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In-situ clad geometry measurement in wire laser metal deposition process

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Abstract

Wire Laser Metal Deposition (w-LMD) is a promising technique that could generate significant cost reductions. However, process control still needs to be developed to ensure product quality. Due to the high temperature of the melt pool and the resulting light radiation, current commercial equipment can only measure the geometry of the clad after the process or between the deposition of different layers. They also require a stop in the process which affects the heating and cooling cycles of the part and the total manufacturing time. In this work, a measurement system based on a side mounted vision camera and laser light projection is developed, which allows an in-situ measurement of the clad geometry data. This enables to know the nozzle-to-part distance, the surface condition where the successive layers are deposited and the relation between bead characteristics and the quality of the deposition.

Keywords: LMD; coaxial; wire; control; monitoring

1. Introduction

The Laser Metal Deposition (LMD) process is a Directed Energy Deposition (DED) technique that consists of a laser beam that melts metal powder or wire to generate a geometry layer-by-layer. The main advantage of this method with respect to subtractive manufacturing technologies is that the amount of raw material required to produce the final part is significantly reduced [1].

Moreover, the addition of wire instead of powder is also an advantage in terms of efficiency. Whereas in the case of powder it is only possible to melt between 20% and 80% of the input material, depending on the process parameters, nozzle design and the deposited alloy [2], in the case of Wire Laser Metal Deposition (w-

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LMD) almost the entire material is melted, so an efficiency of nearly 100% is obtained. Conversely, in the w-LMD process, the material feed rate and the distance between the nozzle and the workpiece must be carefully adjusted [3]. To overcome these aspects, monitoring and controlling the geometry of the melt pool is of particular interest in order to increase the robustness of the process. Thus, the most critical parameter to be monitored to guarantee the stability of the process is the height of the part, or consequently, the distance between the part and the nozzle.

The methodologies used to monitor the height of the part have been in practically all cases based on artificial vision, given the high temperatures that rise during the process and which prevent a measurement by contact with the part [4]. Several authors have attempted to extract the height of the part by acquiring the image of the melt pool by a visible camera [5-7] or infrared camera [8] placed laterally. One of the difficulties faced by this method is the complexity of determining the clad boundaries due to the intense illumination of the melt pool and the appearance of flames and emissions from the process vapors.

An alternative is to introduce an external illumination, usually a laser line projection, and try to detect the height profile of the part by imaging with a visible camera. Due to the high light emissions of the melt pool, most authors placed the projection of the laser line at a certain distance from the melt pool [9, 10]. However, this means that the process corrections cannot be applied at the precise moment when the height of the part is being measured and that the measurement can only be made in one direction. To achieve omnidirectionality of the measurement, Donadello et al. [11] introduced a measurement system based on laser triangulation in which the illumination laser was placed in the optical port of the head at a certain angle.

Another promising alternative is the Optical Coherence Tomography (OCT) measurement system [12] in which a measurement of the distance to the part based on interferometry is performed around the melt pool. These solutions could lead to an omnidirectional measurement, although they increase the complexity of the optical system and their effectiveness has yet to be demonstrated for contributions of certain complexity.

Finally, some studies have used commercial measurement systems based on laser triangulation or structured light projection to obtain a measurement of the part between the deposition of consecutive layers [13-15]. This approach does not allow an in-situ correction of the process and thus, adjustments in process parameters must be introduced in the following layers.

The aim of this article was to study the feasibility of measuring the clad at the precise moment when it is being deposited. A laser line was projected onto the melt pool in different configurations. In this study, the goal was not to quantify the height of the part, but rather evaluate different configuration alternatives and verify the feasibility of taking measurements on the melt pool or near it despite the high light emissions of the process.

2. Experimental setup

Fig. 1 shows the experimental set up used in this work. A coaxial three laser beam w-LMD head was used. A Continuous Wave (CW) 4kW fiber laser and a wire feeder were used. The input material was Ti6Al4V wire. Two wire diameters, 0.8 mm and 1.2 mm were supplied to try to evaluate the performance with different process parameters (laser power, traverse speed, wire feed rate, focusing distance and wire feed rate).

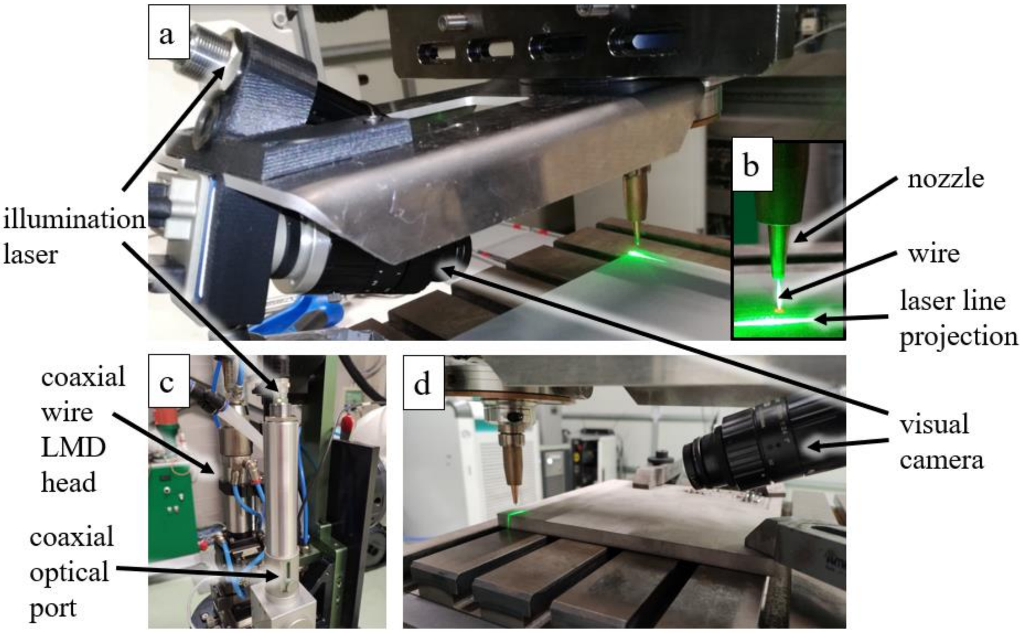

Fig. 1. Camera and illumination laser configuration used in the development of the work. (a) Lateral laser configuration at an angle with respect to the camera; (b) detailed view of the deposition nozzle and laser projection at a certain distance from the laser spot; (c) coaxial arrangement of the illumination laser in the optical port of the laser head; (d) visual camera placed laterally.

The measurement of the geometry of the clad was carried out using a CMOS camera with a resolution of 1936 x 1216 pixels which, with the employed set-up, was equivalent to 15.94 µm/pixel. An acquisition rate of 20 frames per second was used. The camera was placed laterally at an angle of 21° with respect to the horizontal plane. Green laser line illumination at a 532 nm wavelength with 40 mW power was projected on the clad. The visible camera was equipped with a narrow band filter with a FWHM of 1 ± 0.2 nm around the wavelength of the illumination laser. Two different laser configurations were tested.

In the first configuration the laser was placed laterally at an angle of 11° with respect to the camera (Fig. 1a). The laser line was projected at a certain distance from the laser spot (1 mm and 5 mm), as shown in the detail view of Fig. 1b. In a second configuration, in order to reduce the directionality of the measurement, the laser was placed at the optical port of the head (Fig 1c). The visual camera was placed in the same position for both configurations (Fig 1d). The used coaxial w-LMD head divides the processing laser beam into three beams and then refocuses them again on the work area. Therefore, the same applies to the illumination laser beam. In Fig 2a the appearance of three lines can be noticed when the distance between the workpiece and the nozzle is increased. Fig. 2b shows the image of the vision camera when the robot head is moved vertically, i.e. defocusing the illumination laser. In any case, the vertical displacement of the laser projection in the images is evident when varying the distance between the nozzle and the working plane.

In both configurations, an attempt to obtain the laser projection as close as possible to the melt pool and with the sufficient contrast was made.

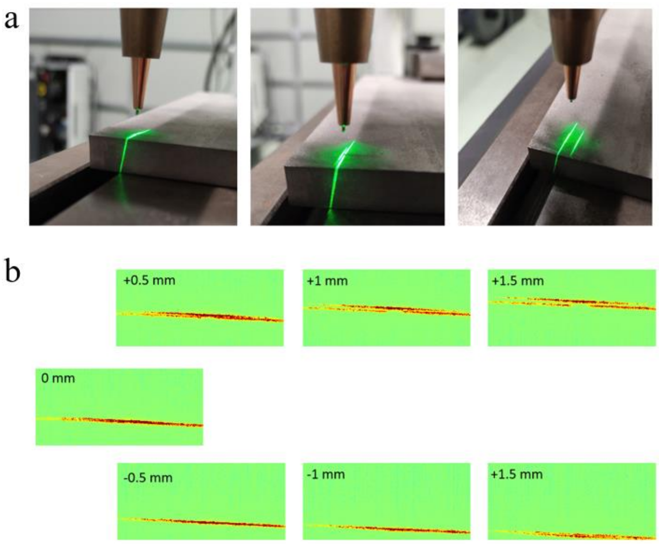

Fig. 2. Projection of the laser line through the optical port of the head. (a) Projection of the line on the substrate when the nozzle is moved upwards; (b) image of the laser projection taken with the visible camera.

3. Results and discussion

3.1. Case 1. Side laser line projection at 5 mm from the melt pool center

First, the side laser configuration was used, at a certain distance from the center of the melt pool, which is the most used configuration in the literature. In this case the distance was fixed at about 5 mm from the center of the melt pool. Single track walls of 40 mm length consisting of 10 layers were manufactured. The process parameters used exposed in Table 1. The result of the lateral monitoring for different layers is shown in Fig. 3. The direction of movement was towards the camera as indicated by the symbol in the top right corner of the images. To visualize the height deviation as more layers are added, a horizontal discontinuous line has been drawn adjusted to the laser projection on the substrate in the first layer. In this way, it can be seen how, as more layers were added, the projection of the laser on the bead was lower than the discontinuous line. This indicates that the bead grew less than the theoretical layer height.

Table 1. Process parameters used in the case 1 with the side laser line projection at 5 mm from the melt pool center.

Laser power (W)	Traverse speed (mm/s)	wire speed (m/min)	Layer height (mm)	Wire diameter (mm)
2200	15	1.8	0.9	1.2

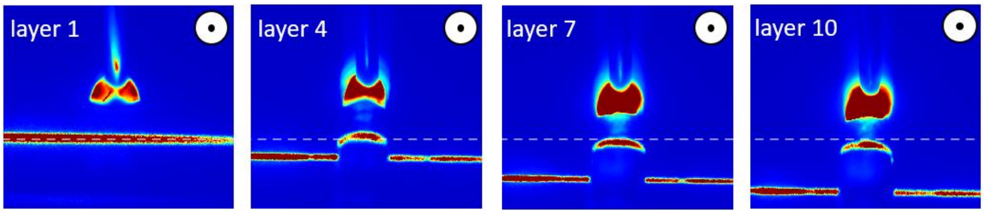

Fig. 3. Side laser line projection on single track wall at 5 mm from the melt pool center. Movement towards the camera.

This configuration is therefore valid for detecting height deviations. However, projecting the line at a certain distance from the melt pool causes on the one hand that a correction on the feed rate can not be applied at the instant when the measurement is being made. This could be solved by introducing the correction with a certain delay. On the other hand, in the case of a solid part with a zig-zag filling pattern, one of the sides of the part could not be measured at a distance from the part edge equal to the distance between the laser line and the melt pool. Thus, corrections can only be applied in one of the feed directions. For this reason, the following sections try to reduce this distance between the laser line and the melt pool.

3.2. Case 2. Side laser line at 1 mm from the melt pool center

In this case the line was projected approximately 1 mm from the center of the laser spot. The process parameters were initially the same as in Case 1. However, the exposure time of the camera was reduced to try to avoid saturation of the image in the melt pool. The tests in this case were performed in both directions of movement. In Fig. 4a the deposition was carried out moving towards the camera, while in Figure 4b moving away from the camera as indicated by the symbols at the top right corner of the images.

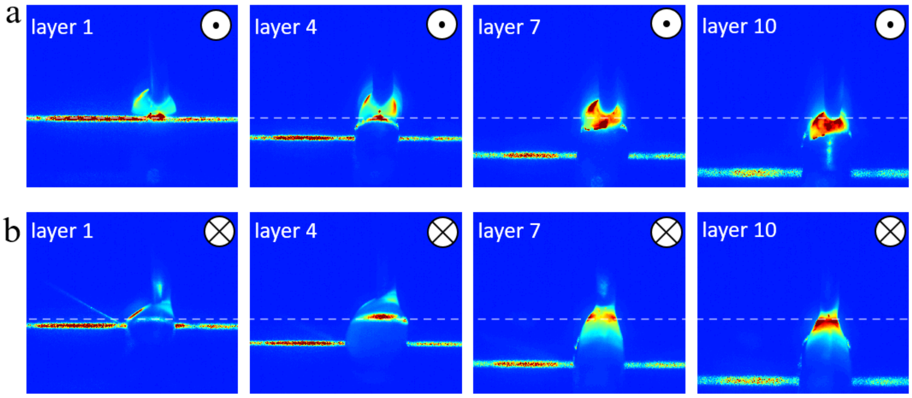

Fig. 4. Side laser line projection on single track wall at 1 mm from the melt pool center. (a) Movement towards the camera; (b) movement away from the camera.

It can be seen in the deposition of the first layers that the laser line could easily be identified even though it was close to the melt pool, so it would be possible to determine the clad height, but once a certain height was reached it was more difficult to identify the line projection on the clad. This could be justified by the deviation from the theoretical height or by a higher heating of the part which made the emission from the melt pool more intense. Also, in the direction away from the camera, it was more difficult to determine the projection on the clad because of the higher temperature. The difficulty of determining the height becomes more evident with the deposition of more layers.

In order to make it easier to identify the laser line projection on the clad, more favorable parameters were used (Table 2). Thus, the laser power and consequently the traverse speed and the wire feed rate were reduced. The results of the monitoring are again shown in Fig 5. With this combination of process parameters, the clad grew slightly more than the theoretical value. In these more favorable conditions, it can be seen how it was possible to identify the clad geometry properly.

Table 2. More favorable process parameters used in the case 2 with the side laser line projection at 1 mm from the melt pool center.

Laser power (W)	Traverse speed (mm/s)	Wire speed (m/min)	Layer height (mm)	Wire diameter (mm)
1500	10	1.3	0.9	1.2

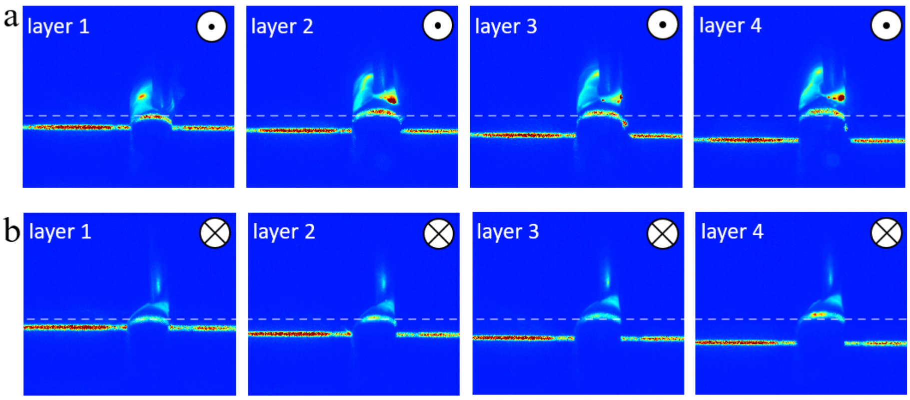

Fig. 5. Side laser line projection on single track wall at 1 mm from the melt pool center with more favorable process parameters. (a) Movement towards the camera; (b) movement away from the camera.

3.3. Case 3. Coaxial line projection on the melt pool

In an ideal configuration, the laser projection is performed directly on the melt pool. However, in the previous tests, the difficulty of recognizing the line projection on the molten material was demonstrated. In order to test the laser line projection directly onto the melt pool, in this case the illumination laser was placed in the optical port of the head (Fig. 1c). The process parameters used were those in Table 3. In this case a wire diameter of 0.8 mm was used. As it can be seen in Fig. 6, due to working with a defocus of 1.5 mm, two lines instead of one are already visible in the first layer (see Fig. 2a). Although it was not possible to identify the laser line projection on the melt pool, as expected, it was possible to visualize it in the surrounding area. Thus, it could be possible to extract the height of the parts from the areas around the melt pool and at the same time to know the surface waviness on which the next deposited layer.

Table 3. Process parameters used in the case 3 with the coaxial laser line projection and 0.8 mm diameter wire.

Laser power (W)	Traverse speed (mm/s)	wire speed (m/min)	Overlap distance (mm)	Focus distance (mm)	Wire diameter (mm)
800	6	1	1.5	1.5	0.8

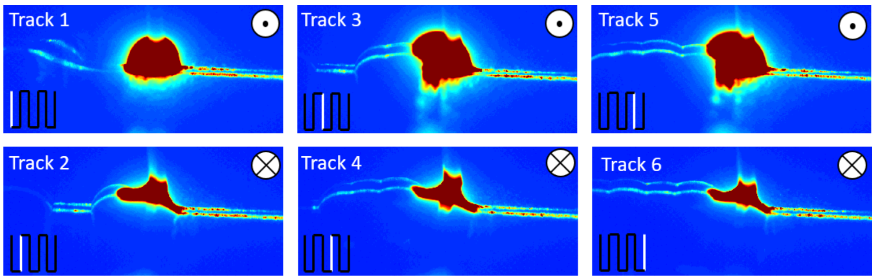

Fig. 6. Coaxial laser line projection on overlapped tracks with 0.8 mm wire diameter.

A similar test was carried out with a 1.2 mm diameter wire containing four layers with the process parameters of Table 4. The result of the monitoring is shown in Fig. 7. The difference in size of the individual beads and the resulting surface waviness comparing Fig. 6 and Fig.7 is evident. Furthermore, the projection of the laser line results in a significantly higher contrast in the first case.

Table 4. Process parameters used in the case 3 with the coaxial laser line projection and 1.2 mm diameter wire.

Laser power (W)	**Traverse speed (mm/s)**	**wire speed (m/min)**	**Layer height (mm)**	**Focus distance (mm)**	**Layer height (mm)**	**Wire diameter (mm)**
2500	14.5	3	1.54	0.5	1.54	1.2

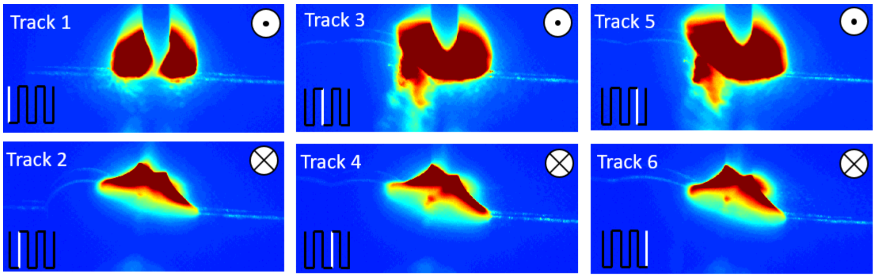

Fig. 7. Coaxial laser line projection on overlapped tracks with 1.2 mm wire diameter.

Finally, Fig. 8 shows the first and last tracks for the four deposited layers. These images show how the shape of the melt pool also changes along the layers. In some cases, as the part increases in height, actions are required at the edges of the part such as increasing the feed rate or depositing additional perimeters to prevent material from falling. These images could be used as an indicator to make these corrections or to increase the process knowledge.

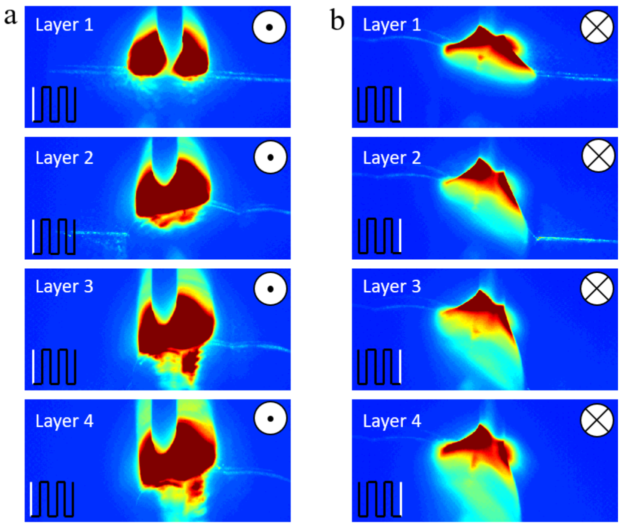

Fig. 8. Coaxial laser line projection on multilayer overlapped tracks with 1.2 mm wire diameter. (a) First track; (b) Last track.

4. Conclusions

In this article, different laser projection configurations have been used to measure the geometry of the deposited clad as close as possible to the melt pool. The aim was to reduce the directionality of the measurement and to obtain it as close as possible to the area where the material is being fused.

First, the illumination laser was placed laterally at a certain angle to the visual camera and the laser line projection was carried out at 5 mm distance from the melt pool, this being the most used configuration in the literature. It has been verified how it is possible to obtain the height profile of the part, despite only being able to apply it in one direction. Nevertheless, it is difficult to identify the laser line as the projection is closer to the melt pool, in this case at 1 mm distance from it. Particularly unfavorable is the case in which the piece grew less than its theoretical value, as the laser line was projected directly onto the melt pool, making it difficult to identify.

Furthermore, a configuration was tested in which the laser was placed coaxially, thus reducing the directionality of the measurement. Although it was not possible to identify the laser projection in the molten material, it was possible to obtain the projection on the part in the surrounding area and the surface waviness as a result of adjacent tracks. This information can be of great interest to determine the quality of the surface on which the consecutive layers are applied or for the detection of material drop at the edges of the part. Moreover, this strategy could be used as height control for simple workpieces with a constant input direction. However, for more complex geometries with changes in direction, a more complex configuration would be necessary.

Future steps could include the use of a higher power laser illumination, at a different wavelength or with a focusing lens with more concentrated illumination, e.g. the projection of a dot instead of a line. Additionally, once the most suitable configuration has been defined, tests should be conducted with different process parameters and deposition trajectories.

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