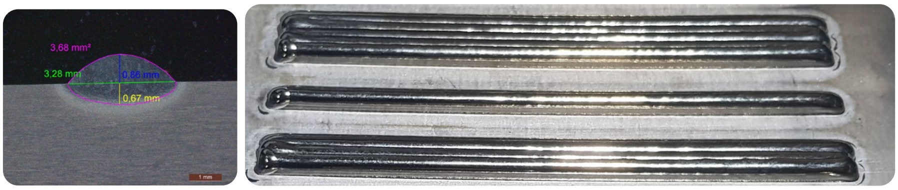

Fig. 2. (a) Cross section of a single track; (b) Multitrack deposited material.

Metallographic evaluation was also performed onto built up material with 10 overlapped tracks and 48 layers. As it is observed in Fig. 3 columnar prior-β grains are predominant, oriented nearly perpendicular to the substrate along the build direction (z-direction), and slightly tilted in the direction of cooling (wall laterals). Macrographic analysis does not reveals presence of defects as lack of fusion, cracks or pores.

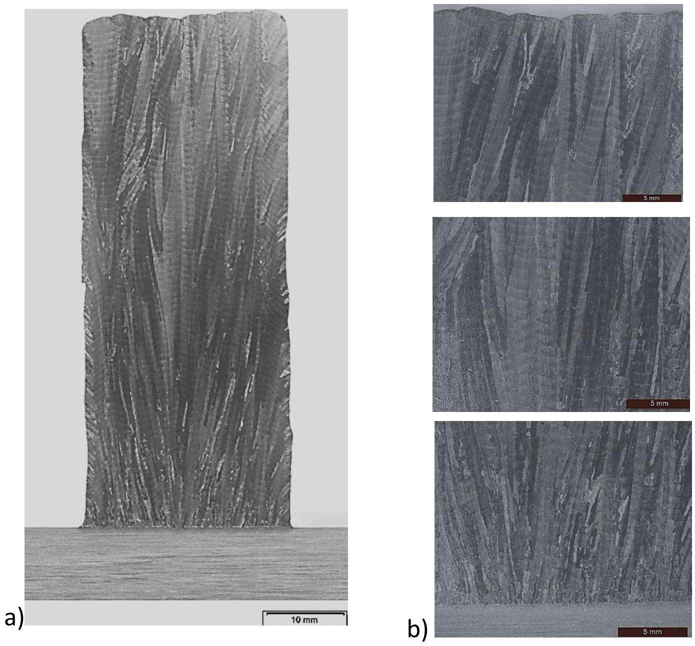

Fig. 3. (a) Metallographic cross section of deposited material; (b) Detailed view from top, medium and bottom of the macrograph.

Analysis of the composition of the deposited material was performed by Inductively Coupled Plasma Atomic Emission Spectrometry, according to ASTM E2371. Determination of N2, O2 and H2 has also being performed according to ASTM E 1409 and ASTM E 1447 respectively. Results from this analysis show that composition of de deposited material is within the limits specified on the standard AMS 4999.

Table 2. Composition of deposited material of Ti grade 5 (filler wire and base material).

	Element	Al	V	Fe	O2	C	N	H	Others Each	Others total
Deposited material	%	6.72	4.46	0.24		0.045		0.0063	<0.10	<0.40
Reference AMS 4999	% Min	5.50	3.50	-	0.11	-	-	-	-	-
	% Max.	6.75	4.50	0.30	0.20	0.08	0.05	0.015	0.10	0.40

Finally, tensile tests have been performed to evaluate the mechanical resistance of the deposited material as well as the elongation. In this case test coupons have been extracted parallel to the build-up direction, considered the worst-case scenario in terms of mechanical properties. Two conditions have been tested: as built and after stress relief heat treatment. Results show acceptable values of yield strength and ultimate tensile strength in as built condition (Rp02> 823MPa, Rm >918MPa respectively), reaching higher values on coupons tested after stress relief heat treatment (Rp02>861MPa, Rm>986MPa). In concordance with these results the elongation is lower on coupons tested after heat treatment, although the values exceed the minimum elongation required for the deposited material (>5.5%).

3.2. Process modelling and manufacturing strategies

Most of the FE (Finite Element) analyses for DED processes utilize transient models with a moving heat source, but in those models the calculation speed grows up exponentially as the scale of the model increases, and detailed studies on large-scale models are not feasible from the point of view of computational cost. Smaller-scale models are limited to reduced domains, therefore, to study the behaviour of a component at a global level, simplified models (distortion model) are required. In this case, the knowledge on simulation and additive manufacturing process at distortion level, allow us to establish some assumptions which directly impact on model simplification. For example, detail of the deposited material and melt pool fluid dynamics are not solved, and the metallurgical evolution of the material is not considered.

The development of FEM model for distortion analysis was performed considering the properties of Ti6Al4V alloy, and the real distortion and thermal data recorded from the manufacturing of small-scale parts. Several manufacturing sequences have been considered to carry out the calibration and validation against experimental data:

- One side manufacturing: manufacturing three full layers of the reference part recording the local distortion and the local thermal evolution.
- Both sides manufacturing (alternating layers): manufacturing of one layer per side up to second layer, continuing with 5 layers per side.

Distortion data recorded and results from simulation model have been plotted. As it can be observed in Fig. 4, the behaviour on distortion predicted by the simulation is similar to real data recorded from the manufactured sample. It is worth mentioning that in both cases higher distortion takes place on the first two layers, so to reduce the final distortion of the part in addition to both sides manufacturing it is advisable to compensate the distortion in the first layers.

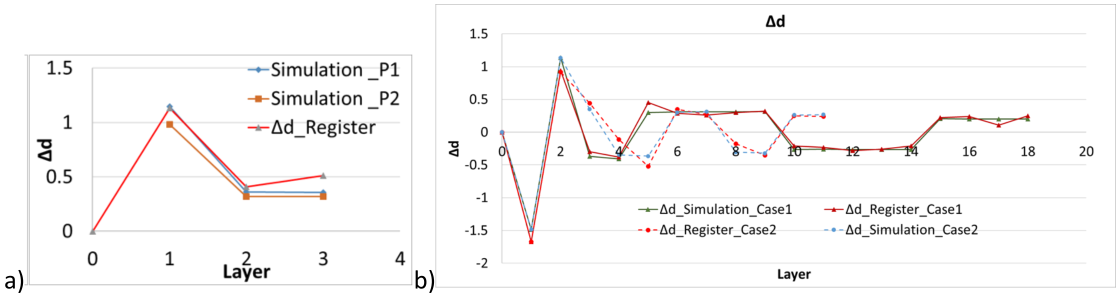

Fig. 4. Distortion data from simulation vs distortion recorded during manufacturing: (a) One side manufacturing; (b) Both sides manufacturing.

Before the manufacturing of the flap track structure, same procedure was followed in a larger part (500x300mm), with similar geometry of the flap track. In this case the manufacturing strategy lies on splitting the geometry into three different blocks. Each block was alternately deposited on both sides of the base plate until completion of the first layer on each side of the base plate, following with one full layer per side. With this strategy, the distortion is halved with respect to previous strategies. Distortion predicted by simulation in this case also shows a good matching with the distortion measured during the experimental trials as it is observed in Fig. 5.

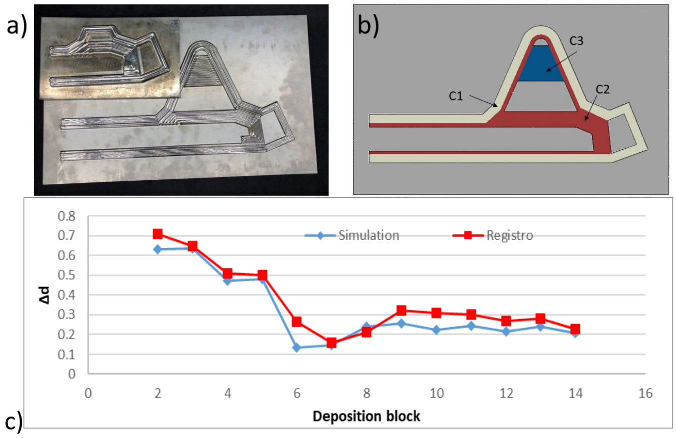

Fig. 5. (a) Manufactured samples; (b) Regions in which the part was split for manufacturing; (c) Distortion data from simulation and experimental.

3.3. Manufacturing of flap track demonstrator

Selected process parameters and simulation models previously validated against experimental data have been used to manufacture the flap track demonstrator.

From the 3D model of the flap track, the manufacturable geometry has been generated (oversized geometry adapted to the size of a track) and PowerMill software has been used to produce the path planning and the sequences which define the available manufacturing strategies. Based on the results from different manufacturing strategies, alternately deposition on each side of the substrate (being the substrate part of the final component) is the key strategy to reduce the distortion effect.

The flap track demonstrator has been manufactured and dimensional control of the part has been performed in as built condition by 3D scanning. Scanned data has been assessed and, although the distortion has not been quantified, the final geometry of the flap track fits inside the manufactured part, so low distortion of the manufactured demonstrator is foreseen.

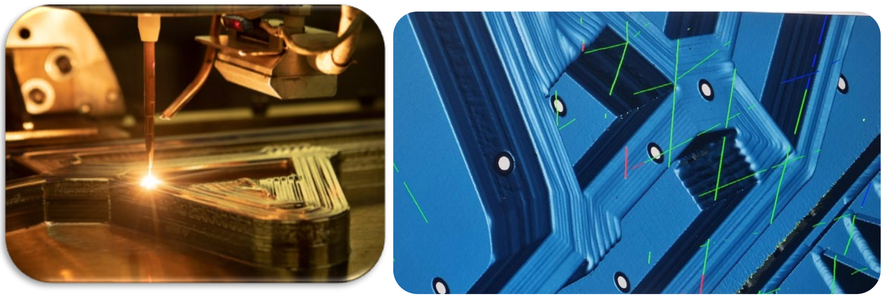

Fig. 6. (a) Manufacturing of the near net shape for the flap track demonstrator by W-DED-LB process; (b) Dimensional control by 3D scanning.

4. Conclusions

In this work the manufacturing strategy to manufacture a titaniun grade 5 demonstrator by laser wire DED process was set up. Process parameters for laser wire DED on titanium alloy Ti6Al4V have been optimizes and distortion has been evaluated, experimentally and by modelling. From the previous analysis following conclusions are reached:

- Process parameters have been selected according the best balance between dilution, geometry, and process stability.
- Macrostructure analysis reveals columnar growth of prior-β grains wall structures. Layered bands are clearly observed in wall structures .
- Chemical composition of the deposited material fulfills the requirements stablished by the ASM 4999 standard for Titanium Alloy Direct Deposited Products.
- Under simplified conditions considered for modelling, the simulation models show a strong correlation with the real data. According to simulation results, maximum distortion of the base plate takes place in the first two layers, being highest in the first deposited layer.
- 3D geometry of the flap track demonstrator fits in the geometry of the manufactured demonstrator, so according to those first resuls minimum distortion of the substrate/demonstrators is foreseen.

Acknowledgements

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