Study of the Impact of the Synergic Line and the Strategy of Conception on Ti-6Al-4V Wire Arc Additive Manufacturing Process (WAAM-CMT)

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Abstract. In additive manufacturing, technologies based on the fusion of a metallic wire using an electric arc represent an interesting alternative to current manufacturing processes, particularly for large metal parts, thanks to higher deposition rates and lower process costs than powder or wire-laser technologies.

A versatile 3D printing device using a DED-W Arc (Direct Energy Deposition by wire-arc) station to melt a metallic filler wire is developed to build titanium parts by optimizing the process parameters and control the geometrical, metallurgical and the mechanical properties of produced parts.

In this study, the impact of two different CMT synergic lines on the energetic and geometric behavior of Ti-6Al-4V single deposits is highlighted. These are related to first order parameters: wire feed speed (WFS) and travel speed (TS). The results show difference on energy, geometric of deposits and different deposition regime between these two law with identical process parameters.

The second part of this study focuses on the transition from single deposits to walls and blocks. By first choosing the best set of process parameters to make the construction of thin walls (composed of stacked layers), and then the research the optimal horizontal step of deposition (overlapping) for thicker constructions, results obtained made it possible to validate transition from single deposits (1D) to thick walls (3D) without any weld pool collapse or lack of fusion.

Introduction

The Wire Arc Additive Manufacturing (WAAM) is a Direct Energy Deposition Wire-Arc (DED-W Arc) approach derived from welding. This technology employs a wire as filler metal and an electrical arc as heat source to produce wire melting and matter deposition to produce part preform, layer by layer [1]. In addition to a low investment compared to other additive manufacturing techniques, thanks to machines and components directly derived from welding industry [2], the use of an electric arc as a source of fusion offers a number of processing advantages, compared to electron beam and laser [3].

Thus, electric arc offers a higher efficiency fusion source than laser and electron sources [4]. This is of benefit from an energy consumption perspective, in particular, for reflective metal alloys such as aluminium, copper [5] and magnesium [6]. The processing characteristics may also make the DED-W Arc process preferable compared to the alternative fusion sources. For example, DED-W Arc does not need a vacuum environment to operate as required in electron beam-based methods [7].

Finally, the use of wire as an input material in DED-W Arc offers an advantage compared to powder additive manufacturing process, such as a higher deposition rate, materials saving due to no need for powder recycling [8], and reducing health and safety concerns. Wire is also offering a significant reduction in price per unit weight compared to powder in a large range of engineering materials such as for the aerospace alloy Ti-6Al-4V [9]. This alloy is widely used in the aerospace field thanks to its very good mechanical properties and good resistance to corrosion, and will be the material employed in this study. The aim of this paper is to produce a comprehensive approach to determine influence of process parameters, deposition strategy and synergic laws on material health, geometry of single deposits, thin walls and thick structures.

Experimental Method

Two different synergic lines (a non-pulsed line, called NIBAS and a pulsed line called 1007), from database R01-1663 (DB 0164) are tested on Ti-6Al-4V alloy wire to produce 120 mm long single deposits on 150 mm x 30 mm x 10 mm substrates. Subsequently, according to geometric and metallurgical criteria, a selection of sets of parameters for the two synergic lines is carried out, in order to manufacture thin and thick walls with Cold Metal Transfer DED-W Arc process.

For these two synergic lines, a first study according to the travel speed (TS) at fixed wire feed speed (WFS), then a second study according to the wire feed speed at fixed travel speed are carried out (Table 1). The energy parameters during the process are directly recorded by the FRONIUS machine. The widths and contact angles of the simple deposits are measured on numerical models obtained by the ATOS 3D scanner, using the ABViewer 14 software. The heights and penetration depth of the single cords are measured by optical microscopy in cross section after cutting (Fig. 1) and etching with the KROLL reagent.

Table 1 – Experiment design parameters for DED-W Arc deposits

	NIBAS synergic line	**1007 synergic line**
Wire feed speed (WFS) [m.min^{-1}]	2 to 10	2 to 12
Travel speed (TS) [m.min^{-1}]	Fixed at 0.36	Fixed at 0.36
Wire feed speed (WFS) [m.min^{-1}]	Fixed at 8.5	Fixed at 8.5
Travel speed (TS) [m.min^{-1}]	0.06 to 1.2	0.06 to 1.2

The DED-W Arc process cell is composed of a 6-axis robot (KUKA KR100-2 HA 200) with its controller (KUKA KR C2-05 AK9) and welding station (FRONIUS TPS 3200 CMT Remote) and wire feeder (FRONIUS VR 7000-CMT 4R/G/WF++). The O_2 protection during the DED-W Arc deposit is 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, 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.

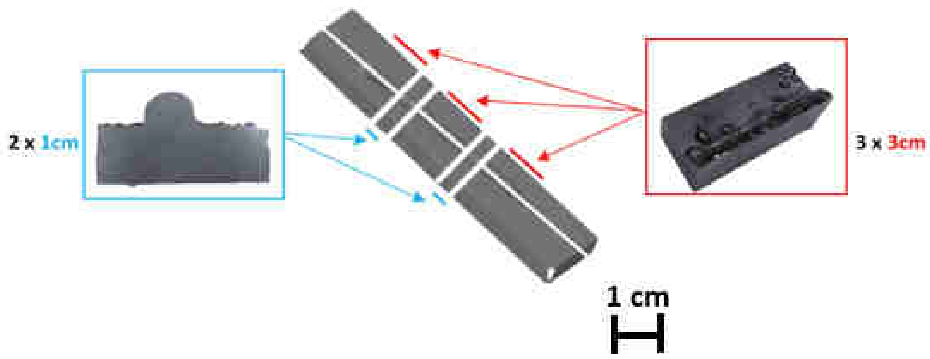

Figure 1 – Sampling and analysis plans for DED-W Arc single deposits

Results and Discussion

- **Impact of the variation of the travel speed (TS) on single deposits:**

By increasing the travel speed during deposition, the width of the deposits decreases whatever the two synergic lines. On the contrary, the deposited are more and more spread out with higher contact angles. Thus, a wider deposition profile in the middle than at the bottom of the deposit, incompatible with any type of construction is observed for the lowest deposition speed (TS = 0.06 $m.min^{-1}$).

Moreover, the travel speed seems to impact the regularity of the deposits as shown in the Fig. 2. Thus, the best deposition regularities are obtained for intermediate travel speeds (between 0.3 and 0.6 $m.min^{-1}$) for the two synergic lines. For these parameters, the electric arc is the most stable.

The deposits obtained with the NIBAS synergic line are more regular than those of the 1007 pulsed line. In fact, a large number of projections is generated by the 1007 line; these projections sometimes merge with the deposit increasing its width locally.

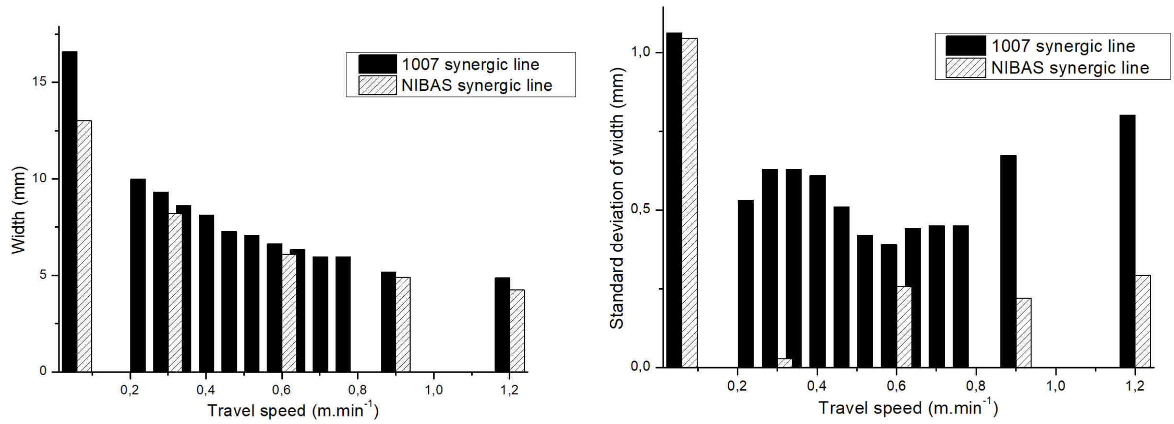

Figure 2 - Evolution of the width and its standard deviation of the deposits according to travel speed (TS)

Concerning energetic behavior of the CMT process, an increase in robot speed leads to a decrease in energy density delivered per unit volume for the two synergic lines tested, with however an energy delivered higher for the 1007 line compared to the NIBAS line for identical process parameters.

- **Impact of the variation of the wire feed speed (WFS) on single deposits:**

By increasing the wire feed speed, the width of the deposits increases. Likewise, the profile of the deposits changes as a function of the WFS. Below 10 $m.min^{-1}$, the contact angle is greater than 90° and above it is greater than 90° with the NIBAS law (fig. 3). One must notice that this behavior is not observed for the 1007 pulsed line, where the deposits exhibit contact angles greater than 90 °.

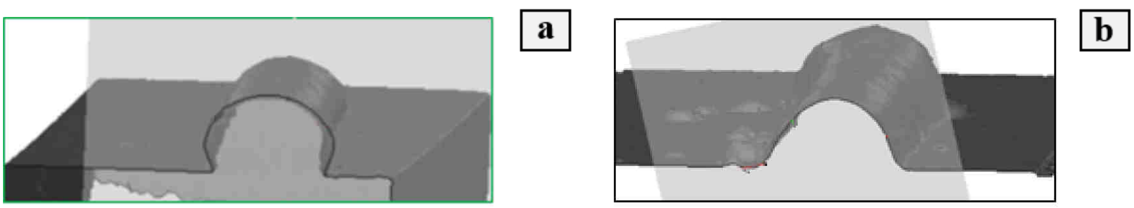

Figure 3 – Cross section of single deposit with (a) NIBAS and (b) 1007 synergic line / WFS = 10 m.min-1 / TS = 0.36 m.min-1

The variation in the wire feed speed also seems to impact the regularity of the deposits. An increase in the WFS thus leads to increasingly regular deposits for the two synergic lines tested. This is due to a different deposition regime of the molten metal droplets between low and high wire feed speed. In the first case (low WFS), the drop deposition is made directly on the substrate since the small amount of wire previously deposited does have time to spread out. On the contrary, by depositing at high wire feed speed, the liquid metal previously deposited does not spreads over the substrate generating an actual stick-out of deposit slightly lower than for low wire feed speed, and a drop deposition distance gets shorter, eliminating numbers of projections. This phenomenon indirectly contributes to the irregularity of the printed deposit for low WFS by increasing the number of projections, since these projections attract the initiation of the electric arc towards it during deposition causing a deviation of the deposit, resulting in wavy deposits as shown in Figure 4.

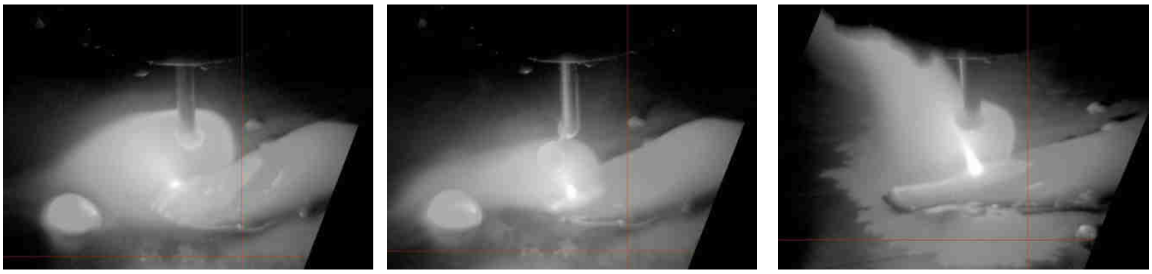

Figure 4 – Behavior of the liquid deposit in the presence of projection (1007 synergic line / WFS = 4 m.min-1 / TS = 0.36 m.min-1)

Note that contrary to the energetic behavior during the variation of the travel speed, the variation of the wire feed does not lead to an evolution of the quantity of energy per unit volume of material, generating a quasi-stability in deposits metallurgy [10].

- **Construction of thin walls:**

In order to build thin walls, a set of parameters was selected for each synergistic line, taking into account geometric parameters in order to avoid a collapse of the bath or poor stacking of deposits. For the pulsed 1007 synergic line, the pair of parameters: WFS = 6.5 $m.min^{-1}$ / TS = 0.36 $m.min^{-1}$ has been chosen (Fig. 5, a) while the pair of parameters WFS = 8.5 $m.min^{-1}$ / TS = 0.6 $m.min^{-1}$ was chosen for the NIBAS law (Fig. 5, b).

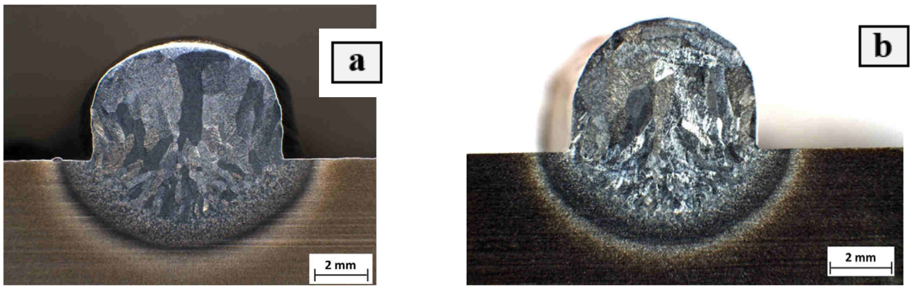

Figure 5 – Cross section of the deposits selected for the construction of thin walls; (a) 1007 line, (b) NIBAS line

For the construction of thin walls, a stack of layered deposits in a round-trip direction without pause time was followed, with a Z increment (vertical direction) equal to the height of the single deposit.

Two walls with dimensions of 120 mm long and 55 mm high were thus built with each type of synergic line.

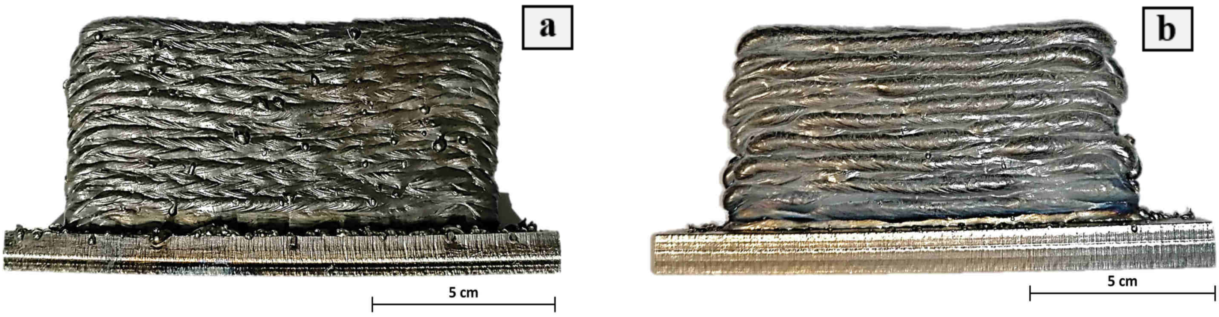

Figure 6 – Thin walls built with 1007 (a) and NIBAS (b) synergic lines

No weld pool collapses or lack of fusion occurred during construction. The machining of these walls allowed to obtain completely smooth walls with thicknesses between 3 and 3.7 mm.

- **Construction of thick walls:**

For the construction of thick walls, the 1007 pulsed synergic line was chosen thanks to a more spread out profile of deposit and higher contact angles than those of the NIBAS synergic line. Two constructions strategies (linear and zigzag) were tested. The set of parameters chosen for printing (with both strategies) is: WFS = 8.5 m.min^{-1} and TS = 0.9 m.min^{-1}.

Before any construction, an experimental study was carried out to find the correct overlap steps in the 2D plane. This search allows to find the correct overlapping of deposition avoiding the lack of inter-deposit fusions or a too close superposition causing a loss of flatness of the 2D plane (and thus a stick-out variation), and the appearance of lack of fusion (due to an initiation of the electric arc on the side deposit and not the deposition substrate) as shown in Figure 7. This study made it possible to set an overlapping deposition equal to 3.3 mm for the linear strategy and 4 mm for the zigzag strategy of deposition.

Note that several authors have numerically followed this step of correct overlap deposition research on DED-W Arc process [11, 12].

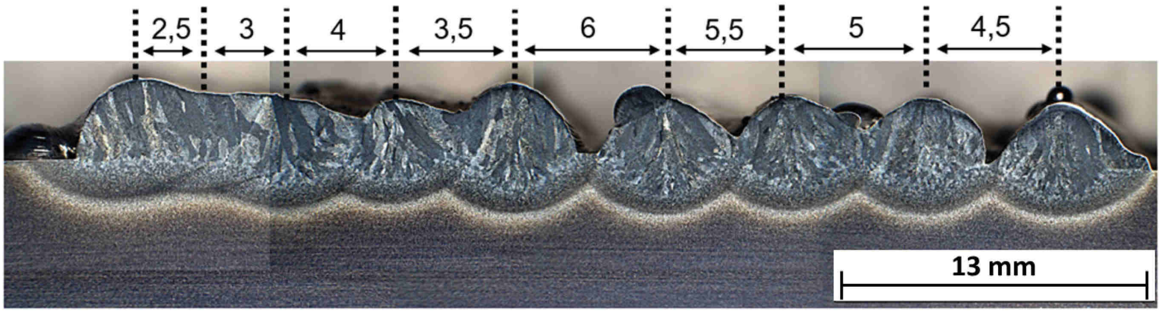

Figure 7 - Evolution of the deposits profiles as function of the overlapping distance (1007 synergic line)

For the construction of the linear deposition wall (Fig. 8), a stacking of deposits in one direction and without pause time was followed within the considered horizontal plane, while an inversion of the direction of deposit of the next layer and a pause time was carried out between each planes. During construction, an increment in Z (vertical direction) equal to the height of the single deposit is performed.

Dimensions of the two walls are 120 mm x 55 mm, with a 25 mm width for the linear strategy and 30 mm width with the zigzag strategy. Both were produced with the pulsed 1007 synergic line. No weld pool collapse or lack of fusion occurred during constructions.

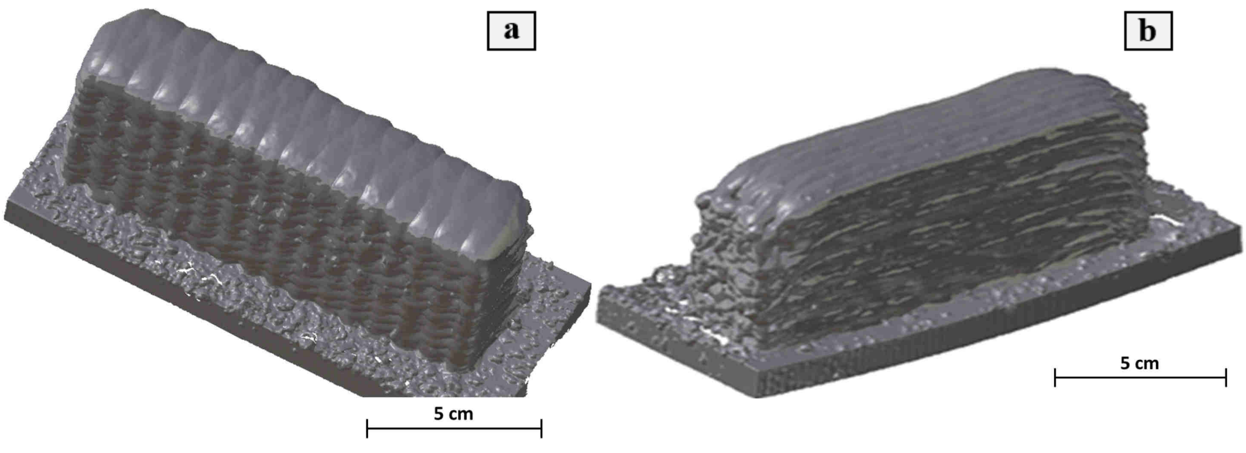

Figure 8 – Thick walls with 1007 pulsed synergic line with (a) zigzag, and (b) linear deposition strategy

Summary

(1) With similar process parameters, the deposits made with the NIBAS synergic law are higher and narrower than those obtained by the pulsed 1007 synergic line.
(2) With the two synergic lines, the regularity of deposits seems to be better for intermediate travel speeds and high wire feed speed.
(3) Above a wire feed speed of 10 $m.min^{-1}$, and for a robot speed equal to 0.36 $m.min^{-1}$, the deposit profile tendency is reversed with the NIBAS synergic line, contrary to the 1007 one.
(4) Thanks to its geometric profile, the NIBAS synergic line deposits seems suitable for the construction of thin walls, while the 1007 line ones seems suitable for wide constructions.

Acknowledgments

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