Instantaneous powder flux regulation system for Laser Metal Deposition

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ABSTRACT

A new control system for regulating the powder flux during the laser metal deposition process (LMD) has been designed, developed and validated. The powder regulation system is based on a solenoid, which is coupled to the LMD nozzle and controlled by means of a Pulse Width Modulation (PWM) signal. Thanks to this system, the deposited clad height can be regulated depending on the process parameters, what allows obtaining a more homogeneous layer height and results in a more stable process. The material over-height at the beginning of the clad has been completely avoided when the control is applied. The material accumulation in corners where the deposition direction is changed has been also reduced from 0.65 mm to 0.35 mm. Furthermore, simulations of the nozzle and the powder particle stream have been carried out in order to validate the designed system and analyze the powder particle distribution at the nozzle exit.

***Keywords**: Laser, LMD, powder flux, regulation, solenoid valves.*

1. Introduction

Laser Metal Deposition (LMD) is an Additive Manufacturing process that enables to build whole geometries or the repair of an already existing but damaged part. The process uses a laser beam as a heat source and is based on slicing the desired geometry and building it layer-by-layer using powder or a wire feedstock as additive material. One of the main advantages of the LMD process comparatively with arc welding is the small total amount of energy introduced to the part. Therefore, a minimum heat affected zone is generated and geometrical distortions caused by the successive heating and cooling cycles are reduced [01].

In order to achieve the desired geometry, usually many layers are to be overlapped and process stability is of great relevance when obtaining a constant clad height. However, multiple parameters are involved in the LMD process, in which several physical phenomena are interrelated with each other and have a direct influence in the resulting clad geometry. In this direction, the LMD requires a different approach compared with traditional manufacturing systems and more work and research is required to optimize the process [02].

The first objective when depositing material is the determination of the relationship between the process input parameters (laser power, scanning speed, powder flow rate and carrier gas flow) and the output parameters (clad geometry, mechanical properties and generated microstructure) [03, 04]. However, due to the variability of the LMD conditions, process parameters need to be adjusted according to their instantaneous values. During the last decade, many authors have focused their efforts on monitoring the process and developing new and robust control systems. Many of these works have been collected by Purtonen et al. [05].

Generally, the aim of monitoring the LMD process is the improvement of the reproducibility, reliability and quality of the process, what results in economic saving [06]. When monitoring the process, different systems have been developed. Up to now, the most promising methods are those based on measuring the melt pool temperature or size and acting on the laser power to keep the measured signals within a desired range.

Hofman et al. presented a feedback controller system for the LMD process that uses the melt pool width real time measurements to adjust the laser power [07]. They concluded that the quality of the deposited clad depends on process parameters such as laser power, processing speed and powder feed rate. Other authors have focused their work on improving the LMD process by measuring the melt pool geometry with the aim of obtaining a correlation between its size and the process parameters [08].

Bi et al. developed a closed loop control system based on the infrared temperature signal of the melt pool to overcome the problems encountered in building thin walls. They concluded that the dimensional accuracy of the deposited part is influenced by the size and temperature of the melt pool [09]. Other authors have carried out similar works to analyze the relation between the quality of the part and the measured infrared (IR) signal [10, 11, 03]. They also analyzed the importance of the proper growth between the subsequent layers. If the Z increment matches the real growth of the deposited layer, the powder focus is located exactly in the melt pool generated by the laser beam. Thus, a stable deposition process and good dimension accuracy are guaranteed.

All authors come to the conclusion, that a constant layer height must be achieved in order to guarantee the process stability. However, depending on the final shape of the desired geometry, the CNC machine or robotic arm that controls the position of the LMD nozzle needs to follow complex trajectories. Therefore, the machine has to accelerate and decelerate where direction changes are required or sharp edges are to be manufactured. Because of these variations in the machine feed rate, clad height variations may appear in the process.

Unlike conventional manufacturing processes like milling, the LMD process requires good stability and constant operating conditions. Paul and Anand described the importance of minimizing the geometrical errors during the LMD process [12]. As it has been underlined previously, the deposition rate is a key factor in the process and hence the main challenge is to keep the deposition rate as constant as possible. With this objective, Boisselier et al. developed an algorithm that gains smooth trajectories with stable processing conditions [13]. In the same direction, Ren et al. studied the influence of the different toolpath generation methods on the deposition of this wall structures. They concluded that an optimal strategy increases the reliability of the generated part and improves the process efficiency [14].

Nenadl et al. studied the geometry of the generated clad depending on the LMD process parameters [15]. They concluded that the amount of powder and the total heat input per unit length of the laser track are key factors regarding to the deposited clad geometry. The article states that the amount of powder provided per unit length of the laser track is directly related to the clad height. Therefore, when the machine feed rate is slowed down, the clad height is increased. However, there are no references for the powder flow rate regulation at the nozzle tip. More authors have focused their efforts on the powder flow rate in order to obtain a stable LMD process; Ding et al. concluded that measuring the powder flow rate in real time is a key element for achieving an effective powder flux control [16]. They developed an optoelectronic sensor that detects the powder flow rate at the outlet of the powder feeder.

Besides, sustainability is a key factor in today´s manufacturing [17] and thanks to the powder flow regulation, a higher material usage efficiency is achieved and production costs can be reduced. In the LMD process usually rotatory powder feeders are used for achieving a steady powder flux. They consist of one or two rotating disks and varying their rotation speed, the mass flow of powder particles can be regulated. Nevertheless, the powder flux variation by means of the powder feeder is too slow for offsetting the machine feed rate variations. Therefore, a fast powder regulation system is required to avoid the mentioned powder accumulations.

With this objective, in the present work a novel control system based on powder flux regulation has been designed, developed and validated. The developed system provides two main advantages: On the one hand, thanks to the instantaneous powder flux regulation, a more homogeneous clad height can be achieved. On the other hand, the powder flow can be stopped when the process is not depositing material. Consequently, the amount of wasted powder is reduced and this makes the LMD a more sustainable and a cleaner process.

2. Designed powder flux control system

The powder flux regulation has been carried out by means of a solenoid that is able to open and close the path that the powder particles must cover between the powder feeder and the LMD nozzle. With the aim of obtaining a precise powder flux control, a fast response solenoid has been chosen. The solenoid has a direct electric control with a commutation frequency up to 300 Hz (commutation period smaller than 5 ms) and cable connection, what enables positioning the solenoid inside the machine, close to the nozzle, whereas the Arduino board that controls the solenoid is situated safe outside the LMD machine.

The powder flux regulation must go one step-ahead of the LMD machine and therefore, an offline control system has been selected. This control enables to anticipate the machine feed rate variations and actuate the solenoid in advance.

The designed powder flux regulation system has been installed in the coaxial nozzle EHU-Coax 2015, designed and manufactured by the High-Performance Manufacturing Group of the University of the Basque Country [18]. The nozzle needs two gas streams for the proper functioning (see Fig. 1). The first gas stream is the protective gas and fulfils two purposes: On the one hand, protects the melted material from oxidation and on the other hand, protects the nozzle optics from dust or powder particles that have bounced on the surface of the workpiece. The second gas flow is the drag gas and is the responsible for carrying the powder particles into the melt pool with the adequate velocity.

The control system has been designed based on the two positions of the solenoid. First position or Position 1 of the solenoid directs the drag gas (Argon and powder mixture) to the nozzle, whereas Position 2 of the solenoid connects the extra gas (only Argon) directly to the nozzle while the drag gas (Argon and powder mixture) is directed to a recycling container.

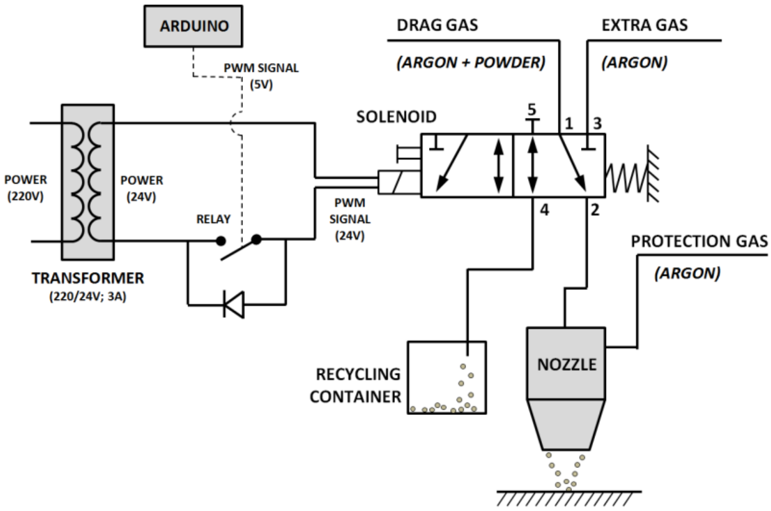


Fig. 1. Diagram of the designed powder flux regulation system.

The first step for the power flux regulation is to determine the real feed rate of the machine. Nowadays, modern CAD/CAM programs can generate toolpaths compatible with the geometrical restrictions of the CNC machines, but the kinematic restrictions of the machines are not considered. Moreover, when determining the real feed rate of the machine, accelerations and speed limitations need to be known. Therefore, the simplest and more reliable way of obtaining all this information, is extracting it directly from the drive motor signals.

Once the velocity vector has been obtained “v_r”, it is compared with the programmed feed rate “v_t”. As a result of the comparison, a velocity error vector “e” is obtained and based on this error vector, a Pulse Wide Modulation (PWM) signal has been defined with the desired frequency “f”.

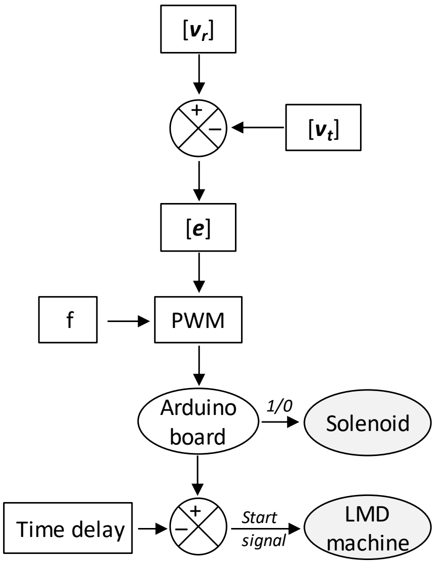


Fig. 2. Block diagram of the developed control system.

Afterwards, the generated PWM vector is introduced to an Arduino together with a time step value and the Arduino is responsible for generating a new output value, “1” or “0”, every time step. When the PWM signal has a unit value, the solenoid changes to position 1 and the powder goes to the nozzle. On the contrary, when the PWM signal has a zero value, the solenoid changes to position 2 and the powder is directed to the recycling container.

3. Experimental tests

Hereafter, the experimental tests carried out for the validation of the designed powder flux regulation system are detailed. First, the solenoid position has been switched at different frequencies and the system response has been analyzed using a high-speed camera (without using any laser source). Once the proper operating of the system has been ensured, the laser has been switched on. Firstly, straight lines varying the powder flux have been deposited and their geometry has been evaluated. Secondly, with the aim of obtaining constant height clads and avoiding powder over-accumulation at direction change corners, "L" shaped clads have been deposited and the resulting geometry has been evaluated. Metallic powder AISI 304 stainless steel, with a grainsize between 45 and 125 microns, has been used during all the experimental tests.

3.1. Powder regulation system dynamics

The objective of these tests is to analyze the response of the designed powder flux regulation system. First, the powder regulation system has been tested outside the LMD machine in a coaxial discrete nozzle, the DCN-EHU V4. The reason for choosing a discrete nozzle is the simple inner geometry. Therefore, any influence of the nozzle inner geometry is avoided when testing the regulation system.

As it can be seen in Fig. 3, different working situations have been tested. In these first tests, the recycling container has been removed and the pipe that leads the powder toward the container has been located next to the nozzle (the blue pipe in Fig. 3). The figure in the left shows the process when the solenoid is in position 1 and powder is dragged to the nozzle exit through the four discrete injectors. The figure in the middle shows the process when the solenoid is in position 2 and powder is dragged through the blue pipe towards the recycling container. The figure in the right shows the process when the solenoid is working with a 20 ms commutation period and therefore, powder is directed to both, nozzle and recycling container.

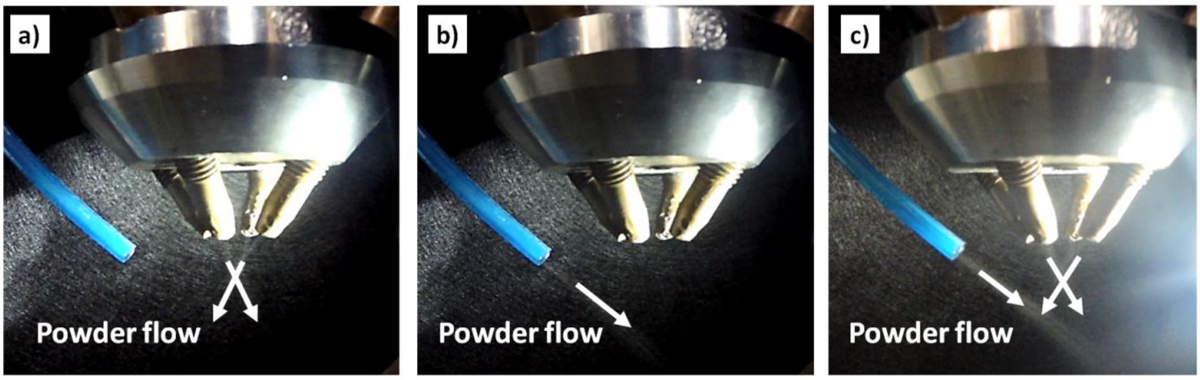


Fig. 3. Different working situations: a) Solenoid in position 1; b) Solenoid in position 2; c) 50 Hz commutation frequency of the solenoid.

With the aim of verifying the process stability when the solenoid switches from position 1 to 0 and vice versa, a high-speed camera has been used with a 1000 fps recording velocity. The solenoid has been fed with a 50 % duty cycle and 50 Hz frequency PWM signal. Thanks to the high frequency of the PWM signal, the powder outlet from the nozzle resulted constant. No powder flux variation has been detected during to the solenoid position change, but the resulting mass flow rate was reduced.

Once the solenoid proper operation has been verified, it has been installed inside the LMD machine coupled with a coaxial nozzle, the EHU-Coax2015. As it can be seen in Fig. 4, the solenoid is situated upstream the nozzle and therefore, the powder regulation system has a delay regarding the PWM signal that actuates the solenoid. In order to fix this delay, the solenoid has to be actuated in advance. The system response time between the solenoid position change and the powder flux variation at the nozzle exit has been measured using a high-speed camera and a time constant of 0.4 s has been defined for both directions of switching: from position 1 to 2 and from position 2 to 1.

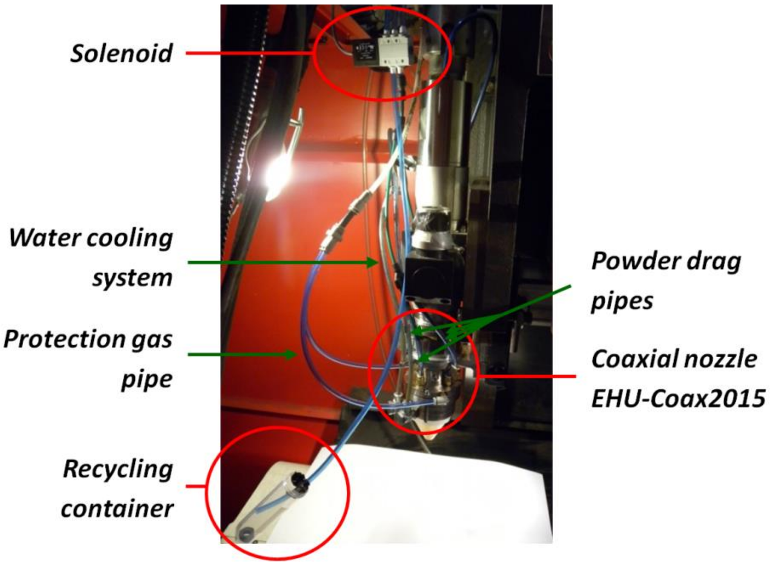


Fig. 4. Experimental setup of the solenoid inside the LMD machine.

3.2. Straight line deposition

Once the proper operation of the solenoid has been validated, different straight lines have been deposited varying the powder flux. The conditions for the deposited straight lines are detailed in Table 1, where "DC" and "T" are the duty cycle and the time period of the PWM control, respectively.

Table 1:
Conditions for the straight line deposition

Line	Power [W]	Machine feed rate [mm·min^{-1}]	Powder mass flow [g·min^{-1}]	DC [%]	T [s]
1	500	500	2	100	1
2	500	500	2	50	4
3	500	500	2	50	0.020

The first line is deposited without any powder flux control and a constant 2 g·min^{-1} powder mass flow reaches the substrate surface. In the second line, the solenoid switches between positions 1 and 2 every two seconds. Therefore, the powder reaches the substrate surface intermittently. In the third line, the solenoid changes its position with a very high frequency. Consequently, the powder flux can be assumed to be constant at the nozzle tip downstream. This assumption has been validated using a high-speed camera in section "*3.1. Powder regulation system dynamics*". The amount of powder that reaches the substrate surface is reduced proportionally to the duty cycle of the control signal, because powder particles are directed to the recycling container when the solenoid is in position 2.

3.3. Corner tests

As it has been mentioned in the introduction, when a direction change is required as a consequence of the designed trajectories, one axis has to decelerate and the other axis has to accelerate. Therefore, when the machine real feed rate varies, also does the amount of powder introduced per substrate surface unit area. The objective of these tests is to quantify this phenomenon and reduce it by controlling the powder flux.

The test carried out is shown in Fig. 5. Using a 45x45 mm base workpiece, two “L” shaped trajectories have been deposited, firstly moving 30 mm in the Y+ direction and afterwards 30 mm in the X+ direction.

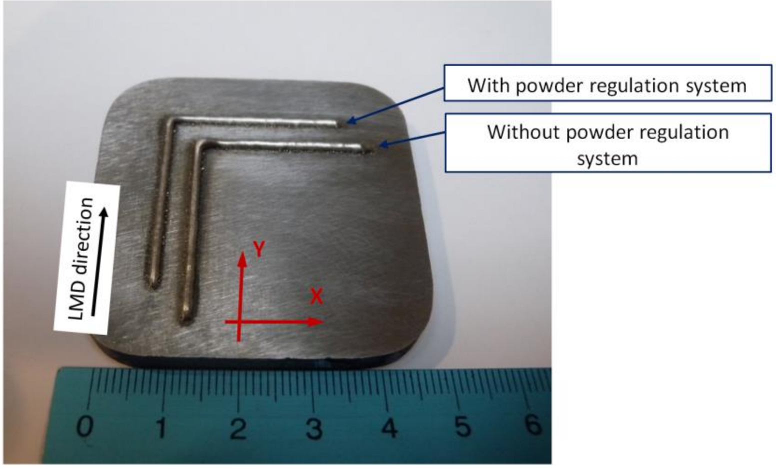


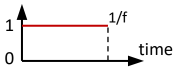
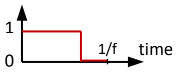
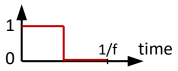
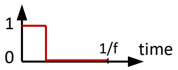
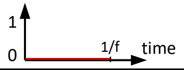
Fig. 5. The deposited right angles.

The used LMD machine has a Fagor 8070 numeric control. This control enables to extract the real velocity vector, “v_r”, with a 4 ms sampling period through the oscilloscope mode of the CNC. Afterwards, this vector has been compared with the programmed 500 mm·min^{-1} reference velocity value “v_t” and the instantaneous velocity error vector, “e”, has been obtained.

$$e = \frac{v_r - v_t}{v_t} \tag{1}$$

Due to the commutation frequency restrictions of the solenoid, a 20 ms period (50 Hz frequency) has been stablished for the PWM control and therefore the average of every 5 instantaneous error values, “$\bar{e}$”, has been calculated. As it is detailed in Table 2, the 20 ms period time has been divided into 4 steps of 5 ms each. When the average error is between 0 and 0.2, it means that the velocity error is almost zero and therefore a 100 % duty cycle (DC) is defined or, what is the same, the solenoid is in position 1 during the 20 ms period. When the average error is between 0.2 and 0.4, a 75 % DC is defined, or what is the same, the solenoid is in position 1 during the first 15 ms of the period and in position 2 during the last 5 ms, and so on.

Table 2:
Correlation between the velocity error vector and the generated PWM signal.

$\bar{e}$	DC [%]	Time in position 1	Time in position 2	PWM signal
$0 \leq \bar{e} < 0.2$	100	20 ms	0 ms	
$0.2 \leq \bar{e} < 0.4$	75	15 ms	5 ms	
$0.4 \leq \bar{e} < 0.6$	50	10 ms	10 ms	
$0.6 \leq \bar{e} < 0.8$	25	5 ms	15 ms	
$0.8 \leq \bar{e} \leq 1$	0	0 ms	20 ms	

The velocity vectors for the programmed right angle are shown in figure Fig. 6. At the beginning of the clad, the machine has to accelerate and therefore, a velocity error is detected. The same happens when the deposition direction is changed. Based on the obtained error vector and using the criteria explained in Table 2, the PWM vector has been constructed.

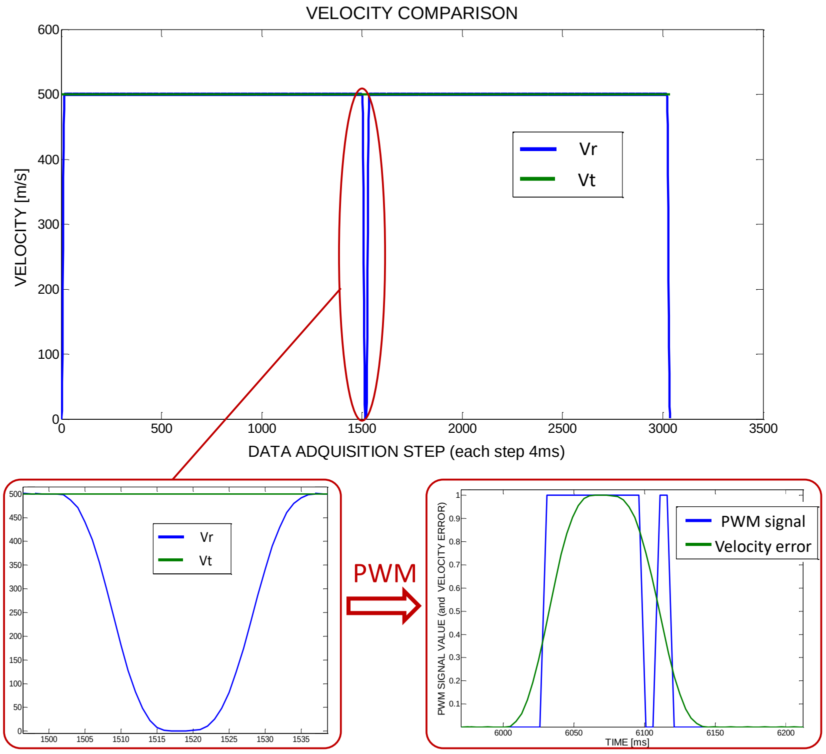


Fig. 6. Obtained velocity vectors when depositing the "L" shaped clad and the generated PWM signal based on the velocity error.

4. Powder particle simulation

One of the most critical factors in the LMD process is the powder concentration at the working plane. Powder concentration must remain constant in order to guarantee the process stability. Another important parameter is the particle velocity, because it defines the interaction time between the particles and the laser beam. The interaction time between the laser beam and the powder particles is inversely proportional to the particle velocity; the lower velocity, the higher interaction time and vice versa. Therefore, when the particle velocity is reduced, they are more likely to be melted and added to the hot substrate surface, resulting in higher powder catchment efficiency.

In previous works, a CFD model of the nozzle was carried out using Ansys Workbench together with the CFD program Fluent and good agreement was obtained between the simulated nozzle and the real one [18]. Thus, this model has been used to analyze the powder particle concentration and velocities.

The same conditions used in the deposition of the straight lines have been used for the simulations. In Table 3, the boundary conditions for the three simulations are detailed, where "$\dot{m}_{IN}$" is the powder mass flow that reaches the solenoid and the "$\dot{m}_{OUT}$" is the powder mass flow that reaches the nozzle after the powder regulation. Furthermore, the influence of the "Extra gas", see Fig. 1, has been analyzed by means of these simulations.

Table 3:
Boundary conditions used in the simulations.

Case number	Protection gas flow [l·min^{-1}]	Drag gas flow [l·min^{-1}]	Extra gas flow [l·min^{-1}]	$\dot{m}_{IN}$ [g·min^{-1}]	DC [%]	$\dot{m}_{OUT}$ [g·min^{-1}]
1	12	3.5	3.5	2	100	2
2	12	3.5	3.5	2	50	1
3	12	3.5	0	2	50	1

The skewness factor has been used to evaluate the mesh quality and a 0.8 maximum value has been fixed for ensuring the convergence of the simulations. A 10^{-4} convergence criterion has been stablished for all the parameters to guarantee the correct convergence of the simulations. Simulation results are discussed in section 5.3.

5. Results and discussion

5.1. Cross sections of the straight lines

The topography of the three clads deposited in section "3.2. Straight line deposition" has been evaluated using a Leica DCM 3D confocal microscope. With the aim of measuring the average height and width of the clads, five different transversal profiles have been analyzed per line, resulting on a total of 15 measurements.

In the case of Line 2, the solenoid is in Position 2 during 2 seconds, so there is no deposited material and the dimensions of the clad are zero in this zone. Hence, the dimensions of the second line showed in table 4 correspond only to the clad zone where the solenoid is in Position 1.

As it was expected, height values for Lines 1 and 2 are similar; because the powder flow is the same in all cases when the solenoid is continuously in Position 1. However, Line 3 has been deposited using a high frequency PWM signal. In this case, powder flow rate is reduced and so happens with the clad height. On the contrary, the clad width is maintained almost constant. This is because the clad height is directly related with the amount of powder, whereas the clad width is proportional to the laser power. This result is consistent with the conclusion reached by Nenald et al. [13].

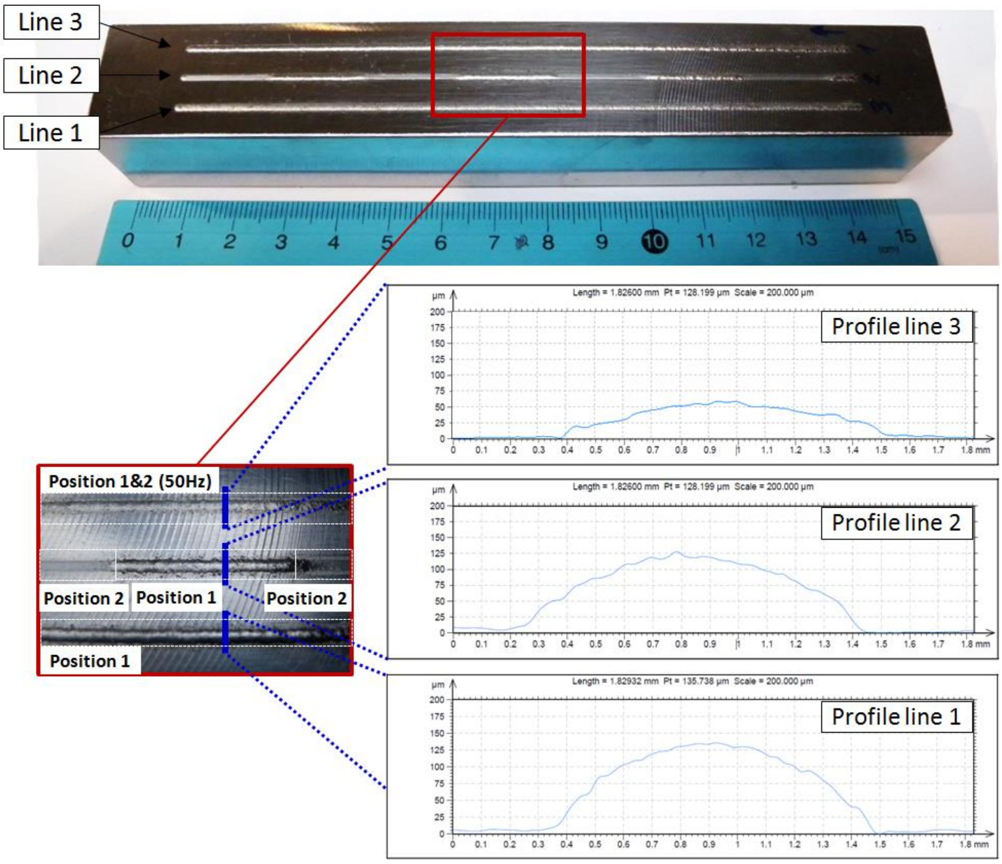


Fig. 7. Lines 1, 2 and 3 with their respective cross section profiles.

Table 4:
Average height (H) and width (W) of the deposited lines.

Line	H [µm]	W [mm]
1	138	1.15
2	128	1.19
3	60	1.17

5.2. Geometry of the deposited clads in the corner tests

Corner tests present some local effects; especially, the beginning of the clad and the direction change corner are the most critical points regarding to process stability. This has been noticed when analyzing the error vector defined as the difference between the programed and the real velocities, see Fig. 6. At the beginning of the clad, the LMD machine has to accelerate from zero to the programmed velocity value. Therefore, if no control over the powder flux is applied, the amount of powder added to the substrate per unit area is higher than the expected. As a result, a higher clad height is obtained and this phenomenon is amplified with each layer. For the used deposition conditions, a 0.1 mm height increase has been measured for each layer and a total height of 1 mm has been reached after the overlap of 10 layers.

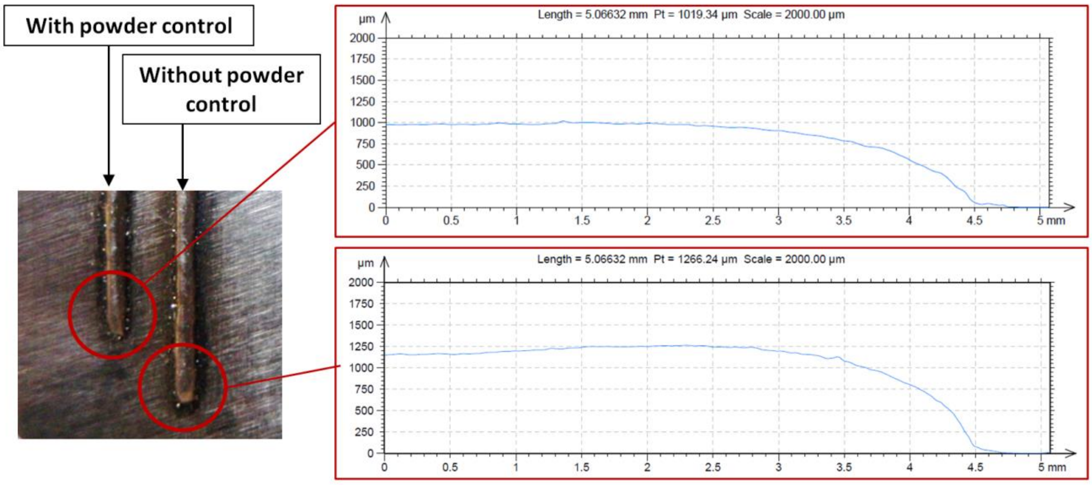
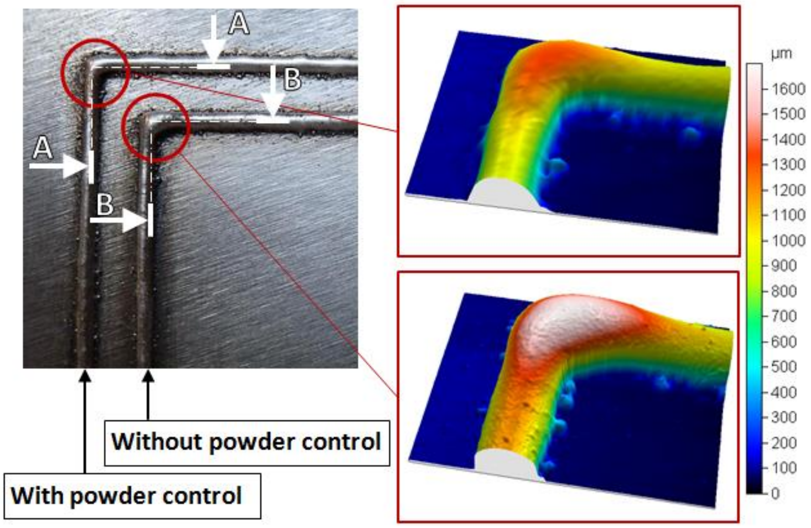
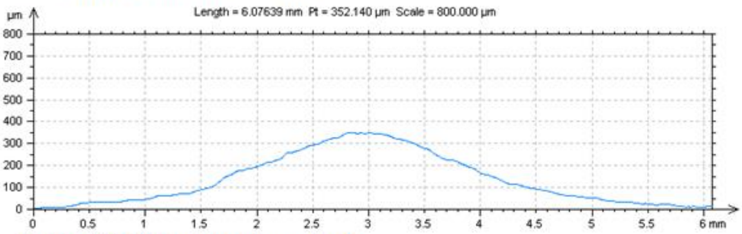


Fig. 8. Analysis of the clad beginning with and without powder control.

For the analysis of the clad over-height at the beginning, the longitudinal profiles of the clads have been obtained using the software Leica Map. As it can be seen in Fig. 8, when no powder control is applied, the clad has a 266 µm over-height, whereas, when the powder control is applied this over-height is reduced to less than 20 µm.



Section AA: With powder control



Section BB: Without powder control

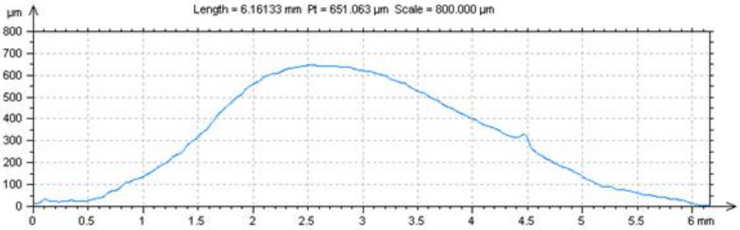


Fig. 9. Clad over-height analysis when the deposition direction is changed.

As it has been mentioned before, another critical point in the LMD process is when the deposition direction is changed abruptly. As it was expected, a material accumulation has been detected at the corner. If no powder flux control is activated, a 650 µm over-height has been measured. This means a 65% deviation from the expected clad height and resulted in process instabilities when overlapping the subsequent layers. If the powder flux regulation is applied, the clad over-height has been reduced to a value of 350 µm; or what is the same, the clad over-height is reduced to the 46% relative when no control has been used.

5.3. Simulation results

In order to evaluate the optimum gas flows and analyze the importance of the extra gas when the solenoid is in Position 2, a CFD simulation of the LMD nozzle and the developed powder flux regulation system has been carried out. The simulation results show the necessity to use the extra gas, with the same flow as the drag gas for obtaining a stable LMD process. If this extra gas stream is not used, the particle velocity is lowered and their distribution at the nozzle exit varies; consequently, the regulation system loses its validity.

If no extra gas is introduced when the solenoid is in Position 2, the gas flow that carries the powder particles towards the nozzle is reduced in the same proportion as the powder particle mass flow and this has a direct effect on the particle velocity. In the simulated cases Case 1 and Case 2, a maximum particle velocity of 1.85 m·s^{-1} has been obtained, whereas in the third case (Case 3) the particle maximum velocity has been reduced to a 1.59 m·s^{-1} value. Therefore, it can be concluded that, if the gas flow that carries the powder particles to the nozzle is maintained constant, the velocity of the particles does not vary.

The variation of the powder particle velocity is not just detrimental for the process because it changes the interaction time between the powder particles and the laser beam. If the Argon flow is varied, the powder distribution changes and consequently, the powder focal plane is also displaced in the vertical axis.

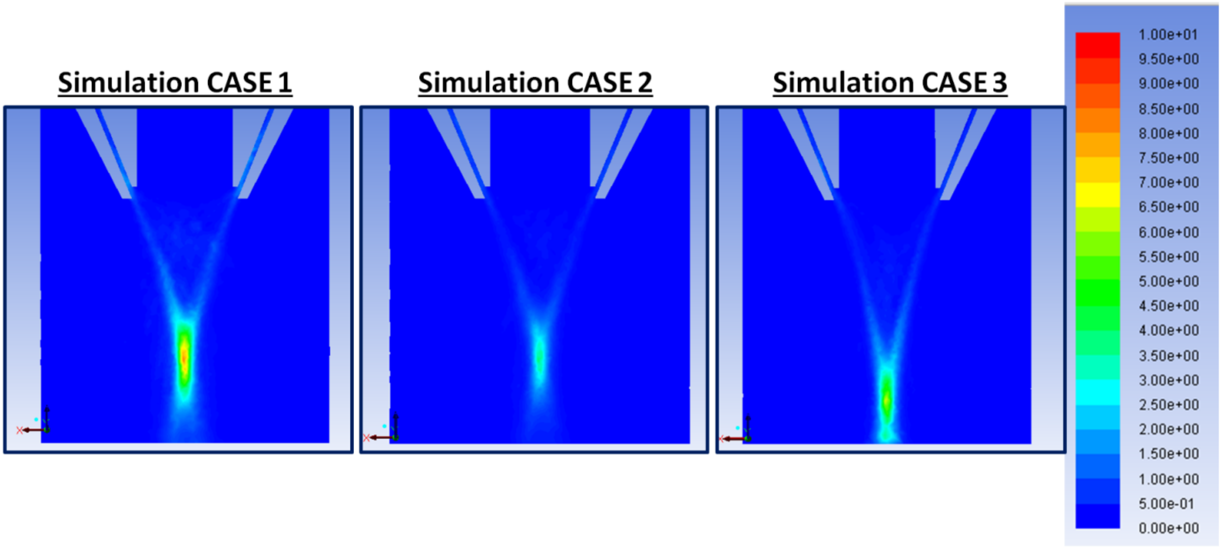


Fig. 10. Powder concentration in [kg·m^{-3}] for the three simulated cases in the XZ plane that comprises the rotation axis of the nozzle.

For the simulations where the extra gas is used (Cases 1 and 2), the powder distribution is maintained constant at the nozzle exit and the focal plane and is situated at a constant 14.5 mm distance from the nozzle tip. On the contrary, if no extra gas is used (Case 3) the powder distribution at the nozzle exit is changed and the focal plane is displaced until a 19 mm distance from the nozzle tip.

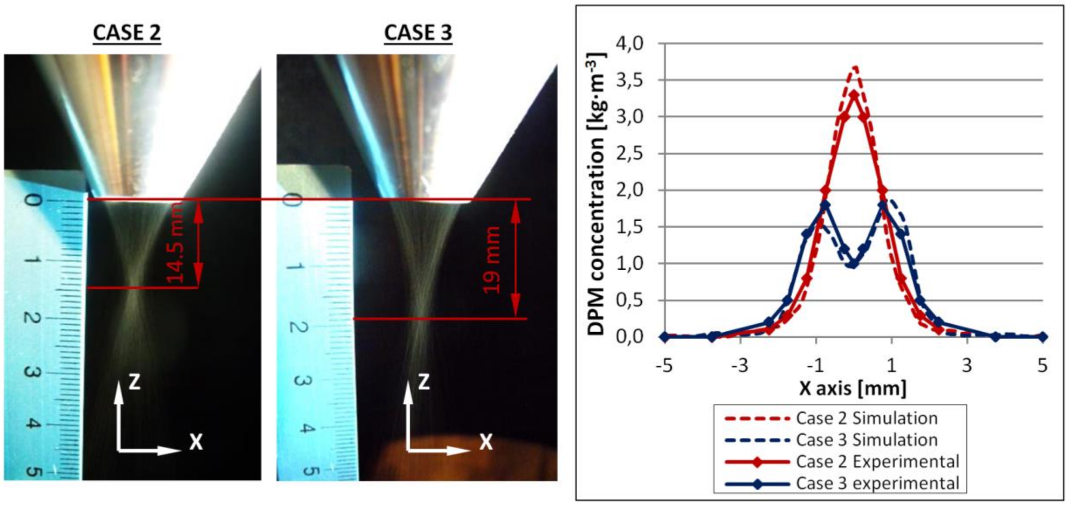


Fig. 11. Powder particles at the nozzle exit when extra gas is used (case 2) and when no extra gas is used (case 3). The diagram in the right shows the DPM concentration in the X axis at a 14.5 mm distance from the nozzle exit.

The results of the simulations have been validated experimentally. In Fig. 11 the variation of the powder focal plane is shown. In the diagram on the right in Fig. 11 a comparison between the simulation predictions and the experimental results for both cases (Case 2 and 3) is displayed. The plotted discrete phase concentration (DPM) corresponds to a radial section at a 14.5 mm distance from the nozzle tip. The experimental powder concentration has been measured by a mechanical system developed by Tabernero et al. [19], where a set of containers with different diameters is used. Obtained results show good agreement between the simulation and experimental results.

6. Conclusions

By means of the designed powder flux regulation system, the capability to control instantaneously the mass flow rate at the nozzle exit has been obtained. Hereafter, the main conclusions reached after the realization of the present research work are detailed:

- A novel powder flux regulation system has been developed and validated.
- The powder flux regulation system is based on a comparison between the real and theoretical velocity values of the machine. Due to the delay of the system, the control must be actuated on advance, what obliges to use an offline control.
- An extra gas flow is required for maintaining the powder particle velocity constant at the nozzle exit. The extra gas flow needs to be equal to the drag gas flow in order to guarantee the stability of the process and ensure good results.
- Stable clad height has been obtained during the deposition of straight lines. Material accumulation at the beginning and at the end of the clad has been completely avoided. At the

direction change corners the clad over-height has been reduced to the 46% compared when no control has been used.

- In the present research paper, no wear of the solenoid has been detected, but powder particles may reduce the service life of the solenoids. This aspect may be especially critical if abrasive powders, such as ceramic materials, are injected.
- The possibility to switch on or off the powder flow at the nozzle exit enables to stop the powder flux when the process is not depositing material, for example void movements or when the nozzle is approaching to the starting point of the LMD process. The collected powder in the recycling container is completely clean and can be reused with no drawbacks to the process. This fact results directly in material saving and a cleaner process.

Acknowledgements

Thanks to La Caixa foundation for its financial help.

Special thanks are addressed to the Industry and Competitiveness Spanish Ministry for the support on the DPI2013-46164-C2-1-R TURBO project and RTC-2015-4194-5 AddiClean project.

References

[01] Toyserkani E. Laser Cladding. CRC Press LLC, 2005. ISBN 0-8493-2172-7.

[02] Esmaeilian B, Behdad S, Wang B. The evolution and future of manufacturing: A review. J Manuf System 2016; 39:79–100.

[03] Peng L, Shengqin J, Xiaoyan Z, Qianwu H, Weihao X. Direct laser fabrication of thin-walled metal parts under open-loop control. Int J Mach Tool Manuf 2007;47:996–1002.

[04] Tan H, Chen J, Zhang F, Lin X, Huang W. Process analysis for laser solid forming of thin-wall structure. Int J Mach Tool Manuf 2010;50:1–8.

[05] Purtonen T, Kalliosaari A, Salminen A. Monitoring and adaptive control of laser processes. Phys Procedia 2014;56:1218–1231.

[06] Pavlov M, Doubenskaia M, Smurov I. Pyrometric analysis of thermal processes in SLM technology. Phys Procedia 2010;5:523–531.

[07] Hofman JT, Pathiraj B, van Dijk J, de Lange DF, Meijer J. A camera based feedback control strategy for the laser cladding process. J Mater Process Tech 2012;212:2455–2462.

[08] Ocylok S, Alexeev E, Mann S, Weisheit A, Wissenbach K, Kelbassa I. Correlations of melt pool geometry and process parameters during laser metal deposition by coaxial process monitoring. Phys Procedia 2014;56:228–238.

[09] Bi G, Gasser A, Wissenbach K, Drenker A, Poprawe R. Characterization of the process control for the direct laser metallic powder deposition. Surf Coat Technol 2006;201:2676–2683.

[10] Bi G, Gasser A, Wissenbach K, Drenker A, Poprawe R. Investigation on the direct laser metallic powder deposition process via temperature measurement. Appl Surf Sci 2006;253;1411–1416.

[11] Bi G, Schürmann B, Gasser A, Wissenbach K, Poprawe R. Development and qualification of a novel laser-cladding head with integrated sensors. Int J Mach Tool Manuf 2007;47:555–561.

[12] Paul R, Anand S. Process energy analysis and optimization in selective laser sintering. J Manuf System 2012;31:429–437.

[13] Boisselier D, Sankaré S, Engel T. Improvement of the laser direct metal deposition process in 5-axis configuration. Phys Procedia 2014;56:239–249.

[14] Ren L, Sparks T, Ruan J, Liou F. Process planning strategies for solid freeform fabrication of metal parts. J Manuf System 2008;27:158–165.

[15] Nenadl O, Ocelík V, Palavra A, Hosson JTMD. The prediction of coating geometry from main processing parameters in laser cladding. Phys Procedia 2014;56:220–227.

[16] Ding Y, Warton J, Kovacevic R. Development of sensing and control system for robotized laser-based direct metal addition system. Addit Manuf 2016;10:24–35.

[17] Giret A, Trentesaux D, Prabhu V. Sustainability in manufacturing operations scheduling: A state of the art. J Manuf System 2015;37:126–140.

[18] Arrizubieta JI, Tabernero I, Ruiz JE, Lamikiz A, Ukar E. Continuous coaxial nozzle design for LMD based on numerical simulation. Phys Procedia 2014;56:429–438.

[19] Tabernero I, Lamikiz A, Ukar E, López de Lacalle LN, Angulo C, Urbikain G. Numerical simulation and experimental validation of powder flux distribution in coaxial laser cladding. J Mater Process Technol 2010;210:2125–2134.