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Height control of laser metal-wire deposition based on iterative learning control and 3D scanning

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ABSTRACT

Laser Metal-wire Deposition is an additive manufacturing technique for solid freeform fabrication of fully dense metal structures. The technique is based on robotized laser welding and wire filler material, and the structures are built up layer by layer. The deposition process is, however, sensitive to disturbances and thus requires continuous monitoring and adjustments. In this work a 3D scanning system is developed and integrated with the robot control system for automatic in-process control of the deposition. The goal is to ensure stable deposition, by means of choosing a correct offset of the robot in the vertical direction, and obtaining a flat surface, for each deposited layer. The deviations in the layer height are compensated by controlling the wire feed rate on next deposition layer, based on the 3D scanned data, by means of iterative learning control. The system is tested through deposition of bosses, which is expected to be a typical application for this technique in the manufacture of jet engine components. The results show that iterative learning control including 3D scanning is a suitable method for automatic deposition of such structures. This paper presents the equipment, the control strategy and demonstrates the proposed approach with practical experiments.

1. Introduction

Production of complex metal structures, by means of traditional manufacturing, often requires expensive precision castings or oversized forgings that need extensive machining. For large and complex structures that are manufactured in small quantities using high-cost materials, e.g. jet engine components, traditional methods lead to significant production costs, due to high scrap rates and long lead-times. Rapid manufacturing techniques based on additive layer manufacturing have therefore gained an increased attention due to their ability to fabricate fully dense metal shapes without the need of dies or extensive machining. If rapid manufacturing can be included as a supporting technique to traditional manufacturing methods, the production costs and lead-times can be decreased. The flexibility of rapid manufacturing can also allow for late design changes or repair of worn out parts. Moreover, the technique enables the use of other materials and new designs, utilizing, e.g. sheet metals, which can help to reduce the total weight of the final component.

Since their first introduction three decades ago, additive manufacturing techniques for metal have been developed and commercialized in the industry under names such as Direct Metal Deposition [1], Laser Engineered Net Shaping [2], Shaped Metal Deposition (SMD) [3], Selective Laser Melting [4], and Electron Beam Melting [5]. Apart from the SMD system, which utilizes metal wire, the parts are built from powderized feedstock either in a powder-feed process [1,2] or a powder-bed process [4,5]. The heat source used for melting the additive material is usually a high power laser, an electron beam or a tungsten inert gas (TIG) welding source. Traditionally, the powder based processes have been developed towards the manufacture of small and complex geometries with less focus on the deposition speed. For large structures with moderate complexity, such as flanges or bosses, it is more rewarding to use wire based techniques since these will give a better surface finish, could lead to better material quality, and also higher deposition rates [6,7]. The use of wire will also give better process efficiency and cleaner working environment since all wire that is fed into the melt pool is utilized, in comparison to a substantial amount of scattered powders that are not melted when currently available powder based techniques are used.

Basic process characteristics of wire-based additive manufacturing and material properties of deposited beads and 3D parts have been studied by many authors [3,8–20]. Combination of wire

Abbreviation: ILC, Iterative learning control

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and powder feeding has also been reported [21–23]. A conclusion can be drawn that a wire-based deposition process is sensitive to wire position and orientation relative to the melt pool and the deposition direction. Careful tuning of the wire feed rate, the heat input, and the travel speed are also important in order to obtain defect-free beads. Moreover, in [24] it is further argued that in order to achieve good process stability for multi layered deposition, continuous process monitoring and control of, e.g. the wire feed rate, is also necessary. In [25] a camera-based monitoring system is developed for closed loop control of straight-bead deposition and in [18] a temperature monitoring system is investigated for a laser metal-wire deposition process. However, apart from the mentioned references this subject has not yet been investigated to any great extent in the literature. By contrast, there are several publications on this subject for powder-based systems, e.g. monitoring and process control using cameras [26–28], closed-loop height control using photo diodes [29–32], powder flow control based on motion system speed profile [33], temperature measurements using pyrometers [34–36]. However, transferring these results to wire-based deposition systems is not a straightforward task since the two processes are dissimilar in many ways.

A robotized laser metal-wire deposition system has been developed at University West, Sweden, in close cooperation with Swedish industry. For this process a camera-based monitoring system and closed loop control of bead width and height has been developed and demonstrated for straight bead deposition [25]. The work presented in this paper is a continuation of that work. The main contribution is a generalized height controller based on iterative learning [37] that can cope with arbitrary deposition patterns. It uses height information from preceding layers, obtained by means of 3D scanning, and prevents the deterministic disturbances (which the controller learns during the deposition), and compensates for non-deterministic temporary disturbances. The result is a stable deposition process with small errors and low control activity. The material considered in this paper is Ti–6Al–4V deposited on plates of same material.

2. System hardware

The deposition system is a modified laser welding system consisting of a high power laser, a deposition tool, an industrial robot arm, an inert gas tent, a data acquisition system, an operator interface, and a control system.

The laser heat source is an IPG Photonics fiber laser with a maximum power of 6 kW. The use of a laser as a heat source is grateful since it gives low heat input into the substrate (compared, e.g. to a TIG heat source) leading to less residual stress and less deformation. The robot, which generates the movement of the tool relative to the substrate, is an ABB 4400 industrial robot arm with six degrees of freedom. The use of a robot enables high flexibility in terms of feasible geometries and objects that can be modified or repaired.

2.1. Deposition tool

The deposition tool consists of an optical system, which focuses the laser beam, a wire feeder, a laser scanner, and a camera. The optical system consists of a collimator and a focusing lens, which together generate a 1.5 mm wide spot in focus. However, since the chosen wire diameter is 1.2 mm the laser beam is defocused into a larger spot (roughly 3.6 mm on the deposition surface) in order to allow for a more flexible interaction between the wire tip and the melt pool. The focus point is placed below the surface in order to avoid plasma generation. Here, the choice of wire diameter is a matter of convenience. Other wire diameters are equally possible with proper choice of laser spot diameter. The wire feeder is a self-regulated push/pull feeding system from Fronius. A push mechanism is mounted at the wire spool and a smaller pull mechanism is mounted at the nozzle. This setup has a fast response and ensures good compliance with the desired wire feed rate at the nozzle. The tool is illustrated in Fig. 1.

2.1.1. Laser scanner

A laser scanner is utilized for the purpose of obtaining a 3D height profile of the manufactured part after each deposited layer. In this work a laser scanner from Micro-Epsilon (scanControl 2810-25) is used that operates according to the principle of optical triangulation. That is, a laser line is projected onto the target surface and the reflected light is captured by a two dimensional sensor from which a single-line height profile is calculated. Resolution of the scanner in the z-axis is specified to 10 µm. A 3D height profile is obtained by a relative movement between the scanner and the part in the x-direction (for coordinates see Fig. 1), generated by the robot, during which the scanner is triggered by an in-house developed software to perform measurements. The part is scanned with a speed of 5 mm/s, and each 50 ms a new profile is extracted. This results in 250 µm spatial resolution along the x-axis. At the currently chosen measurement distance (between the scanner and the part) the length of the laser line is around 35 mm. The maximum number of measurement points per scanned line is 1024, however, in order to limit the amount of information generated for each scanning, 256 points/line are used. A 35 mm wide laser line gives a spatial resolution of 140 µm along the y-axis.

During deposition it is important to protect the scanner from the high power laser reflections and the heat radiation from the built part. For this purpose, a linear drive unit, on which the scanner is mounted, is utilized such that it lifts the scanner away from the melt pool during the actual deposition, and lowers it

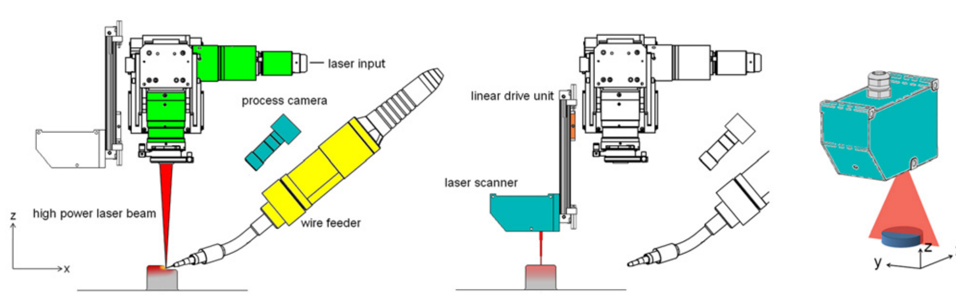

Fig. 1. Deposition tool with the laser scanner. Left, deposition mode; middle, scanning mode; right, coordinate axes during scanning.