Additive Manufacturing of Ti6Al4V with Wire Laser Metal Deposition Process

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Abstract. Additive manufacturing (AM) using wire as an input material is currently in full swing, with very strong growth prospects thanks to the possibility of creating large parts, with high deposition rates, but also a low investment cost compared to the powder bed fusion machines.

A versatile 3D printing device using a Direct Energy Deposition Wire-Laser (DED-W Laser) with Precitec Coaxprinter station to melt a metallic filler wire is developed to build titanium parts by optimizing the process parameters. The geometrical and metallurgical of produced parts are analyzed. In the literature, several authors agree to define wire feed speed, travel speed, and laser beam power as first-order process parameters governing laser-wire deposition. This study shows the relative importance of these parameters taking separately as well as the importance of their sequencing at the start of the process. Titanium deposit are obtained with powers never explored in bibliography (up to 5 kW), and wire feed speed up to 5 m.min^{-1} with a complete process repeatability.

Introduction

Additive layer manufacturing (ALM) often called 3D printing has demonstrated to be very effective in shortening the time to manufacture with respect to traditional machining approaches [1]. Among the other advantages allowed by these techniques, we can cite a saving of material and cost due to low material waste [2]. For example, the buy-to-fly ratio for a part machined from a forged billet is typically 10 – 20 [3] and can potentially drop to nearly 1 when produced by AM techniques [4]. This material saving and reduction in manufacturing times is all the more important for the additive manufacturing techniques based on wire, thanks to a material used close to 100% and much higher deposition rates than the rates using in additive powder manufacturing [5, 6].

Complementary in the aerospace industry, wire-based additive manufacturing techniques have received much less attention than powder-bed techniques despite the increasing demand for these technologies, thanks to their significant potential, particularly for large parts manufacturing. This work focuses on a Ti-6Al-4V titanium alloy, which is one of the most expensive alloys, but also one of the most used in the aerospace industry, because its low density, its very good mechanical properties and its resistance to corrosion [7].

In this paper, the importance of the sequencing of the first order parameter at the start of DED-W Laser process is discussed and demonstrated. This understanding of the impact of the sequencing of all the parameters governing the laser wire deposition for the TA6V wire made it possible to define the complete operating range of the Coax Printer laser head with 100% process repeatability.

Experimental Method

During this study, two campaigns of about thirty, 120 mm long, single deposit (fig. 1) were carried out to determine the operating range for the Coaxprinter laser head and the impact of the sequencing of first order process parameters on the deposit. The experimental design was generated by Corico software [8]. All the deposits are made with Ti-6Al-4V wire of diameter 1.2 mm on 150 mm x 30 mm x 10 mm Ti-6Al-4V plates.

The DED-W Laser process cell is composed of a KUKA KR60-HA 6-axis robot with its controller KUKA KRC4. The energy used to meld wire and substrate is provided by a 6 kW TRUMPH TruDisk 6001 laser source with a wavelength of 1030 nm. The laser head mounted on the robot leads the laser beam through several lenses to obtain a focal spot which has the geometry of a ring (PRECITEC CoaxPrinter). The wire is conveyed at the center of the ring spot thanks to a wire feeder (DIX WD 300) (fig. 1).

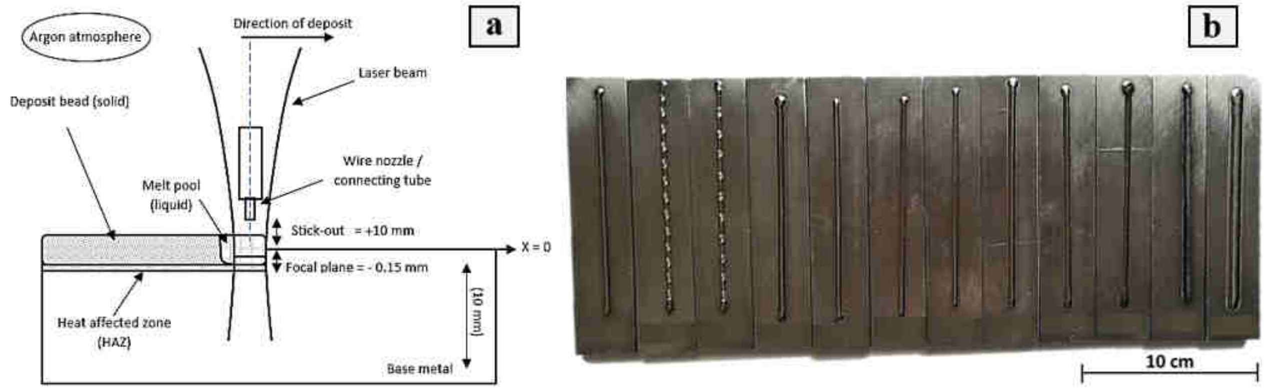

Figure 1 – (a) Schematic drawing of the DED-W Laser process [9], (b) Optical observation of few single deposits made by DED-W Laser

The gazeous protection during the DED-W Laser deposit for the two campaign is maintained similar and ensured by an argon inerted chamber. The chamber design is based on the fact that argon is heavier than the air: by pushing argon continuously on the box bottom, the air is progressively expelled out of the chamber. Moreover, to avoid perturbation due to welding torch displacement and trapped oxygen the argon flow must be laminar and continuous.

The only parameters varied between the two campaigns are the sequencing of the order of laser beam start, wire and robot movement at the beginning of the process as shown in figure 2. During the first campaign deposits, wire feed was initiated 0.2 second after the laser was set on, and the robot movement was started 0.1 second after. The process was therefore initiated about 0.3 seconds before the robot begun to move. During the second campaign, the order of starting the laser beam and the arrival of the wire is reversed. The wire was thus sent first, followed by the start of the laser beam after a time specific to each set of parameters tested. This time, called $X_{(WFS)}$, corresponds to the required by the wire to travel the distance separating it from the substrate. The robot movement was always initiated 0.3 seconds after the laser beam starts.

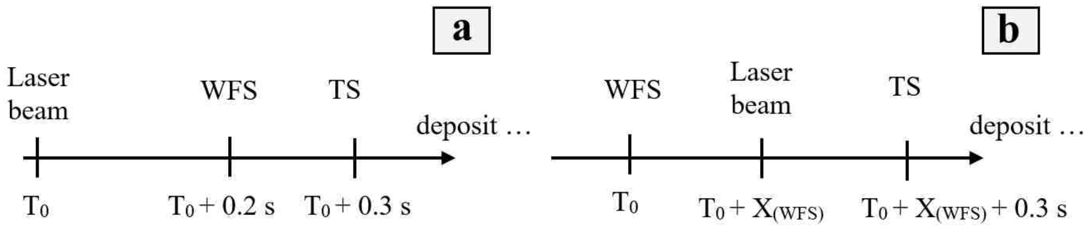

Figure 2 – Sequencing of the first order parameters on first (a) and second (b) campaign

The ranges of variation of laser power (P), wire feed speed (WFS) and travel speed (TS) during these two campaigns are given in the table below.

Table 1 - Ranges of first order parameters variation during first and second campaign

	First campaign	Second campaign
Laser Power (P) [kW]	1 to 3.25	1 to 5
Wire feed speed (WFS) [m.min^{-1}]	0.8 to 6.4	1.1 to 5
Travel speed (TS) [m.min^{-1}]	0.3 to 2.35	0.24 to 3

In order to have a follow-up of the thermal deposit during the process, a thermal camera (SWIR WiDy SenS 640V-ST) is used. The obtained deposits are then scanned with the 3D ATOS scanner and the microscopic characterizations are carried out with the binocular (Leica wild M420) and the optical microscope (Olympus PMG3).

Results and Discussion

- **Optimization of the LMD-w process:**

If the laser and then the feed of the wire were on (test campaign 1), many problems occur when starting the deposits. The formation of a drop of molten titanium appears at the end of the wire and rises by capillarity towards the contact tube, which causes its fusion (fig. 3b). The contact tube also melts for any laser beam power greater than 3 kW preventing any deposit of wire because of the reflection of the beam on the substrate (fig. 3a). Then the laser power was limited to 3.25 kW during the first campaign.

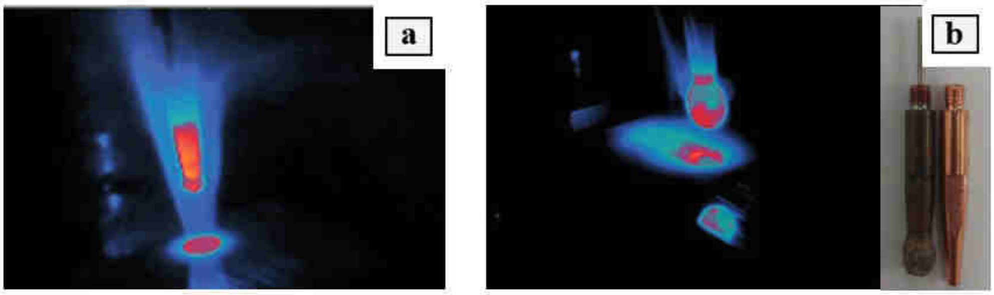

Figure 3 – Thermal image indicating the various problems encountered at the initiation of the DED-W Laser process: formation of liquid drop (a) contact tube fusion (b) (first campaign)

By reversing the sequencing of wire and laser start-up, these deposit initiation problems are resolved. Indeed, starting the laser beam after the arrival of the wire makes it possible to melt the wire and the substrate at the same time. The rising of liquid metal by capillarity as well as the reflections responsible for the fusion of the contact tube no longer occurs (fig. 4).

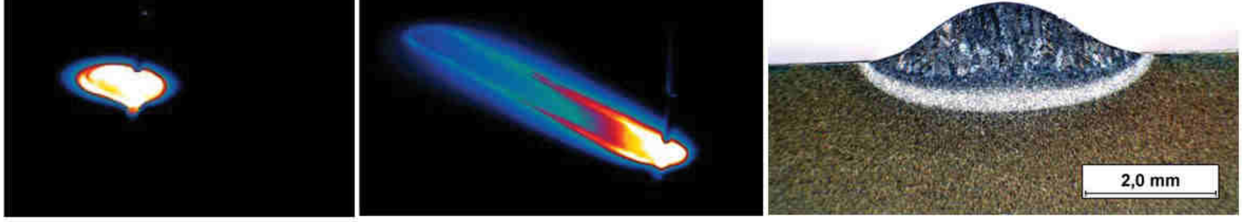

Figure 4 - Initiation (a), deposition (b) and cross section (c) of the deposit at P = 5 kW (second campaign)

These improvements of the starting procedure of the DED-W Laser process have made it possible to extend its field of use and allowed to explore a broader range of process parameters (fig. 5).

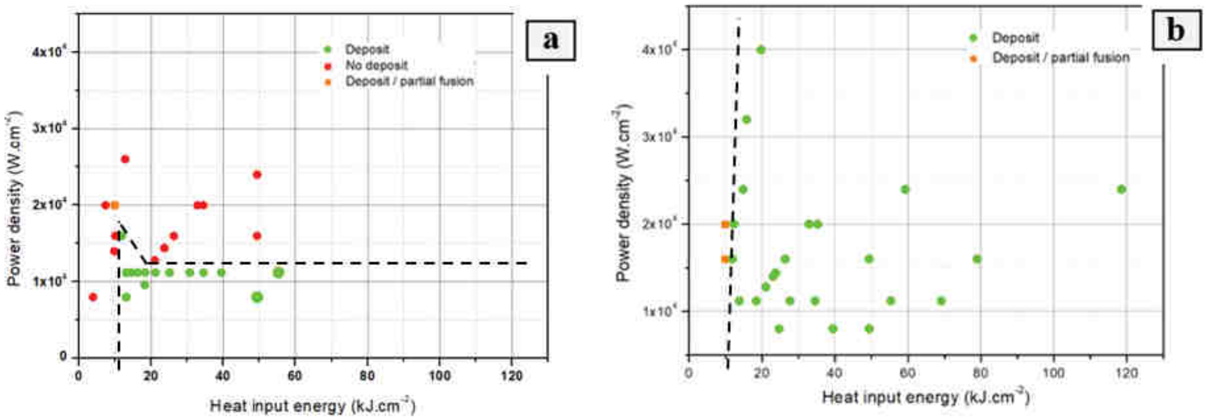

Figure 5 - Determination of the deposition operating ranges for the first (a) and the second (b) campaign according to power density and heat input energy parameters in DED-W Laser process

A minimum energy equal to 10 kJ.cm^{-2}, is necessary to melt the wire on the substrate. If the energy value is between 10 and 12 kJ.cm^{-2}, the deposit is partially melted with the substrate as evidenced by the micrographs in section of the beads (fig. 6).

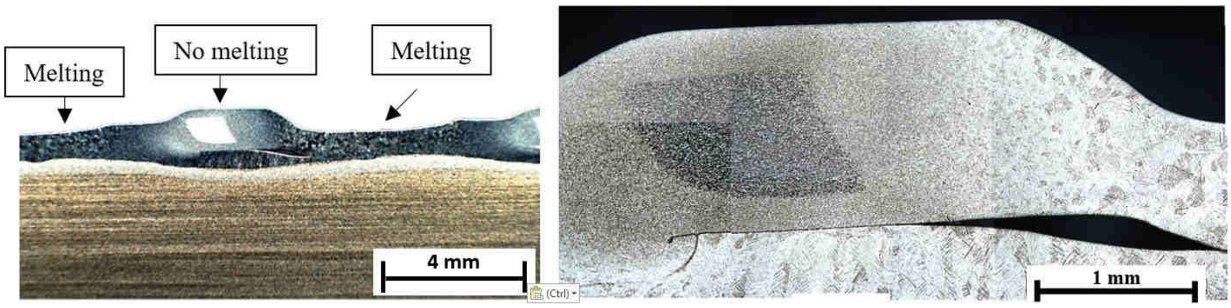

Figure 6 - Longitudinal section micrography of Ti-6Al-4V DED-W Laser deposit with heat input energy equal to 10 kJ.cm^{-2}

- **Construction of thin wall:**

In order to build thin walls, a set of a parameters has been chosen, taking into account geometrical parameters such as: the shape of the deposit, its wetting angles in order to avoid a collapse of the bath or poor stacking of deposits, but also metallurgical parameters such as the depth of the remelted zone or the material health in order to ensure sufficient mechanical properties of the built walls.

For this construction, the set parameters are: P = 2 kW / WFS = 1.8 m.min^{-1} / TS = 0.3 m.min^{-1} (Fig. 7a).

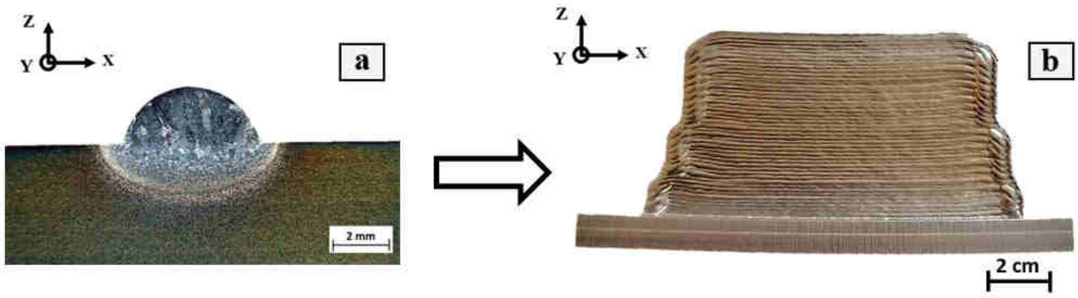

Figure 7 – Cross section of the deposit selected for the construction (a), front view of thin wall (b)

For this wall, a stack of layered deposits in a round-trip direction with 2 min pause time between each layer was followed. This allowed to build this thin wall composed by 44 stacked layers with dimensions of 120 mm long (at the base) and 55 mm high were thus built, and no weld pool collapse or lack of fusion occurred during construction.

During the thin wall construction, the stick-out was manually corrected 4 times. This is due to a sagging of the bead deposited due to the heat accumulation generated by the process, a vertical (Z direction) increment equal to the height of the single deposit is no longer sufficient in this case. 2 offsets along the horizontal axis (X direction) were carried out to compensate for the slight collapse of the deposit at its ends and keep a good stick-out, avoiding the degeneration of the LMD process. The rough surface finish of the wall is very regular, with a maximum roughness found of 180 µm thanks to a study by 3D microscopy.

- **Construction of thick walls:**

For the thick walls construction, the following set of parameters was chosen: P = 3 kW / WFS = 2 $m.min^{-1}$ / TS = 0.3 $m.min^{-1}$. Two construction strategies were tested: a strategy of linear deposition and a interlacing deposition strategy (Fig 8). To prevent any lack of fusion or stick-out variation during construction, an experimental study was carried out to find the correct overlap steps in the 2D plane. This study allowed to fix an overlapping of deposit of 4.7 mm for a deposit width equal to 6.62 mm. However, it turned out during the construction that this set of parameters is too energetic (from the 3rd layer deposited) in relation to the deposition substrate used and we feared an overheating in the building chamber. This one was thus abandoned despite a good stacking of layers and an absence of porosities or lack of fusion in the 3 stacked 2D planes as shown in the following microscopic image.

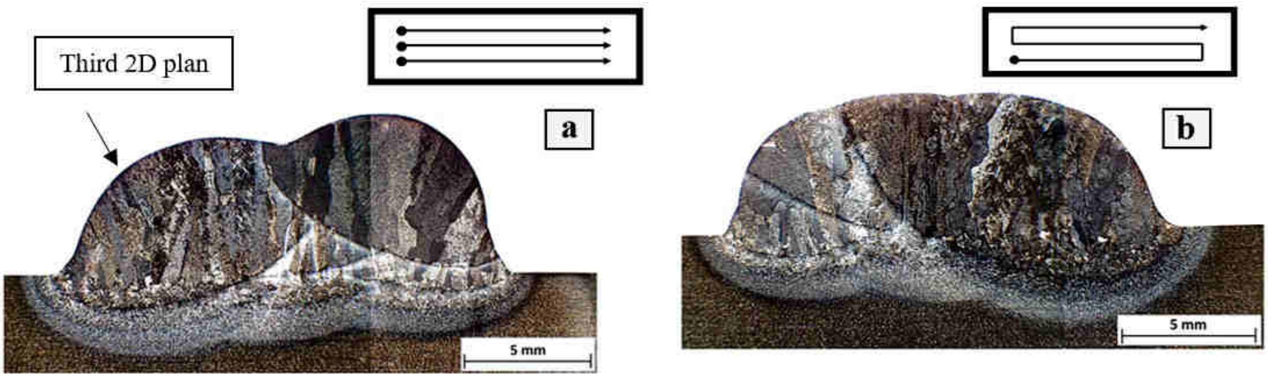

Figure 8 – Cross section of the first three 2D plan built with linear (a) and zig-zag (b) strategy

To overcome this problem, two new set of less energetic parameters are tested. A power variation law is also used to better control the thermal of the weld pool during the process. This law is summarized in a lowering of the power as the construction progresses, as explained in the table below. Note that a contour path has been added around the interlacing strategy during the following constructions (fig. 9).

Table 2 – Process parameters used in the construction of thick walls

	First set	**Second set**
Wire feed speed (WFS) [$m.min^{-1}$]	1.4	1.4
Travel speed (TS) [$m.min^{-1}$]	0.9	0.9
Laser Power (P) [kW]	1.4 (first two 2D plans) 1.4 to 1.2 (for 4 min) 1.2 (until end)	1.6 (first two 2D plans) 1.6 to 1.4 (for 4 min) 1.4 (until end)

The use of these 2 set of parameters associated with a Z-increment height equal to that of the single deposit allowed the continuous construction of a thick wall with the first set of parameters and two walls with the second set. These are 100 mm long, 55 mm high and 11 mm thick, and each were built in 36 minutes. No process-stop or stick-out correction were made during the deposits.

Finally, no lack of fusion or weld pool collapse were observed and a particularly smooth surface finish is observed (maximum roughness of 100 µm for the 3 walls).

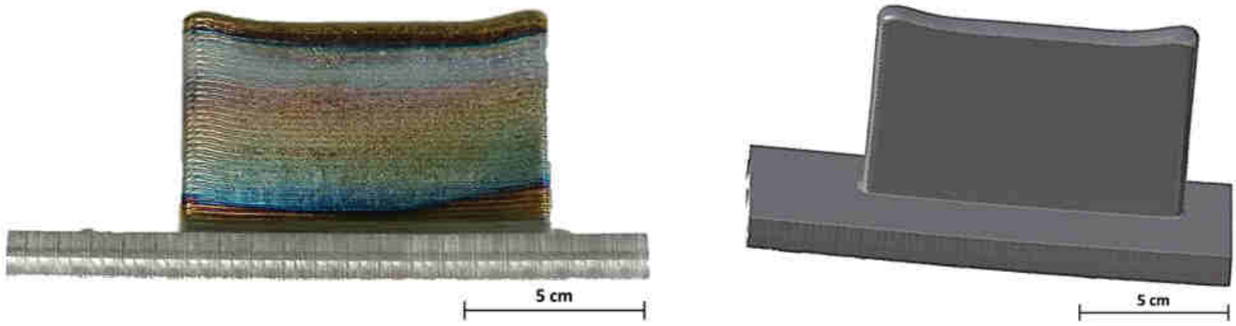

Figure 9 – Front view of thick wall made by LMD-w process. (a) optical observation, (b) 3D morphology obtained by digital reconstruction

Conclusion

(1) During laser-wire deposition with the Coaxprinter laser head, the sequencing at the start of the first order parameters has a great influence on the initiation and the deposition in DED-W Laser process.
(2) With the Coaxprinter head, deposits with a maximum laser beam power of 5 kW, a wire feed speed of 5 $m.min^{-1}$ and a travel speed of 3 $m.min^{-1}$ can be made.
(3) To completely melt a Ti-6Al-4V wire with a diameter of 1.2 mm, a minimum heat input energy of 12 $kJ.cm^{-2}$ is necessary in DED-W Laser process.

Acknowledgments

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