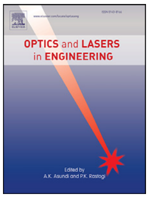
Optics and Lasers in Engineering 112 (2019) 136–144

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Monitoring of laser metal deposition height by means of coaxial laser triangulation

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ARTICLE INFO

Keywords:
Directed energy deposition
Laser metal deposition
Additive manufacturing
Optical monitoring
Laser triangulation

ABSTRACT

Laser metal deposition (LMD) is an additive manufacturing technique, whose performances can be influenced by several factors and parameters. Monitoring their evolution allows for a better comprehension and control of the process, hence enhancing the deposition quality. In particular, the deposition height is an important variable that, if it does not match the process growth, can bring to defects and geometrical inaccuracies in the deposited structures. The current work presents a system based on optical triangulation for the height monitoring, implemented on a LMD setup composed of a fiber laser, a deposition head, and an anthropomorphic robot. Its coaxial and non-intrusive configuration allows for flexibility in the deposition strategy and direction. A measurement laser beam is launched through the powder nozzle and hits the melt pool. A coaxial camera acquires the probe spot, whose position is converted to relative height. The device has been demonstrated for monitoring the deposition of a stainless steel cylinder. The measurements allowed to reconstruct a spatial map of the height variation, highlighting a transient in the deposition growth which can be explained in terms of a self-regulating mechanism for the layer thickness.

1. Introduction

Additive manufacturing has gained interest in many research and industrial fields, from aerospace to biomedical applications, introducing big advantages in terms of flexibility for the design and direct realization of solid objects with complex and custom geometries [1]. Within such context, the laser metal deposition (LMD) process consists in melting a metallic powder by means of the thermal energy provided by a high-power laser beam. Typically the powder is carried by an inert gas and sprayed by a nozzle, with a coaxial laser beam passing through the nozzle and overlapping with the powder flow, hence generating a melt material pool on a substrate. A solid layer is obtained along the deposition track after the material solidification, and three-dimensional (3D) structures can be build by repeating the procedure over the previous layers.

The LMD process depends on several parameters, including the laser power, the deposition speed, and the powder flow rate. Moreover, the deposition can be influenced by physical quantities which can vary during the process, such as the substrate temperature. In fact, if the temperature changes due to unbalance between heat accumulation and conduction, the powder melting can be eventually favored, introducing variability in the deposition growth which can lead to the formation of defects or irregularities in the deposited structure. The quality requirements in production environments and the high costs of additive manufacturing encourage the development of specific feedback systems for the adaptive control of the process parameters [2–5]. For this reason several aspects of the deposition process have been monitored and studied with different techniques, such as pyrometers or camera vision systems for measuring the substrate temperature or the deposition growth, as reported in many research works [6–11].

The distance between the nozzle and the substrate, called standoff distance (SOD), is another important parameter of the LMD process. As a matter of fact, the deposition rate is strongly influenced by the deposition height, since the latter determines the overlapping factor between the focused laser beam and the convergent powder flow [12,13]. If the SOD departs from its optimal value, the powder-laser interaction can be altered, resulting in process growth variations and, consequently, reduced deposition quality and geometrical inaccuracies [14,15].

Several approaches for studying the deposition growth in LMD and laser cladding can be found in literature. Firstly, the deposition height can be included in models developed from numerical simulations [16–18]. These allow to explore generic geometrical configurations and process parameters, with the main drawback of a high computational cost which must be carried out offline. Otherwise, an indirect control of the process parameters can be obtained by correlating the height information to other physical quantities, which can be deduced by analyzing the melt pool images acquired with cameras during the process [19,20]. However, such kind of method might not be robust against variations

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https://doi.org/10.1016/j.optlaseng.2018.09.012
Received 26 May 2018; Received in revised form 3 August 2018; Accepted 14 September 2018

Nomenclature

SOD	standoff distance
H	height of the deposited structure
h	thickness of a single deposited layer
D	height programmed to the robot
d	incremental height programmed to the robot
z_1	distance between focal plane and target
z_0	initial value of z_1 at the reference SOD
Δz	relative height with respect to the reference z_0
y_1	probe spot position in the target plane
y_2	probe spot coordinate on the camera sensor

of the process parameters, requiring the development of specific, and possibly complex, semi-empirical models.

The deposition height can be also extracted from the 3D reconstruction of the deposited object, e.g., obtained by means correlation analysis algorithms for images taken with off-axis cameras from one or more points of view as reported by several studies [21–25]. These approaches give rich information and seem to be suitable for research purposes, while their usage for production applications might be limited by the complexity of the monitoring setups, whose size might also obstruct the movements of the deposition equipment.

A wide class of optical methods for the deposition growth monitoring is based on the triangulation principle. Its classical implementation exploits a tilted laser beam probing the target surface, with an image sensor used for detecting the probe spot position. A custom configuration of such working principle was previously demonstrated on a wire-LMD setup for the process control [26]. Subsequent works reported the usage of commercial laser displacement sensors [27–30] or 3D scanners [31]. In general, these kinds of high-precision instruments are characterized by a nominal resolution of few micrometers, allowing very accurate measurements during the process. Their intrinsic limits are mainly related to the off-axis arrangement of the probe beam. In fact, this may introduce anisotropy in the measurement direction, possibly suffering of blind zones or shadowing effects, hence limiting the flexibility of their application, especially in the case of deposition of complex and big geometries.

The method presented in the current work reinterprets and simplifies the common triangulation implementation for monitoring the deposition height during the LMD process, introducing several advantages. In fact, the proposed system represents a simple, non-intrusive, and cheap solution for monitoring inline the deposition growth, as well as a non-destructive diagnosis tool of the deposited structure [32]. The device for the in situ height measurement has been integrated on a setup composed of a fiber laser and a robotized deposition head. The coaxial configuration of the probe laser beam shares the optical path of the high-power laser within the deposition head, allowing for flexibility in the deposition strategy and being independent on the direction of the transverse movements. The direct measurement of the melt pool distance does not require the development of process models, which may depend on the deposition parameters and materials.

The triangulation system has been operated while building a multilayer hollow cylinder from stainless steel powder, demonstrating its robustness against the direction of the robot movements. The results highlighted a self-regulating mechanism in the layer thickness. The latter, after an initial transient, tends to an equilibrium condition, interpreted as a result of compensation between concurrent thermal and powder defocusing effects. A 3D spatial reconstruction obtained from the measurements allowed to visualize structural defects of the deposited cylinder along the growth direction. Although the sensitivity of the proposed method might be lower if compared to some of the optical instruments utilized in the studies cited before, this is sufficient for many applications, such as the detection of sub-millimeter height mismatches or the implementation of closed-loop feedback controllers on the actual layer thickness, while flexibility in the measurement is gained due to the coaxial configuration. Finally, the examined monitoring device is composed by simple and low-cost components, which are promising factors for its usage even in industrial environments, with minimal changes to existing setups.

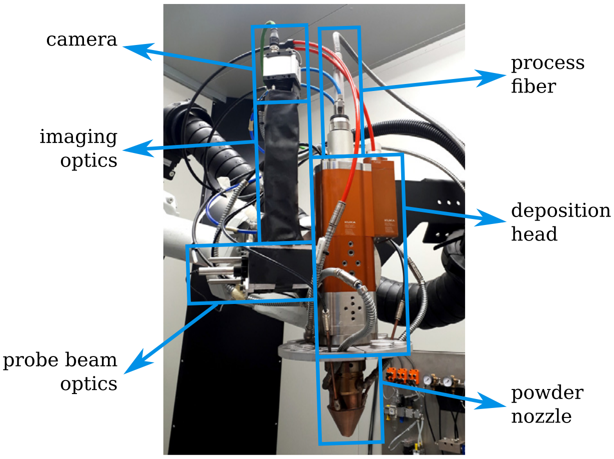

Fig. 1. Side view of the experimental setup for the height monitoring during the LMD process.

Table 1
Characteristics of the LMD setup.

Process laser source	IPG YLS-3000
Maximum laser power	3 kW
Laser emission wavelength	1070 nm
Deposition head	KUKA REIS MWO-I
Anthropomorphic robot	ABB IRB 4600-45
Powder nozzle	FRAUNHOFER ILT 3-JET-SO16-S
Reference standoff distance	12 mm
Process lens focal length	f_1 = 200 mm

2. System design and implementation

2.1. LMD setup

The monitoring system has been implemented on the LMD setup illustrated in Fig. 1, whose characteristics are summarized in Table 1. The equipment is based on a deposition head (KUKA REIS MWO-I) mounted on a 6-axis anthropomorphic robot (ABB IRB 4600-45). The optical energy source is a 1070 nm active fiber laser (IPG YLS-3000) having 3 kW maximum power. The 50 μm feeding fiber of the laser is connected to the 400 μm process fiber through a fiber-to-fiber coupler, delivering the optical radiation to the deposition head. The process laser beam is collimated with a 129 mm lens, then it gets focalized toward the deposition region by the lens L_1 with focal length f_1 = 200 mm.

The metallic powder to be deposited is fed to the three-jet powder nozzle (FRAUNHOFER ILT 3-JET-SO16-S) of the deposition head by a powder feeder (GTV TWIN PF 2/2-MF), using nitrogen both as vector and nozzle shielding gas. The powder is ejected by three orifices configured at 120° from each other, converging to the deposition zone and generating a powder cone. The standoff distance between the nozzle tip and the substrate is set to the reference value of 12 mm at the beginning of the process.

2.2. Coaxial triangulation setup

The setup for the deposition height monitoring includes a probe laser beam and a coaxial imaging system, both housed in a custom unit attached sideways to the deposition head as illustrated in Fig. 1. The op-