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Effects of WAAM process parameters on metallurgical and mechanical properties of Ti-6Al-4V deposits

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Abstract. Additive manufacturing is a revolution for many sectors of the industry. These new manufacturing processes allow a substantial saving of raw material while optimizing the geometry, and at the same time reducing development costs, by reducing the time between the concept and deployment phases of a product. A 3D printing device using a Cold Metal Transfer (CMT) arc welding station to melt a metallic filler wire is developed to build titanium parts by optimizing the process parameters to control metallurgical and mechanical properties of parts. In this study, two parameters (wire feed speed and movement speed of the robot) have been studied. Their impact on the metallurgical, dimensional process stability and mechanical properties of materials have been analyzed. Microstructure and mechanical properties vary depending on the energy expended during manufacture. This energy remains constant or decreases respectively when the wire feed speed or the robot head travel speed increases. Indeed, the electric generator adapts its power according to the speed of the wire. Regardless of the energy parameters, the movement speed of the robot seems to influence the wetting angles, the depth of melted zones, remelted and heat affected zones and the metallurgy with a refinement of the substructure of the deposits.

Keywords: Ti-6Al-4V alloy, Wire and Arc Additive Manufacturing, Cold Metal Transfer, Microstructure.

1 Introduction

Additive Manufacturing (AM) is a promising way to produce near-net shape metallic parts with complex geometries. It offers many advantages compared to machining processes, as reductions in the manufacturing lead-time and cost due to low material waste (Frazier 2014).

The Wire and Arc Additive Manufacturing (WAAM) is a Direct Energy Deposition (DED) additive manufacturing process derived from welding that uses a wire as filler metal and an electrical arc as heat source to produce wire melting (Williams *et al.* 2016). It is a promising process, especially because of its high deposition rate (Ding *et al.* 2015) (Martina *et al.* 2012), high energy efficiency (Dupont and Marder 1995), low-cost of raw materials, low material losses, and its capability to manufacture large parts (Williams and Martina 2015). Among the various arc processes that can be used for wire melting, the Cold Metal Transfer (CMT) process seems to be one of the more suited for WAAM, thanks to its controlled current waveform and filler wire feeding that allow to obtain regular deposited weld bead and a mechanical control of the detachment of the molten drops ensuring the deposition of weld seams without or with very few projections (Gomez Ortega 2018).

Currently, few studies have been done on single-deposits Ti-6Al-4V produced by CMT. Most of the studies on CMT Ti-6Al-4V have been done on walls, and the impact of layer superposition on microstructure and mechanical properties has been studied. Ding et al. (Ding et al. 2015) show that the height of the seams increases and their width decreases with the translation speed of the laser. Zhang observes a decrease in the penetration depth of the bead and of the wetting angles as a function of the speed of the robot by CMT on magnesium alloys. The present work is a contribution to the knowledge of the effects of these parameters (movement speed of the robot and wire feed speed) on the metallurgical and mechanical properties of material added on parts made by the CMT process to bring new functions.

2 Experimental procedure

2.1 Description of process

The cell is composed of a 6 axis robot (KUKA KR100-2 HA 2000) with its controller (KUKA KR C2-05 AK9) and a welding station (FRONIUS TPS 3200 CMT Remote) and a wire feeder (FRONIUS VR 7000-CMT 4R/G/W/F++). We choose a Ti-6AL-4V wire from the supplier Technalloy, its diameter is 1.2 mm. The welding process is inside an argon inerted chamber to ensure the protection of the Titanium weld bead against oxidation. The chamber design is based on the fact that Argon is heavier than the air: by pushing argon continuously in the box bot- tom, we progressively expel the air definitively. The chosen welding process is a derivate MIG/MAG process developed by FRONIUS and it's called CMT (Fronius International GMBH 2018). We choose the synergic law 1011 from the data-base R0981. The synergic law combines the wire feed speed and the delivered energy. Our experimental approach is to separate the robot speed and the wire feed speed. For that purpose, we print 10 seams from 0.5 to 1.3 cm.s^{-1} for movement speed of the robot and 10 seams from 6 to 10.5 m.min^{-1} for the wire feed speed. Current and energy measurements are measured and supplied directly by the FRONIUS machine

2.2

Characterization techniques

Dimensional analyzes of seams were measured with 3D ATOS scanner and analysed with CATIA V5 and ABviewer 12 software. All the seams were mechanically sectioned along the longitudinal and transverse directions from the central part (figure 1). The specimens were prepared in epoxy mount, ground with 600, 1200, 2500 grit SiC paper under water, polished with OPS solution with hydrogen
peroxide to a mirror finish. They were then etched with the Kroll attack reagent composed of 3 mL of 40% hydrofluoric acid, 2 mL of 68% nitric acid and 95 mL of distilled water. Matter health and microstructure were observed by optical (Leica wild M420 binocular and Olympus PMG3 microscope) and scanning electron microscopy (SEM JEOL JSM-7000F) on polished and etched specimens. EBSD analyzes (Oxford Nordlys II F+ camera) were done to determine the fine microstructure of each zone of the seam. Finally, longitudinal and transverse Vickers hardness filiations were made using a ZWICK ZHU 2,5 durometer with a load of 5 kg.

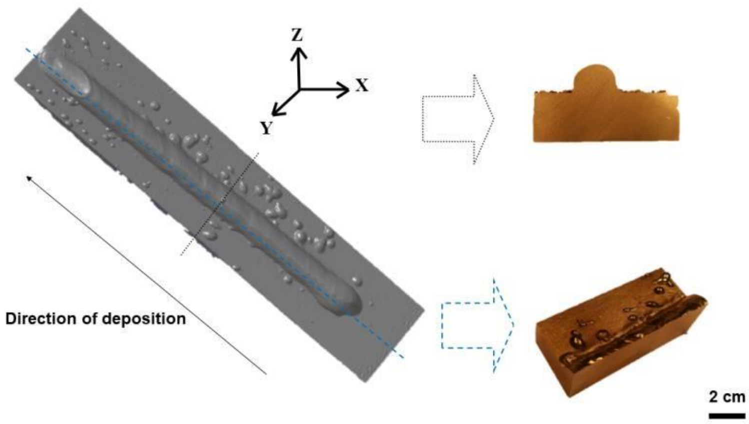

Fig. 1 Transverse (YZ) and longitudinal (XZ) sampling sections

3 Results and discussion

3.1 Deposits geometry (shape and size)

The morphology of the seams was first observed by optical microscopy before cutting (Figure 2). The geometry of the seams is regular. They do not exhibit coloration induced by the phenomenon of oxidation. Projections are observable on the edges of some seams. In both cases, sampling according to the YZ and XZ plans were carried out as shown above in order to have as much information as possible on the evolution and the stability of the process.

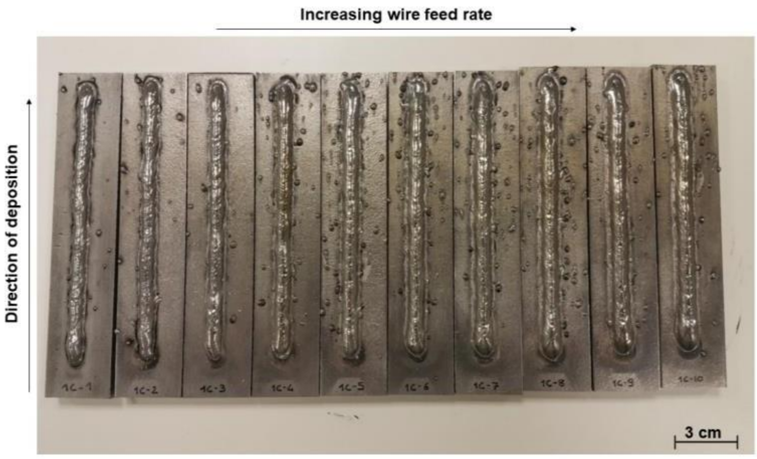

Fig. 2 Ti-6Al-4V deposits manufactured by varying wire feed speed

The height of the seams increases with the wire feed speed and decreases with the speed of translation of the robot. It is the same for the width of the seams (figure 3). In conclusion, the amount of material deposited increases with the wire feed speed and decreases with the movement speed of the robot.

It was noticed a singular behavior of the deposit with a wire feed rate of 8.5 m/min compared to all the deposits.
This is due to an unexplained increase in projections when printing this deposit, which merged with the deposit increasing its width locally at the expense of its height.

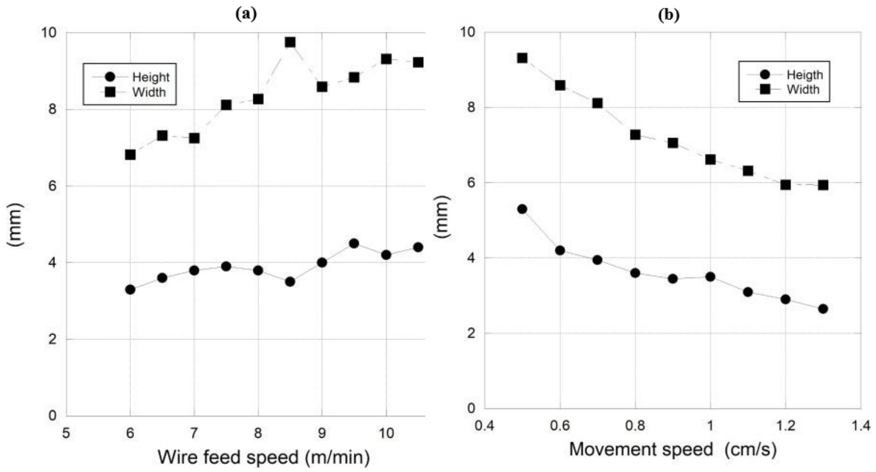

Fig. 3 Evolution of the depth of the main zones according to the wire feed speed (a) and robot's head speed (b)

The variation of these two parameters does not affect the stability of the process, where a similar regularity of the deposits and an almost constant number of projections have been noticed above 7.5 m.min^{-1} of wire feed rate.
The wetting angles were also measured. It has been found that the wire feed speed does not affect these parameter, however the increase in the movement speed tends to increase the wetting angle (figure 4). Ding et al., conclude also that increasing the speed of the robotic head causes an increase in the wetting angle for Ti-6Al- 4V alloy (Ding et al. 2015).

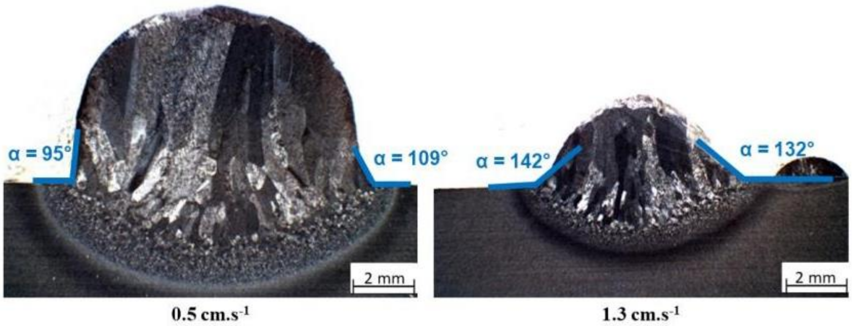

Fig. 4 Evolution of the wetting angle according to the movement speed of the robot

3.2 Defects and Microstructure

Some porosities of sizes between 16 and 375 microns have been detected at the deposit / remelted zone interface and in the remelted zone. These porosities are generally spherical, distributed in filiation or punctually. The characterization according to the transverse plane YZ showed a small constant porosity rate all along the process deposition.

The macrostructural study shows β grains oriented in the direction of the thermal gradient. This type of microstructure was observed for Ti-6Al-4V by Martina (Martina et al. 2012). The width of these β grains is stable as a function of the wire feed speed with average widths between 0.4 and 0.6 mm for all the deposits and an orientation relative to the vertical between 77° and 81°. On the other hand, a decrease in the width of the ex-grains β as a function of the movement speed of the robot has been observed, passing from an average width of 0.56 mm for the lowest speed to 0.34 mm for the highest speed (figure 5), this decrease reflects faster cooling rate. The orientation of these ex-grains is between 77 ° and 84 °.

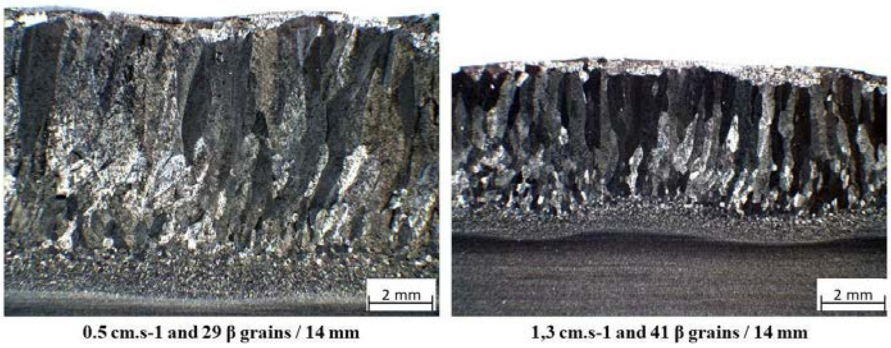

Fig. 5 Evolution of width of β grains according to the movement speed of the robot

The seams manufactured by CMT are composed of three different regions as shown in the figure 4. These regions are (from top to bottom): the melted zone, the remelted zone and the heat affected zone, the lower is the base metal.

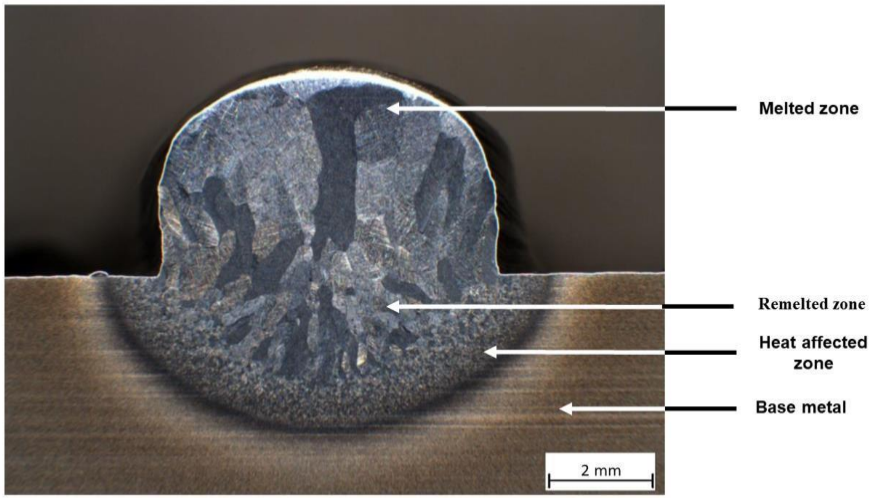

Fig. 6 Micrography of cross section of Ti-6Al-4V deposit

It has been noticed an evolution of the dimensions of these zones according to the parameters (figure 7). Indeed, in the case of the variation of the wire feed speed, the height of the deposits increases and confirms the dimensional analyzes made before. The deposit with the wire speed of 8.5 m.min^{-1} has a very large width because of the many projections merged with the deposit. On the other hand, the depth of remelted zone and heat affected zones (HAZ) are quite similar varying from 1.5 to 2.5 mm for the remelted zone and 0.7 to 0.9 mm for the heat affected zone (HAZ). The remelted zone and HAZ depth, however, varies more according to the movement speed from 5.2 to 2.7 mm for the remelted zone and from 1.15 to 0.6 mm for the HAZ for the fastest robot speed. These observations were observed by Zhang (Zhang et al. 2015) for CMT applied to a magnesium alloy.

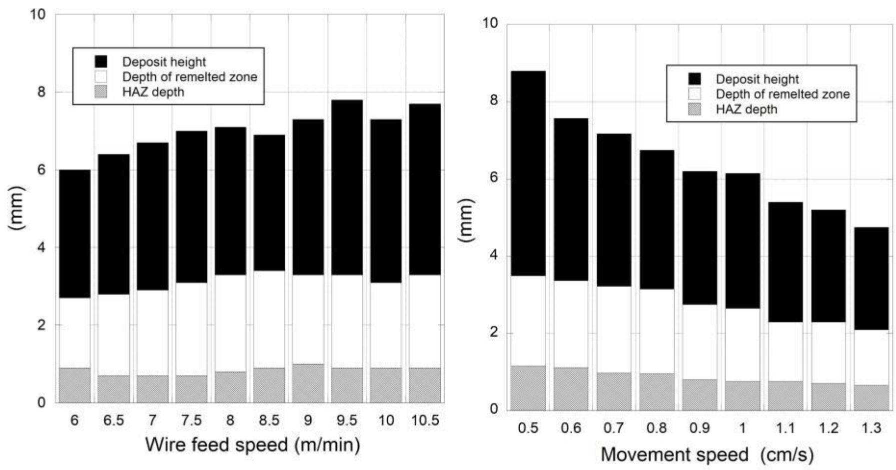

Fig. 7 Evolution of the depth of the main zones according to the wire feed speed and movement speed of robot

The microstructural study shows a microstructure of Widmanstätten for all the deposits studied, which indicates a high cooling rate during the beta / alpha transformation, of the order of 8000°C / min (Lütjering 1998). This type of microstructure has been observed by Antonysamy and Wang (Antonysamy 2012) (Wang et al. 2013). So, the size of the lamellae α does not vary as a function of the wire feed speed. A slight variation in the size of the α-lamellae, which are finer for the most important movement speeds of robot as shown below which confirms the existence of relations between movement speed and Ti-6Al-4V cooling rates.

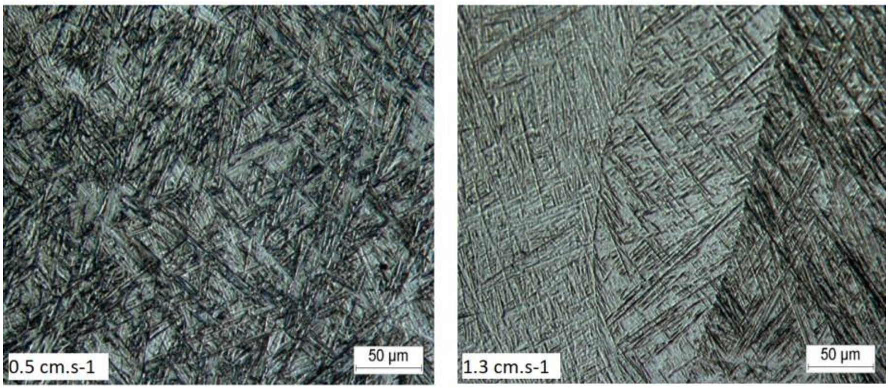

Fig. 8 Microstructure of deposits 1C-11 (left) and 1C-19 (right)

It has also been noticed a gradient of α lamellae width which are increasingly thinner at the bottom of the deposits compared to their upper parts as shown in the Electron Back Scatter Diffraction (EBSD) analysis below.

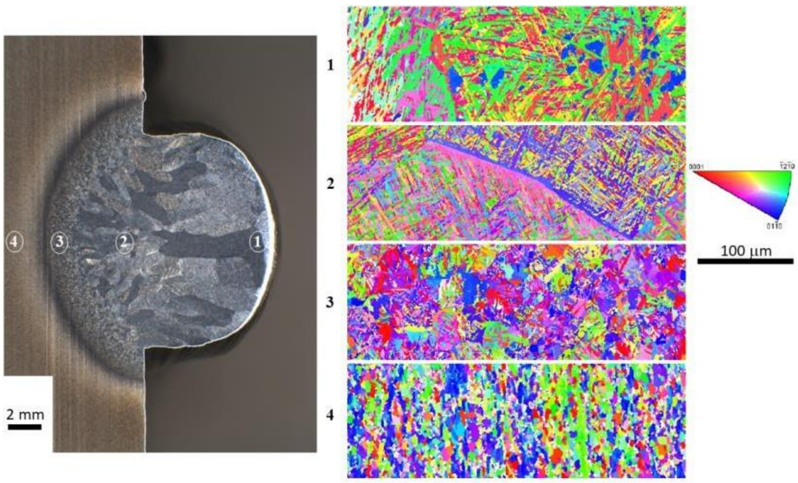

Fig. 9 Inverse Pole Figure of cross-section obtained by EBSD analysis of a Ti-6Al-4V CMT deposit

This difference is due to the Ti-6Al-4V support plate on which the seam is deposited, and which plays the role of heat sink, enabling the conduction of the heat generated by the CMT process in the base zone of the deposits.

3.3 Mechanical properties

The hardness of deposits is presented in the figure below.

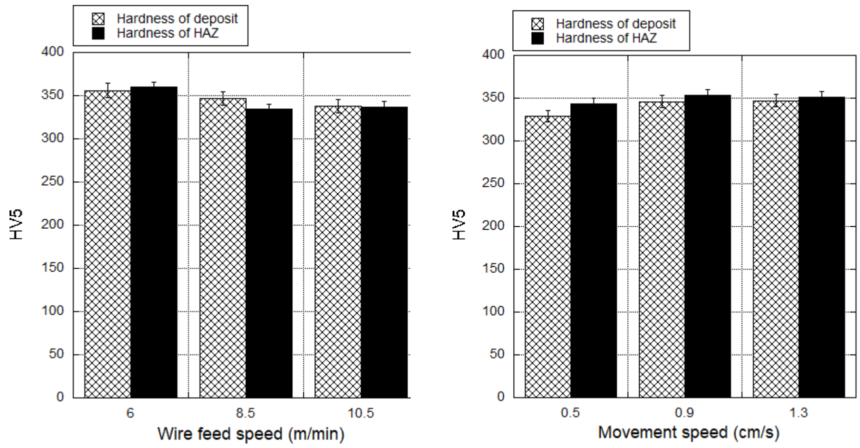

Fig. 10 Mean hardness of the Ti-6Al-4V deposits according to the wire feed speed and movement speed of robot

The wire feed speed does not affect the hardness of the as-built deposits whereas increasing the speed of the robot head induces a light increase of hardness of deposits up to a robot speed of 0.9 cm.sec^{-1}, beyond the hardness remains constant. However, a threshold is reached around 350-360 HV. These results are similar to those found by Brandl (Brandl et al. 2010). The hardness of the HAZ is always greater than the hardness of melted and remelted zones.

In order to have a better understanding of the phenomena observed, a study of the energy parameters is carried out. The Fronius generator automatically adjusts the energy density delivered during wire feed rate variation. On the contrary, it is not adjusted during the evolution of the head speed; the energy per volume of deposited material decreases according to the movement speed as shown in the figure 11.

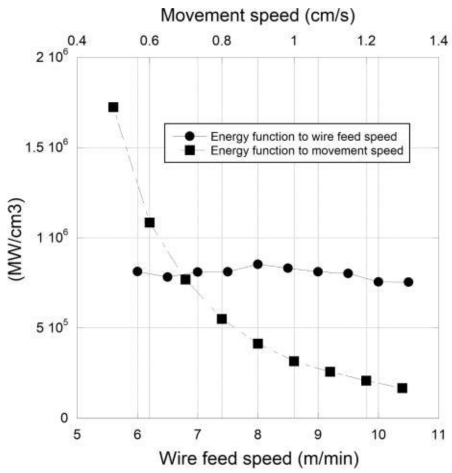

Fig. 11 Energy density delivered per volume of deposited material during the CMT process

These observations support the results found previously, explaining the different cooling speeds during the variation of the movement speed of the robot, which on the contrary do not vary during the increasing wire feed speed resulting in similar metallurgical and mechanical properties for all deposits of this study regardless of the flow of material introduced into the molten bath.

8 Conclusion

The influence of two process parameters such as the wire feed speed and the speed of movement of the robot head was evaluated for the production of Ti-6Al-4V seams by WAAM method. Oxidation-free seams were made. Only the speed of movement of the robot entails a change in the size and shape of the seams and the different zones that compose them. Wire feed speed has a limited influence on the seams as the generator compensates by varying the power density. The microstructural evolutions and the properties of the seams are thus linked to the energy variations per unit of material deposited during the process.

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