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A feedforward controller for tuning laser cladding melt pool geometry in real time

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Abstract: In this paper, a feedforward proportional-integral (PI) controller is developed to effectively control and tune the laser cladding melt pool geometry in real time. Width setpoint is included in the computer numerically controlled (CNC) programming, making possible its instantaneous change in relation to the position and time, as opposed to conventional controllers that do not have real-time information about these variables. The new concept of variable setpoint at different positions applied to laser cladding represents a great improvement in its use for changeable geometry applications such as blade fabrication. Several experiments are performed to characterize the behaviour of the system, revealing some key factors from monitoring system and image processing crucial for the controller. Laser power is selected as the input control variable, and the clad width is chosen as the output. The width of the melt pool is obtained based on measurements of CMOS camera images and an in-house image processing software algorithm. Closed-loop parameters are identified from the experimental data and Matlab simulations. The architecture of the controller consists on a conventional PI feedback loop and a feedforward module that shows low overshoot and fast response times. Instantaneous connections between laser, CNC, and PC systems allow for knowing the relationship among the exact position and real and setpoint melt pool values. The performance of the controller is verified in the fabrication of cladded parts with variable widths and in real time.

Keywords: Laser cladding; Melt pool measurement; Process monitoring; Real-time control; Clad width control; Feed forward control.

1 Introduction

Laser cladding is a technique that allows to add material directly from laser-melted powder and deposit it over a substrate. It is an additive manufacturing process capable of producing coatings or structures in detail in specified areas, and on the contrary of other adding material techniques, it is done over a piece previously fabricated by other method. This technique provides a unique characteristic such as the selectivity of the process, a minimum heat-affected zone that presents a very high joining quality between the cladded material and the substrate, layers with a height less than 0.1 mm that permit a high spatial resolution for achieving any geometry or a minimum thermal distortion into the piece. However, the technique is still not mature enough in industrial terms because of the complexity of the process. Regarding the process, the main difficult that laser cladding presents is the variety of physical phenomena that take part, such as powder particle flow, the substrate heating and the generation of the melt pool, among others. Laser cladding can present a limited repeatability of the obtained results in spite of having the same working conditions. Small variations of the mass flow, laser power, scanning speed, gas, substrate heat or particles interferences can create notable geometrical changes. Calleja et al. [1] and Hanzl et al. [2] studied the impact of these parameters on the cladded material properties and optimized them in order to select the optimum process conditions.

Due to the high casuistic of the implied phenomena, several parameters and methods are used for monitoring the process. Everton et al. [3] showed a summary of the in-situ monitoring modules currently available from additive manufacturing machine manufacturers. Nonetheless, the state of the technique still needs to be optimized by robust monitoring and control systems that allow to know online measurements and possible alterations, being capable of guarantying a stable process. Bi et al. [4, 5] monitored the temperature measurement in order to determinate the effect of the part geometry, power density and oxidation, so that it permits the control of process, quality and reproducibility. Krauss et al. [6] used thermographic measurements for monitoring the temperature distribution to gather information about the part quality and the process stability. One of the most monitored parameters is the melt pool geometry because it provides relevant information about the track dimensions, guarantying a controllable geometry and zero defect cladding areas during the process. Its online monitoring usually takes place through cameras situated coaxially into the cladding head, such as Asselin et al. [7] that used CCD cameras to monitor it and to achieve the melt pool dimensions by means of algorithms and image treatments.

Regarding the melt pool geometry, both the height and the width were studied. Toyserkani et al. [8] controlled laser pulse energy to maintain the height constant, whereas Fathi et al. [9] used the scanning velocity as the input control variable and clad height as the output. Song et al. [10] developed a hybrid controller to control the clad height and the temperature by means of adjusting laser power online to maintain constant clad height. Hofman et al. [11] used a CMOS camera and software algorithms to obtain the width of the melt pool, adjusting power in real time to compensate for heat accumulation in such a way that the width remained at the user defined value. Both the obtaining and processing of this information can be done in real time, making easier the control of the cladding process.

Image processing is a relevant step of the whole process, so there have been great efforts to optimize it. Prometec developed a commercial system for image analysis that allows the processing of the captured images, whereas Rodríguez-Araujo et al. [12] designed a known system based on the binarization of the obtained images.

In conclusion, laser cladding is based on the use and optimization of different physical phenomena. Optical diagnosis and process control improve, in a notable way, their knowledge, addressing to the achievement of industrial objectives in sense of repeatability and stability, revealing new opportunities for simultaneous improvement of piece quality, process control, energy and material efficiency and environmental aspects.

The aim of this study is to develop a feedforward proportional-integral (PI) controller to effectively control and tune the laser cladding melt pool geometry online for part production by CMOS digital image monitoring. This work takes advantage of the concept of variable setpoint at different positions or time, conventional in machine tool industry but not introduced in laser cladding technology, providing the opportunity to apply it in applications that require variable geometry.

2 **Experimental procedure**

2.1 Experimental setup

The whole experimental setup is situated into a six-axis machine tool controlled by a computer numerically controlled (CNC) and equipped with laser protection windows. The system consists on a 2-kW fibre laser system (Rofin FL020, wavelength 1070 nm) combined with a Precitec cladding head and a fibre of 400-μm diameter. The optical path is formed of a 150-mm collimation unit and 200-mm focus length. The power density distribution was analyzed, and the spot size was determined in different planes from the nozzle. It was showed a 0.546-mm minimum spot laser at 10.6 mm from the nozzle. This position was used as the working distance.

The powder is stored in a Sulzer Metco Twin-10C powder feeder with two stations that can operate and be controlled independently. The hoppers were heated up 40 °C by individual heating covers. Argon 99,991 % was used as carrier gas and a powder distributor 1 to 4 injected it into a coaxial nozzle that was chilled by water. The powder cone was optimized by 2 l/min additional and coaxial gas flows, and its minimum size plane coincides with the focus laser plane, optimizing the powder capture.

A Photonfocus MV-D1024E-160-CL CMOS camera of 150 fps is situated coaxially to the nozzle to monitor the melt pool. A Dalsa Xcelera-CL-PX4 frame grabber governs the camera and sends the picture to a PC to be analyzed.

In order to achieve the best melt pool image, tests with different filters were done, eliminating non-desirable contributions from laser and powder. The combination of a notch filter (1064 nm, FWHM 73 nm) and a long pass filter of 700 nm optimizes the quality of the monitored melt pool, eliminating brilliant signals from powder and power that can falsify the measure. The camera was aligned with the machine axis and calibrated, obtaining an equivalence of 25 μm/pixel.

2.2 Arrangement of the experiments

In the tests, Inco 718 was used as substrate material and MetcoClad 52052 powder as cladding material. Both compositions are shown in Table 1. The powder has a granulometry of −106 + 45 μm and was manufactured by gas atomization. During the tests, the substrate was fixed and the cladding head was moved perpendicularly to it.

Table 1: Chemical composition of the substrate and powder (wt.%)

Material	Ni	W	Cr	C	Si	Fe	B	Nb	Mo	Ti	Al
Inco 718 plate	50	–	17	0.08	0.35	19	0.01	4.75	2.8	0.65	0.2
MetcoClad 52052 powder	30	50	2.5	1	1	0.5	0.1	–	–	–	–

Experiments were carried out varying process parameters in order to determine the optimal process window. Monolayer tracks of 20-mm length were cladded. All tests were performed heating the substrate at 300 °C by a hot plate. Previously cladded samples at room temperature showed cracks transversally to the cladding direction. The deposited tracks were characterized geometrically by metallographic analysis. This procedure has consisted on sectioning the area of interest for easier handling; cutting it; encapsulating the specimen into a compression mounting component; grinding with water; and polishing with diamond solutions of 6, 3, and 0.1 µm. The probes were etched with Kalling′s etchant.

Table 2 shows the values of scanning speed, laser power and powder feeding rate that produce good cladded tracks. Values higherthan400 W, 600 mm/min or13.5g/min produce plasma, non-continuous clads and bad adhesion, respectively.

Table 2: Input parameters.

Laser power (W)			150-450		
Cladding speed (mm/min)		400	600	800	
Powder feed rate (g/min)	0	6.6	9.03	13.5	18.2

In Fig. 1, it can be noted an increase in the width when power increases, being more gradual without powder. At low power values, the width at zero mass flow is bigger than tracks with powder. This can be explained because in experiments without mass, power is the dominant parameter, whereas using powder, the power is affected by it in two different ways. At low powers, the energy is not enough to melt the powder, creating an effect of mask and decreasing the width. On the contrary, at medium-high power values, there is enough energy to melt the powder, and at the same time, the wetting angle decreases, producing tracks with more width and less height.

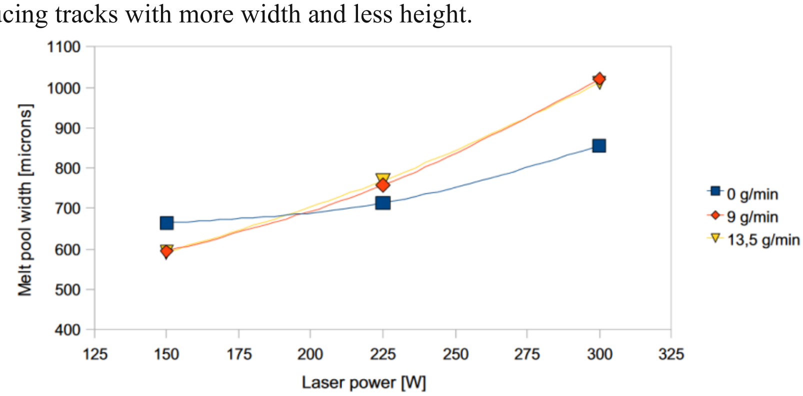

Fig. 1 Measured widths obtained from metallographic probes.

3 Feedforward control system

The feedforward controller was designed on the basis of an identified model and produced a control action appropriate for the desired setpoint. The feedforward took advantage of the desired clad width knowledge to compute an appropriate control action that was injected in the closed-loop system.

3.1 Image processing

The feedforward control system used camera for real-time detection and monitoring of melt pool dimensions, using inhouse image processing algorithms. The code was implemented in Open CV and optimized for speed resulting in a processing time of 10 ms, using also this value as exposure time. Digital amplifications and LinLog technology were tested in order to improve the pixel response and, therefore, the detection of the real melt pool.

As the same time as the tracks were cladded, melt pool images were captured with the CMOS camera and transferred to the PC by the frame grabber where each image was binarized by means of a user-defined threshold value, eroded and dilated favouring the elimination of laser and powder bright sparkles. Figure 2 shows the original and the last binarized image, which was approximated to an ellipse, and from it, melt pool area and minor and major axes were calculated. This procedure allows the comparison between the geometrical characteristics measured offline and the melt pool dimensions grabbed in real time, observing a high influence of the powder in the monitored signal.

Analyzing the results, it was observed that tests with powder are noisy; that is, at same process parameters, they had higher variation with respect to the average value than tests without it. Thus, for the melt pool area, the percentage of deviation varied from 5 to 42 %, from 3 to 40 % for major axis and from 2.8 % to 27 % for minor axis. Based on these values, it was concluded that the non-desirable artefacts of the powder affect and distort the monitored signals, being the minor axis the stablest one. On the other hand, these monitored values have to be compared with a physical parameter in order to verify the agreement. In this sense, it was considered that the minor axis corresponds to the width of the cladded tracks, and as mentioned before, it was less affected by the powder, so it was selected as the more appropriate parameter to work with. In Fig. 3, the minor axis of tests with and without powder was represented.

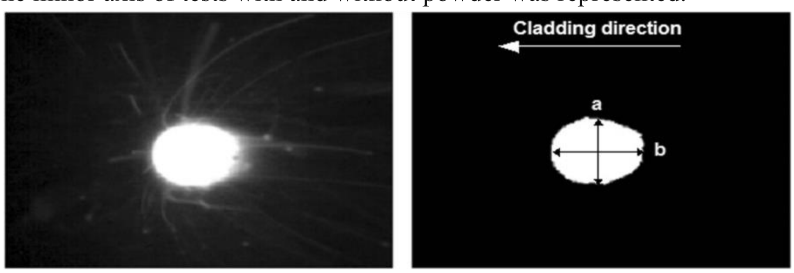

Fig. 2 Left: original image. Right: binarized image. The image shows cladding direction, minor (a) and major axes (b).

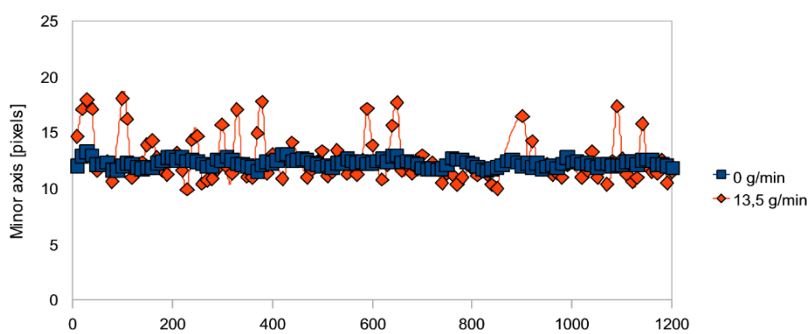

Fig. 3 Minor-axis evolution for tracks without powder and with 13.5 g/min mass flow.

Images without powder were used to determine the correct threshold, as there is no powder that can alter the monitored melt pool. Knowing the equivalence between pixel and millimetre, minor-axis values were compared with the width measurements in order to achieve the similar monitored and measured widths. The results show an ideal threshold of 65, valid for the whole power range of the process window.

3.2 Feedforward controller

The dynamics of the process were evaluated using several laser powers and cladding speeds. Figure 4 shows a linear increase in the clad width with the laser power, whereas variations of the speed maintain the signal constant. Requested laser power P was taken as the input for this plant [13], whereas the output consisted of the melt pool width W as obtained from the camera image processing. The system identification showed a response signal independent of the time (Fig. 5), so the plant was considered as a gain and its value calculated from the experimental data.

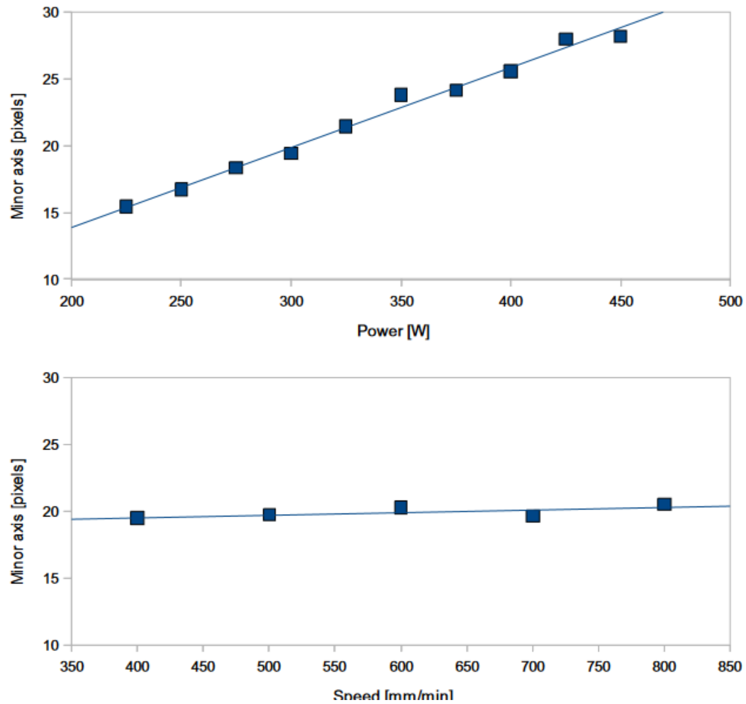

Fig. 4 Power and speed influence over the clad width

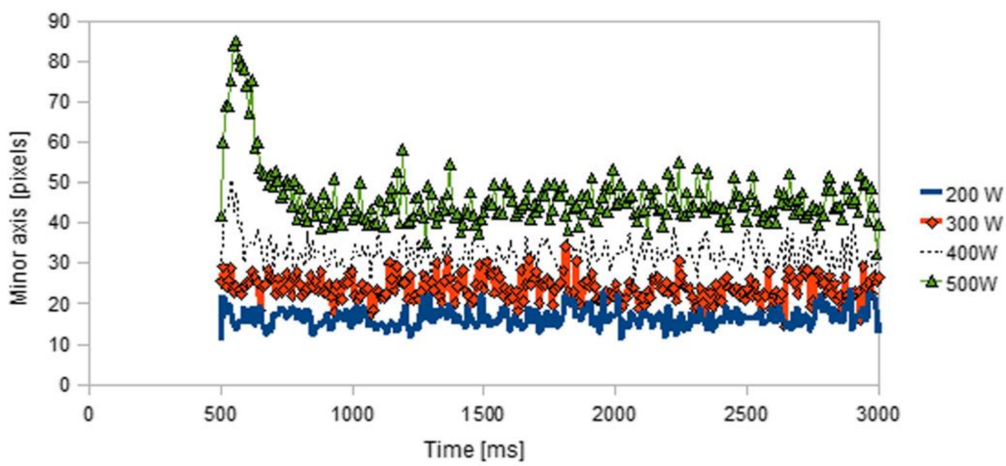

Fig. 5 System response signal in function of the time.

Initially, experiments with a closed-loop feedback PI were done. Derivative term was not considered due to the amplification of the existing noisy data. Figure 6 shows the performance of the PI controller at different proportional and integral gains. Previously, Matlab simulations were done in order to estimate good Kp and Ki values. With increasing proportional gain, the system response speed increases, but a too high value involves an overshoot in the clad width. Decreasing integral gain too much generates also a not desirable overshoot. This indicates that there must be a compromise between Kp and Ki in order to have the quicker response speed with the lower overshoot. Kp = 0.02 and Ki = 0.018 were considered as the ideal parameter values for this plant.

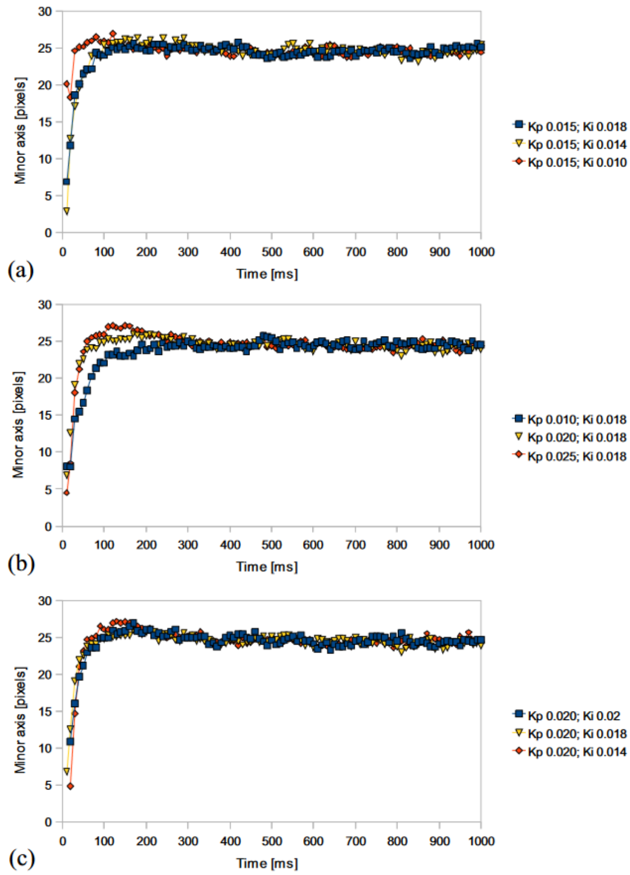

Fig. 6 Performance of PI controller a at different integral gains, b at different proportional gains and c optimizing the combination of Kp and Ki values.

Figure 7 shows a significant delay in the programmed initial position of the tracks, generating a lack of cladded material. In addition to that, although the PI gains were optimized, the system response speed was considered slow; i.e. in this test, 500 ms was needed to achieve the melt pool setpoint, which was considered too much for a PI controller. As a result, a new controller was developed and two improvements were done with reference to the initial one: (1) a feedforward path was added to improve and speed up the response time of the system; (2) a delay time was added to the block diagram in order to have the correct cladded material during the stabilization time of the signal. An overview of the feedforward controller layout is presented in Fig. 8.

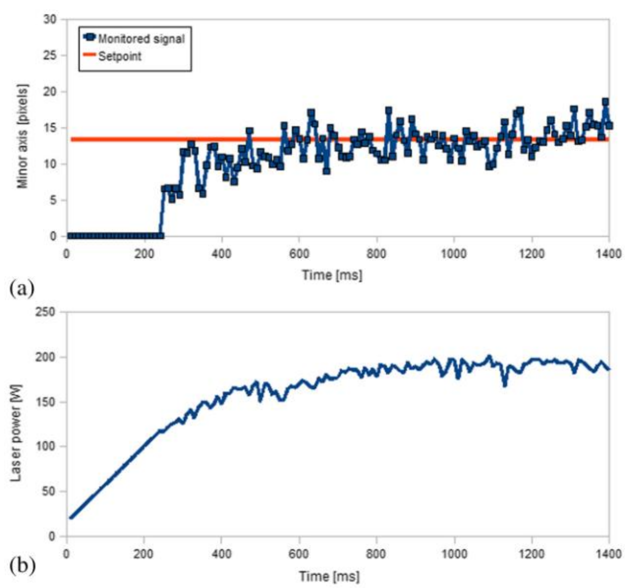

Fig. 7 Performance of feedback PI controller. a Monitored minor axis signal. b Laser power regulation.

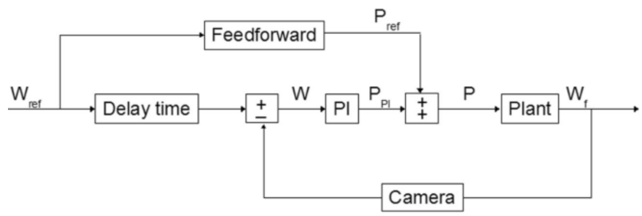

Fig. 8 Block diagram of feedforward controller.

In order to be able to obtain the best PI controller response, different power signals were added by a feedforward module, testing the speed and behaviour improvement. Using a suggested power below the ideal (Fig. 9a), the answer of the system was slowed down, taking more time for reaching the objective value and showing an overshoot caused by the need of having quickly a higher power. At suggested powers near the ideal one, both the system response and overshoot were better. On the contrary, at higher powers, the system showed the biggest overshoot and acquired an inertial movement that generated a non-desired wavy signal.

On the other hand, looking for the ideal delay time value experiments was carried out using a suggested power similar to the required one and evaluating different delay time values (Fig. 9b). Same time was needed for getting the objective minor value, but a better response was showed for 0.03 s; therefore, it was considered as the ideal delay time. Longer or shorter values exhibited overshoot and more instability. Therefore, in the new proposed PI controller, comparing signals with the ideal delay time value (0.03 s), less time was required for achieving the objective signal of minor value by choosing a suggested power close to the correct one.

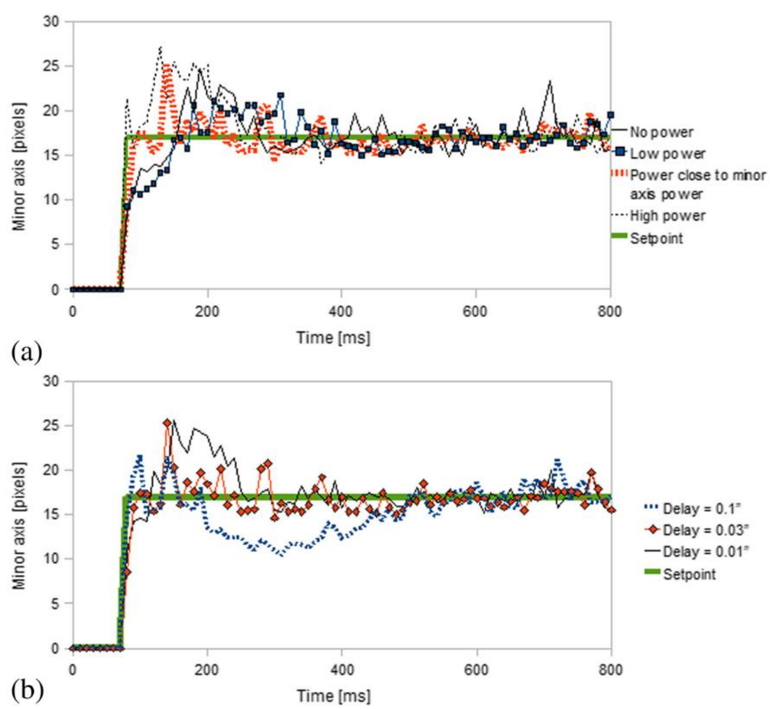

Fig. 9 Optimization of the PI controller a at different power values and b at different delay time values.

The performance of the proposed system for cladded walls was checked (Fig. 10). It can be clearly noticed that melt pool geometry tends to increase with time, due to the increase in surface temperature as the laser beam was applied for longer time. On the contrary, activating PI controller cladded walls followed the setpoint value by means of decreasing the laser power, with no overshoot or delay time.

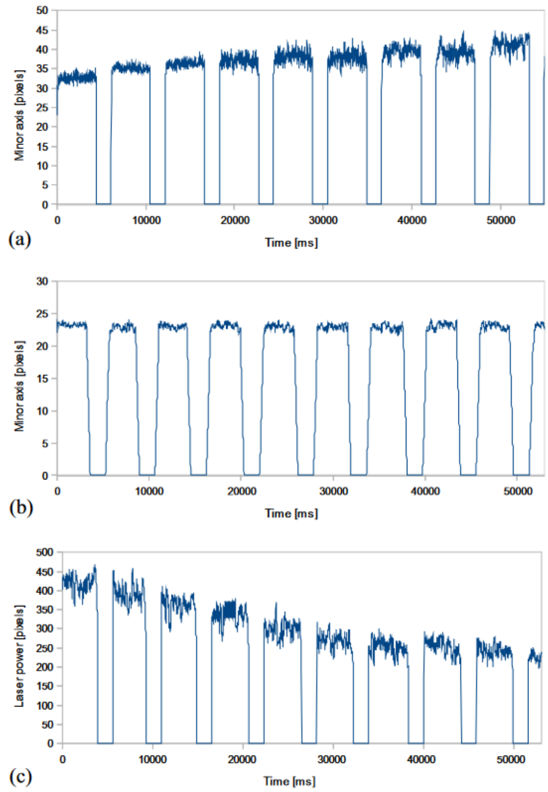

Fig. 10 Melt pool geometry of a cladded wall a without PI and b with PI. c PI laser power adjustment.

Similar behaviour was showed in clads with helical geometry. Two tests were carried out with and without control in order to confirm the effectiveness of the control system in complex geometries. Figure 11a exhibits an increase in minor axis with the time, whereas activating the PI, a uniform value of 6 pixels was obtained thanks to the adjustment of laser power. Figure 11 shows two views of the fabricated helixes with and without the proposed control system. As seen, the increase in minor axis brought on undulation and roughness on the upper surface and at the side surfaces.

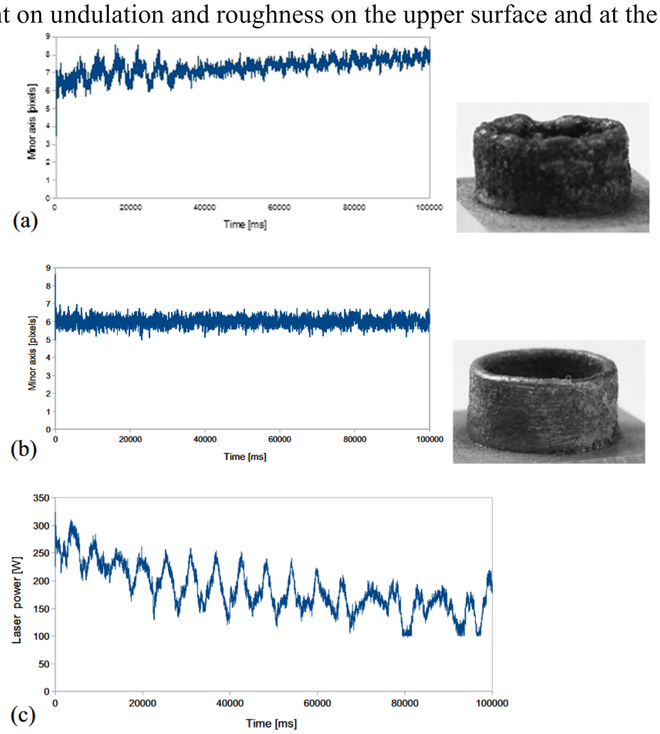

Fig. 11 Melt pool geometry of cladded helixes (a) without PI and (b) with PI. (c) PI laser power adjustment.

3.3 Real-time controller performance

Actual laser cladding PI controllers are installed in systems that do not have instantaneous communication between the CNC and the PC. In this study, both equipments are continuously connected receiving and sending real-time information about the exact position and the monitored and set values of melt pool geometry. The synchronization was done by threads that worked in parallel, the main one responsible of the communication with the CNC and the others in charge of camera and PI tasks. Thanks to this characteristic, melt pool geometry can be adjusted online in each instant.

In order to investigate the capability of the developed feedforward PI controller in the production of a part, a test was carried out to generate a sinusoidal shape as shown in Fig. 12. Figure 12a shows that the closed-loop system followed the setpoint with very good accuracy, exhibiting a standard deviation of 3.5 pixels. In Fig. 12b, the corrections that the PI controller makes in order to follow the defined melt pool geometry are shown.

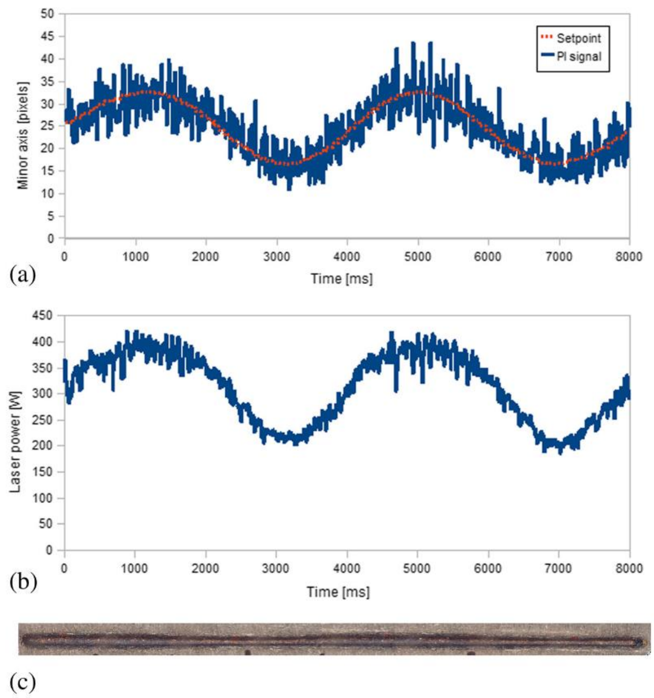

Fig. 12 Closed-loop system performance in depositing a sinusoidal shape. a Process output and setpoint. b Process input and setpoint. c Cladded track

Thanks to the new concept of variable setpoint at different positions for laser cladding developed in this work, applications such as blade fabrication with changeable and controlled geometry can be addressed.

4 **Conclusions**

In this paper, a feedforward controller was designed on the basis of an identified model taking advantage of the known desired clad width to compute an appropriate control action. MetcoClad 52052 cladded tracks were deposited, monitoring and controlling in real time. Monitoring system and image processing were crucial for obtaining precise melt pool values. Initially, a PI feedback closed-loop was designed based on monitored CMOS digital images. Laser power and clad width were used as input and output signals, respectively. System identification showed a proportional relationship between both. Results exhibited a significant delay of the cladded tracks with reference to the programmed initial position and a low system response speed. An improved controller, consisting of a feedforward path and a conventional PI feedback loop, was selected as the best choice. The use of a suggested power close to the real and the utilization of a delay time in the block diagram of the closed-loop controller displayed a remarkable improvement of the system behaviour. Controller performance was tested in the production of parts with simultaneously changeable position and melt pool geometry.

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