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In-situ laser beam melting investigation with multi-wavelength digital holography

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ABSTRACT

Over the past two decades, laser beam melting has emerged as the leading metal additive manufacturing process to produce small and medium-sized structures. Due to the complex physical phenomena involved in the lasermaterial interaction, instabilities in the melt pool morphology affect the final quality of the structure and remain difficult to predict by simulation. Several monitoring approaches, based on the radiation of the melt process or on a secondary illumination source, have been developed to measure its length, width and height. Nevertheless, the final morphology of the part is influenced by the volumetric forces as well as by the capillary forces applied to the melt. Thus, the shape of the melt surface is of primary interest to control the stability of the melt. Due to its intrinsic heterogeneity, its motion on the powder bed and its own dynamics, the measurement of the melt pool surface shape requires a full-field "one-shot" acquisition with a short exposure time of a few microseconds. In this paper, we propose multi-wavelength digital holography for the in-situ investigation of the melt pool.

Keywords: optical diagnostic, laser beam melting, digital holography, multi-wavelength holography

1. INTRODUCTION

Through the last two decades Laser Beam Melting (LBM) emerged as the major metal additive manufacturing process to produce small to medium size structures. Metal additive manufacturing processes, mainly used in the aerospace, energy, automotive and medical sectors, are divided into two main families: powder bed processes (LBM/SLM, EBM and Metal Binder Jetting) and concentrated energy deposition processes (WAAM, EBAM and CLAD/LENS). The proximity of the LBM process to laser joining processes such as welding will allow readers in the field to find certain similar defects such as pores. Everton et al.¹ listed defects that may occur during the process: pores (gas), balling, inflated powder, and cracks. Sames et al.² identify the same defects and delve deeper, compared to Everton et al, in the relationships between process inputs and defects. Grasso and Colosimo³ proposed to classify defects into 6 categories: porosity, *balling*, geometric defects, surface defects, residual stresses/cracks/debonding, and microstructure inhomogeneity. Due to the complex physical phenomena involved in the laser-matter interaction, melt pool morphology instabilities affect the final quality of the structure and remain challenging to foresee by simulation. Several monitoring approaches, based on the melt pool process radiation or with a secondary illumination source, have been developed to measure its length, width and height.^{4–15} Nonetheless, the final track morphology is influenced by volumetric forces as well as capillary forces applied to the melt pool. So, the melt pool surface shape is of primary interest in order to monitor the melt pool stability. Because of its intrinsic heterogeneity, its movement over the powder bed and its own dynamic, the melt pool surface shape measurement requires a single-shot full-field acquisition with a short exposure time of few micro-seconds. Among optical approaches for surface shape measurements, two-wavelength digital holography has demonstrated to be a relevant tool for desensitized testing. Examples are found with steep

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optical surfaces (aspheric mirrors and lenses),¹⁶ large deformation of structures¹⁷ or also surface shape profiling.¹⁸ Such an approach can also be used for surface roughness measurements when the roughness is large compared to the wavelength.¹⁹ A wide range of applications of multi-wavelength holography was also demonstrated, such as endoscopic imaging,^{20,21} calibration of mechanical structures,²² erosion measurements,²³ or also in-line industrial inspection.²⁴ When dealing with off-axis digital holography and spatial multiplexing of two-wavelength digital holograms, the method becomes real-time, in the sense that the surface shape can be measured at each instant at which the holograms are recorded. In this paper, we propose multi-wavelength digital holography for in-situ investigation of the melt pool. It has the advantage of being contact-less, non-intrusive, and yields full-field surface shape data without any requirement for scanning.

2. BASIC FUNDAMENTALS OF TWO-WAVELENGTH DIGITAL HOLOGRAPHY

Two-wavelength digital holography has many advantages over single wavelength holography. With a unique wavelength, the measured surface height of any non polished object is ambiguous if larger than the wavelength. Since the object surface also includes roughness, then the surface shape cannot be reconstructed because the phase extracted from the digital holograms results from a speckle pattern. The ambiguity and randomness of this phase can be mitigated with the use of another/several wavelengths leading to what is known as the synthetic wavelength. It follows that the unambiguous range becomes increased from microns to millimeter or larger. Considering two wavelengths λ_1 and λ_2 , the synthetic wavelength is given by $\Lambda = \lambda_1 \lambda_2 / |\lambda_1 - \lambda_2|$.²⁵ The surface height of the object, h(x, y), is calculated with the following equation (here is considered that illumination and observation of the surface are at normal incidence):

$$h(x,y) = \frac{\Lambda}{4\pi} [\varphi_2(x,y) - \varphi_1(x,y)], \qquad (1)$$

with φ_1, φ_2 the optical phases extracted from the two holograms at the two wavelengths.

3. SET-UP FOR OPTICAL DIAGNOSTIC OF THE MELTING POOL

The proposed method is based on off-axis digital holography and spatial multiplexing of two-wavelength digital holograms. The optical arrangement to measure φ_1 and φ_2 is depicted in Fig. 1(a). It permits to the method to be "real-time" in the sense that the surface shape of the area under inspection can be measured for each recorded hologram.²⁶ With a high-speed camera and appropriate laser sources, the exposure time can be reduced to a few microseconds and real-time control can be achieved. The device is equipped with two linearly polarized lasers (20 mW He-Ne laser at 632.8 nm and 50 mW CRL-DL635-050-SO-Optical-Isolator diode laser at 635.1 nm). Thus, the synthetic wavelength is equal to 174.73 μ m. Each laser beam is expanded through beam expanders (BE1, BE2), before separation with polarizing beam splitters (PBS1, PBS2) in order to generate the reference beams and the probe beams. Along the reference paths,²⁷ the light impacts the sensor with a slight tilt angle to provide off-axis recording of the holograms. The two reference beams are combined onto a single reference beam using splitter cube C2. Along the probe path, both illumination wavelengths impact the surface at normal incidence. The beams are shaped with BE3 and focusing lens L1 to produce a spot between 0.5 mm and 1 mm in diameter.

The digital holographic system is coupled to a laser fabrication machine (LBM) depicted in Fig. 1(b). The fusion laser is a continuous monomode laser with power adjustable from 50 W to 500 W (SPI laser SM-S00472-8) emitting at 1064 nm and equipped at the end of the fiber with a QBH connector associated with a collimator. The beam expanded BE4 and focusing lens L2 makes it possible to obtain, after reflection on the dichroic plate D2 (cut-off wavelength 980 nm), in the fusion zone, a spot of variable diameter (minimum diameter of 70 μ m). In practice, the diameter varies between 100 μ m and 200 μ m. It should be noted that the estimation of the diameter carried out after shooting on an anodized plate was not very accurate. This laser is equipped with a 632.8 nm coaxial laser source for alignment which allows checking the position of the fusion laser and more particularly to check the superposition with the control beams on the powder bed (not shown in Fig. 1). Note that dichroic plate D1 cuts the thermal radiation from the fusion area by only passing wavelengths around 630-640 nm. This permits to avoid saturation of the sensor with the near infrared light back propagated from the surface to the imaging system.



Figure 1. (a) Two-wavelength holographic set-up for LBM monitoring, (b) laser fabrication machine (BE: beam expanders, PBS: polarizing beam splitters, M: mirrors, C: beam splitter cubes, D1: dichroic plates, W: protection window, L: lenses).

From the surface plane to the sensor plane, the light reflected from the surface propagates through a quarter wave plate in order to rotate the polarization for transmission into PBS3. Then, an imaging system in $f_1 - f_2$ telecentric configuration is used so as to produce an image focused at the sensor plane (image-plane digital holography²⁸). A circular pupil is inserted in the imaging system in order to control the spatial bandwidth of the digital holograms. In addition, the pupil sets the spatial resolution in the image plane. At the sensor plane, a Photron Fastcam MC2 is used to record sequences of digital two-wavelength holograms.

Figure 2(a) depicts the basic scheme of image-plane digital holography for the LBM surface measurements. Figure 2(b) illustrates the spectral distribution in the Fourier domain of the digital hologram in spatially multiplexed off-axis two-wavelength holography. The useful +1 order has a spectral spatial bandwidth with diameter $2R_u \approx 50 \ mm^{-1}$, and the extraction of the order is performed by the binary spectral filter having the same bandwidth. It follows that the spatial resolution in the image plane is $\approx 20 \ \mu m$ and almost $\approx 6.6 \ \mu m$ at the melt pool plane (optical magnification $\approx \times 3$).

4. EXPERIMENTAL RESULTS

In this section, some preliminary experimental results for in-situ diagnostics of the melt are provided. Figure 3 shows double aluminum beads on an aluminum substrate. Figure 4 shows the topography of the melt on a 316L metal foil with a feed rate of 100 mm/s.



Figure 2. (a) Imaging of the melt pool through the off-axis digital holographic system, (b) Spectral distribution in the Fourier domain of the off-axis digital holograms.



Figure 3. Topography of double aluminum beads on an aluminum substrate.

5. CONCLUSION

This paper proposes two-wavelength digital holography for real-time, in-situ an full-field measurement of the melt pool in metal additive manufacturing process. The holographic system is coupled to the LBM machine and high speed camera permits to record spatially multiplexed two-color holograms at both the temporal and spatial scales of the running process. The surface topography at the melt pool plane depends on the synthetic wavelength generated by the two wavelengths. Experimental results are provided: double aluminum beads on an aluminum substrate and topography of the melt on a 316L metal foil with a feed rate of 100 mm/s. To the best of our knowledge, these are the first results of in-situ full-field melt pool and track surface shape measurements in LBM process.

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Figure 4. Topography of the melt on a 316L metal foil with a feed rate of 100 mm/s.

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