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Inspection of additive-manufactured layered components

D. Cerniglia [a,*], M. Scafidi [a], A. Pantano [a], J. Rudlin [b]

[a] *Dipartimento di Ingegneria Chimica, Gestionale, Informatica, Meccanica (DICGIM), Università di Palermo, viale delle Scienze, 90128 Palermo, Italy*
[b] *TWI Ltd., Granta Park, Abington, Cambridge CB21 6AL, UK*

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ABSTRACT

Laser powder deposition (LPD) is a rapid additive manufacturing process to produce, layer upon layer, 3D geometries or to repair high-value components. Currently there is no nondestructive technique that can guarantee absence of flaws in LPD products during manufacturing.

In this paper a laser ultrasonic technique for in-line inspection of LPD components is proposed. Reference samples were manufactured from Inconel and machined flaws were created to establish the sensitivity of the technique. Numerical models of laser-generated ultrasonic waves have been created to gain a deeper understanding of physics, to optimize the set-up and to verify the experimental measurements. Results obtained on two sets of reference samples are shown. A proof-of-concept prototype has been demonstrated on some specific deposition samples with induced flaws, that were confirmed by an ultra-high sensitivity X-ray technique. Experimental outcomes prove that typical micro-defects due to the layer-by-layer deposition process, such as near-surface and surface flaws in a single layer deposit, can be detected.

1. Introduction

Laser powder deposition (LPD) is an additive manufacturing process where layers are deposited, one after the other, to produce 3D geometries or to repair high-value components. A high-power laser beam is used to melt the powder material and, at the same time, a thin surface layer, so that they are bonded together [1–3]. The geometry of the component is built up, layer-by-layer, programming the path of the nozzle for the material deposition. Better accuracy and complexity can be achieved in products through additive manufacturing as compared to traditional manufacturing methods. Moreover, mechanical properties of additive manufacturing components approach and in some cases exceed the properties found in conventionally processed structures, as shown in [4]. The layer size is typically 0.5–2 mm wide and 0.3–0.5 mm deep. Interlayer and intralayer defects are often observed in laser deposited components as investigated in [5] using scanning electron microscopy and microcomputed tomography. The use of laser metal deposition to repair internal cracks in metallic components has been assessed in [6] although porosity is observed at the boundaries between the original part and the added material. The feasibility of laser metal deposition for repair applications with a procedure that leads to defect-free layers is shown in [7].

Additive manufacturing seems to be a potentially growing market in every manufacturing sector. In fact, in recent years, laser powder deposition has been established in several applications in a number of industries, including automotive, aerospace, military and medical. New and improved technologies, large application area and ease of development of custom products are the major drivers that can push the additive manufacturing market. However, a few factors restraining the growth of this market are material characterization during development, process control and quality control. In-line inspection has important implications for those sectors where validation of components, made using additive manufacturing techniques, has until now been difficult to achieve. Conventional nondestructive testing (NDT) techniques cannot cope with the complicated geometries and small sizes typically produced by additive manufacturing. Currently, the quality of LPD components is assessed by destructive testing or by X-ray computed tomography (CT) after the part is finished, which means that a sample may be rejected after all the manufacturing is completed. Moreover, the inspection should be carried out through many different slice images and X-ray CT may not have enough resolution for large parts.

For critical requirements of quality even in parts with complex forms, the desired solution is a nondestructive technique that allows the inline inspection and the detection of flaws as the layers are deposited, so that the process can be controlled and corrected. Some NDT methods have been investigated. The use of an

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* Corresponding author. Tel.: +39 091 23897258.
E-mail address: donatella.cerniglia@unipa.it (D. Cerniglia).

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ultrasonic squirter probe with a standard industrial robot to inspect a 3D metal deposition structure is demonstrated in [8]. Laser-generated surface waves have been used in [9] to interrogate LPD parts, in both stainless steel and titanium, with pores that are simulated using blind holes. The potential of an all-optical scanning acoustic microscope instrument for online inspection of additive manufacturing products is shown in [10].

The laser ultrasonic technique was identified as a method that might be deployed for the inspection of LPD parts to detect near-surface and surface defects. The use of a laser transmitter and receiver and the interaction of the incident ultrasonic wave with sub-surface and surface defects have been widely investigated for many different applications, as demonstrated in [11–16].

The aim of this work is to prove the laser ultrasonic technique is a practicable solution for the inspection of LPD parts during manufacturing. A proof-of-concept prototype has been assembled and tested on different sets of reference samples and deposition samples with induced flaws. The performance of the inspection system is finally shown and discussed in the last part of the work.

2. Laser ultrasonic technique: experimental and numerical procedure

2.1. Experimental set-up

The laser ultrasonic system consists of an infrared Nd:YAG pulsed laser, used as source of acoustic waves, and a laser receiver, which combines a continuous-wave laser and an interferometric unit, to record the surface displacement. The two lasers have been assembled to create a laser system prototype. Wideband ultrasonic waves are generated with nanosecond laser pulses in the thermoelastic regime. The laser receiver produces a time-varying analog signal that is proportional to the instantaneous nanometric surface displacement. The output signals from the laser receiver are digitized at 8 bits by an analog-to-digital board converter, triggered by the pulsed laser, and transferred to a workstation for further signal processing and display. Fig. 1(a) shows the typical displacement of the surface wave (A-scan); its Fourier transform is shown in Fig. 1(b). The scanning procedure consists of acquiring a set of A-scans on the surface of the sample, following a line along the deposited layer. The two lasers beams are focused on two points of the line at a distance of 1.0 mm. The linear translation of the inspection system is possible by means of the LPD robot on which the system is mounted. The evaluation of the samples is done by acquiring the ultrasonic signals and the relative coordinates along the line, during scans at 0.1 mm steps. The data acquired on a line is processed through an algorithm to produce a B-scan image. For the complete inspection of the layer, more lines at an opportune distance are inspected producing more B-scans. The surface wave is monitored for sub-surface and surface defects, while reflection of bulk waves indicate inner discontinuities.

The laser system prototype was mounted on an attachment plate, bolted to the end plate of the LPD robot (Fig. 2). In this way, the inspection system needs only a translation from the robot deposition path, and then follows then the same path for the inspection.

The system should be able to determine the presence of a flaw in the component for a go/no-go selection of it. As described later, different sets of defective samples have been manufactured to determine the limits, in terms of size and depth, of the detectable flaws.

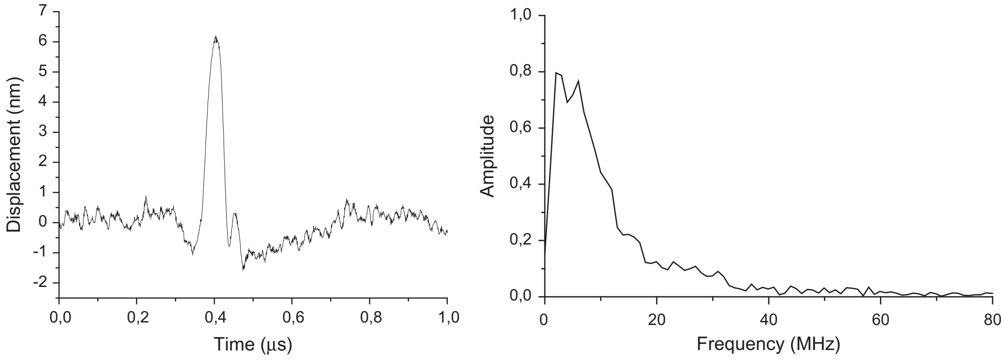
2.2. Samples

Reference samples, manufactured by TWI Ltd., have been used to establish the settings and to define a procedure for the inspection. Machined flaws were created in standard geometries to establish the sensitivity to defect detection. Laser machining and micro-Electric Discharge Machining (EDM) drilling were used to create holes in the Inconel samples, with different diameters (ϕ) and depths (d) below the surface. Two geometries of test samples are shown here: the first set (Type A) is an Inconel sheet with holes at different distances from the edge (Fig. 3(a)), the second (Type B) has a raised portion, representing the first layer above the substrate, where holes were drilled (Fig. 3(b)). After manufacturing, dimensions and depths of the holes were measured by high resolution microscopy. A summary of flaw sizes and depths in Type A and B samples is reported in Fig. 9, in the Results section.

Another set of samples was made with an Inconel substrate and a single layer deposit. Flaws were induced in each sample using different powder feed rates, laser power and speed of movement. Fig. 4 shows a typical flaw in a sectioned sample. Some samples had some substrate removed to determine the effect of the surface roughness on the technique.

2.3. Numerical analysis

Numerical models of laser-generated ultrasonic waves have been created to gain a deeper understanding of physics, to optimize the set-up and to verify the experimental measurements. Previous works [17–19] demonstrate that an explicit dynamic analysis together with the use of diagonal element mass matrices is computationally very efficient for the analysis of models with relatively short dynamic response times, as is the case for wave propagation with frequencies in the MHz range in relatively large



(a) (b)

Fig. 1. Typical displacement of the surface wave (a) and its frequency content (b).