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In-process measurement and monitoring of a polymer laser sintering powder bed with fringe projection

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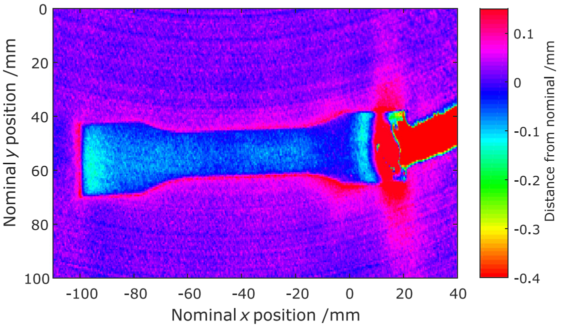
HIGHLIGHTS

- In-process fringe projection measurements provide early detection of defects.
- Height drop due to consolidation is a suitable measure of successful processing.
- Maximum height from powder bed surface identifies both random defects and curling.
- The data analysis presented is suitable for process control decisions.

GRAPHICAL ABSTRACT



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ABSTRACT

We investigate the feasibility of using fringe projection to monitor the powder bed of a polyamide 12 polymer laser sintering machine. In particular, we demonstrate the ability of fringe projection to identify a number of defects arising during the printing process by recording the three-dimensional structure of the sintered powder bed after the completion of each layer. The defects identified ranged in size from hundreds of micrometres to hundreds of millimetres. The three-dimensional analysis of the powder bed data has shown the ability to quantify effects, such as curling, powder spreader blade interactions and the consolidation of a sintered layer. It has, therefore, been shown that the use of fringe projection in polymer laser sintering machines can provide deeper understanding and monitoring of the dynamic behaviour during the process. Fringe projection has shown potential to become part of a feedback and control system that interrupts the build and corrects for in-process defects where possible.

1. Introduction

Additive manufacturing (AM) is a fast growing family of processes that build parts directly from three-dimensional (3D) model data in a layer-by-layer process [1, 2] in contrast to more traditional techniques, such as machining of bulk material, casting and forging. In comparison to classical 'subtractive' production methods, AM is generally characterised as having greater design freedom and reducing material waste [3, 4].

The specific AM process investigated in this work is polymer laser sintering and is part of a family of methods called powder bed fusion (PBF). Despite laser sintering being an established industrial process, the process control available is minimal and generally not closed-loop [4–6]. The subsequent lack of process reliability at the level required by many industries is one of the main reasons why laser sintering is not more widely used for end-use manufacturing [7].

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2. Background

Laser sintering of polymers involves the scanning of a focussed laser spot across a powder bed consisting of polymer particles, usually of around 50 μm in diameter [8]. The powder bed is usually heated to the melting onset point of the material in order to reduce thermal stresses from non-isotropic cooling induced by the laser that could cause the build to fail [8]. When the powder bed is heated to the melting onset point, the scanning laser spot provides enough energy to cause the material under the laser spot to melt without causing significant material degradation [9]. Between layers, the powder bed is lowered by a pre-set layer height, generally double the diameter of the average particle size. Finally, a new layer of powder is prepared for the next laser beam pass, by spreading a thin powder layer across the powder bed. There are many process parameters which contribute to a successful build [10], and both process monitoring and process control are vital to ensuring manufactured parts are within acceptable tolerances.

To identify whether fringe projection can be used to detect and provide feedback on structural defects created during laser sintering of polymers, the parameter ranges where defects are created need to be ascertained. To obtain the appropriate parameter ranges, a mapping of the parameter space is essential to allow monitoring in known processing conditions. This mapping identifies what is measured in both successful and failing builds.

2.1. Process mapping

Process mapping is used to explore the parameter space available in a process, by characterising the outcome of the build with regards to a measured property of the produced part for specific combinations of input parameters. Examples of these properties are surface texture and part porosity [11, 12]. Process mapping enables the determination of the acceptable ranges of important process parameters, which guarantee manufactured part specification within tolerances [13–15]. Of the numerous formalised methods of process mapping, design of experiments [16] and Taguchi [15] are notable examples. Successful mapping allows the selection of specific combinations of parameters which achieve the desired part properties (such as mechanical performance or production time).

Process mapping of AM materials has been carried out previously in a range of laser sintering machines [17–20] and has been used for improving the process parameters for specific structures [15, 21]. However, these improved parameters are only applicable to the specific combination of machine and material and are only found after numerous test builds have been completed. In this work, we performed an iterative search methodology for process mapping to ensure maximum coverage of failure modes in an EOS P100 laser sintering machine with 50% recycled polyamide 12.

2.2. Process monitoring

To ensure the builds remain within the desired parameter ranges, process monitoring and control are required, even with a complete process map. Process monitoring and control are especially required where the acceptable parameter ranges are small or when the parameters are pushed to the limits of their ranges for a specific reason (e.g. maximum scan speed), and temporal variation is critical. Process control takes in-process measurements of process signatures as input [22]. Examples of laser sintering process signatures include height drop due to consolidation, curling of consolidated parts and the temperature of the polymer illuminated by the laser spot. Measurements of process signatures enable closed-loop control of process parameters to keep the produced part within specified tolerances, something which is in high demand from industry [4]. An implemented alternative to process control, used to counteract the uncertainties of end part geometries and properties, is computer simulations [23, 24]. Whilst simulation can help to reduce the occurrences of reproducible errors or distortions, it does not improve control over errors caused by the inherent variability in the AM process.

Process monitoring has already been developed for metal PBF. These systems of process monitoring and control can be applied to polymer laser sintering and so these techniques will be referenced in this document. Comparisons can be made between techniques which view the whole bed at once [25, 26], with those that scan the powder bed [27] often in tandem with the laser spot [28–30]. Literature on techniques that view the whole bed at once mainly focus on measuring the geometry of the consolidated material, generally relying on high resolution imaging [31–33]. Current methods of measuring such defects, including differential lighting [31, 32], do not give a measurement of the height above the powder bed, and they do not give conclusive information about the process instability measured. Fringe projection provides quantitative height information and insight into process stability, enabling deeper understanding of the production of parts.

2.3. Fringe projection

The monitoring technique used in this work to identify structural defects was fringe projection [34, 35]. Fringe projection was selected as it is more suitable to be used in-process because of the ability for real-time data processing [36–38]. Furthermore, fringe projection has been shown to operate well with diffusely scattering white materials such as polyamide 12 [39, 40].

In fringe projection, a camera observes the distortions of a light pattern projected onto the object's surface induced by the object's shape, see Fig. 1. Several depth cues can be used in the reconstruction of the surface shape and the least-squares phase shifting algorithm was used for reconstruction in this study [41]. This specific algorithm uses N images of projected sinusoidal fringe patterns that are phase shifted by $2\pi/N$ with respect to the previous pattern.

The irradiance distribution of the fringe patterns is given by

$$I_i(x,y) = I_0\left[1 + \cos\left(\frac{2\pi x}{p} + \delta_i\right)\right] \quad (1)$$

where i denotes the i^{th} image, I_0 is the modulation of the irradiance, p is the sine wave period and δ_i is the absolute phase for the i^{th} image. In most implementations, $N \geq 3$ since there are three unknowns when solving for the surface height. The N measurements of the fringe

Fig. 1. A sinusoidal fringe pattern projected onto a polymer AM part from the bottom right hand corner of the image. The irradiance distribution across the part is used to reconstruct the surface.