International Journal of Machine Tools and Manufacture 130–131 (2018) 65–72

Contents lists available at ScienceDirect

International Journal of Machine Tools and Manufacture

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

Laser powder bed fusion at sub-atmospheric pressures

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ARTICLE INFO

Keywords:
High-speed imaging
Laser powder bed fusion
Sub-atmospheric pressure
Vacuum

ABSTRACT

The perceived advantages of laser powder bed fusion (PBF) at reduced pressure include a more stable melt pool and reduced porosity. In this study, high-speed imaging was used to investigate the interaction of the laser beam with the powder bed at sub-atmospheric pressures. At atmospheric pressure, the laser plume produces a flow in the ambient atmosphere that entrains particles toward the melt pool. As the pressure decreases, this hydrodynamic entrainment increases but eventually the expansion of the laser plume prevents the particles reaching the melt pool: profiles and cross-sections of the track reveal a drastic reduction in its cross-sectional area. As the pressure decreases further, into the molecular flow regime, particles are only repelled by the plume away from the melt pool. The regime between 1 bar and ~50 mbar (the threshold pressure at which the penetration depth no longer increases) could provide a window for successful processing but might require a pre-sinter to maintain the integrity of the powder bed. Lower pressures would definitely require a pre-sinter, for which the additional processing time and increase in process complexity might be justified for porosity-critical applications.

1. Introduction

Metal powder bed fusion (PBF) is an additive manufacture process in which thermal energy selectively fuses regions of a powder bed [1]. In laser PBF, a focussed laser beam melts each powder layer in an inert atmosphere (typically argon) at or very close to atmospheric pressure. The process is sometimes referred to by manufacturers' names, for example selective laser melting (SLM) and direct metal laser sintering (DMLS). Production components can be manufactured by commercial PBF systems, but generally require part-specific process settings to be determined in order to control thermally-induced residual stresses and defects. Therefore, understanding and improving the PBF process is an active area of research to increase productivity.

A small number of researchers have begun to investigate laser PBF of metals at sub-atmospheric pressures [[2],[3],[4],[5]]. The stated advantages of sub-atmospheric pressure include reduced porosity and surface roughness in the fabricated part, similar to that achieved with laser welding: any pores that do remain would not be filled with shield gas and could therefore be removed more effectively by hot isostatic pressing. Other potential advantages stated by these authors include reduced oxidation and the control of crystal orientation. These papers describe initial studies on single powder layers: the pressure and laser settings required for a successful process have not been established and no multi-layer builds were undertaken. Indeed, the process settings reported in these papers are somewhat contradictory as described next.

Zhang et al. melted single layers of pure Ti powder with a fibre laser at 100 μbar [2]. At this single pressure, the authors varied the laser power and scan speed and found acceptable density (close to 100%) and surface porosity only at very low scan speeds, ≤0.02 m/s. The density was already reduced to 95% at a laser scan speed of 0.1 m/s, decreasing steadily to 70% at 0.6 m/s. The width and height of a single melted track were both significantly reduced, which was attributed to increased metal vaporization due to the reduction in boiling temperature at low pressure. The authors claimed that balling was completely avoided at low pressure.

In a subsequent publication, the same group scanned single tracks in stainless steel powder and investigated the effect of reducing the chamber pressure from 1 bar to 1 mbar whilst again varying the laser scan speed [3]. This time, consolidated tracks were only observed at pressures ≥100 mbar for 0.1 m/s scan speed: below 100 mbar, no powder was consolidated and only re-melting of the solid substrate occurred. The lack of powder consolidation below 100 mbar was again explained in terms of increased metal vaporization due to the reduced vaporization temperature at low pressure. The authors concluded that reduced pressure requires an increase in scan speed (or a decrease in laser power) to limit material vaporization. The apparent contradiction with their previous observations [2] at 100 μbar and low scan speeds was not addressed.

Sato et al. [4] melted single layers of Ti-6Al-4V powder on to stainless steel substrates at 50 nbar. At a very low scan speed of 10 mm/

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https://doi.org/10.1016/j.ijmachtools.2018.03.007
Received 16 January 2018; Received in revised form 26 March 2018; Accepted 28 March 2018

s, they observed a surface roughness ($R_a = 0.40\,\mu m$) which was significantly lower than the most abundant powder diameter of 35 μm and the largest powder diameter of 88 μm. Imaging at 60 frames per second (fps) revealed that no spatter was produced from the melt pool at this low scan speed. At 100 mm/s, the surface roughness ($R_a = 25\,\mu m$) and spatter had both increased to resemble the PBF process more closely. The authors concluded that, at sub-atmospheric pressures, the sputter free process at low laser scan speeds improves the surface roughness.

Matthews et al. [5] investigated the depletion of metal powder particles (denudation) in the zone immediately surrounding the solidified track, which can affect the porosity and surface roughness of built parts. The width of the denuded region was measured after scanning laser tracks across layers of Ti-6Al-4V powder in a vacuum chamber. The width increased as the pressure was reduced from 1 bar down to 13 mbar, and was attributed to the increased velocity of the evaporation plume from the melt pool and the associated increase in particles entrained towards the melted track by the inward flow of the ambient gas. The width then decreased from 13 mbar to a local minimum at 3 mbar, before increasing again as the pressure was further reduced to 660 μbar. The decrease and subsequent increase in the denuded zone width was attributed to the onset of molecular (or rarified) flow and the outward expansion of the evaporation plume counteracting and eventually dominating any inward flow of the ambient gas. An alternative explanation involved asymmetrical heating of particles close to the laser spot which were then propelled away by the vapour flux generated, transferring momentum to remove adjacent powder particles. However, this second explanation was not preferred because smaller diameter particles were preferentially removed below 3 mbar, whereas asymmetrical heating should affect particles of all diameters equally. High-speed images were recorded close to the melt pool at atmospheric pressure using a localized jet of inert gas, and so this mechanism at lower pressures was not confirmed.

Laser welding at sub-atmospheric pressure is well established in the literature [6] and has received increased attention recently for joining thick materials using solid state fibre and disk lasers. The penetration of a keyhole weld is typically twice that achieved at atmospheric pressure, with an associated reduction in voids in the weld seam and an increase in weld pool stability. The deep, narrow weld is similar to that achieved with electron beam welding but without the production of harmful x-rays associated with that technique. The improved penetration at reduced pressure is attributed to two principal effects: the reduction in the metal vaporization temperature, so that less energy is required to create and maintain the keyhole; and the increase in laser energy reaching the workpiece due to reduced absorption and scattering of the beam by the atmosphere. These two effects are discussed in more detail in following two paragraphs. Clearly it is not necessarily the objective to introduce a keyhole during PBF, but the effects of laser processing at sub-atmospheric pressures are informative for this study.

In laser welding, the keyhole depth increases as the ambient pressure decreases [6,7] due to the decrease in vaporization temperature at reduced pressure: the mean temperature of the molten keyhole surface is reduced [8] so that the same incident laser power is absorbed along the surface of a deeper keyhole. The penetration depth becomes independent of the ambient pressure below some threshold pressure. This effect has been explained in terms of the total pressure acting inside the keyhole to keep it open, which is the sum of the atmospheric pressure, surface tension, hydrostatic pressure and weld speed pressure [8]. Ignoring the relatively small contribution from the hydrostatic pressure, the lowest pressure that can exist in the keyhole occurs for low weld speeds under a complete vacuum and is the pressure P_C due to the surface tension only. Hence reducing the atmospheric pressure below $\sim P_c/10$ has no noticeable effect on the penetration depth. At sub-atmospheric pressures, the reduced vaporization temperature accounts for ~40% of the increase in penetration depth seen in laser welding [7,8].

Absorption of the incident laser beam in the laser evaporation plume (metal vapour and plasma) occurs via the inverse Bremsstrahlung process. The improved penetration depth at reduced pressure for CO_2 lasers operating at a wavelength $\lambda\tilde{}\,10\,\mu m$ has been explained in terms of reduced inverse Bremsstrahlung absorption [9]. The lower temperature of the vapour plume, combined with its reduced density, reduced the degree of ionization to the extent that the plasma was almost completely suppressed at low pressure. However, the solid state fibre and disk lasers used for welding and PBF operate at $\lambda\tilde{}\,1\,\mu m$. They produce weakly ionized plasmas (< 5%) and the inverse Bremsstrahlung absorption, which varies with λ^2, is therefore 100 times less significant than for a CO_2 laser. Kawahito et al. measured the attenuation of a probe laser beams propagating through the laser plume above a keyhole [10] and showed that it scaled with λ^{-4}. They therefore concluded that Rayleigh scattering dominates due to small particles of condensed metallic atoms with diameter ~100 nm, at least in the plume above the keyhole; neither Mie scattering from larger agglomerations of condensation particles (which has no λ dependence) nor inverse Bremsstrahlung absorption are significant. At sub-atmospheric pressures, reduced Rayleigh scattering due to the reduced density of small condensation particles accounts for an increase of 10–20% in the incident laser power [8,10]. This effect, combined with the reduced vaporization temperature discussed in the previous paragraph, accounts for the doubling of the penetration depth observed in practice.

In this paper, we report the first high-speed imaging of the interaction of the laser with the powder bed at sub-atmospheric pressures. We investigate single powder layers in order to resolve the inconsistences in the PBF literature regarding suitable process settings for sub-atmospheric pressures. We report the penetration depth obtained in PBF at these sub-atmospheric pressures in order to gain further insight into the process. Finally we discuss the implication of our findings for potential PBF in the different flow regimes encountered at sub-atmospheric pressure.

2. Experimental system

We previously reported the design and characterisation of an open-architecture PBF system for in-situ measurements [11]. For this work, the system was encased in a custom-made vacuum chamber, Fig. 1(a). A key feature of the PBF system is computer control for the automated build of fully dense components, enabling in-process measurements under realistic build conditions. However, for this study, the laser interaction with a single powder layer was investigated in order to understand the process conditions that might enable multiple layers to be built in the future.

The vacuum chamber incorporated access windows to illuminate and image the powder bed. The window for the PBF laser was an anti-reflection coated, high-vacuum viewport assembly (Thorlabs VPCH42-C) providing ~30 mm clear aperture. Similar viewport assemblies, but without anti-refection coatings on the windows, were used for white light illumination and imaging of the powder bed. These two windows were positioned asymmetrically with respect to the vertical so as to avoid direct scatter of the illumination into the camera, Fig. 1(b). The imaging window provided a top view of the powder bed with the camera angled at ~20° to the vertical. The two end windows were not used in this study.

Experiments were performed on layers of 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. These layers were spread on stainless steel 304 L build plates (coupons) which had been roughened by manual, circular rubbing with P400 sandpaper. The powder layer thickness for all experiments was 50 μm, determined by the height of the powder spreader above the coupon surface [11]. Individual tracks were melted with a single mode fibre laser (SPI 400 W continuous wave, 1070 nm) focussed to a spot with a Gaussian beam profile and 4Dσ diameter of 50 μm in both the x- and y-directions.