Optics and Lasers in Engineering 54 (2014) 62–67

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Resistance measurements for control of laser metal wire deposition

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ARTICLE INFO

Article history:
Received 5 July 2013
Received in revised form
10 October 2013
Accepted 10 October 2013
Available online 29 October 2013

Keywords:
Laser metal wire deposition
Automatic control
Resistance
Additive manufacturing

ABSTRACT

A method for controlling robotized laser metal wire deposition on-line by electrical resistance metering is proposed. The concept of measuring the combined resistance of the wire and the weld pool is introduced and evaluated for automatic control purposes. Droplet formation, detachment of the wire from the weld pool and stubbing can be hard to avoid during processing due to the sensitive process and short reaction times needed for making on-line adjustments. The implemented system shows a possible route for automatic control of the process wherein such problems can be avoided automatically. The method proves to successfully adjust the distance between the tool and the workpiece through controlling the robot height position, thus increasing stability of the laser metal wire deposition process.

1. Introduction

The process of adding metal powder or wire through laser melting, herein referred to as laser metal deposition (LMD), can be very advantageous for a number of manufacturing and repair applications [1–7]. Opportunities lie in saving time, material and weight [1,8]. Systems for performing LMD such as Direct Metal Deposition [2,9] and Laser Engineered Net Shaping [10] have been reported in the past. The named systems both utilise metal powder as the delivery form of the added material. The other method of material delivery is by feeding wire instead of powder into the weld pool [8,11,12]. Also hybrid systems with both powder and wire have been reported [13,14].

Laser metal deposition with wire as filler material (LMD-w) has previously proved to be a promising method for additive manufacturing within the aerospace industry [8]. The principle of LMD-w is shown in Fig. 1. A laser is used to melt wire which is fed into the weld pool. The wire nozzle and the laser is moved relative to the substrate in order to produce a bead. Beads are placed side-by-side and layer-upon-layer to form the deposit. The method utilises standard, off-the-shelf laser welding equipment, an industrial robot and a laser line scanner together with an Iterative Learning Control (ILC) system for regulating the height of deposits through controlling the wire feed rate and robot height position. The main problem with LMD-w has been to maintain a stable deposition process. Positioning and orientation of the wire relative to the laser and the weld pool is of uttermost importance [8,15]. Unlike with powder feedstock systems, the laser cannot be turned off during deposition. Furthermore, the wire must be fed into the weld pool established by the laser radiation and never leave it since this would disrupt the process entirely. This makes uneven substrates much harder to process since the distance between the deposition tool and the substrate must be very well controlled. This control has previously been carried out through 3D-scanning of the deposit before and after each deposited layer and subsequent adjustments of the deposition path [16]. Even as the challenges for this wire based method are substantial, so are the benefits. There is almost a 100% material usage and there is no need for handling of excess powder. Also, for simpler and larger geometries, LMD-w enables higher deposition rates and might also give better surface finish and material quality than powder based LMD [8,17].

The geometry of the LMD-w weld pool, especially viewed from the side, is affected by the distance from the wire tip to the substrate as seen in Fig. 2 [8]. If a change in pool geometry due to a change in distance between the tool and the workpiece results in a measurable change in electrical resistance, it would be possible to monitor said distance by resistance measurements. This idea and its implementation for control purposes is the main contribution of this work. The prospects of this idea lie in its simplicity and ease of use. Monitoring voltage across, and current through, the weld pool and the wire is relatively simple from an implementation perspective. The current needed for resistance measurements can be provided by either a dedicated voltage/current-source or by using the welding source while employing the hot wire deposition technique. This technique, where current is led through the wire and the weld pool in order to introduce energy resistively into the weld, can act as a complement to laser power sources [18]. It also allows for tailoring of weld bead cross-section geometry through

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0143-8166/$ - see front matter
http://dx.doi.org/10.1016/j.optlaseng.2013.10.010

the distribution between the laser and resistive power introduced [18,19]. A successful control system based on resistance measurements might prove the line scanner previously mentioned unnecessary or serve as a complement to the scanner. The line scanner, apart from being an additional instrument bringing costs and implementation efforts, takes time from the deposition itself since scanning and processing are not carried out in parallel.

In this paper, the control strategy is introduced, followed by an empirical model of weld pool and wire resistance followed by the controller design. The implemented control system's performance is evaluated by comparison with an uncontrolled system. Finally, the possibilities of improvement are briefly discussed.

2. Control strategy

As concluded by Heralić et al. [16], the distance between the tool and the workpiece, d, affects the weld pool geometry as indicated in Fig. 2. If d gets too large, the material transfer link between the wire and the pool, indicated in red in the figure, is broken. A weak but sustained link does not typically present a problem. However, it indicates that the limit of the process window is nearby and that d should not be increased any further. If the material transfer link is broken, the weld pool will be sustained by the laser, while a droplet will form at the tip of the wire. This droplet will eventually grow enough to get pulled down by gravity into the weld pool. A new droplet is formed and so the process continues until interrupted [8]. The quality of the deposit might not be inherently bad from a material perspective, but the irregular shape of the deposit makes deposition of the following layer very difficult. If d is too small, the wire will be plunged through the weld pool into the base material. This causes rapid oscillations of the wire tip and is called stubbing. Stubbing may lead to lack-of-fusion defects in the deposit since the substrate material is not properly melted and this deposition state should, because of this, be avoided [8]. The goal of a controller should therefore primarily be to avoid stubbing. The secondary goal should be to prevent drop-transfer mode and the tertiary should be to maintain a distance well in between these boundaries. In the current project, the distance d is controlled by robot height adjustments downwards or upwards.

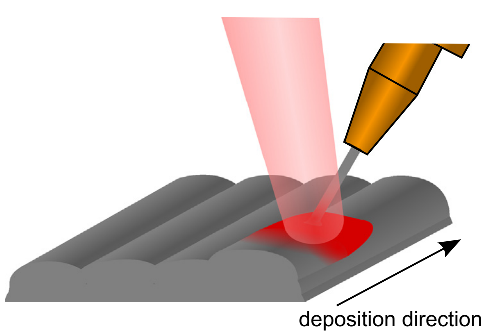

Fig. 1. Principle of laser metal wire deposition. Laser irradiation creates a melt pool into which the wire is fed. This creates deposit beads which can be placed side-by-side and layer-upon-layer.

A number of factors might be of importance for the resistance of the weld pool and the wire. However, since d and the wire feed rate, v, are the process inputs that are most likely to be varied for control purposes, these are the ones investigated in this study. Process parameters such as material, wire diameter, laser power and robot traverse speed also could affect resistance. These were however not investigated in this study, since the goal is solely to prove the possibility of using resistance measurements for control purposes. This is the reason for this study being conducted for a certain parameter combination, and not for the entire process window. When another set of parameters is used, it is possible to perform a similar investigation for that combination of parameters. Mapping the entire process window with all possible relations therein could prove extremely difficult and laborious.

The control strategy is illustrated in Fig. 3. The figure shows a MISO-model where the control signals, $\mathbf{u}$, such as d, v and traverse speed are used for controlling d. The resistance of the weld pool and the wire is determined during processing by measuring the voltage, V, and current, I, separately and applying Ohm's law

$$R = \frac{V}{I} \tag{1}$$

Through a resistance model, described in Section 4.2, this information is translated into a distance from the tool to the workpiece. It is here assumed that the weaker the transition between the wire and the weld pool and the longer the wire stick-out, the higher the resistance. The tool-workpiece distance is compared to a nominal value, and their difference is used for controlling $\mathbf{u}$. The resistance model is calibrated with experimental data where the d and $\mathbf{u}$ are excited independently.

3. LMD-w system

The LMD-w system has many subsystems which are integrated into a set of tools for planning, performing, monitoring, controlling and evaluating laser metal deposition with wire.

3.1. Hardware

Among the hardware components used in the deposition system, there is an ABB IRB-4400 industrial robot, a welding source (Fronius TransSynergic 4000) and a wire-feeder from Fronius. An IPG Nd:YAG fibre-laser with a maximum power output of 6 kW is led through an optical fibre and focused with welding optics from Permanova laser systems. Deposition is carried out with an out-of-focus spot with a diameter of approximately 3 mm. Signal acquisition hardware from National Instruments is used for measuring current, voltage and for connecting to some of the robot input and output signals. The welding current is measured with a Hall effect current sensor integrated with transducer electronics which give an

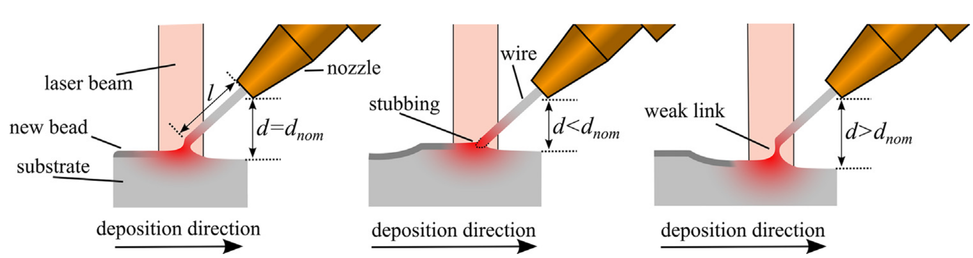

Fig. 2. Transfer modes, to the left: desired transfer with $d = d_{nom}$. In the center: $d < d_{nom}$ causes stubbing. To the right: $d > d_{nom}$, with risk of droplet formation. Stick-out length, l, is indicated in leftmost illustration. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)