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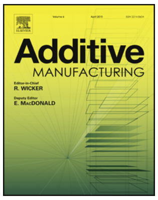

Full Length Article

An open-architecture metal powder bed fusion system for in-situ process measurements

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ABSTRACT

We report the design of a metal powder bed fusion system for in-situ monitoring of the build process during additive manufacture. Its open-architecture design was originally determined to enable access for x-rays to the melt pool, but it also provides access to the build area for a range of other in-situ measurement techniques. The system is sufficiently automated to enable single tracks and high-density, multiple layer components to be built. It is easily transportable to enable measurements at different measurement facilities and its modular design enables straightforward modification for the specific measurements being made. We demonstrate that the system produces components with >99% density. Hence the build conditions are representative to observe process fundamentals and to develop process control strategies.

1. Introduction

Metal powder bed fusion (PBF) is a well-known process category in additive manufacture (AM) in which thermal energy selectively fuses regions of a powder bed [1]. It is sometimes referred to by manufacturers' names, for example selective laser melting (SLM) and direct metal laser sintering (DMLS). The PBF system described in this paper was designed as part of a feasibility study to use x-rays for in-situ imaging of the melt pool during metal PBF. The open-architecture design of the system also enables flexible access for other process measurements in addition to x-ray imaging, including high-speed imaging, shield gas flow and temperature. In this paper we describe the design of the open-architecture PBF system and validate its performance. The results of specific process monitoring applications, and the understanding of process fundamentals provided by them, will be reported elsewhere.

The design of the PBF system was determined by the requirements for x-ray access. The aim of the x-ray measurements in the feasibility study is to yield process understanding, rather than validating the quality of parts during their build. Such images will yield new insight into the physical processes that occur during PBF, including the powder melting and solidifying, fluid dynamics in the melt-pool and the formation of pores. One example where this insight might be useful is in improving the high-cycle fatigue life of titanium components produced by AM, which is dominated by cracks that nucleate at near-surface pores. Many factors can contribute to pore formation, including instability of the melt pool [2], lack of fusion between powder particles [3,4], the laser keyhole leaving a trail of voids [5], narrow powder particle size distribution reducing the packing in a layer [6,7], scanning strategy with insufficient overlap between adjacent tracks [8,9] and spatter and oxidation due to lack of shielding gas [10]. A better systematic understanding of the relationships between the process parameters and the size, density, and three-dimensional spatial distribution of pores might be used to eliminate their detrimental effect on fatigue life, without resorting to additional costly process steps such as hot isostatic pressing.

X-ray access to the powder bed is extremely difficult in a commercial PBF machine. Obviously the complex and compact machinery is not optimized for x-ray passage to the powder bed and modifications to the powder delivery system, build platform and laser delivery would be prohibitively expensive. Bespoke PBF systems to implement process monitoring and imaging have been reported. Craeghs et al. [11] developed a PBF system for real-time melt pool monitoring to see in-situ process defects; Sercombe et al. [12] reported post-process x-ray micro-tomography measurements of the deformation and failure of scaffolds; Vlasea et al. [13] proposed the design of a PBF system to asses in-process monitoring techniques and intermittent metrology of the powder bed between layers; Land et al. [14] discussed a PBF system fitted with non-contact metrology systems to measure layer characteristics to

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be compared with the final components. None of these systems has been designed for in-process x-ray imaging.

2. Requirements for the PBF system

Our objective is to record in-process x-ray images around the melt pool in a metal powder bed. We are interested in imaging a region ~500 μm long that incorporates the melt pool with un-melted powder in front and solidifying material behind. Of particular importance is realistic heat conduction away from the melt-pool and for the ability to monitor pores through multiple build layers. A short exposure time is required to effectively freeze the motion of the melt-pool as it moves across the powder bed at speeds up to several hundred mm/s. Successful x-ray imaging therefore requires that:

- the intensity of the x-ray source is sufficient to record short exposure images through the build plate and any other metal in the beam path;
- the spatial resolution is sufficient (~1 μm) for individual powder particles to be imaged;
- the image contrast is sufficient to resolve small variations in x-ray absorption in the powder layer above noise in the image.

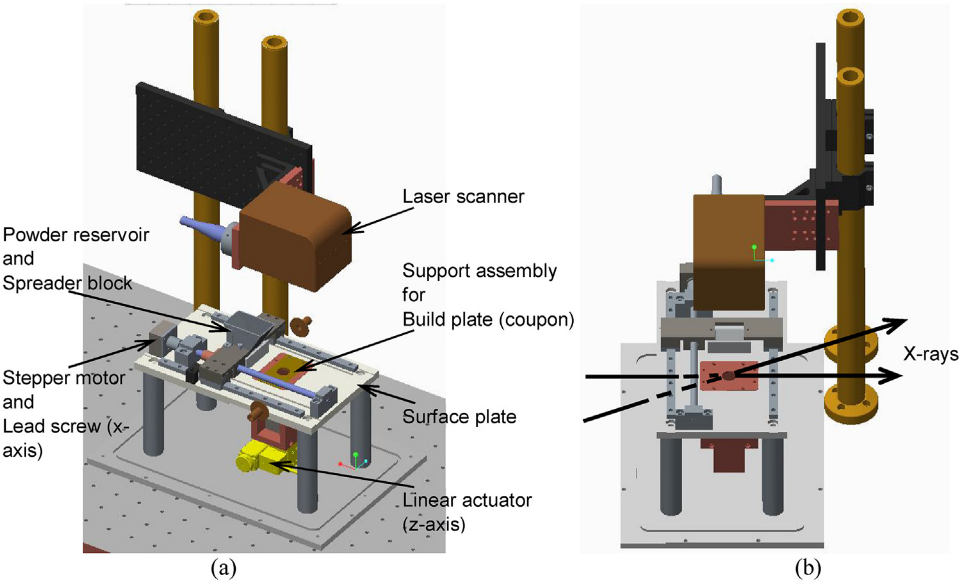
X-ray sources with these characteristics can be set up at the Science and Technology Facilities Council Central Laser Facility (STFC CLF) in the UK. The ultra-high intensity Vulcan laser (power ~10^{15} W, light intensity 10^{21} W/cm^2 pulses) can drive a compact particle accelerator when focussed on a solid foil target [15]. The short laser pulse (~few ps) produces a plasma and drives electrons at relativistic energies through the foil. These electrons interact with the solid material of the foil to generate high-energy bremsstrahlung x-rays that emerge from the rear surface of the foil in a diverging cone from a spot of less than 100 μm across. These x-rays have a broad energy spectrum (10's keV to 5 MeV), a duration of a few picoseconds and sufficient intensity to record projection images through thick metallic objects [16,17]. The time between x-ray pulses is ~15 min, determined by the repetition rate of Vulcan laser. The diverging x-ray beam emerges horizontally into a test room, with an included angle of approximately 40°. The operator is stationed in a separate control room to avoid exposure to the burst of x-rays, gamma rays and charged particles produced by the compact accelerator.

Clearly then, the PBF system must be sufficiently portable to operate in the x-ray test room with automated operation from the control room. Its design should minimize the amount of metal in the x-ray path to the melt-pool. Experiments require a small number of fully fused layers to be deposited, over which a powder layer is spread in readiness for the x-ray pulse. The x-ray pulse is requested from the Vulcan control room, and PBF system laser is synchronized to scan across the powder bed and to be at the centre of the imaging region when the x-ray pulse arrives. It must be possible to deposit multiple layers automatically and remotely in order to monitor the development of pores between successive layers.

3. PBF system design

The open-architecture PBF system is shown in Figs. 1 and 2. It comprises a powder reservoir and spreader block that are moved as a single unit by a stepper motor and lead screw. The powder is gravity-fed and deposited in the build area as the spreader block moves linearly in one direction; the excess powder is removed as the spreader block returns. The build plates are 80 × 40 mm^2 coupons that are bolted to a rectangular support assembly that is rigidly connected to the vertical stage (z-axis). A circular hole in the support assembly leaves clear passage for the x-rays to pass from below the powder bed and will be discussed in more detail in the next paragraph. Powder layers of the desired thickness are produced by lowering the support assembly with the vertical stage (Standa 8MVT40-13-1, ~10 nm resolution). The rectangular support assembly moves as a 'piston' within the surface plate: a Teflon O-ring around the edge of the rectangular support prevents powder falling through the gap with the surface plate.

As noted above, the STFC Vulcan x-ray beam emerges horizontally into the test room with a total included angle of 40°: the desired x-ray beam diameter and direction are selected from within that cone with lead bricks. Two x-ray imaging directions are accommodated in the current design. The length of the slot in the spreader block can be set to <1 mm in the y-direction so that a thin line of powder is deposited in the x-direction. In this case, the PBF system is positioned so that the central region of the x-ray cone passes horizontally through the test region, as shown in Fig. 1(b). However, a



(a) (b)

Fig. 1. (a) Schematic of the open-architecture powder bed fusion system. (b) Passage of x-rays, either at 12° to 57° to the horizontal, or horizontally, through the powder-bed.