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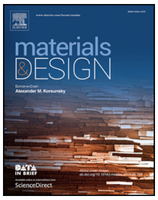

Evaluation of selective laser sintering processes by optical coherence tomography

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ABSTRACT

Selective laser sintering (SLS) enables the fast, flexible and cost-efficient production of parts directly from 3D CAD data. Unlike more established machine tools, there is a marked lack of process monitoring and feedback control of key process variables. In-situ analysis techniques permit the emergence of repair techniques, in-process optimization of production parameters, and will also serve to save time and material. In this study, optical coherence tomography (OCT) is used for the first time to evaluate components produced by SLS. Using a Polyamide-PA2200, surface defects are analyzed and the limiting factors associated with the measurement technique are quantified. OCT is shown to be a useful technique for evaluating surface irregularities alongside sub-surface defects that have resulted from poor sintering or non-homogeneous powder spreading. We demonstrate detection and quantification of surface defects such as cracks, pores and voids on a ~30 μm scale. Furthermore, we show that this technique can resolve 'built-in' fine features within a 200 to 400 μm depth below the surface, covering typical layer thicknesses used by this process. This capability paves the way for real-time monitoring of the SLS process for assurance, or even dynamic correction of defects during the build.

1. Introduction

Additive manufacturing (AM) is an emerging technique that provides an alternative solution to traditional, subtractive manufacturing in many situations where fast and cost-efficient fabrications are required [1]. AM is currently undergoing a transition from application in prototype [2–4] and pilot production technology towards scalable and high-value manufacture of bespoke components. Accelerated uptake will be aided by improved process control and dynamic correction. Selective laser sintering (SLS) is a maturing additive manufacturing technique, first demonstrated in the 1980s [5,6], which enables fast, flexible and cost-effective fabrication of highly complex monolithic polymer parts. The freedom of design afforded by SLS allows significant mass and cost reductions. The rapid set-up and build time enable one of the quickest routes from product design to market launch, which is of benefit to application in the medical sector [7–10], as well as aviation and space industries [11]. However, the SLS process can be affected by a number of factors associated with the properties of the material used and with the sintering process itself [12,13]. For example, temperature, gravity and capillary effects make it difficult to achieve 100% density in the manufactured elements. Common failure modes in SLS-built parts include: pores and cracks inside or at the edge of specimens, irregular surface finishing, closed holes or gap fusion, missing or thin walls and loose powders inclusion [13]. Such failures, caused by poor sintering or non-homogeneous spreading in previous layers, will result in a reduction of the part's lifetime.

Manufacturing methods for the high value markets (e.g. aerospace, healthcare) are characterised by the level of process monitoring that govern their operation. These are commonly used to 'feedback' into the process to rectify wayward conditions and also 'feed-forward' to help with the specification of rework. Manufacturing of the future is set to be more data rich than it is today with advent of initiative such as "Industry 4.0" and "cloud manufacturing". While process control is common in modern machining centres and available often as a low cost add-on, this technology is yet to be developed for AM tools in any meaningful way. The most significant barrier to the uptake of AM processes is the high cost per part and a lack of confidence in part integrity. Furthermore, where certification of a process is required, assurances must be provided that the product matches specification. Non-destructive evaluation (NDE) methods including X-Ray Computed Tomography (XCT) [14,15] have proven useful for determining the integrity of additively manufactured parts, but are expensive and typically only allow 10–100 μm spatial resolution. In addition, faults originating

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in the early stages of a lengthy manufacturing run are not recognised until after processing is complete. It is proposed that in-situ analysis techniques will be incorporated into additive manufacturing systems in order to monitor the manufacturing process and identify defects as they occur. This will permit the emergence of repair techniques, closed-loop in-process optimization of production parameters and will also serve to save time and material if a build must be aborted.

Optical coherence tomography (OCT) is a non-contact imaging technique which allows video-rate 3 dimensional (3D) representation of the structure with axial resolutions <10 μm. Now widely employed in ophthalmology [16,17], oncology [18,19] and cardiology [20,21], the main drive is towards cost reduction and system performance enhancement to accelerate wider uptake in clinical diagnosis. Fewer reports exist on the use of OCT outside the biophotonics community, but these include the examination of glass-fibre reinforced polymer matrix composites [22], defects in polymer solar cells during roll-to-roll manufacture [23] and the study of fine art [24]. The scope of OCT could be extended to the functional imaging of a large number of materials that are transparent to the wavelength of the light source used, such as polymeric parts, which are broadly transparent in the near-IR. Compared with XCT for the assessment of SLS specimens, OCT has three main advantages. First, OCT can provide 3D volume images with spatial resolution <10 μm compared with ~50 μm for typical XCT. It therefore has the potential capability of imaging single powder particles, as well as measuring pores or voids typically found inside SLS parts. Second, with development of computer processing and optical sensor technology, the scanning speed of OCT could reach speeds of 100 kHz, which will allow more than 390 frames/s. That is, real-time monitoring of the SLS procedure could be achieved due to the high scanning speed. Third, an OCT system could be easily integrated within an SLS system in order to enable in-situ analysis. Since the only elements of the OCT system that need to be inside the working space consists of a galvo mirror, an optical fiber and a small optical train. Compared to XCT systems, current class are of the order of 2200 cm^3 in their most compact form. It is therefore difficult to envisage an entire XCT technology being integrated within the SLS system in this way.

In this study, OCT is used for the first time to assess components produced by SLS with commercially available polyamide 12 laser sintering material (PA2200, EOS Ltd). Specimens with different features and failure modes were fabricated and measured using the OCT system in order to test the feasibility of using OCT to examine polymeric parts. OCT is therefore demonstrated as a process control tool for SLS.

2. Methods and materials

2.1. OCT system

In this work we utilize a commercially available, multi-beam, Fourier-domain, swept source OCT system (EX1301, Michelson Diagnostics, Kent, UK). The simplified schematic diagram of this system is shown on Fig. 1. The OCT system is equipped with a laser with a central wavelength of 1305 ± 15 nm and a sweep range of 150 nm at 10 kHz (HSL-2000, Santec, Japan). The axial optical resolution when applied to polyamide PA2200 is <10 μm, while the lateral optical resolution, determined by the system optics, is approximately 7.5 μm. The maximum scan width is 7 mm with a penetration depth of up to 2 mm when applied to biological tissues. Common commercially available OCT light sources have central wavelength at 800 nm, 1000 nm and 1300 nm respectively. The penetration depth decreases with wavelength and is work piece material dependant. Therefore, the 1300 nm light source was chosen as it could provide the maximum penetration (measured ~400 μm) of polymeric material (i.e. multiple layers of sintered powder), whilst offering a resolution capable of resolving individual powder particles, typically >30 μm in size.

OCT performs cross-sectional imaging by measuring the magnitude and echo time delay of backscattered light. Cross-sectional images are generated by performing multiple axial measurements of echo time delay (axial scans or A-scans) and scanning the incident optical beam transversely. This produces a two-dimensional data set, which represents the optical backscattering in a cross-sectional plane through the tissue. Images, or B-scans, can be displayed in false color or grey scale to visualize tissue pathology. Two scanning modes may be used for imaging. In the free-run mode, the laser beam is scanned only in one

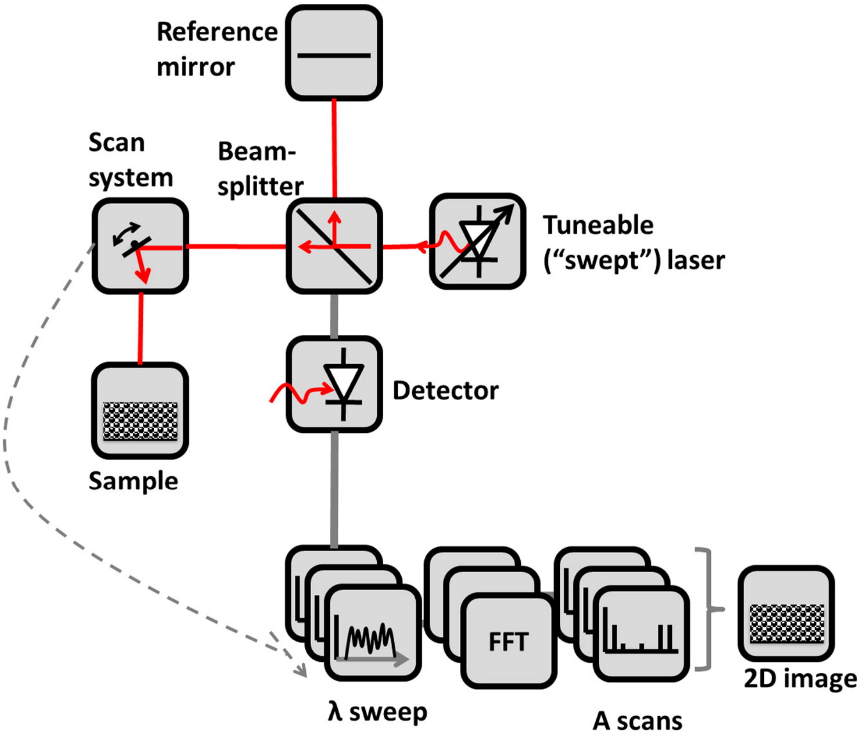

Fig. 1. Schematic diagram of a typical swept laser OCT setup.