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Additive Manufacturing by Wire based Laser Metal Deposition

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ABSTRACT

Laser additive manufacturing with metals is gaining more and more attention, and represents a large market in industrial applications, specifically for the aerospace sector in the future. The increasing diversity of applications requires the continuous development of specific process implementations: For high metal deposition rates, developments have focused on arc technologies (Wire Arc Additive Manufacturing, WAAM), based on conventional welding techniques. For high definition 3D parts, the development of laser technologies allowed the implementation of layer-based metal solidification on powder beds known as Selective Laser Melting (SLM). These two processes have specific characteristics, such as high deposition rate with low accuracy for WAAM and low deposition rate with high accuracy for SLM. In this paper, we will present the interest of wire-based deposition technologies with lasers, often referred to as laser metals deposition by wire (LMD-W). This new approach presents the best compromise between high deposition rates and good accuracy which corresponds to the need of the aerospace industry to build "cubic meter sized" parts. It meets the requests in terms of mechanical resistance and process duration. The first tests of the present study are carried out on aluminum alloy. The results show a good aptitude of aluminum despite of a recognized difficulty to implement this alloy in additive manufacturing due to problems with process stability at the edge of the deposit, filling strategies, and many more. In the present paper we focus our developments on the deposition rate in order to realize large aeronautics components.

Keywords: Wire based Additive Manufacturing, SLM, 3D parts, High Metal Deposition Rate, High Throughput Manufacturing;

1. INTRODUCTION

In the recent past, additive manufacturing (AM) has gained a lot of attention in the manufacturing industry, especially in aeronautics. A good overview of the history of AM has been summarized in a recent publication [1]. AM first emerged in 1987 with stereolithography from 3D Systems, a process that solidifies thin layers of ultraviolet light-sensitive liquid polymer using a laser. These AM processes are initially applied to fabricate polymer as components for communication or inspection tools. The capability of producing prototypes in a short period directly from CAD models helps to shorten the product development steps.

In order to meet the demands from the aerospace [2], automotive [3], and rapid tooling industry [4], the recent focus of AM research has shifted from plastic material to metals, including titanium and nickel alloys. The aim was to fabricate complex-shaped metal components that can't be economically produced using conventional methods like milling.

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The competitive advantage of AM for metal components relative to alternative manufacturing processes is directly related to the geometrical complexity and production volume. AM is suitable to fabricate parts with medium to high geometrical complexity at relatively low quantities. Compared to the conventional manufacturing (e.g. CNC machining), AM has two major advantages. First, it is possible to automate the AM process completely from part design to fabrication in a CAD/CAM environment. This reduces both the production time and the amount of time of an operator to handle the machine. Second, AM and in particular wire-based AM, is a cost-effective approach for fabricating components made of expensive material such as titanium and nickel alloys in the aerospace industry. In addition, AM is capable to generate single-component structures with complex 3D shapes like injectors which are impossible to build as a single part by conventional processes without additional assembly steps.

In AM production industrial grade SLM machines based on the powder bed technology are already in the market, where each layer is typically built of 25 µm of thickness. While being highly effective in the generation of small parts, the production for structures beyond a height of 100mm takes 4000 layers which results in rather long production times of up to several days.

In order to further enhance the productivity additional efforts are needed to increase the deposition rate in AM without impairing the accuracy of 3D fabrication e.g. due to heat deformation. Arc based technologies (WAAM) have demonstrated to have high deposition rated however suffer from low accuracy of the metal deposition and deformation due to excessive heat [5]. Therefore, the laser remains a precise tool for heat and metal deposition. The approach in laser-based AM of replacing the powder by a wire feed has been published recently [6] and is equally followed in the presented work. In this we aim to take the AM a step forward towards better control of power deposition and heat dissipation to generate large aeronautical structures with high metal deposition rates and reasonable accuracy. For the delivery of the according laser power we compare low-cost direct diode lasers with high brightness fiber lasers and evaluate their usefulness for wire based additive manufacturing.

2. EXPERIMENTAL

The set-up of these experimentations is based on the comparison of two laser sources. First, we used an IPG YLR1200 / 1200-QCW fiber laser emitting at 1070 nm, with a maximum CW power of 1220 W and a 200 µm process fiber. Second, we used a BWT DLS-1000 diode laser emitting at 915 nm, with a maximum CW power of 1021 W and a 300 µm process fiber.

Each source is injected into a PRECITEC YW52 200 mm focused welding head, mounted on an AEROTECH Z axis to control the spot size by defocusing.

The focus spot size varies depending on the laser used, due to the wavelength difference and the diameter of the process fiber. It is necessary to recalculate specific defocus distances in order to work with the same spot size and thus compare the results with the same power density. So the complete beam caustic for each laser have been build by simulation with Rezonator software (Fig.1,) and compared to measures realized with OPHIR SPIRICON BeamWatch AM (Fig.2).

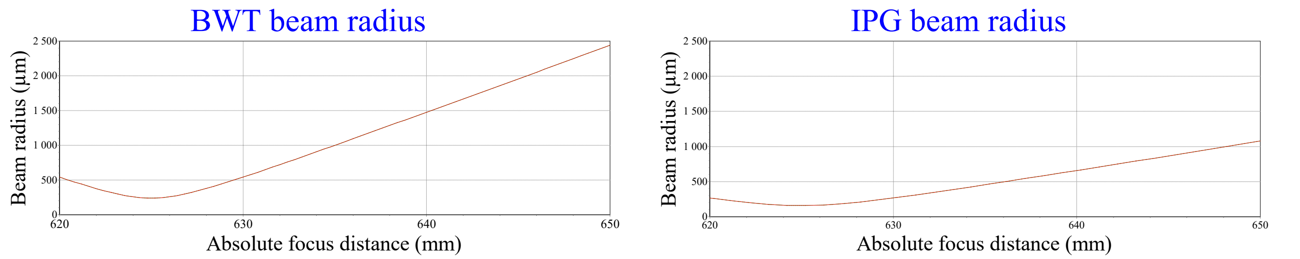

Fig. 1. (Left) The figure shows the simulated caustic of BWT laser beam focalised by YW52 PRECITEC welding head (Right) the simulated caustic of IPG laser beam focalised by YW52 PRECITEC welding

In these two beam caustic, we can clearly observe a major difference in beam divergence which requires to define in each case a specific defocus to obtain the same spot size. The focus spot sizes are 480 µm for BWT and 320 µm for IPG. Measures realized with BeamWatch indicates the real focus spot sizes are 465 µm for BWT and 310 µm for IPG, which confirmed with a good reliability the simulation estimation (less than 4% error). Complete beam caustic have also been confirmed with measures of the divergence: 173 mrad for BWT and 87 mrad for IPG.

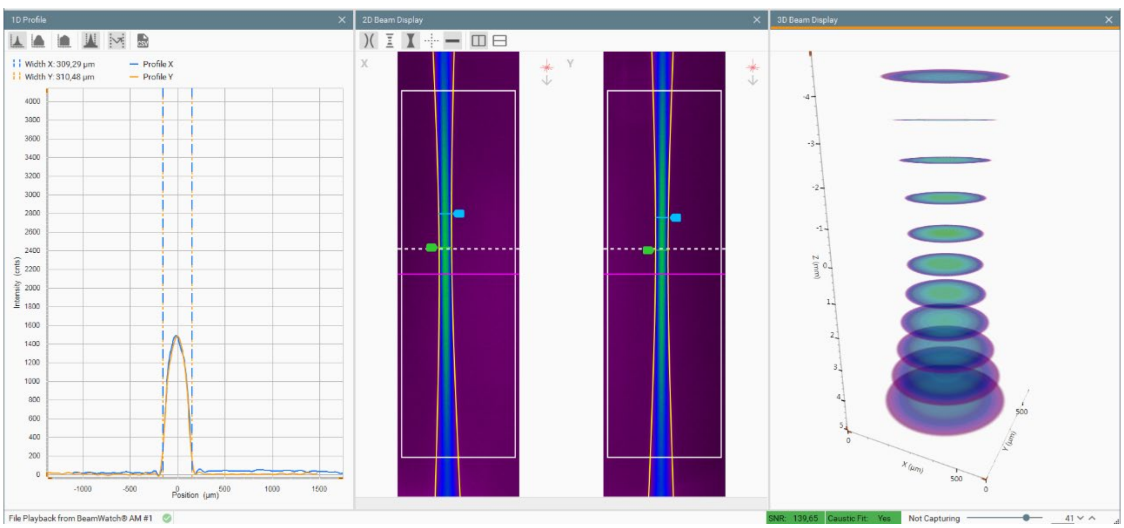

Fig. 2. IPG beam measure with OPHIR SPIRICON BeamWatch AM

The wire feeder used is a FRONIUS TransPuls Synergic 3200 with hot wire capacity and specific track for aluminum alloys. It allows for wire speeds of up to 10 m/min, which represents a 1.9 kg/h aluminium alloy deposit with a 1.2 mm diameter wire.

The first tests are carried out on 4043 aluminum alloy from FSH Welding, its chemical composition (%) is presented in Table 1 below.

Table 1. Chemical composition of AA4043 alloy form FSH Welding, 1.2 mm diameter wire

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Other	AL
AA 4043	5.0	0.15	0.001	0.03	0.003	0.003	0.006	X	base

This aluminium alloy makes possible to study the technical difficulties of aluminium (high reflectivity and high thermal diffusion) with a solidification phenomenon favouring due to a rate of silicon close to eutectic. The substrates used for metal deposition are an AA5083 aluminum alloy plate.

Second, TI6AL4V titanium alloy have been tested, chemical composition (%) is presented below:

Table 2. Chemical composition of TI6AL4V alloy form FSH Welding, 1.2 mm diameter wire

	C	Fe	Al	Va	Y	Ti
Ti6Al4V	<0.05	<0.22	6.0	4.0	<0.005	base

This material represents a high potential for cost reduction by AM processes in the aerospace industry, because it is the preferred material for structural stability in aircraft design but comes at a high material cost. So the reduction of material waste can largely contribute to savings in production.
The gas protection is ensured by an overflow tank. The shielding gas used is argon of high purity class. In order to verify the regularity of metal deposition single layer lines from a wire of 1.2 mm diameter were deposited on substrate of the same material in the first step. The substrate together with the shielding gas tank, were translated by a 2 axis AEROTECH system.
To study a wide parametric range, the following parameter were kept fixed and only one parameter was altered to identify the suitable parameter range. An overview of the most significant parameters is given in Table 3:

	Laser power	Wire angle	Spot size	Stick out	Hot wire
AA 4043	1020 W	30°	600 µm	10 mm	no
Ti6AL4V	1020 W	30°	1700 / 2180 µm	10 mm	no

3. MATERIAL DEPOSITION RATE AND COMPARISON WITH OTHER PROCESSES

Single layer deposits are made to study a wide parametric range with the IPG laser emitting at 1070 nm. Criteria are defined in order to compare the most significant parameters.
First results, on aluminium alloy, show that we can reach a deposit rate of 0.53 kg/h with a power of 1.2 kW at 1070 nm. The figure 3 presents the process stability between wire speed and process speed for some tests. A stable process is defined by a regular material deposition, free from shape defects and complete wire melting on the substrate.

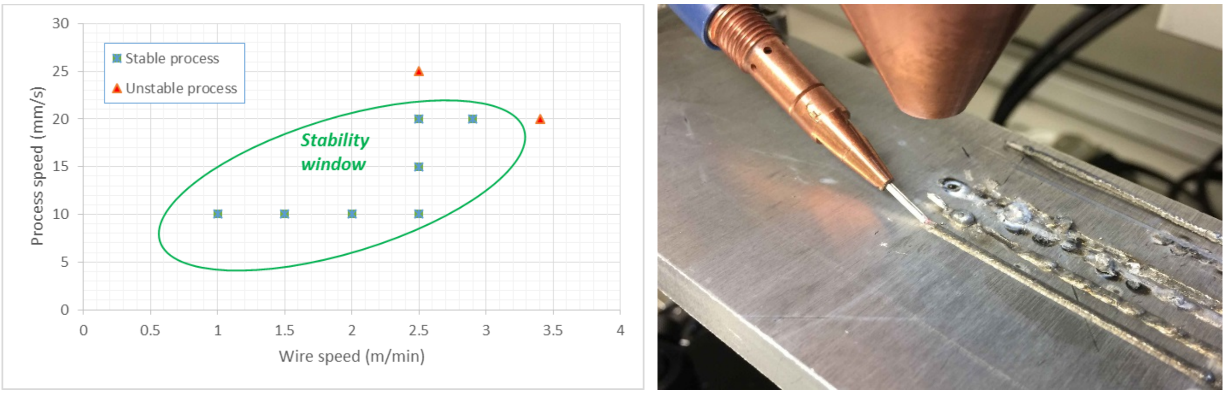

Fig. 3. (Left) Stability of some aluminium tests realized with IPG laser source emitting at 1070nm, average power 1200W (Right below) Stable process (right above) Unstable process

This deposit rate represents a volume deposition rate of 200 cm^3/h (with a single laser source), compared to classical values of 10 cm^3/h of Single Layer Melting (SLM) processes or 100 cm^3/h of Direct Metal Deposition with powder (DMD-P). High deposition rates are obtained with a relationship between process speed and wire speed, usually called Feed Factor. A 2.5 m/min wire speed and a 25 mm/s process speed induce an unstable process for a 0.45 kg/h deposit rate, while a 2.9 m/min wire speed and a 20 mm/s process speed induce a stable process for a 0.53 kg/h deposit rate.
These results are interesting because they are obtained with a power of 1.2 kW, sufficient to obtain, in a first approach, a power density capable of melting 1.2 mm diameter aluminum wire. That suggests that higher deposition rates can be achieved with multi-kW sources to build structures.
Tests with TI6AL4V were also carried out with the same set up (1.2 kW at 1070 nm). As for aluminium alloy tests, figure 4 presents the stability process function of the wire speed and the process speed. In this case, we obtain a maximal deposition rate of 0.45 kg/h, corresponding to a volume deposition rate of 102 cm^3/h.

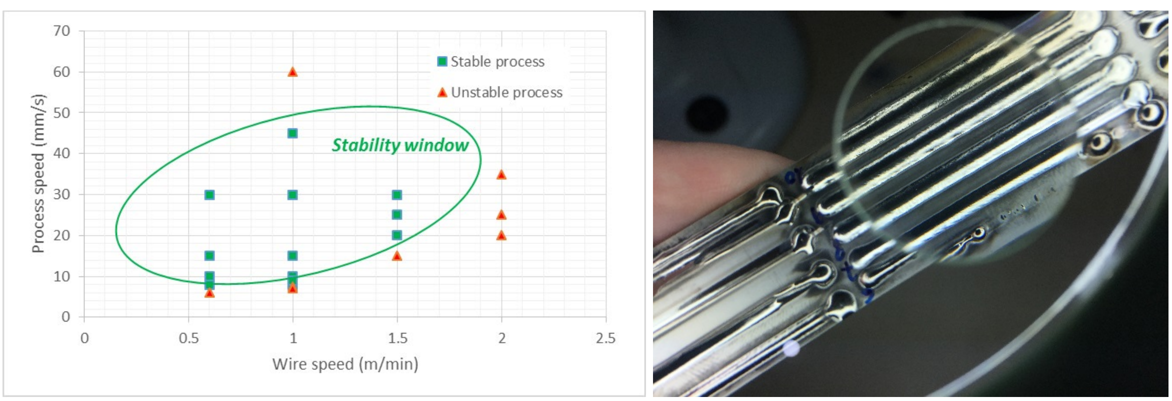

Fig. 3. Left: Stability of some titanium tests realized with IPG laser source emitting at 1070nm, average power 1200W.
Bottom right: Unstable process with melting balls of material. Top right: Stable process

The stability defects are very different from the case of aluminum alloys. This seems to be mainly due to the low thermal diffusion of the titanium alloy. The energy provided by the laser beam is absorbed by the wire but not transmitted to the substrate. There is thus a lack of fusion between the molten wire and the substrate.
Two main phenomena are then observed:

- For high process speed: the thermal diffusion between the melted wire and the substrate does not have time to settle, one thus notes the formation of molten balls of material (see figure 3, middle lines),
- For high wire speed: the thread is partially melted and partially bonded to the substrate.

4. COMPARISON OF FIBER LASER WITH DIRECT DIODE LASERS

These first results confirm the state of the art in AM, which deposition rates can be attended for a 1.2 kW fiber laser source emitting at 1070 nm. The interest of the study will be to compare these results with those will be obtained with the BWT source emitting at 915 nm. This laser source has the advantage of emitting at a wavelength close to the absorption peak of the aluminum in the IR, where the absorptance increases from 5% to close to 15% in a narrow window between 850 an 980nm.
Figure 4 presents the aluminum reflectance spectrum for a range of 250 nm to 2500 nm wavelength. It shows the two different levels of reflectance obtain with 915 nm and 1070 nm wavelength.
By selecting the tailored laser wavelength, the process efficiency and stability can be largely improved in case of aluminum AM. It also presents an economic interest both in terms of purchasing costs (direct diode laser less expensive than fiber laser) in terms of efficiency with a Wall Plug Efficiency (WPE) of 30% compared to the WPE of fiber sources at around 24%.

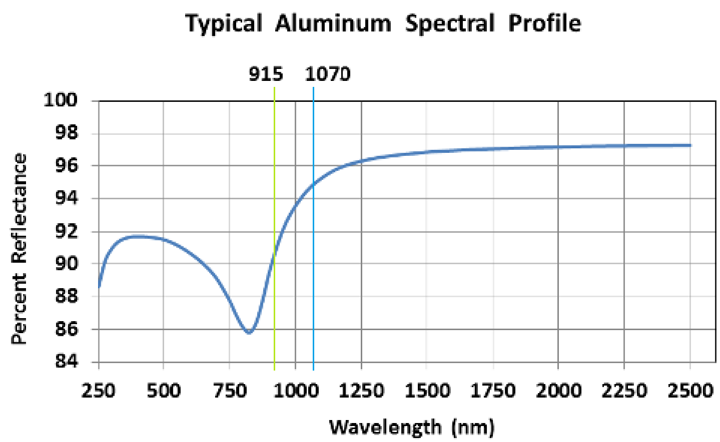

Fig. 4. Aluminum reflectance spectrum

CONCLUSION

These first tests give an interesting perspective for metal-based AM. We show that the use of laser technology for melting metal wire to construct structures by additive fabrication is a young technology with lots of optimization potential. The obtained rate of metal deposition is higher than the values conventionally known in powder-based processes, in agreement with the construction of large structures expected by the aerospace industry.
The demonstration carried out with a single laser power source, around 1 kW, indicates the prospect of further increasing the deposition rates and thus increasing the productivity of such processes.

This productivity can also be compatible with environmental energy priorities with the use of improved output source, with diode laser technologies for example. This will be the perspective to be followed future work.

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