Acta Materialia 142 (2018) 107–120

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Fluid and particle dynamics in laser powder bed fusion

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ARTICLE INFO

Article history:
Received 19 July 2017
Received in revised form
5 September 2017
Accepted 21 September 2017
Available online 22 September 2017

Keywords:
High-speed imaging
In situ
Powder consolidation
Finite element modelling (FEM)
Theory and modelling (kinetics, transport, diffusion)

ABSTRACT

In this work, we employ a combination of high-speed imaging and schlieren imaging, as well as multiphysics modelling, to elucidate the effects of the interaction between the laser beam and the powder bed. The formation of denuded areas where the powder was removed during single line and island scans over several layers were imaged for the first time. The inclination of the laser plume was shifted from forwards to backwards by changing power and scan speed, resulting in different denudation regimes with implications to the heat, mass and momentum transfer of the process. As the build progressed, denudation became less severe than for a single powder layer, but the occurrence of sintered and fused powder agglomerates, which were affected by the plume, increased. Schlieren imaging enabled the visualisation of the Ar gas flow, which takes place in the atmosphere above the bed due to the plume, in addition to its interaction with affected particles. Numerical modelling was used to understand and quantify the observed flow behaviour, through the hydrodynamic treatment of the laser plume as a multi-component Ar-Fe plasma. These results promote the characterisation of fluid dynamic phenomena during the laser powder-bed fusion (LPBF) process, which constitutes a key factor in the prevention of defects in additively manufactured parts.

1. Introduction

Detailed imaging of the interaction between the laser beam and the powder bed whilst building multiple layer islands with metal powder bed fusion (PBF) has not been reported previously. It is extremely challenging to record images through the viewing window of commercial PBF systems with sufficient magnification or contrast to see individual powder particles in the powder bed. Higher magnification images have so far focussed on the melt pool whilst scanning a single laser track in a representative powder layer. In this paper, we report detailed, in-process imaging of the interaction of the laser beam with the powder bed during the PBF build of fully dense parts. We demonstrate that the PBF process is more dynamic than is generally appreciated and involves considerable motion of the powder particles and agglomerates in and above the powder bed. This motion is driven by the laser-induced plume of metal vapour and plasma above the melt pool. We therefore develop the first finite element model for PBF that incorporates the laser plume and inert atmosphere in order to explain the observed motion of the fluids and powder particles in and above the powder bed.

Metal powder bed fusion (PBF) is a category of additive manufacture (AM) process in which thermal energy selectively fuses regions of a powder bed [1]. Commercial PBF systems are already used to manufacture production components; but these components generally require intensive, part-specific process setting refinement to reduce distortions caused by residual stresses, to determine process settings that reduce defects and to determine acceptable positions for support structures. In the future, software will simulate a full-build and reduce the time required to determine process settings, but that approach still requires better process understanding so that residual stresses, porosity and surface finish are predicted reliably for different process regimes.

Imaging of the PBF process is one approach being used to achieve this improved understanding. Qiu et al. [2] undertook a systematic study of the effect of laser scan speed and powder layer thickness on porosity using a commercial Concept Laser M2 system. SEM images of sample surfaces revealed an increase in surface roughness and weld track irregularity when either the scan speed or powder layer thickness were increased above certain (process-specific) thresholds. Increases in surface roughness were correlated

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https://doi.org/10.1016/j.actamat.2017.09.051

with an increase in internal porosity. High-speed videos were recorded at 10,000 frames per second (fps) through the system viewing window. The optical resolution of ~150 μm per pixel was insufficient to resolve individual powder particles and their interaction with the laser, although the number of incandescent powder particles ejected backwards from the melt pool was observed to increase with increased thickness of the powder layer. Grasso et al. [3] recorded images with a similar magnification at 300 fps through the viewing window of a Renishaw AM250 system. Again, the interaction of the laser with the powder particles could not be resolved. However, the intensity evolution through time at each pixel from an image sequence was successfully used to identify areas of the powder layer that experienced overheating and therefore the location of potential defects.

Higher magnification imaging of the melt pool in a representative powder layer was reported by Matthews et al. [4], who investigated the depletion of metal powder particles in the zone immediately surrounding the solidified track (denudation), which can affect porosity and surface roughness. It was proposed that denudation at ambient pressure is caused by the intense evaporation of metal vapour from the melt pool, which produces an inward flow of the ambient gas towards the melt track due to the Bernoulli effect. The inward flow of the ambient gas is sufficient to entrain powder particles, which can become incorporated into the melt pool or ejected with the metal vapour. Imaging of the melt pool with an optical resolution of ~5 μm per pixel enabled this particle motion to be observed, with particles ejected backwards with respect to the scan direction [4] or vertically upwards [5], depending on the process setting. The experimental system for imaging comprised scanning a single laser track in a powder layer that had been spread manually on to a metal substrate, protected with an inert gas from a localized jet. Gunenthiram et al. [6] noted the complexity of performing diagnostics during the PBF build process and so recorded single track images in a similar system to [4] but with a powder layer that moved on a translation stage below the laser. Motion of powder particles towards the melt pool due to the metal vapour was again observed, but again high magnification on the melt pool prevented the formation of the denuded region from being imaged. Zhao et al. [7] used synchrotron radiation to image the interaction of 1 ms laser pulses with a powder layer at 50,000 fps. Vapour-driven particle motion was observed and, additionally, the dynamic keyhole development beneath the powder bed could be seen. In this case, the powder bed was only 450 μm wide to enable transmission of the x-rays and a single laser spot was illuminated.

These single track and single spot measurements should prove useful for informing powder-level numerical models but are not part of a characterised build process. To date, the behaviour of the powder bed away from the melt pool has not been imaged, nor have the effects of scanning adjacent tracks and multiple layers during a full build been investigated.

Despite the direct impact of the ambient gas on the process, state of the art powder-scale models [8,9] do not yet include any interaction between the melt flow and atmosphere. In such models, the recoil pressure generated by the evaporated gas is calculated by the Clausius-Clapeyron equation [10] and used as a contribution to the momentum in the melt pool; however, transport phenomena in the gas or plasma phase above the powder bed based on the evaporated mass are not modelled. Approximate calculations in Ref. [5] based on the model in Ref. [8] estimated the vapour ejection velocity at ~700 m/s. Heat transfer calculations suggest that temperatures during PBF sufficiently high to form metal vapour and plasma [11], which is supported by the physical observation of light emission from the laser plume, but the associated phase change dynamics from liquid to vapour and plasma have not been modelled to date. Masmoudi et al. [12] did model the diffusion of iron vapour into the argon atmosphere above the powder bed using a meso-scale finite volume model. However, the laser plume was not modelled: instead an assumed mass fraction from elements that exceeded the vaporization temperature of the metal was used as vapour input to the gas phase. As a consequence, the estimated maximum vapour flow velocity was <50 m/s at atmospheric pressure, which is insufficient to account for the particle motion observed experimentally. Furthermore, convective and diffusive species transport incorporating the physical properties for a multicomponent Ar/Fe mixture were not included.

In the work presented here, detailed high-speed imaging of the interaction of the laser with the powder bed is shown at a range of laser powers and scan speeds. We observed that powder particles entrained in the atmospheric gas flow were drawn in towards the melt pool and ejected backwards with respect to the scan direction or vertically upwards at different process settings, as reported previously. But by imaging the wider powder bed, we could image the denudation produced by these effects for the first time. We also observed effects that have not been reported previously at other process settings, including the forwards ejection of entrained particles and denudation arising due to their interaction with the laser plume, and particles being driven *away* from the melt track at atmospheric pressure. More importantly, the imaging has been extended from single tracks to multilayer builds, in order to observe for the first time how these effects manifest in the powder bed during a full build.

Having noted the impact of the ambient gas on the PBF process, we develop a pragmatic finite element (FE) model for the powder bed and fluid dynamics observed, including a hydrodynamic treatment of the laser-induced plume and atmospheric flow for the first time in PBF. We draw on the literature concerning evaporative and plasma phenomena occurring in arc welding, laser welding and laser ablation studies as a basis for the analysis in the context of PBF. We use high-speed schlieren imaging for gas flow visualisation of the density gradients in the gas flow, not attempted for PBF previously, both to elucidate aspects of the physical phenomena involved and also to validate the FE model. The modelling and schlieren imaging support our direct, high-speed imaging observations of gas flow-induced powder particle motion in the PBF process.

2. Experimental system

We have previously reported the design and characterisation of an open architecture PBF system for in-situ measurements during PBF [13], which is shown schematically in Fig. 1. A key feature of the system is computer control for the automated build of fully dense components. The computer controls the vertical movement of the build plate between layers, the movement of the silicon cord powder spreader and the laser illumination and scanning. The system has complete flexibility for laser power and speed, and scan geometry including hatching. Hence it is possible to achieve high resolution imaging not only whilst melting single tracks in the powder bed, but also during multiple layer builds under conditions known to produce parts with >99% density. Minor modifications were made to the top and end faces of the Perspex shielding chamber to incorporate viewing windows. For top views of the powder bed, a window of diameter 50 mm made from infra-red absorbing KG glass was added, Fig. 1. Side viewing windows were added, made from Zerodur glass flats of diameter 75 mm, polished to λ/4 on both surfaces.

All the experiments reported here were undertaken with gas-atomized stainless steel 316 L powder (Renishaw PLC) with particle diameters in the range 15–45 μm and a mean diameter of 30 μm