THERMAL MONITORING AND CONTROL BY INFRARED CAMERA IN THE MANUFACTURE OF PARTS WITH LASER METAL DEPOSITION

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1. INTRODUCTION

Additive manufacturing of metal components has been increasingly developed in recent years and is now considered one of the most promising technologies. Its main advantages over traditional subtractive techniques are material saving and the ability to manufacture complex and customized parts with reduced weight. In addition, additive manufacturing by direct deposition of metallic material by means of laser, called Laser Metal Deposition (LMD), is capable of manufacturing large-sized parts with higher contribution rates [1].

However, there is still a wide margin of improvement for the reliability of the process to ensure certain quality in the constructions. The robustness of the process lies in the uniformity and repeatability of the deposition bead throughout manufacture [2] which, in turn, depends on the process parameters (mainly laser power, deposition rate and deposition velocity) and the process conditions (temperature of the part or distance between nozzle and substrate, among others). In the construction of 3D geometries, variations in the process conditions during manufacture make it difficult to establish the process parameters. In order to make the technology robust and stable, it is necessary to implement parameter adaptation according to the conditions [3].

In order to improve the capabilities of additive manufacturing, monitoring and control techniques have received increased interest. Monitoring allows to know the conditions during the process by measuring different signals [4]. To develop control algorithms, it is essential to understand the relationship between the recorded signals, the process parameters and the characteristics of the manufactured part. Chua et. al. [5] analyzed and classified the factors involved in additive manufacturing to integrate later control strategies. In his study, he categorized the factors as follows: process parameters, observable dynamic characteristics and parameters that characterize the quality of the part.

In the literature, there are several works about additive manufacturing in which a control system is integrated to homogenize the characteristics of the deposition bead as the construction progresses. The thermal conditions during deposition determine the characteristics of the bead, so a large part of the control systems proposed are based on monitoring the molten pool through the optical port (coaxial). The main acquisition devices used are pyrometers [6] and visible [7] or infrared range cameras [8]. Some works [6–8] have compared the results obtained in systems where closed-loop controls were implemented to adapt the laser power as a function of the monitoring, achieving better results compared to other uncontrolled schemes. However, the brightness of the molten pool can vary with the irregularities of the substrate, obtaining erroneous measurements of the temperature or the geometry of the molten area [9].

Another problem encountered in the construction of 3D geometries using additive technologies is the difficulty in dissipating heat. This causes higher temperatures in the part, and surface monitoring (off-axial) offers the possibility of knowing the global thermal distribution and evolution of the part. In [10] the influence of cooling times between layer depositions on the thermal conditions of the walls during gas and metal arc welding (GMAW) manufacturing was analyzed. It demonstrated the reduction of heat dissipation capacity with wall growth and the attenuation of this effect by increasing the cooling time. Thus, the walls that reached higher temperatures during manufacture obtained a less uniform surface.

After analyzing the literature, this paper proposes off-axial thermal monitoring aimed at recording the thermal conditions of the component during manufacture by LMD. In addition, in order to increase the capacities of three-dimensional components, a control system based on the adaptation of the waiting times between layers from the global temperature of the component is proposed. The experimentation described in this study shows that the stability of the thermal conditions throughout the manufacturing process gives homogeneity to the constructions by LMD.

2. EXPERIMENTAL STUDY OF TEMPERATURE IN GEOMETRIC UNIFORMITY

In order to propose a control strategy based on the signal from the thermographic camera, it is important to analyze the correlation between the process parameters and the temperature of the manufactured part. This section describes the equipment and acquisition system involved in the experimental tests, as well as the methodology used in the manufacture of walls and the analysis of the monitoring data.

2.1. EQUIPMENT AND ACQUISITION SYSTEM

Experiments are conducted using a LMD system. A Rofin DY022 2.2kW Nd:YAG laser is used as power source, guided through a 600 µm diameter fiber to a Precitec YC50 coaxial laser head. The powder is guided and distributed by a discrete delivery nozzle developed by Fraunhofer ILT. The laser hits the working area on the surface where the material is fed in and melts it, generating the fusion. A Sulzer Metco Twin-10C powder feeder is used to supply the metal material. The set of systems that make up the LMD feeder head is mounted on the end of an ABB 6-axis IRB4400 manipulator robot, so this is the one that provides the movement of the feeder system.

A Flir A325 infrared thermal camera is used to measure and monitor the temperature of the deposited surface. It has a spectral range of 7.5-13 µm and a resolution of 320x240 pixels. The camera has been installed completely facing the manufactured part, at the same height as it, and at a distance of 0.5 m to avoid being reached by the precipitated hot dust particles (figure 1). Under these conditions, the spatial resolution of the camera is 2.2 pixels/mm. The camera has been previously calibrated for three temperature ranges, but in this work only the largest of them has been used, which covers temperatures from 300 °C to 2000 °C.

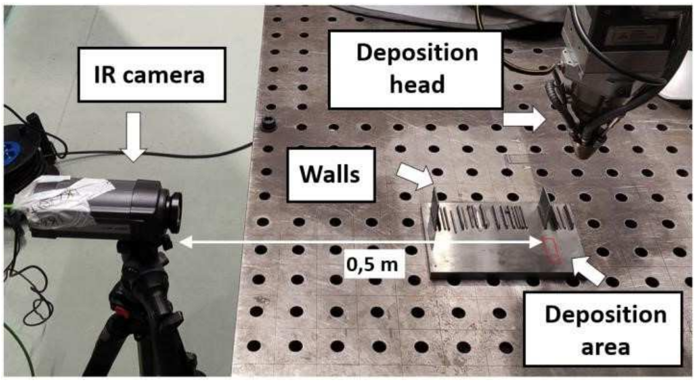

Fig. 1. Arrangement of the systems during the experiment

The metal powder used in the experiments is martensitic stainless steel AISI 431, marketed as Metco 42C and whose melting temperature is 1494-1545 °C. Deposition is performed on C45E carbon steel substrates.

2.2. TESTING METHODOLOGY

In order to analyze the influence of temperature on the geometric homogeneity of the deposited material, it is proposed to produce wall-shaped 3D geometries composed of 140 individual beads of 40 mm overlapped vertically and deposited alternately in one direction and the other. All the walls are manufactured using the same process parameters, taking as a variable the waiting time used between the deposition of one layer and the next.

The first experimental series, aimed at studying the influence of temperature on geometric homogeneity, consists of 6 walls where a constant waiting time of 0, 1.2, 3, 5, 8 and 12 seconds has been used in each of them, corresponding to the *A-F* tests.

In these tests, the geometric quality of the walls is analyzed by measuring the evolution of the wall thickness. A direct relationship has been considered between the ability to maintain constant deposition conditions and the uniformity of the structure obtained. The increase in temperature as manufacturing progresses leads to an increase in the molten pool area and in the amount of material deposited, which generates larger dimensions of the beads.

Figure 2 shows the processing of the images of the sections of the walls cut by abrasion, where contour recognition is carried out from the pairs of points (red/yellow) representing the wall thickness. The geometric homogeneity is measured by the Relative Standard Deviations (RSD) of the thickness evolution.

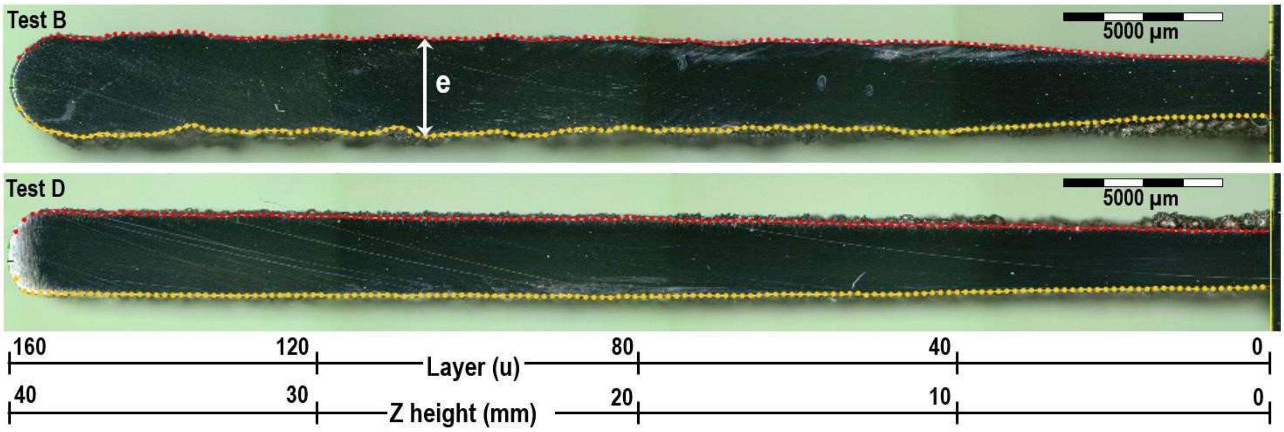

Fig. 2. Processing of wall profile images for the calculation of thickness evolution by automatic contour identification. Test B has been manufactured with a constant 1,2 second waiting time between layers and test D with a 5 second waiting time

2.3. THERMAL MONITORING ANALYSIS

Figure 3 shows the recorded monitoring of the thermal distribution and evolution of the wall during the process. In this case, the thermal distribution after the deposition of the 100th layer of test *D* at the time of completion of the bead and after 1.25 and 5 seconds. In this image it can be seen that the highest temperatures accumulate in the upper part after the interaction of the laser, around the molten pool. As the heat dissipates, the heat distribution is more and more uniform over the entire surface.

It is considered that the thermal conditions given in the upper zone directly influence the temperature that is reached during the deposition of the next bead, since it is the base on which the next layer is deposited. Therefore, the processing of the signal received from the camera consists in the conversion of the brightness intensity into the temperature value for each pixel. In addition, the area of interest commented on, indicated by a black box in figure 3, is identified and the average temperature is calculated.

The thermal camera used captures the intensity of the brightness in the infrared range and calculates the temperature as a function of the emissivity value which, in turn, depends on several variables, such as the surface finish or the wavelength, among others. Due to the variability of its value, a constant value is estimated according to the emissivity of the heat-treated steels (0.5). Therefore, instead of using absolute temperatures, this work is based on a qualitative treatment of the temperatures.

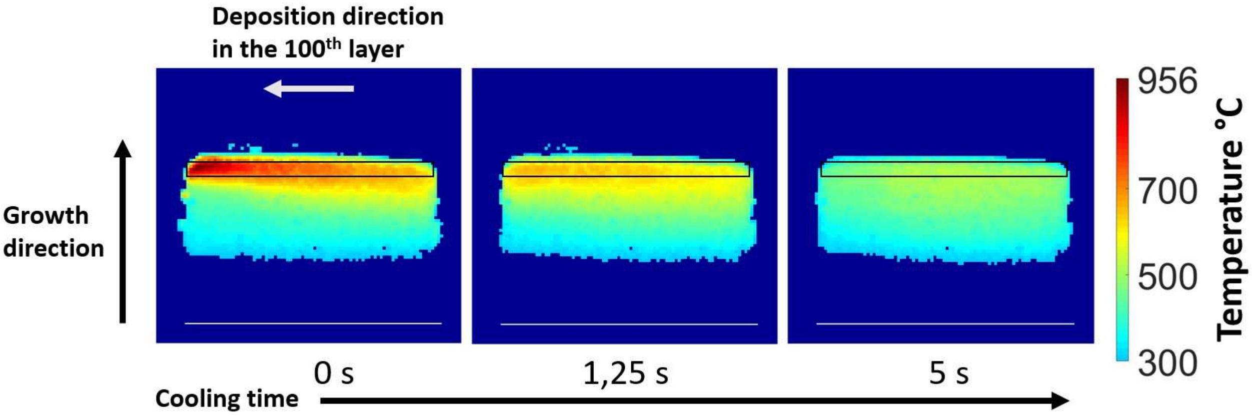

Fig. 3. Thermal evolution and distribution of the wall surface during cooling after deposition of the 100th layer at the time of completion and after 1.25 s and 5 s

3. NEW CONTROL APPROACH BASED ON THE ADAPTATION OF WAITING TIMES BETWEEN LAYERS

Due to the influence of waiting times on the temperature of the part during manufacture and, therefore, on the geometric conditions, as shown in the following section, this study proposes a control method based on the adaptation of waiting times. By controlling the thermal conditions during deposition, the aim is to achieve a greater degree of homogeneity in the depositions and, consequently, in the manufactured parts. By manipulating the starting time of the deposition of each next bead, it is possible to control the time available for the wall to dissipate the accumulated heat and, therefore, the temperature of the wall at that instant. Thus, it is possible to deposit all the beads on equal thermal conditions. In this way, in addition to keeping the process parameters constant, the thermal conditions prior to each deposition are also maintained.

The new control strategy is based on the information captured by the camera through a developed code implemented in Matlab®. After processing, the controller sends to the manufacturing system the signal that allows the deposition of each bead to begin. From the moment each bead is completed, the code calculates the temperature of the section mentioned in each frame received, observing the cooling evolution. The starting signal is sent when the calculated temperature reaches the desired temperature, the moment at which the next bead starts to be deposited. In this way, the adapted waiting time corresponds to the time needed for the wall temperature to fall to the established limit.

4. RESULTS

4.1. CONSTANT WAITING TIMES

The results obtained on the 6 walls are then analyzed (*A-F* tests). Figure 4 shows the heat accumulation produced in the construction as a function of the number of layers deposited and its effect on the resulting thickness. B graph represents the evolution of the temperature at the moment that precedes the deposition of each bead and the evident effect of the waiting times. The use of longer times favors the cooling of the construction between layers which, in addition to providing a slower rise in temperature, ends up stabilizing at lower values due to the compensation between heat introduced and dissipated.

The comparison of both graphs reflects a clear relationship between temperature and thickness. In the first layers, the evolution of thickness (A graph) also shows an upward trend that is accentuated in the walls where shorter waiting times have been used. However, when the temperature stabilizes, not all walls show a stable thickness value. The higher the pre-deposition temperature, the greater the thickness and the greater the degree of thickness irregularity. Therefore, the geometric homogeneity decreases with increasing temperatures.

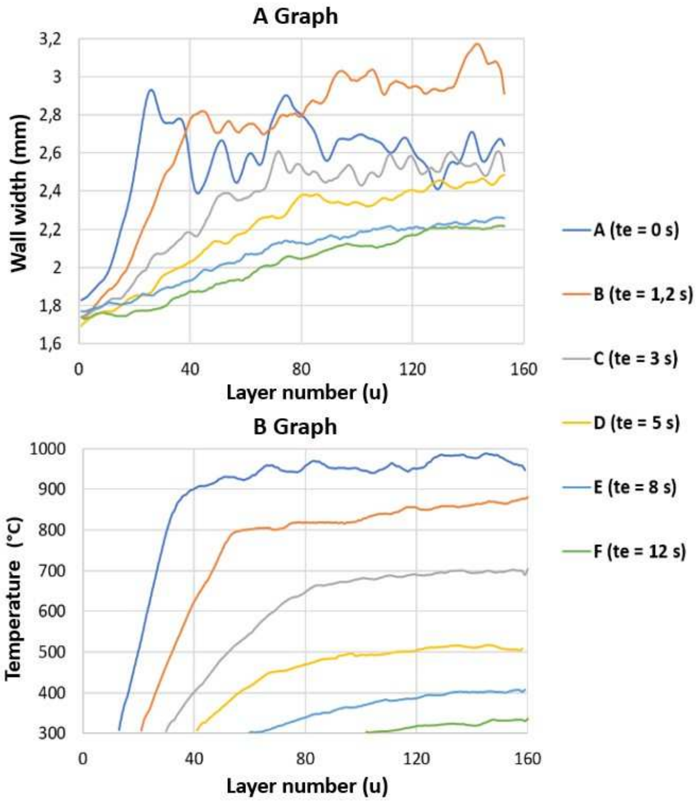

Fig. 4. Graphs about the results of the walls (A-F tests) manufactured with different waiting times (te): Evolution of the wall thickness
(A Graph) and evolution of the temperature at the moment before the starting of the deposition of each layer (B Graph)

Once this relation has been defined, the implementation of control systems based on the adaptation of parameters is proposed. In this case, the control of thermal conditions based on the adaptation of waiting times is considered an effective method to obtain the required geometric characteristics of the thickness.

4.2. VARYING WAITING TIMES

In order to validate the proposed control system, a second experimental series is carried out, consisting in the manufacture of 3 walls (*T1*-*T3*). The adaptation of the waiting times makes it possible for all the beads of each wall to be deposited on similar thermal conditions. The values of 400 °C, 500 °C and 600 °C, respectively to *T1*, *T2* and *T3*, have been chosen so that, in each test, this is the value at which the wall temperature has to fall to start the deposition of each bead.

Graph A in figure 5 shows the waiting times between the end of the deposition of one layer and the start of the next, where the increase in waiting times is shown as manufacturing progresses. This is due to the reduction in heat dissipation capacity. Similarly, the lower the temperature at which deposition starts, the longer the waiting times are required. In other words, the longer the heat dissipation time.

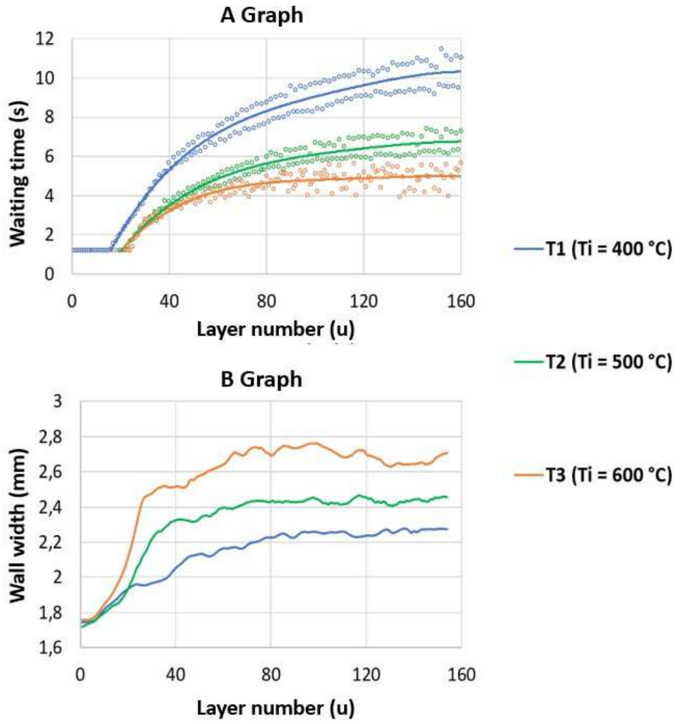

Fig. 5. Graphs about the results of the walls (T1-T3) manufactured with the control based on waiting times: waiting times by layer number (A Graph) and evolution of wall thickness (B Graph)

In the first layers of the walls, the waiting time is kept at 1.2 seconds, which is the minimum time needed to turn the laser off and on. For this reason, at this stage, the temperature at the beginning of the depositions is lower than the defined one, but it increases during the first 20 layers approximately until the control system is activated. This causes lower thicknesses with an upward trend in the first layers, as can be seen in graph B (figure 5). As soon as the control system starts to act by adapting the waiting times, the thickness evolution becomes more stable.

4.3. CONTROL SYSTEM VALIDATION

The advantages obtained with the proposed control system are demonstrated by a comparison between the walls manufactured with constant waiting times and the walls with varying times. On the one hand, tests *E* and *D*, in which the temperature ends up stabilizing at 400°C and 500°C respectively (figure 4, graph B). On the other hand, the walls in which the time control is implemented and the start temperatures are maintained at 400°C (*T1*) and 500°C (*T2*).

The graph in figure 6 shows that the relationship between temperature and thickness is maintained in the most stable areas of the walls where the temperature coincides, the upper half of *E* and *T1*, and of *D* and *T2*. However, by controlling the thermal conditions in the walls where the control is implemented, the thickness reaches stable levels in lower layers.

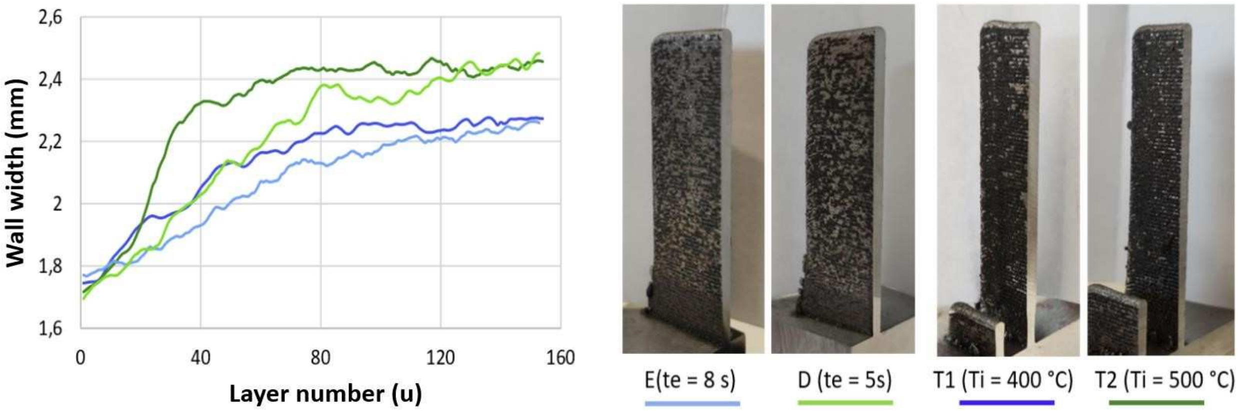

Fig. 6. Comparison between the results of both experimental series from the tests considered thermally equivalent. Graph of the evolution of thickness (left) and images of the cut walls (right)

To validate the geometric stability, the calculation of the RSD is performed. Considering the upper half of the walls to ignore initial irregularities, the RSD values for the *T1* and *T2* tests are 0.67% and 0.57% respectively, while for the *E* and *D* walls they are 1.55% and 1.85%. This means less variation of the wall thickness when the adaptation of the waiting times is applied in the manufacturing process. The greater geometric homogeneity obtained demonstrates the validity of the proposed control system.

In addition to maintaining constant thermal conditions, starting each deposition at the right time avoids wasting useful time. This reduces the duration of the complete process in the manufacture of the geometries proposed by between 4% and 8%.

5. CONCLUSIONS

This study shows that in the LMD manufacturing of 3D components, maintaining constant process parameters is not enough to achieve stable deposition characteristics. Due to the variation of the thermal conditions of the part during the process, geometric irregularities are produced in the beads. Moreover, it validates a new control system based on the adaptation of waiting times from the temperature monitored off-axially with an infrared camera. With which, in addition to increasing the geometric homogeneity of the walls, it optimizes the time needed for their manufacture.

This study is part of a wider development on monitoring and control in LMD and is taken as an experimental process to demonstrate the functionality of thermal off-axial monitoring. More advanced control could include the methodology proposed as a complement to coaxial monitoring of the molten pool and power adjustment. While coaxial monitoring acts during deposition, off-axial monitoring would act between deposition of the layers, preventing the component temperature from reaching excessive values. In this way, the capacities of LMD technology in terms of manufacturing medium and large functional components for sectors such as the automotive, energy or aeronautical industries would be increased.

In addition, the use of the thermal camera will be further developed in an off-axial way by monitoring the upper surface instead of the side, that is the last deposited layer. With the aim of extending its functionality to the manufacture of three-dimensional components of any geometry, where it could act on both the waiting time and the deposition toolpath.

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