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Medium Wavelength Infrared (MWIR) Imaging for High Speed Control of Laser Metal Deposition (LMD)

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Laser metal deposition (LMD) is a material processing technique widely used in industry for part reconstruction, coating or rapid prototyping. The inherent non-repetitiveness of the technique makes mandatory a closed-loop control of the process when homogeneous results are required, since it is affected by the material, size, and geometry of the part. Based on the use of uncooled PbSe image sensors working in the medium wavelength infrared (MWIR) range (1 to 5 μm), we present a novel high speed closed-loop control for LMD. Controlling laser power at high speed (1 kHz) based on measurements from the melt pool thermal image down to 200ºC enhances current solutions based on complementary metal-oxide-semiconductor (CMOS) images, blind to temperatures under 600ºC. To demonstrate the performance of the controller, claddings on different surfaces and geometries were carried out. Experimental results demonstrate the advantage of this approach in terms of sensitivity to process related magnitudes an overall control stability.

Keywords: *Fibre laser, laser metal deposition (LMD), laser cladding, medium wavelength infrared (MWIR), closed-loop control, PbSe focal plane array (FPA), real-time control*

1 INTRODUCTION

Laser metal deposition (LMD) is a promising additive manufacturing technique for repair and three-dimensional (3-D) printing of near-net-shape metal components. A laser beam is used to melt powder particles injected over a

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defined track path. It is a well established approach to laser cladding or for coating and repair of parts like turbine blades and stamping moulds. This technique is raising increasing attention including modelling [1] and control [2] efforts aimed at the development of novel 3-D printing approaches capable to deliver large metal parts.

In LMD energy and mass inputs are key parameters that drive heat transfer dynamics, with a key role in determining the properties and geometry of the manufactured parts. Marangoni forces affect the flow and temperature distribution and the melt pool geometry, and eventually may produce stress and deformation; moreover, this dynamics changes from one layer to another, depending on the geometry of the sub layers [3,5].

In practice, different process parameters (traverse speed, laser power, powder feed rate) determine the interplay between energy and mass inputs, with a variable impact on the properties of built parts; therefore, best process settings or a process window that deliver results with the required quality are usually defined after a number of tests varying these parameters under the conditions imposed by the manufacturing process characteristics (equipment, materials).

In recent years a number of closed-loop control systems have been proposed to improve the laser cladding stability during the process [2]. Some approaches have been proposed that monitor the melt pool based on temperature and height monitoring [6]. Alternatively, image-based approaches have been proposed to measure the melt pool geometry to control laser power (energy input) [7, 8], since melt pool enthalpy is well known to have a major impact on dilution and other key clad properties [9]; consequently, these systems typically aim at keeping the melt pool width constant, tuning the laser power as needed. These control systems mainly use a coaxial arrangement for the melt pool monitoring (temperature, width), acting on the laser power to keep the thermal distribution profile stable, compensating heat flow phenomena (heat accumulation over layers) by reducing or increasing the laser power; moreover, the use of a field-programmable gate array (FPGA) have shown real-time control capabilities with high speeds [8]. These systems, however, are based on the use of complementary metal-oxide-semiconductor (CMOS) sensors that miss all the information on thermal profiles for temperatures below 800 to 600ºC, depending on the material emissivity.

In this work we report on a novel closed-loop control system based on PbSe focal plane array (FPA) technology sensitive in the MWIR range. In spite of the low resolution of this technology, we report on benefits in terms of image quality with a significant impact on control reliability and stability.

2 THE LASER METAL DEPOSITION (LMD) ROBOT CELL

The system has been deployed in an industrial laser robot cell. A laser head (WT03; Permanova Lasersystem AB) mounted on a 6-axis robot manipulator

(IRB4400; ABB) has been used. The system was powered with a 1.5 kW fiber laser (F015L; Rofin-Sinar GmbH) and the powder was delivered through a (D-57629; GTV Verschleißschutz, GmbH) powder feeder and a coaxial nozzle (Fraunhofer IWS).

The software components developed are integrated in OpenLMD, an open source middleware built upon ROS Indigo (under Ubuntu 14.04) [10] and run in a PC with a 3 GHz Intel i7 Quad Core processor and 8 GB of RAM.

3 APPROACH

3.1 Sensor

An uncooled MWIR camera (TACHYON 1024 µCORE; New Infrared Technologies, S.L.) has been coaxially mounted on the laser head. The camera features a PbSe FPA, sensitive in the MWIR range (1 to 5 µm wavelength) and with a frame rate of 1000 fps, compliant with high speed and real time control requirements.

This is the key distinctive element of our approach. Although a PbSe FPA offers in principle a much lower resolution than CMOS sensors, it brings in practice higher relative measurement accuracy and much better dynamic range to observe thermal emission compared to CMOS [11]. The main reason is that this sensor works in the MWIR range. In this spectral range, thermal emission starts at much lower temperatures while variations in the levels of radiation are much softer compared to the visible range. As a result, a much better use of the available dynamic range of the sensor is possible over the range of process temperatures and the cooling process may be effectively

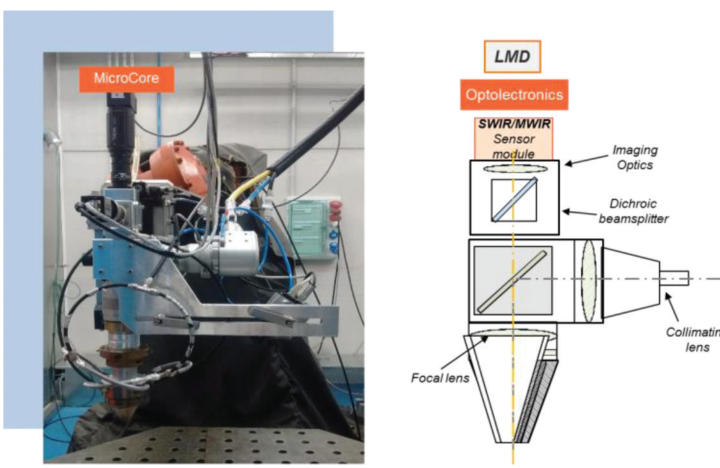
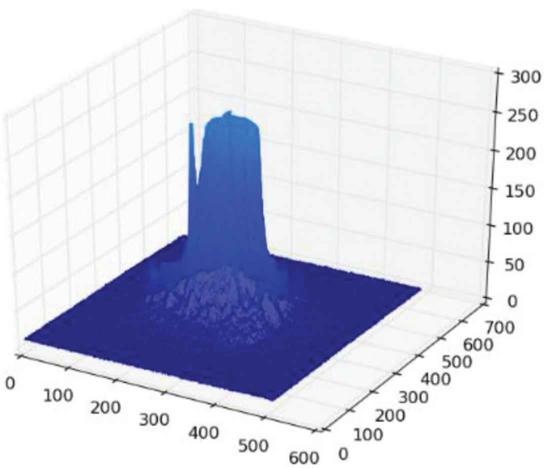
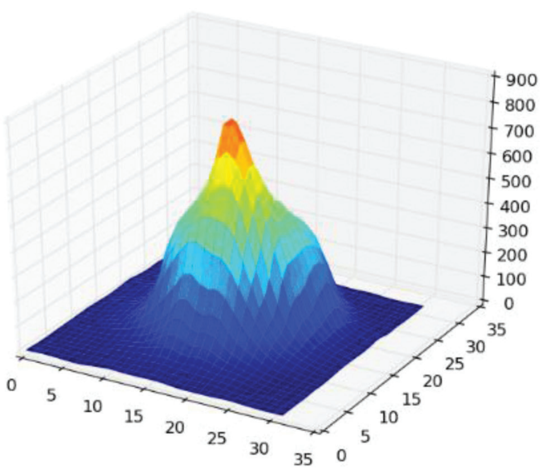


FIGURE 1
Photograph (left hand side) and schematic diagram (right hand side) of the optical assembly in the laser head.



(a)



(b)

FIGURE 2
Plots showing the response from (a) a CMOS sensor compared with (b) a PbSe sensor (right), to a melt pool through the same optical path at the same time.

viewed. This contrasts with the poor performance of CMOS sensors regarding the dynamic range, with a response that goes from zero to saturation and misses thermal gradients in the boundaries of the melt pool. What is more, CMOS are highly sensitive to bright and reflections on powder particles and projections that also produce saturation values and have been observed to affect the measurement of the melt pool geometry. This does not occur in the MWIR range in which images are not saturated and projections elicit a much lower sensor response.

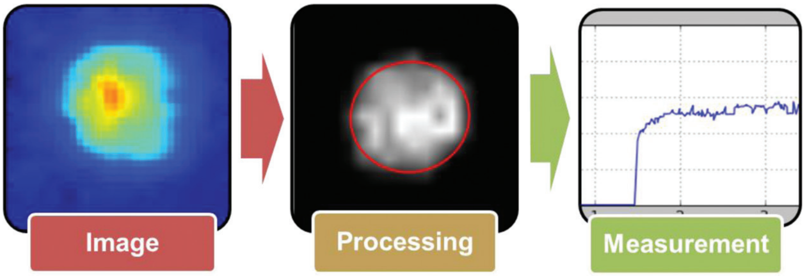


FIGURE 3
Image-based width measurement.

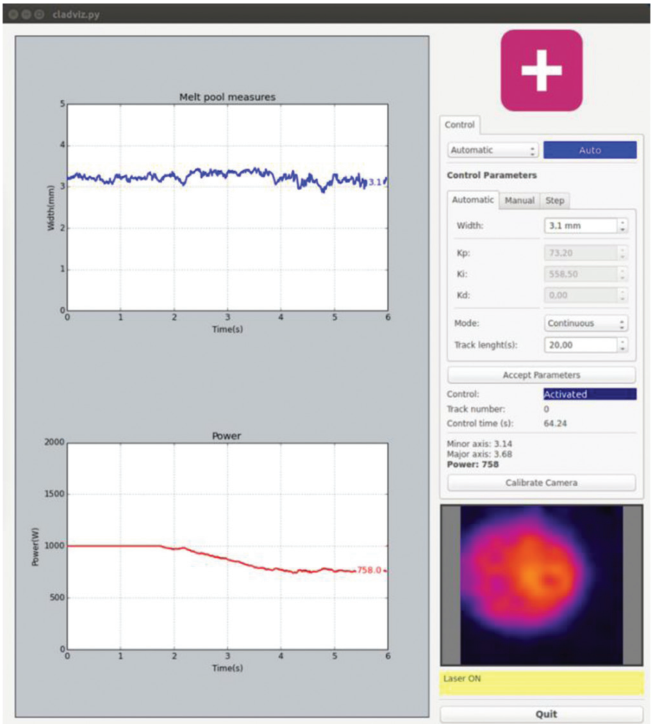


FIGURE 4
Control user interface.

3.2 Geometry measurement

The system is calibrated with a known pattern, so that the images acquired may be scaled and the measurements on the melt pool geometry can be done (in mm). Image processing is simple and light. It consists of an image binarization that segments the melt pool followed by the estimation of the axes of the enclosing ellipse. The minor axis is used as a measurement of the melt pool width.

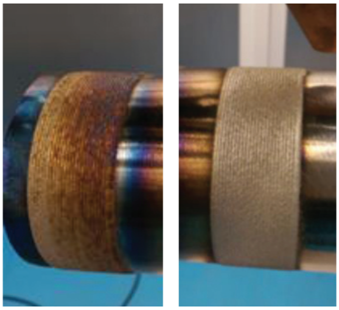


FIGURE 5
Photographs showing the coating test without (left) and with (right) control.

3.3 Closed-loop control

The control system tunes the laser power with the aim to maintain the melt pool width stable. The width measurement feeds a discrete proportional-integral (PI) controller that modifies the laser power to keep it constant at a control rate of 100 Hz. The set point of this controller is selected shortly after the beginning of the process assuming that parameters have been checked for the first tracks, and before thermal issues due to heating and geometry arise. This approach adapts smoothly to the use of the system with different materials and geometries, avoiding the need of much effort on configuration.

The system works both for continuous and discrete modes of operation. In the continuous case, the user has to specify the length of the track in seconds to estimate which reference track should be used to fix the set point value. In the discrete mode, the laser status (ON/OFF) is detected in the image, and tracks are automatically counted so that the user only needs to define the number of track to be used as reference (fixed to three in all our experiments). In addition, the user interface allows selecting the control parameters and graphs the measurements and the actual laser power used in real time.

4 RESULTS

4.1 System test

The system has been tested with carbon steel 316L as powder and base material with a powder flow of 13,3 g/min and 10 l/min of shield gas. The fibre laser power was fixed to start at 1000 W in all the tests. Three representative configurations were chosen: coating of tubes, vertical growing of walls, and vertical growing of a cylindrical structure.

4.2 Coating cylindrical tubes

Coating of cylindrical tubes is a typical and extended application of laser metal deposition. We have tested the use of the proposed real time closed loop

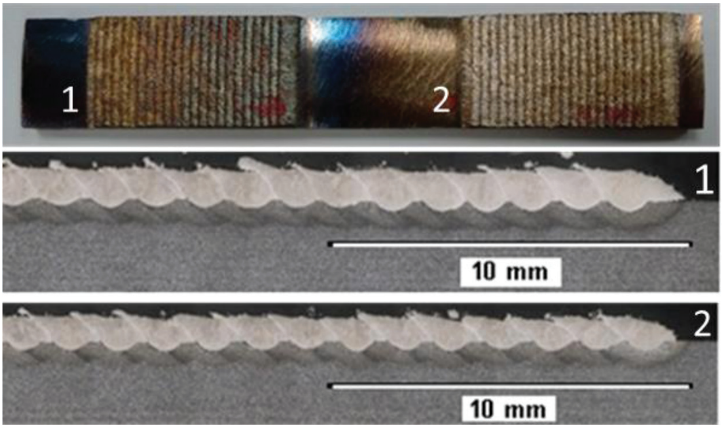


FIGURE 6
Metallography cut of a coating without (1) and with control (2).

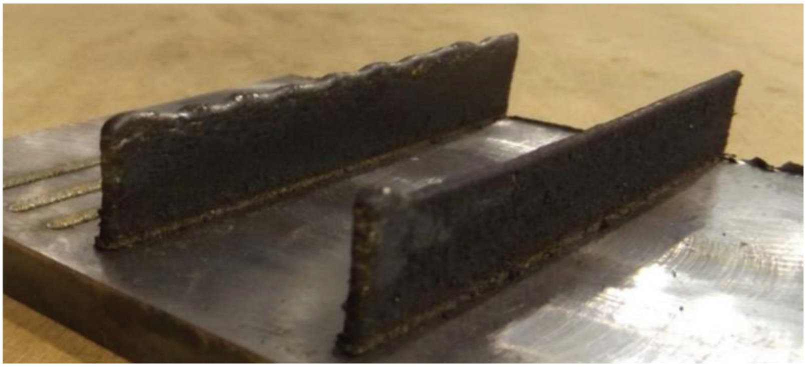


FIGURE 7
Photograph of the vertical growing without and with control.

control system in this configuration. A first well visible effect was a big reduction of surface oxidation because of avoiding the overheating compared to the control case in which every parameters were the same except that laser power was kept constant; furthermore, the real time control of the laser power resulted in a reduced and more uniform dilution as can be observed from a metallography analysis, shown in Figure 6.

4.3 Vertical growing of a wall

In the tests involving vertical growing of a wall, the different between using the closed-loop control or not is even more apparent. A clear wavy form reveals the overheating issues that arise when building without the use of a control approach. All of this disappears when the control is put in place, delivering a wall with a top side flat and a thin profile.

FIGURE 8
Photographs of the cylindrical form fabricated with and without control.

4.4 Vertical growing of a cylindrical structure

A cylindrical tube with 40.0 mm in diameter and 60.0 mm in height was built, by growing 0.5 mm *per* layer. The process could not end in in the case without closed-loop control. Overheating issues resulted in deformation and collapse of the structure before it could be finished. Again, these problems were successfully addressed through the use of the real time control. In this case, it took 30 minutes to build the structure.

5 SUMMARY AND FUTURE WORK

We have reported on a novel closed-loop control system based on medium wavelength infrared (MWIR) images of the melt pool that improves the geometry stability and the mechanical characteristics of the results of laser metal deposition. Using the proposed approach, dilution decreases and become more uniform in the case of coating. As well, the system has shown the capability to enable growing greater heights both of wall and cylindrical structures. Otherwise, the remarkable capability of the sensors used to image the thermal distribution around the melt pool is being explored to implement more elaborated monitoring and control strategies based on state-of-the-art machine learning.

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