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Defect detection in additively manufactured titanium prosthesis by flying laser scanning thermography

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Abstract

Metal additive manufacturing is nowadays a well-established technology for cutting edge applications in the automotive, aerospace, defense and medical sectors. Since additive metal deposition is basically a welding method, which creates parts by successively adding layers of material, there is a chance for defects like pores, cracks, inclusions and lack of fusion to develop. As a matter of fact, interlayer and intralayer defects are often observed in additive manufactured components. However, if one considers the typical end applications along with the high costs involved in metal additive manufactured components, a "zero defect" target is close to mandatory for this technology. Planning an inclusion of the integrity assessment right into the additive manufacturing process would allow for quick corrective actions to be performed before the component is completed. Some effort has been spent in the quest of an efficient in-process flaw inspection, however, no conventional nondestructive testing (NDT) approach has been fully satisfying yet. This work suggests an experimental evaluation of the effectiveness of flying laser scanning thermography, when detecting flaws on an Additively Manufactured acetabular cup prosthesis made in titanium alloy, where some defects have been artificially created. The rough surface scanned is what's typically left by the additive manufacturing process, and has been left so in order to prove the efficacy of the NDT inspection in real conditions. Potential benefits and limitations of the technique are discussed.

Keywords: Additive Manufacturing; IR Thermography; Laser thermography; Defect Sensitivity.

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1. Introduction

Additive manufacturing (AM) is a productive process which, due to the use of various technologies, creates objects (component parts, semi-finished or finished products) by adding layers of material in succession. The main advantages of this manufacturing process, as opposed to traditional manufacturing methods, are summarized as follows: the possibility to create geometrically complex structures, the optimization of material deposition in specific locations such saving raw material and lessening the final weight, an increase in mechanical performances and a high degree of customization. For these reasons, additive manufacturing is a growing market in many sectors such as the automotive, aerospace, military and medical ones. The possibility to print parts in biocompatible materials, such as titanium alloys, combined with the ability to create complex geometries, has fostered applications in the orthopedic replacement surgery field, by promoting patient-specific "custom-made implants" (O'Neill et al. (2018), Huiwu Li et al. (2013), Mediaswanti et al. (2013), Lofgren et al (2010)). One issue is that dense metallic biomaterials such as titanium, tantalum and magnesium cannot be used directly as bulk materials due to a mismatch in the elastic moduli between metal and bone structure, which causes stress-shielding. On the contrary, the 3D printable implant in trabecular titanium overcomes this problem with a porous structure which, while matching the stiffness of the two materials in contact, at the same time provides some space for bone in–growth and vascularization. Indeed, the elastic modulus of porous trabecular titanium is approximately equal to *4 GPa,* which is significantly lower than the value of dense titanium, equal to *110 GPa* (Bobyn et al. (1980)). Since AM deposition is basically a welding method, it may generate defects like pores, cracks, inclusions and lack of fusion. Indeed, interlayer and intralayer defects are often observed in AM components as shown by (Ahsan et al. (2011)) by using scanning electron microscopy and microcomputed tomography. However, considering the bio prostheses field of application, a "zero defect" target and strict quality control procedures are generally required, in order to attain which efficient non-destructive testing techniques are strongly needed. The aim is to employ a non-destructive technique which allows in-line inspection and flaw detection as the layer is deposited, making it so that the process can be controlled and corrected. Effective in-process defect inspection has been difficult to achieve up to now, and conventional NDT approaches are often not able to adapt to the complicated geometries typically produced by additive manufacturing. Some widely employed techniques to evaluate AM components are destructive testing and X-ray computed tomography (Thompson et al. (2016)), both of which are applied to the finished part, thus leading to rejection at the end of the manufacturing process. Some promising outcomes were published regarding ultrasonic inspection. Nilsson (2012) used a flexible method of inspection for complex AM geometries by mounting an ultrasonic water flow probe on a robotized arm, which follows a pre-programmed path to inspect the whole part. Nemeth et al. (2005) used laser-generated surface waves to optimize the inspection of stainless steel and titanium metal AM parts, where defects in the form of blind holes had been artificially created. Clark et al. (2011) have shown the potential of an all-optical scanning acoustic microscope for online inspection of AM products. With the same aim in mind, other authors (Kromine et al. (2000), Klein et al. (2004), Edwards et al. (2011), Pelivanov et al. (2014), Cerniglia et al. (2015)) used both lasers, receiver and transmitter, to develop an UT setup able to detect surface and sub-surface defects. One of the main concerns about laser-laser ultrasonic non-contact inspection resides on the laser receiving equipment part, since it needs a proper finishing of the surface in order to have a good signal to noise ratio. It is well-known how AM part surfaces seldom reach a smooth finish, because of the layer by layer nature of the process, hence the surface roughness in metal AM parts is definitely a challenge for in-line inspection procedures. Laser thermography seems to be less influenced by surface roughness. Furthermore, the laser scanning thermographic technique, proposed by (Li et al. (2011). Burrows et al. (2011) Schlichting (2012)), for detection and characterization of surface micro-cracks in metal samples, has been adapted by Montinaro et al. (2017) to evaluate subsurface parallel flaws in fiber metal laminates, and in (Cerniglia et al. 2017) to detect surface and embedded flaws in Inconel parts, by simulating an in-line inspection and developing an innovative post-processing statistical approach based on the analysis of Regions of Interest (ROI). Specifically, the thermal footprint left by a moving laser heat source is acquired remotely through an IR camera, and defects are then identified by looking for thermal anomalies in ROI via a statistical approach. The flying laser scanning thermography allows for farther, remote, non-contact inspections, thus resulting particularly attractive for all those applications where a sterile environment is desirable and contact test methods may not be ideal or even prohibited altogether, e.g. in medical products. The aim of this work is to prove the effectiveness of flying laser scanning thermography in the detection of flaws in an AM acetabular cup prosthesis. The sample is made of a bio-compatible titanium alloy and defects were artificially generated by micro-drilling in known positions. The scanned surface finish was the same one left by the AM process, i.e. significantly rough, in order to validate the inspection technique in real conditions. The pros and cons of the proposed active IR-NDT thermographic approach are further discussed.

2. Material and methods

2.1 The titanium AM sample

A real additive manufactured acetabular cup made of titanium alloy by Lima® has been considered for the implementation of the proposed IR-NDT technique. Two blind holes with depths of *4 mm* and diameter of *0.7 mm* were micro-drilled, in the annular portion of the cup, along the radial direction (see Figure 1). The artificial defects simulate material discontinuities typical of the AM process such as lack of fusions and pores. After drilling, the effective dimension and position of each hole was measured. In Figure 1, sample geometry and the position of defects are shown.

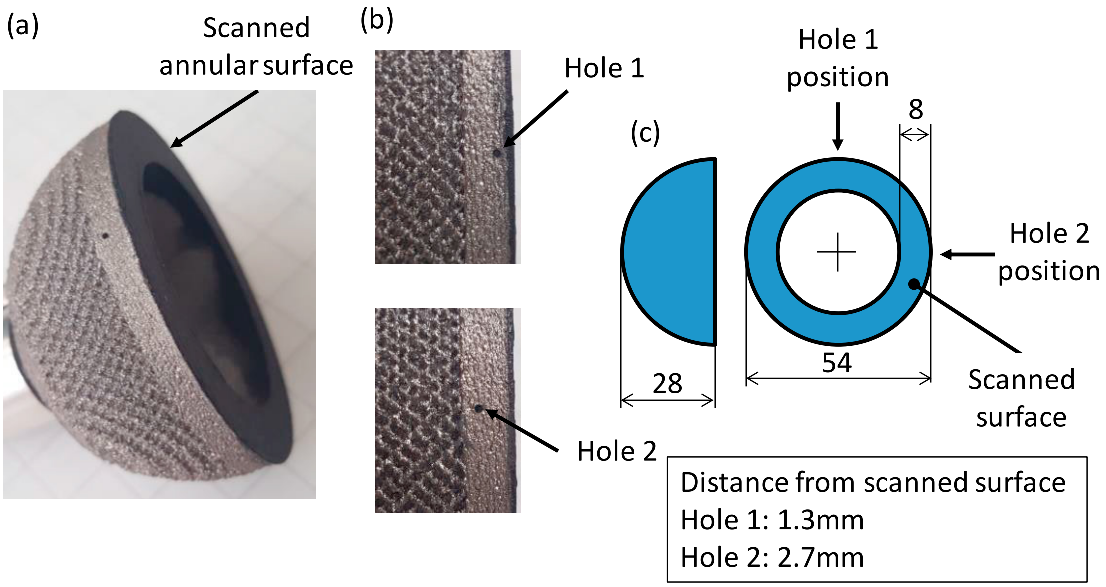

Fig. 1. Picture of the AM titanium sample: (a), frontal view of the two micro-drilled defects at different depth from scanned surface (b), dimensions of the titanium sample and position of the two defects (c).

2.2 The experiments

Figure 2 shows a schematic representation of the set-up used for the laser thermography experiments. Table 1 presents the main parameters and equipment information. The sample is mounted on a motorized rotary actuator controlled by a PC user interface. The continuous wave laser beam is focused into a *1 mm* circular spot via spherical lens in order to inject heat on the scanned annular surface of the sample (see Figure 1a and Figure 3a). The wavelength of the laser is *532 nm* and the power is equal to *1.5 W*. The thermal footprint is acquired by a cooled sensor IR-Camera by FLIR (see specifications in Table 1). The surface thermal evolution, acquired while the sample rotates at constant angular speed, is then evaluated in a ROI placed near the laser spot. The ROI moves at the same speed of the laser maintaining a fixed distance from it (see Figure 3b). The post-processing and the acquisition of the signal has been performed by using the FLIR Research IR v.3.4 software. Both the position and size of the ROI were chosen after taking into account the computational results of Cerniglia et al. (2018), where a parametric study considering different sizes and positions of ROI have been performed by simulating the flying laser scan acquisition on an Inconel sample. One should keep in mind that to increase defect sensitivity, the ROI area must be kept as small as possible (in respect to the defect) and placed in the direction of the highest temperature gradient. If the sample is uniform and sound, the thermal field is expected to remain unmodified under steady state conditions (i.e. constant speed). Figure 4 shows the typical peak and valley evolution of a thermal profile representing the average temperature in the ROI, when the laser flies over a defect. The beginning of the defect, i.e. the moment when the laser spot enters the area above the defect, is represented by an initial rise in temperature, as shown in Figure 4; in particular, when the heat source crosses the area over a defect, the temperature field on the surface is disturbed, due to a temporary barrier action by the material discontinuity against the three-dimensional heat flux. The defect signature is better emphasized by looking at the evolution of the Mean Temperature (MT) over the selected ROI. The thermal properties of Titanium Alloy (Ti6Al4V) used in acetabular cups are: *Specific Heat* 570 J/kg K and *Thermal Conductivity* 7.3 W/m K. The scanning surfaces have been matt black painted before inspection, to enhance and uniform absorption/emissivity of radiant energy, while the surface finish was left untouched. All experiments are performed at three rotational speeds: 0.28 rad/s, 0.46 rad/s and 0.95 rad/s, corresponding to tangential speeds of 6.7 mm/s, 11 mm/s and 22.8 mm/s respectively (calculated at a radius of 24 mm, as shown in Figure 3a).

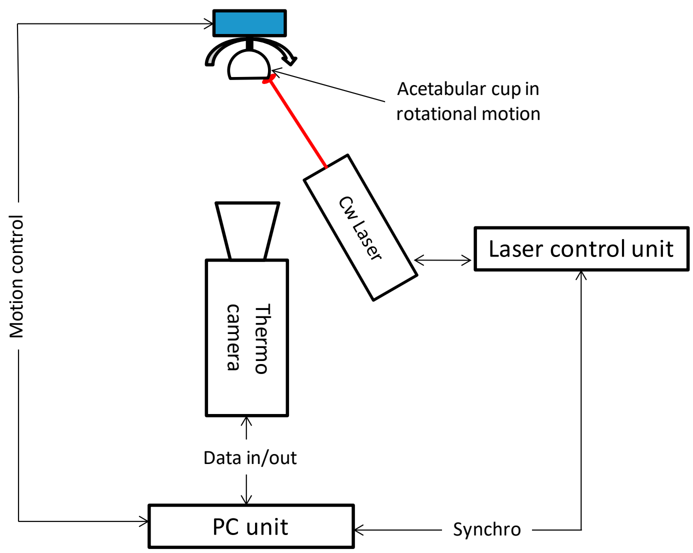

Fig. 2. Set-up of the Flying laser scanning experiments.

Table 1. Parameters of the laser thermography set-up and specifications of the IR camera.

Set-up parameter	Value		Thermocamera
Sample/IR camera distance	~ 300 mm	Model	FLIR – X6540SC
Laser/sample surface distance	~ 300 mm	Sensor	Focal plane array
Rotational speed	0.28 - 0.95 rad/s	Resolution (H x V)	640 x 512 pixels
Region of Interest	1.3 x 1.3 mm^2 4 x 4 pixels	Lens	MW 25 mm 2.0 640 x 51
		Noise (NETD)	20 mK
		Sample rate	20 fps

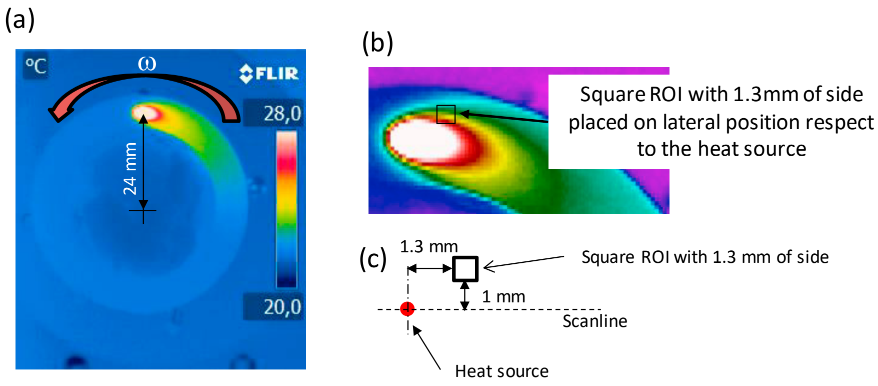

Fig. 3. (a) thermogram acquired during a scan, where the position of the laser is shown; (b) magnification of the heated zones; (c) schematic representation of dimensions and position of the ROI with respect to the heat source.

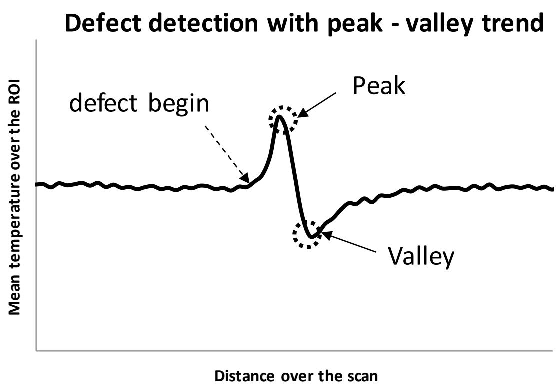

Fig. 4. Typical peak and valley trend generated when the laser flies over a sub-surface defect.

3. Results

The detection mechanism of laser scanning thermography, which is based on the local perturbation of heat conduction, is further discussed and numerically simulated in Montinaro et al. (2017) (2018). Figure 5 shows the plot of the mean temperature evaluated over the ROI versus the sample angular position, from 0° to 270°, at different scan speeds. As mentioned before, experiments were conducted at three different angular speeds, in order to test the sensitivity of the technique, and results are shown in Figure 5a, 5b and 5c for each speed adopted.

As shown in Figure 1c, radial holes #1 and #2 simulating the defects, have been drilled at 120° and 210° with respect to the start position of the scan, thus forming a right angle (90°) between each other.

In Figure 5a the presence of a typical defect signature, characterized by a peak and valley trend of the MT calculated over the ROI, is highlighted by a circle for hole #1. In fact, out of the two drilled defects only the shallower hole #1 was successfully detected, while the deeper one, hole #2, was entirely missed by the experimental setup. The same conclusions can be reached after examining Figure 5b, where the angular speed was increased by 1.64 times, thus reaching the value of 11mm/s (in tangential speed).

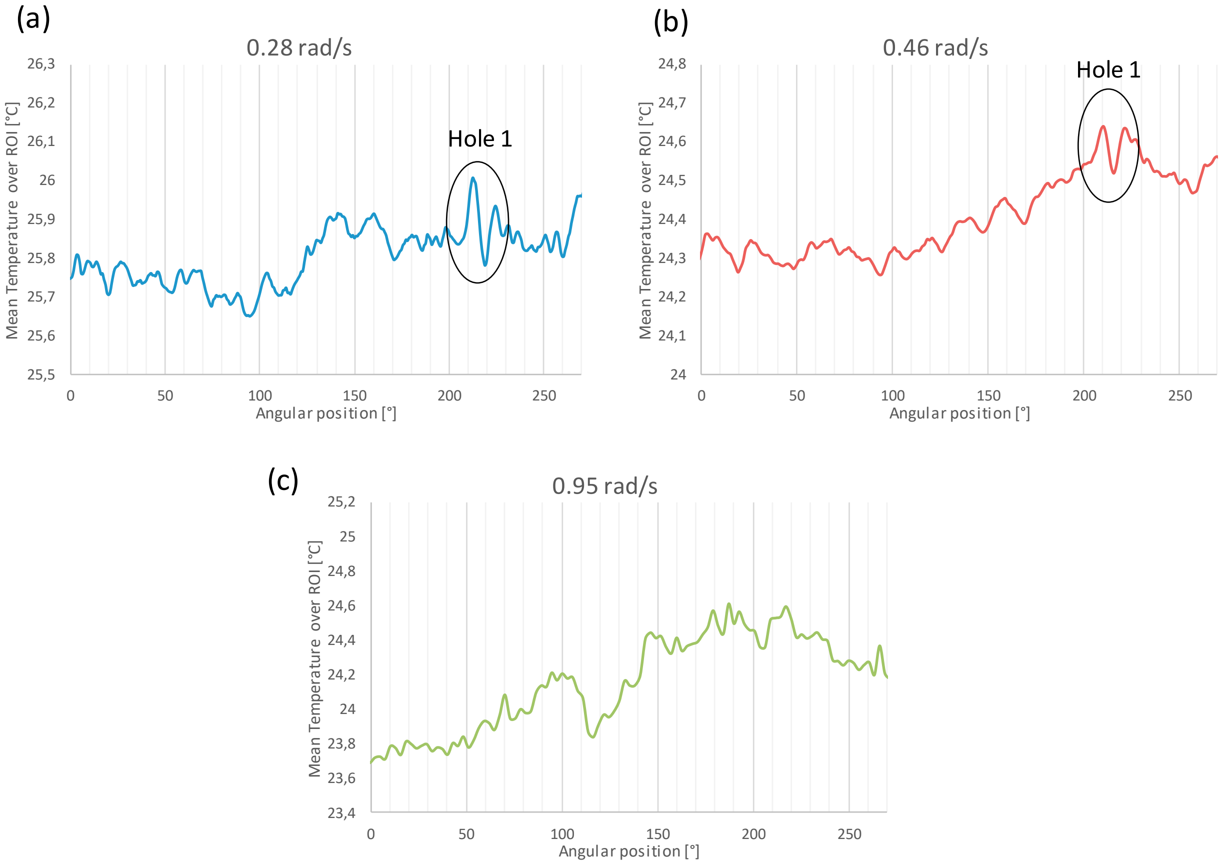

Fig. 5 Plots of the mean temperaure values computed over the ROI versus sample angular position along the circular scan at 24 mm of radius.

Figure 5c shows the evolution of the MT after a further increase of the angular speed by 3.42 times. Here the temperature profile does not show any evidence of the expected defect signature. The authors believe that at this speed the injected power of 1.5 W is no longer sufficient to create a heat flow large enough to interact with the shallow (1.3 mm deep) defect, thus generating a detectable thermal print.

In any case, it is worth mentioning how, typically, the thickness of a layer of material deposited by an AM process is less than one millimetre (< 1 mm), hence the proposed approach shows a good potential to adapt to in-line inspections of sequentially deposited layers, by exhibiting a probing capability (1.3 mm @ 11mm/s) which is enough for the scope even with low power laser generators.

The main pros of the laser scanning thermography technique are its remote and non-contact nature, an easy implementation of the setup and the robustness of results, due to a lower sensitivity to surface conditions when compared to other non-contact techniques (i.e. laser ultrasound).

Moreover, the technique can be easily automated and the probing capability enhanced by increasing laser power wherever the material can handle a bigger temperature increase without suffering any damage (metals, ceramic etc.).

Main cons of the technique are the need to paint the scanned surface, which otherwise would likely be too reflective or would not display a sufficiently uniform emissivity. To overcome the latter issue, an enhanced thermal footprint can be obtained by increasing laser power where possible (material degradation, melting etc...).

Finally, the present implementation of the technique was primarily aimed at investigating defect detectability. However, a more in-depth analysis of the features surrounding defect signatures may pave the way towards a richer defect characterization.

4. Conclusion

3D printing of metal components by additive manufacturing is a fast developing technique, appealing to a variety of sectors such as automotive, aerospace, military and medical. The quality check of manufactured parts is nowadays performed just after the whole object is complete, via destructive tests or X-ray tomography. However, interlayer and intralayer defects are often observed in AM components thus, taking into account both the final customer and cost, a "zero defect" result is close to mandatory.

Some efforts have been expended in the quest of an efficient in-process flaw inspection, nonetheless, conventional NDT approaches are still not entirely satisfactory.

A non-contact approach, called laser scanning thermography, has proven to be a valid alternative to other conventional NDTs in defect detection.

This work applies laser scanning thermography to a real additively manufactured acetabular cup prosthesis made of titanium alloy with ad hoc defects created at known locations, in the form of transverse blind holes embedded under the inspected surface. Specifically, in this work the scanned surface of the sample was preliminarily painted with a matt-black paint (to enhance the thermal footprint), whereas the surface finish was left unmodified (the same as just out of the manufacturing process) in order to prove the efficacy of the inspection in real in-line scan conditions.

Indeed, the results have shown the technique efficacy in detecting sub-surface defects up to depths of 1.3 mm, by using a fairly low laser power of 1.5 W.

Therefore, the main pros of the technique can be summarized in its remote non-contact approach, easy setup, and its potential application in automated inspections along with the robustness of the results which prove less sensitive to surface roughness as compared to other non-contact techniques (i.e. laser ultrasound).

On the other hand, the main cons are the need to paint the scanned surface and the limited capacity to further characterize the defects detected. However, the latter limit could be addressed with an improved optical resolution and with a more accurate post-processing of defect signature features.

Overall, further efforts are needed before this technique could become an alternative to other existing methods.

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