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Intelligent nozzle design for the Laser Metal Deposition process in the Industry 4.0

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Abstract

Laser Metal Deposition (LMD) is an AM (Additive Manufacturing) process that enables to build 3D geometries or enhance the surface properties of the base material by the generation of a coating. With the aim of integrating the AM inside the Industry 4.0 trend and improve the quality of the resulting parts, smart nozzles are required. Therefore, authors have developed an intelligent LMD nozzle by means of the integration of various sensing and control systems in a continuous coaxial LMD nozzle prototype. The nozzle is capable of regulating the laser power based on the temperature measurement of the melt pool. Moreover, it adjusts the powder flux that reaches the processing area according to an algorithm that ensures a constant powder income per surface unit area. Lastly, the nozzle evaluates the geometry of the deposited clad using an optical sensor.

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Keywords: LMD; temperature measurement; intelligent nozzle; clad height.

1. Introduction

The Laser Metal Deposition (LMD), or also called laser cladding, is a laser based additive manufacturing process which use is on increase. This statement is grounded by the numerous applications that have arisen in the recent years, especially in the aeronautical [1,2], die & mold [3,4], heavy industry [5,6] and the naval [7,8] sectors.

The LMD process is based on the generation of a melt pool on the surface of the substrate that is being irradiated by a laser beam, while filler material is injected simultaneously through a nozzle (in powder or wire form) [9]. The correct operation of the nozzle is a key element in the deposition process, because it determines the quality of the generated clad and the process efficiency. Therefore, a proper design of the nozzle is required.

Nowadays there are different nozzles types for the LMD process. Based on their geometry and the powder injection system, three nozzle types can be distinguished, see Fig. 1.

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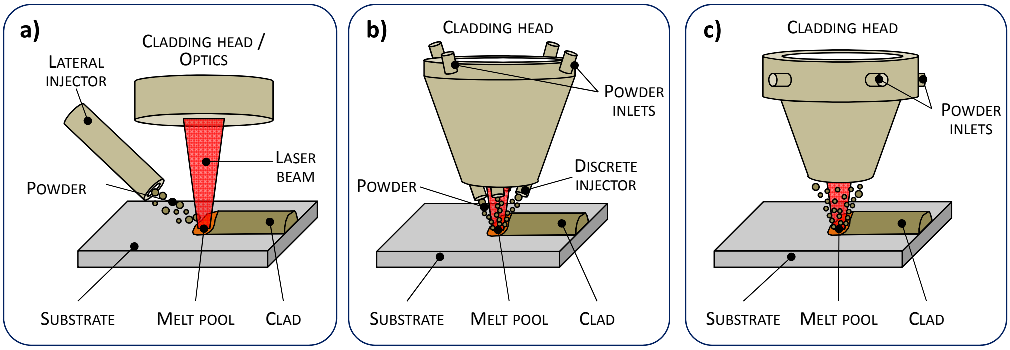

Fig. 1. Different types of nozzles used in the LMD, a) Off-axis nozzle; b) Discrete coaxial nozzle; c) Continuous coaxial nozzle

Off-axis nozzles offer the simplest and more economical alternative for the LMD process. However, this simplicity results to be a drawback itself, because the process turns to be unidirectional and its efficiency is rather low. These types of nozzles are usually used for the coating of rotatory part, where the deposition strategy is unidirectional.

As an evolution of off-axis nozzles, coaxial discrete nozzles have arisen. The coaxial discrete nozzle consists of a fixed number of discrete injectors (usually three or four) that are positioned around the rotatory axis of the nozzle. They offer the possibility to add material in all directions and at an intermediate price. Moreover, coaxial discrete nozzles enable to rotate the cladding head without influencing the powder distribution at the nozzle exit due to the gravity forces. This characteristic allows the usage of this type of nozzle in 5-axis operations where the laser processing head includes tilting movements [10].

Lastly, coaxial continuous nozzles have been developed. Their main characteristic is the fact that they distribute uniformly the powder particles among the whole periphery of the nozzle. Coaxial continuous nozzles have gained a wide acceptance because of their higher efficiency and the capability to deposit material in all directions with a high quality [11]. However, their main disadvantage is the comparatively higher price due to their more complex geometry.

Nevertheless, in the era of the Industry 4.0 a good design of the nozzle is not enough to satisfy the market requirements and it is necessary to develop smart nozzles. With this objective, an intelligent nozzle that predicts the variations of the process parameters and adapts the LMD conditions is required.

Nenadl et al. studied the influence of the input parameters (material feed rate, machine feed rate and laser power) on the resulting geometry of the clad and they developed a recursive model [12]. As it can be seen in Fig. 2, the amount of energy introduced per unit area of the surface of the substrate is directly related with the clad width, whereas the total amount of injected powder per unit area of the substrate surface is directly related with the clad height. Therefore, both laser power and powder flux need to be controlled for obtaining a stable LMD process and improve the quality of the resulting clads.

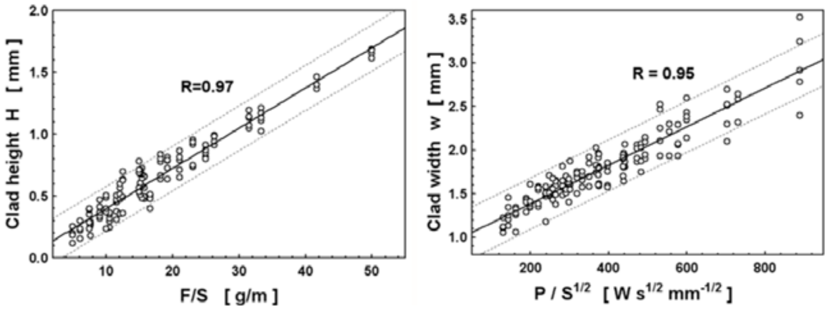

Fig. 2. Empirical dependence of the laser track height "H" and width "w" on combined processing parameters observed for coaxial and lateral cladding setups, for Ni and Co based alloy cladding; from [13] (left) and [14] (right).

In the present paper, the development of an intelligent nozzle for the LMD process is described. The nozzle is able to adapt the laser power and powder flux according to the variations of the process parameters. Moreover, it can analyze the geometry of the previously deposited clads in order to adapt the following layers to the existing substrate.

2. Implemented methodology

In order to achieve a smart nozzle, the following sensing and control systems have been installed in the EHU-Coax2015 LMD nozzle [15]. This nozzle has been entirely designed based on CFD simulations and manufactured by the University of the Basque Country. The whole system is mounted on a 5-axis LMD center and connected to a 1kW fiber laser source.

2.1. Real time temperature measurement and control of the laser power

The LMD process stability depends on the thermal field of the base material, which varies according to the geometry of the base material and the defined deposition strategy. Therefore, a close-loop control system of the temperature of the melt pool is required in order to make stable the LMD process without any dependence of the geometry or the trajectory.

When choosing the appropriate pyrometer, the emissivity of the material is required as an input parameter. However, this problem is solved by the usage of two-color pyrometers, because the temperature of the material is measured regardless the emissivity value. In the LMD process temperatures above the melting point of steel, titanium or nickel alloys are expected, therefore, the pyrometer needs to capable of measuring at high temperatures. Moreover, in many cases temperatures above 2000 °C have been reported.

Consequently, based on the process requirements and the considerations above detailed, an IMPAC IGAR 12-LO Pyrometer (from LumaSense Technologies) has been used, which offers the possibility to measure the temperature of almost any material within a range between 550 and 2500 °C. It works with a spectral range of 1.52 µm and 1.64 µm, two wavelengths close to each other but set far away from the 1.064 µm wavelength of the fiber laser.

With the objective of measuring the temperature of the material exactly at the center of the melt pool, the pyrometer is set coaxial to the laser beam. For this purpose, a dichroic lens is installed in the laser path, see Fig. 3. Thanks to it, the temperature measurement is independent from the direction in which the nozzle is depositing material.

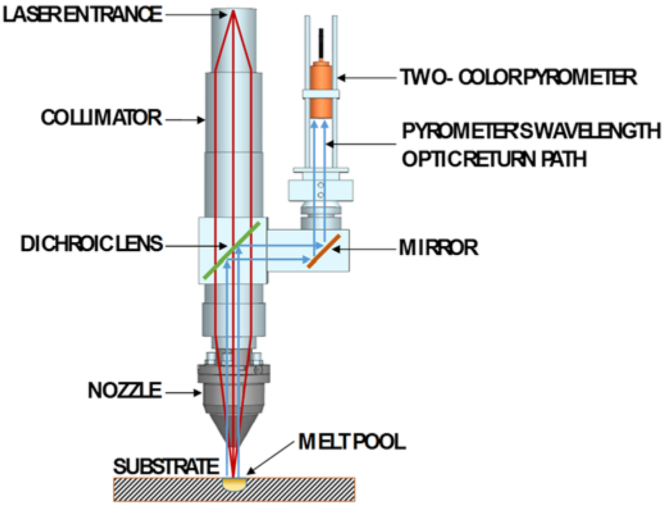

Fig. 3. Optical paths of the laser beam and the two-color pyrometer.

As it is detailed in Fig. 3, the pyrometer is installed coaxial to the laser beam. For this purpose, a dichroic lens is installed inside the LMD head. This Dichroic lens allows the wavelength of the laser pass through, but reflects the other wavelengths. Consequently, the radiation coming from the melt pool is reflected and guided to the pyrometer through a different optic-path from that of the laser (this optic-path is represented in Fig. 3 using blue colored arrows).

Once the temperature of the melt pool is measured by the pyrometer, its value is compared with a previously stablished reference value, see Fig. 4. Afterwards, a proportional-integral-derivative (PID) control algorithm is applied and the resulting signal is used to actuate on the laser power. Therefore, a real-time close-loop control of the temperature is achieved.

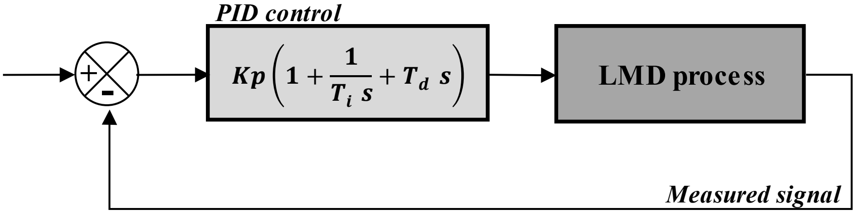

Fig. 4. PID control loop for the temperature regulation in the LMD process.

A two-color pyrometer has the advantage that enables to measure the temperature of a point situated at the surface of the workpiece independently from the emissivity value. Moreover, the measured signal is not influenced by the attenuation of the signal, i.e. due to the existence of dust in the path. This is due to the fact that the two wavelengths in which pyrometer measures are close to each other and the attenuation affects in the same way to both of them. However, the obtained signal needs to be filtered in order to avoid spurious measurements generated by the powder particles that intersect the laser beam of the pyrometer.

In order to develop a PID control, it is necessary to know in advance the function of the process to control. Due to the complexity of the LMD process, the obtainment of the control constant is not a trivial task. In the present case, the second Ziegler-Nichols´ method for tuning PID controls has been used.

The second Ziegler-Nichols´ method is based on the following procedure. First of all, a limit value of the proportional variable is determined, which is named as “K_cr” (critical value). For this purpose, the integrative and derivative constants are set to infinite and zero values, respectively, and the value of

“K_P” that makes the system keep oscillating over time is defined. Afterwards, the value of the period (P_cr) of these oscillations needs to be experimentally measured. Based on their values, the rest of the parameters of the controller can be determined according to the next table.

Table 1. Determination of the control constants based on the second Ziegler-Nichols´ method.

Controller Type	K_p	T_i	T_d
P	$0.5\cdot K_{cr}$	∞	0
PI	$0.45\cdot K_{cr}$	$1.2^{-1}\cdot P_{cr}$	0
PID	$0.6\cdot K_{cr}$	$0.5\cdot P_{cr}$	$0.125\cdot P_{cr}$

2.2. Powder flux regulation system

A powder flux regulation system based on a solenoid that is actuated externally has been proposed. The aim of the solenoid is to reduce the powder mass flux that reaches the nozzle proportionally to the reduction of the feed rate of the machine when the deposition direction is changed. Nevertheless, due to the time delay of the regulation system, the solenoid needs to be actuated in advance and the control needs to predict the velocity variations of the machine before they happen.

The above-mentioned problem has been solved by using an offline control. For this purpose, the real feed rates of the machine are required and based on them a PWM (pulse wide modulation) signal that actuates on the solenoid is generated. The easiest and most accurate way for obtaining these vectors is running once the LMD program without laser or powder and extracting them directly from their corresponding CNC channel.

In the present case, the powder flux regulation is based on a 5/2 solenoid. The position 1 of the solenoid (situation represented in Fig. 5) directs the drag gas (Argon and powder mixture) to the nozzle. Alternatively, the position 2 of the solenoid directs the drag gas (Argon and powder mixture) to the recycling container.

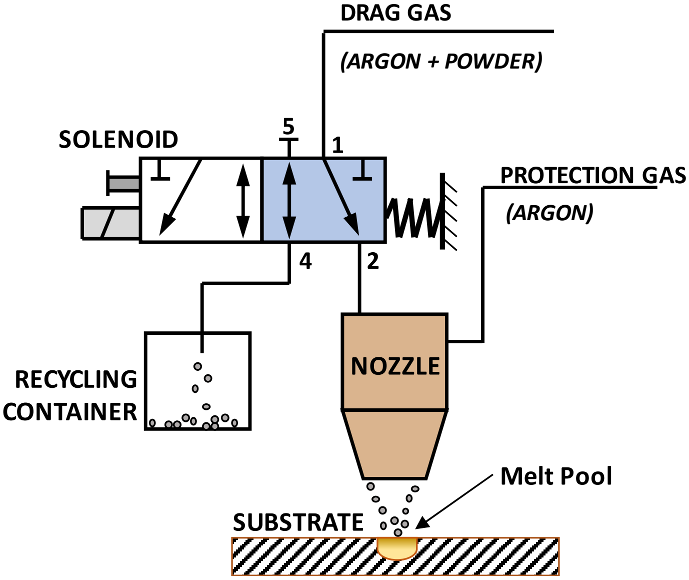

Fig. 5. Scheme of the powder flux regulation system, where the solenoid is in position 1.

Besides regulating instantaneously the powder flux, the designed system enables to stop it when the laser is switched off and reduces the material waste. This powder is collected in a recycling container and can be reused afterwards with no drawbacks to the process. Therefore, the Laser Metal Deposition results in a more environmentally friendly and cleaner process.

2.3. In-situ measurement of the deposited clad height

The determination of the height of the deposited clad is a key element in order to guarantee the stability of the process when overlapping the subsequent layers. The possibility to measure the height of the clad directly inside the machine, without removing the part, eliminates all the positioning errors that would be introduced if the part were loosen, measured outside and tighten again. This information is useful from two points of view.

On the one hand, this information can be used directly for adapting the programmed trajectories of the subsequent layers and maintain the distance between the nozzle tip and the surface of the substrate within the optimal range.

On the other hand, after the deposition process, usually a machining operation (milling or turning) is required in order to achieve the desired surface roughness and dimension accuracy. Hence, this sensor enables to measure the machining ridges directly inside the machine and the machining operation can be adjusted exactly to the geometry of the generated part via LMD. Thanks to it, void movements are reduced and collisions are avoided. This feature is especially interesting in hybrid machines, where both additive and subtractive operations are carried out in a single fixing position and in the same machine.

The sensing device is based on laser triangulation and the selected model (the HG-C1200) has a measuring range between 120 and 280 mm, what allows its positioning in a safe place inside the LMD machine. The laser beam that uses this sensor has a 0.3 mm diameter at the 200 mm focusing distance and offers a 0.2 mm repeatability. This value is considered adequate for the height measurement requirements in the LMD process, because the LMD nozzle has a ±1mm working distance regarding the focal plane position.

Fig. 6. Employed optical sensor (source: Panasonic)

The sensor has been positioned at a small offset distance in the XY plane from the LMD nozzle and measures the height of the clad as a relative value regarding the focal plane position of the nozzle. In Fig. 7, a scheme of the clad height measuring system is detailed. Once the zero reference distance is set, the offset between the nozzle center and the sensing device is introduced and the CNC program of the last layer is executed. This way, the height of the last deposited layer can be measured.

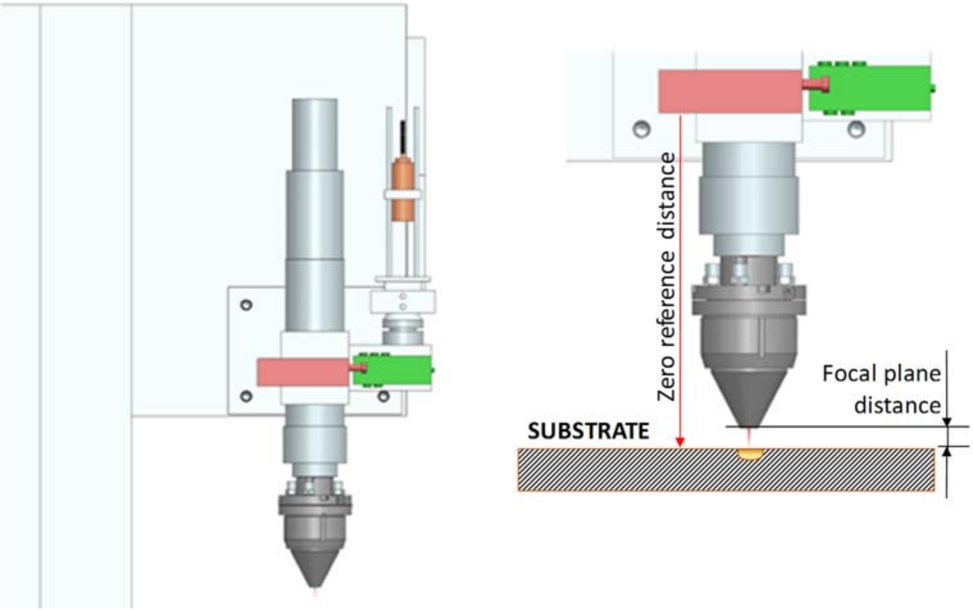

Fig. 7. Scheme of the clad height measuring system.

3. Integration of the nozzle inside the LMD machine

As it can be seen in Fig. 8, the sensing and monitoring instruments are fully integrated inside the LMD machine. Moreover, thanks to their strategical position and reduced size, they have no drawbacks to the accessibility of the nozzle. The whole system has been modeled using a CAD software, what enables its integration in CAM/CAE tools.

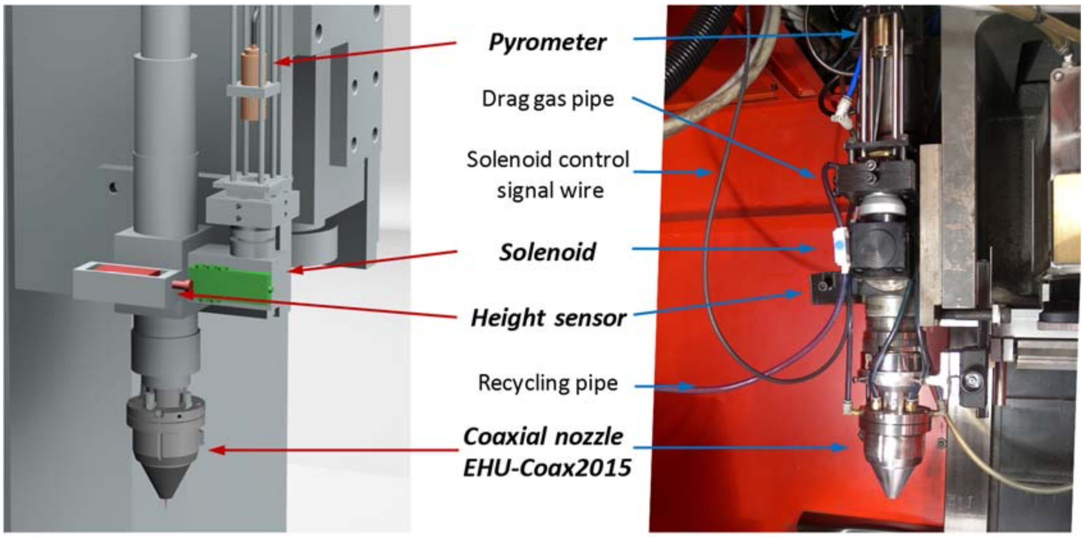

Fig. 8. Scheme and photo of the EHU-Coax2015 nozzle together with the developed sensing and control systems.

4. Conclusions

In the present work, the prototype of an intelligent nozzle for the LMD process has been proposed. Thus, during the LMD process, the laser power and the trajectories of the machine can be adapted in order to maintain the temperature and the distance between the nozzle tip and the workpiece within the desired range. This increases the stability of the process and a higher repeatability of the process is achieved.

Moreover, the possibility to regulate instantaneously the powder flux that reaches the surface of the substrate enables to control the amount of material added per unit area of the substrate. Therefore, material over-accumulations are avoided.

Finally, the possibility to measure the geometry of the deposited material enables to optimize the afterward machining operations and reduce operation times.

Each sensing and control system has been validated individually and they have been proved to enhance the stability of the deposition process. Based on the good results obtained, we are working on the usage of the intelligent nozzle for building thin wall geometries, such as blades.

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