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INCREASING LASER COUPLING USING PROACTIVE LAYER HEIGHT CONTROL IN DIRECT LASER DEPOSITION

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Abstract

Direct Laser Deposition (DLD) is a blown-powder laser deposition process that can be used to quickly produce fully-dense metallic prototypes by a layered manufacturing method. DLD can also be used to repair or modify high-value components. In common with other laser deposition processes, variation in the process parameters (i.e. traverse speed, powder flow rates etc.) often cause height errors in the built part. Layer height control methods are therefore a continually investigated field.

Research carried out at Liverpool University has resulted in a non-feedback layer height controlling process based on controlling the shape of the powder streams emitted from a four-port side feed nozzle. This method limits deposited layer height by causing a sharp reduction of catchment efficiency in the vertical plane at a fixed distance from the powder feed nozzle, and is therefore capable of depositing a consistent layer height in spite of power, powder flow or process velocity variation. A further effect of limiting the powder cloud in this way is a refinement of the top powder cloud interface. This interface refinement can be shown to have beneficial effects on laser power coupling into the workpiece.

This paper shows how this refinement of powder cloud shape can be achieved and discusses the increased coupling effects in terms of existing thermal models of the laser cladding process.

Keywords: rapid manufacturing, layer height control, laser clad

1 Introduction

Direct Laser Deposition (DLD) is an extension of the laser cladding process in that it allows three-dimensional parts to be built by cladding successive layers on top of one another in pre-determined vector paths (the earliest example of producing structures in this manner was in 1978) [1]. Since the layers are fusion bonded to each other, a fully dense metallic part can thus be made using ‘soft tooling’ (i.e. in order to make a different part only the program used to control the CNC equipment needs to be changed rather than needing to change tools or make new moulds). At present, most DLD parts need some post-process machining to finish them to required tolerances [2].

Rapid laser deposition processes such as DLD are increasingly being used to make functional prototypes, modify or repair components, and make ‘bespoke’ parts for individual applications. Projected uses for the process include the manufacture of spare parts for long term space missions [3] or on board ship or submarine [4]. Although DLD parts can exhibit desirable crystal structures for some applications (such as directional solidification), the required post-processing of the part and the high cost of the equipment and powdered material needed have so far prevented large-scale take up of this method of part generation in industry.

Examination of the cladding process indicates that the interdependence of laser power, powder feed rate into the melt pool, relative traverse speed of the workpiece and retained heat effects cause difficulty in retaining a consistent clad bead profile for the purposes of building or modifying parts. Power control has been extensively researched but necessitates in-process monitoring and feedback control in addition to the necessity to calculate (and account for) projected alterations of power density and interaction time for specific geometries.

In addition, when a clad bead is laid onto a previously produced layer, a number of extra considerations in addition to the utilised process parameters affect its generation. One of the most important of these is the effect of whether an elevated temperature persists in this previous layer due to insufficient cooling time or heat retention in the bulk of the part. This effect was recognized by Weerasinghe [5] and has been examined in greater detail by Vasinonta et al [6] who produced an ABAQUS generated model using Rosenthal (1946) [7] conditions which shows that the melt pool length and height increases as the initial temperature of the substrate is increased. Therefore, unless steps are taken to control the layer height during a build, the retained heat in the part from previous layers will result in a cumulative increase in the height of the deposited layer. At dwell areas such as corners this will be magnified [8], causing a significant and progressive build-up beyond the parameters of constant velocity areas of the clad structure.

One of the most common uses for laser deposition processes is in the repair and/or modification of existing parts. Uneven surface profiles on these parts may necessitate rapid alteration of the height of the deposited layer in order to compensate. This would normally require extensive modelling of the surface or extremely responsive feedback systems.

Research carried out at the University of Liverpool has resulted in a method of controlling the deposited layer height by abruptly limiting the availability of powder in the vertical plane at a fixed point relative to the powder feed nozzle [9]. This method employs a four port powder feed nozzle and is dependent upon the configuration of the powder feed tubes as well as on the nozzle usage parameters.

This system entails redirection of powder particles into the main powder stream, flattening the top surface of the powder cloud and refining the upper surface of the powder cloud interface. This paper discusses the effects that this method of layer height control may have upon laser coupling into the meltpool.

2 The method of layer height control

The nozzle system designed to control the deposited layer height appears below in **Fig. 1** below. It consists of four radially symmetric 2mm bore powder feed tubes at 40 degrees to the horizontal. A small-bore (2mm) gas nozzle coaxial with the laser beam is used to direct a gas flow at the area where powder streams emitted from the powder feed nozzles will intersect.

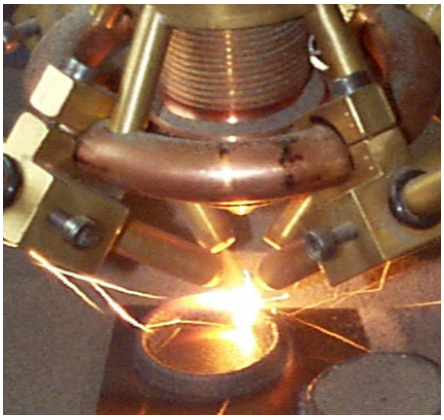

Fig. 1: *The four port nozzle system*

Powder is delivered from the powder feed tubes at a relatively low velocity (<1m/s) and flares as it exits. Due to stratification of differently-sized powder particles (in addition to the Magnus effect for irregular particles), powder flaring from the top of the powder stream consists of smaller particles than the bulk flow. This, coupled with the fact that particles travelling off-axis from the main stream necessarily have lower particle velocities, results in the fact that powder flaring from the top of the powder stream has a lower momentum than that in the main part of the powder stream (**Fig. 2**).

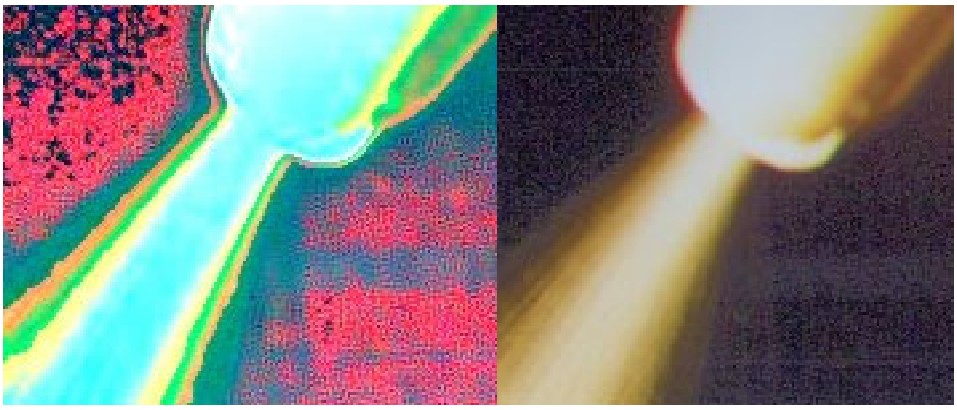

Fig. 2*: A false colour image showing the powder stream exiting a 2mm bore powder feed tube at a* 40^0 *angle under a gas flow rate of 4l/min. The different colours indicate relative density of powder stream based on degree of reflected light. It can be seen that areas of lower powder density at the top of the powder flow are greater than those at the base. A 'raw' photograph of the same feed tube is shown for comparison on the right.*

A coaxial gas flow can thus be used to redirect these off-axis powder particles back into the main powder stream. Experiment has shown that a 'balance point' between the powder assist gas flow rates and the coaxial gas flow rate can be obtained (dependent upon the density and size distribution of the powder) which will result in a refinement of the top interface of the powder streams. An example of this effect is shown in **Fig. 3**.

This refinement of the powder cloud interface causes an abrupt reduction in powder catchment efficiency in the vertical plane at a fixed position relative to the powder feed nozzle. In other words, a deposited layer will build to the top of this interface but can not build any higher due to a lack of available powder. This means that the height of the deposited layer is limited by the physical position of the powder feed nozzle and not by the other deposition parameters, allowing the layer height to be controlled by the incremental step height rather than *vice versa*.

In addition the low particle velocity (< 0.85m/s) assists in the improvement of catchment efficiency [10], offsetting the powder loss that would be a side effect of programming a step height which is less than the unrestricted layer height.

Assessment of the capabilities of this method of layer height control has shown that it is capable of depositing layer heights controllable to within 300 microns of the desired layer height and that height errors are not cumulative in the build. Excess laser power, increased powder feed rate and reduced process velocity do not cause the deposited layer height to increase in proportion [11].

Since the basis for redirection of the top of the powder stream is due to momentum differences of particles within the powder stream it is necessary to obtain a new 'balance point' for different powder material densities.

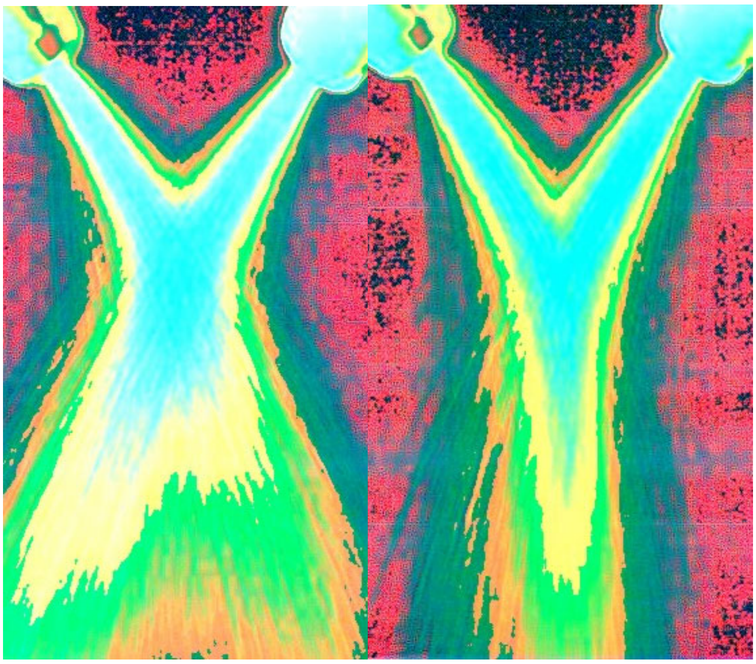

Fig. 3: *These two images show the effect of the use of a 12l/min gas flow through a 2mm coaxial gas nozzle situated 15mm above the intersection of the powder streams. It can be seen that the powder stream on the right has had the top 'penumbra' reduced and shows an increased vertical collimation below the intersection point of the streams.*

Examples of layer height control in building parts

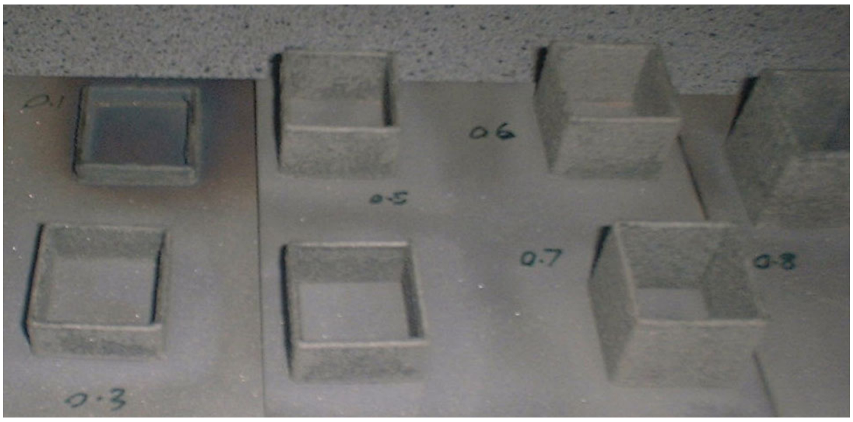

Fig. 4: *Square structures built with different layer heights under constant deposition parameters. Each square is 2cm on a side.*

A simple square structure was used to evaluate layer height control. The abrupt change in velocity as the CNC table alters direction at the corners would normally result in a cumulative height error at the corners. This was shown not to be the case, indicating that the nozzle arrangement was restricting the layer height. To test this layer height restriction further, a set of square structures was built with identical process parameters excepting that the step height between layers was progressively reduced between samples (**Fig.4**). Under these conditions it was shown to be possible to control the deposited layer height to an error of approximately 300 microns. This 300 microns error in height was not cumulative, i.e. increasing the amount of layers present in the part did not increase the overall part height error. A graph of these results is shown (**Fig. 5**).

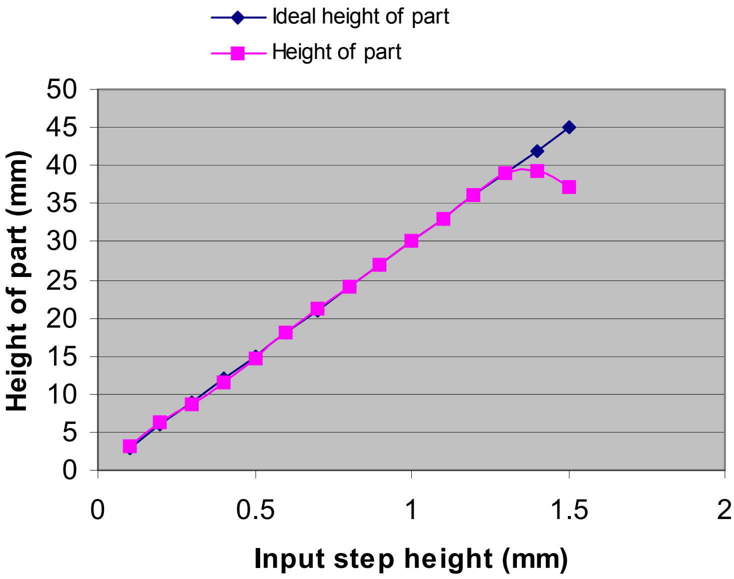

Fig. 5: *Actual height of deposited structures against desired height over a range of layer heights for constant deposition parameters. The falloff in part height beyond 1.3mm step height is due to the programmed step height being more than the possible clad layer height.*

3 Laser coupling effects of this method of clad height restriction

3.1 Reduction in melt front angle to incident beam

The analysis undertaken by M.Picasso et al ("A simple but realistic model of laser cladding"April 1994) [12] shows that the absorption of the laser beam onto the inclined plane of the melt front depends upon the angle of the melt front with the beam. The angle of the melt front for cladding is given by the relationship

$$\boldsymbol{\theta = \arctan (h/(x_{max}-x_{min})} \qquad \textbf{(1)}$$

as shown on the accompanying diagrams for the case in which powder feed rate alone is altered. The melt pool is assumed to be planar (as indicated by the blue line).

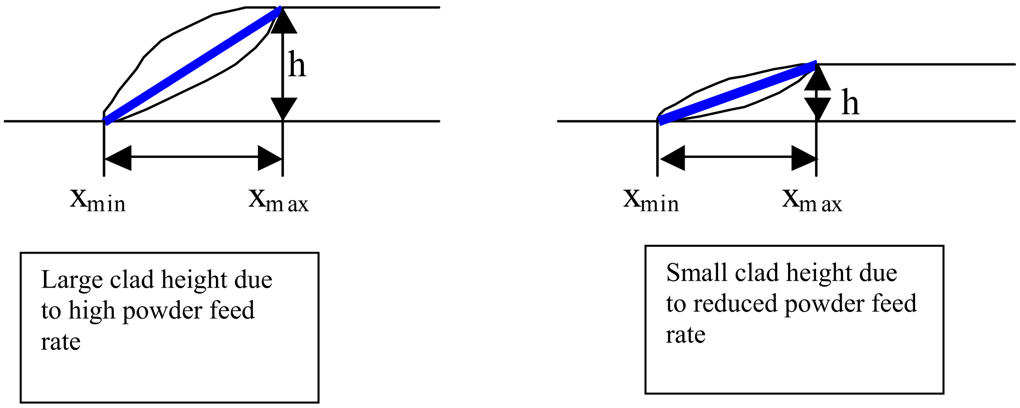

Fig. 6: *Diagram of melt front angle*

From this Picasso defines the workpiece absorption in the x direction as

$$\boldsymbol{\eta P(\theta) = \eta P\ (0)\ (1+ \alpha\theta)} \qquad \textbf{(2)}$$

where α = a proportionality coefficient specific to the material.

For a particular powder mass flow rate, power density, and interaction time the rate of increase of the clad layer height will be fixed. E.g for a traverse speed of 15mm/s, a deposited layer height of 1mm and a spot size of 2mm diameter, the layer has an average vertical build speed of 7.5mm/s. (This is not the same as the solidification rate, but the time taken for the melt pool to grow by the layer height).

Given that the layer height control process causes a sharp fall off in catchment efficiency only above height h defined by the top of the powder interaction zone then, under conditions of step height restriction, angle θ will be reduced relative to the unrestricted clad in unit time by the ratio of the height of the restricted clad to the height of an unrestricted clad created under the same process parameters, i.e using the example above, if the clad vertical build rate is 7.5mm/s but it is restricted to a 0.5 mm layer height rather than 1mm, it will have reached its vertical limit in half the time. Powder will continue to be fed into the parts of the melt pool which have not yet reached that height limit, hence flattening the melt front angle and reducing absorption.

3.2 Advance of melt front

The restricted clad bead melt pool will be at a higher temperature than the unrestricted case due to the reduction in incorporated clad material. Hence surface tension of the molten material will be reduced in proportion (ie wetting will increase) causing a reduction in melt pool front contact angle. This will result in the melt front advancing further than the unrestricted clad bead case. Reduction in the clad bead height caused by this melt front advancement will be corrected by the mechanism described in section 3.1 above.

This advancement in melt pool front is an analogous case to the increase in single track width due to increasing the laser power for a clad track on a flat plate noted by Weerasinghe (1985) [13]. In this case the preceding track is counted as flat along its axis in the x- direction.

The increased advancement of the melt front will raise the temperature of the area about to be clad and therefore increase the coupling efficiency of the laser beam. This increased wetting will also serve to widen the melt pool to an equilibrium value determined by cessation of retained heat increase.

3.3 Reduction of powder attenuation of the beam

Picasso [12] also describes the power incident upon the melt pool as affected by the powder stream in three ways. These are listed as follows:

(a) attenuation of the incident powder by particle shadowing

This is given in terms of the volume fraction of particles in the laser beam, hence

$$P_{attenuated} / P_{laser} = P_{att} / P_{laser} = m_p / 2\rho r_{jet} r_p v_p \cos(\theta_{jet}) \text{ for } r_{jet} \geq r_{laser} \qquad \textbf{(3)}$$

where m_p r_p and v_p are the mass, radius, and velocity of the particles and the subscript "jet" refers to the gas-powder stream.

From this it is apparent that a greater angle between the laser beam and the powder stream results in less attenuation of the beam. In this nozzle system the angle between the powder streams and the laser beam is 60 degrees. This is twice the angle of some other systems.

(b) absorption of the attenuated power by particles and subsequent transfer to the meltpool

$$\text{Particle power transfer to meltpool} = \eta_p \, \beta_p \, P_{laser} \, P_{att} / P_{laser} \qquad \textbf{(4)}$$

where η_p =catchment efficiency and β_p= absorption of the gas-powder stream.

Catchment efficiency for particles passing into the beam is enhanced for this process both by the low particle velocity and by the redirection of off-axis particles by the coaxial gas jet, which causes more of the particles which would normally pass over the melt pool to be redirected into it. Analysis of the powder stream has shown that the stream divergence can be reduced by as much as 38% using this method, from 14.1 degrees to 8.7.

(c) absorption of reflected power from the workpiece by powder particles and subsequent transfer to the meltpool

$$P_{rt} = \eta_p \beta_p P_{laser} (P_{att} / P_{laser}) \times (1- \eta_w P_{laser}) \times (1-(P_{att} / P_{laser})) \qquad \textbf{(5)}$$

where P_{rt} = reflected power transferred back to the meltpool by particles.

Unlike the power from the laser beam, reflected power from the meltpool is scattered over a large angle. Hence particles introduced at a shallow angle close to the surface of the meltpool absorb more of this reflected power and lose less by re-radiation before being incorporated into the melt.

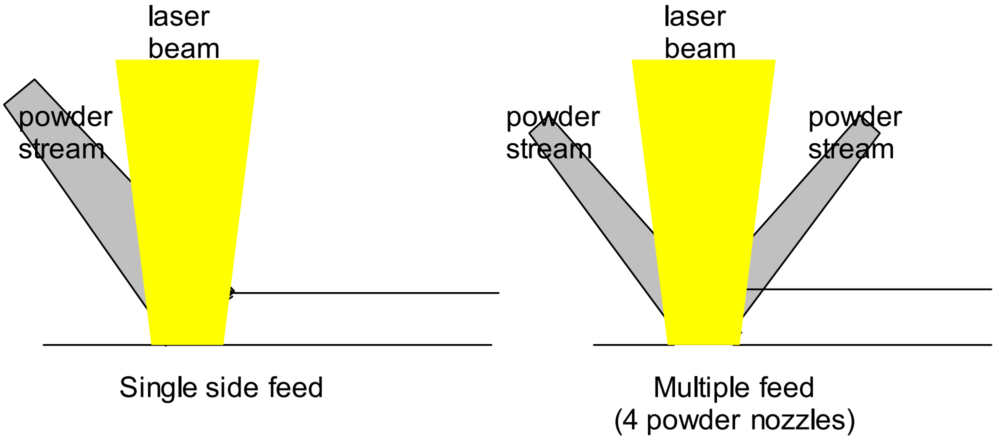

***Fig.** 7: Comparison of shadowing of beam by side feed nozzle types*

A further reduction in beam attenuation by using a multiple side feed nozzle arrangement compared to a single side feed is shown in **Fig. 7**. Where it is seen that if the same mass flow rate and particle velocity is maintained through each nozzle system, it can be seen that particles in the multiple feed system spend half of the amount of time occluding the beam compared to those from the single nozzle system, resulting in half the power attenuation.

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3.4 Photon pressure effects upon the powder stream

Though photon pressure from the laser beam ($p=h/\lambda$) is normally neglected for most laser processes, the low velocity of powder particles entering the beam in this process allows them to be further redirected towards the melt pool, increasing catchment efficiency and hence reducing losses. A calculation for parameters associated with this method of laser deposition is follows (after Steen [14]):

Momentum due to photon $\mathbf{p=h/\lambda}$ **(6)**

h = Planck's constant (= 6.625×10^{-34}Js)
$\lambda = 10.6 \times 10^{-6}$ m for CO_2 laser wavelength

Therefore for a CO_2 laser each photon will have a momentum of

$$p = 6.25 \times 10^{-29} \mathrm{Ns}$$

We will assume that the particle reflects the beam, therefore the momentum change is 2p or 1.25×10^{-28} Ns. Given that the photon energy is 1.85×10^{-20}J, a 1kW beam will consist of 5.4×10^{22} photons per second. This gives a total force of 6.75×10^{-6}N

Over a 2mm diameter laser spot size this equates to a pressure of

$$P = \frac{4 \times 6.75 \times 10^{-6}}{\pi (2 \times 10^{-3})^2} = 2.15 \text{ Pa}$$

Consider a spherical particle of stainless steel 100 microns in diameter.

Force on the particle = pressure x cross sectional area
$= 2.15 \times \pi \times (100 \times 10^{-6})^2 / 4$
$= 1.69 \times 10^{-8}$N

Mass of the particle = density x $4/3\ \pi r^3$
$= 8000 \times 5.24 \times 10^{-13}$
$= 4.189 \times 10^{-9}$kg

Acceleration on the particle due to photon pressure = Force/mass
$= 1.69 \times 10^{-8} / 4.189 \times 10^{-9}$
$= 4.03\ \mathrm{m/s^2}$

A particle travelling through the 2mm beam at 45 degrees from the vertical travels a distance of 5.66mm within the beam. At 0.67 m/s (a typical particle velocity for this system) this equates to 8.4×10^{-3}s. From this it is possible to calculate the vertical translation of the particle due to the beam alone by using Maxwell's equation for displacement (**s**) due to acceleration (**a**) over a specified time (**t**). Since only the translation due to the beam is required, the initial velocity (**u**) will be set at zero.

Vertical depression of 100 micron particle due to beam $\mathbf{s = ut + \frac{1}{2} at^2}$
$= 1.41 \times 10^{-4}$m
= 141 microns

This figure for displacement of the particle by photon pressure may seem small but must be considered in terms of the fact that the powder stream 'penumbra' for this powder feeding process is measured at between 300 and 500 microns without the laser active.

Therefore it is indicated that in addition to the redirection of the particle stream by the coaxial gas jet and the acceleration due to gravity, the powder particle path is also redirected by the beam, increasing the likelihood of a particle being incorporated into the melt pool. This photon pressure redirection of powder particles is dependent upon the time spent within the beam, and would be reduced in proportion with higher particle velocities. As noted in section 2 above this means that the effect upon particles flaring from the top of the powder stream would be proportionately greater and hence act to further refine the powder stream interface. In addition, smaller particles have a greater cross-sectional area to mass ratio and hence would be affected more than the median particle sizes.

4 Conclusions

The mechanism of powder delivery used by this process has proved to be of use in the accurate control of layer height in the DLD process. Side effects of controlling the layer height in this manner are the promotion of conditions conducive to increasing laser power coupling into the part, allowing lower laser powers to be used. Since laser coupling is likely to be higher for this system it may prove necessary to incorporate a feedback system for appropriate laser power reduction based upon melt pool temperatures in order to prevent microstructure coarsening and/or excessive part distortion due to heat retention within the part.

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