COMPENSATION FOR UNEVEN SURFACES WHEN BUILDING LASER DEPOSITED STRUCTURES

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Abstract

Direct Laser Deposition (DLD) is a blown-powder laser deposition process that can be used to quickly produce, modify or repair fully-dense metallic parts by a layered manufacturing method. However, uneven substrate surfaces often cause variation in the deposited layer which is magnified by succeeding layers. Research carried out at the University of Liverpool 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. This paper demonstrates how this method of layer height control can compensate for irregular substrate surfaces in the production of accurate DLD parts.

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 (work began on the process in Liverpool in 1990 with the first paper published in 1993 [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).

The projected usage for DLD include reducing development cycle time by rapidly manufacturing functional prototypes, modifying or repairing high-value existing components, and making components with inbuilt voids for weight reduction [2]. Projected uses for the process include the manufacture of spare parts for long term space missions [3] or on board ships or submarines [4].

DLD is a multivariable process with interdependence of laser power, powder feed rate into the melt pool, relative traverse speed of the workpiece and retained heat effects causing 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 elevated temperatures in this previous layer due to insufficient cooling time or heat retention in the bulk of the part. This effect was recognized by Weerasinghe (1985) [5] and has been examined in greater detail by Vasinonta, Beuth and Griffith (1999) [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 melt pool volume, and hence the height and width of the deposited layer. In addition, this variation of melt pool size affects cooling rates and hence microstructure of the finished part. Alterations in process velocity as the CNC table or flying optics assembly change direction will also cause a change in deposited layer height, which on successive layers will again be magnified [8]. For these reasons deposition is normally carried out on flat surfaces or the surface is carefully modelled before commencement to prevent unwanted alteration of the deposited layer heights.

In the repair and/or modification of existing parts uneven surface profiles 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 self-limiting system enables laser deposition to be carried out on irregular surfaces, as will be illustrated in the following sections.

2. The method of layer height control.

The nozzle system designed to control the deposited layer height appears below in Fig. 1. 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)[10], powder flaring from the top of the powder stream as it exits the powder feed tube 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)
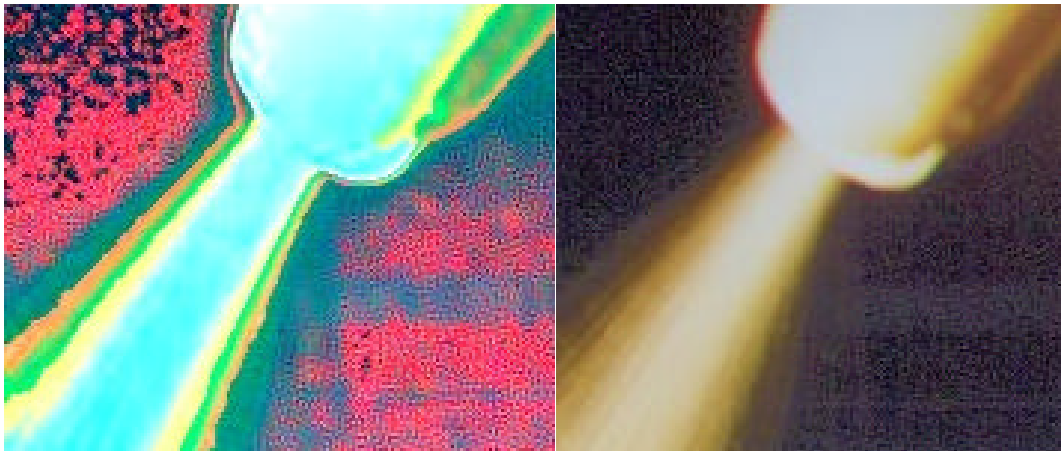
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Fig 2 . A false colour image showing the powder stream exiting a 2mm bore powder feed tube at a 40^0 angle under a gas flow rate of 4 l/min without the effect of a coaxial gas flow. The different colours indicate relative density of powder stream based on degree of reflected light. It can be seen that areas of lower powder density at the top of the powder flow is greater than that at the base. A 'raw' photograph of the same feed tube is shown for comparison on the right.

A gas flow coaxial to the laser beam 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[9]. 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 assists in the improvement of catchment efficiency [5], 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 μm 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 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. An increase in powder particle density will require an increase in the gas flow rate required for adequate transport of the powder through the powder feed tubes, in addition to an increase in the coaxial gas pressure required to redirect off-axis particles. At the

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time of writing, more analysis using different materials needs to be carried out to generate the appropriate relationship .
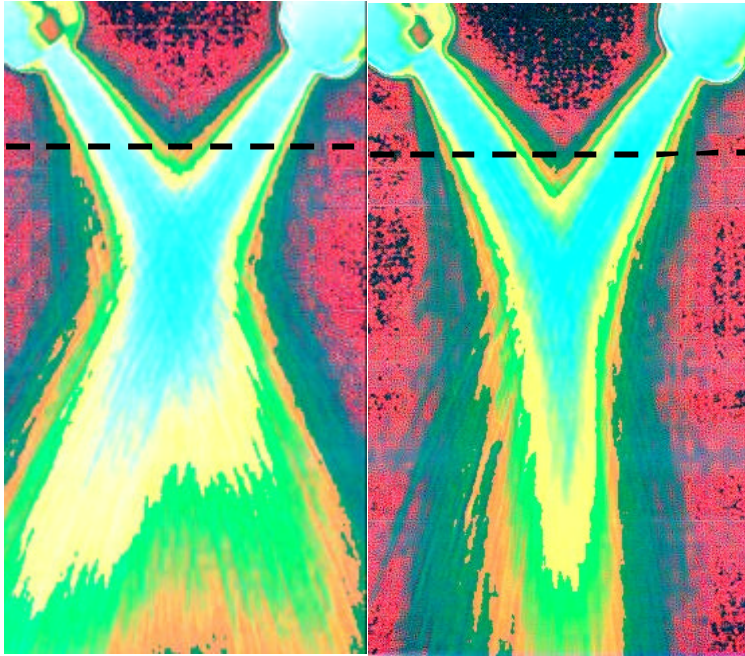

Fig 3. These two images show the effect of the use of a 12 l/min gas flow through a 2mm coaxial gas nozzle situated 15mm above the intersection of the powder streams. It can be seen that the powder stream on the right has had the top 'penumbra' reduced and shows an increased vertical collimation below the intersection point of the streams. (Measurement indicated by dashed line equivalent to restriction point of a 2mm wide layer)

3. Control of layer height on regular surfaces

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. To test the ability of the system in layer height restriction further, a set

of square structures (Fig.4) was built with identical process parameters excepting that the step height between layers was progressively reduced between samples. Under these conditions it was shown to be possible to control the deposited layer height to an error of approximately 300 μm. This 300 μm 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).
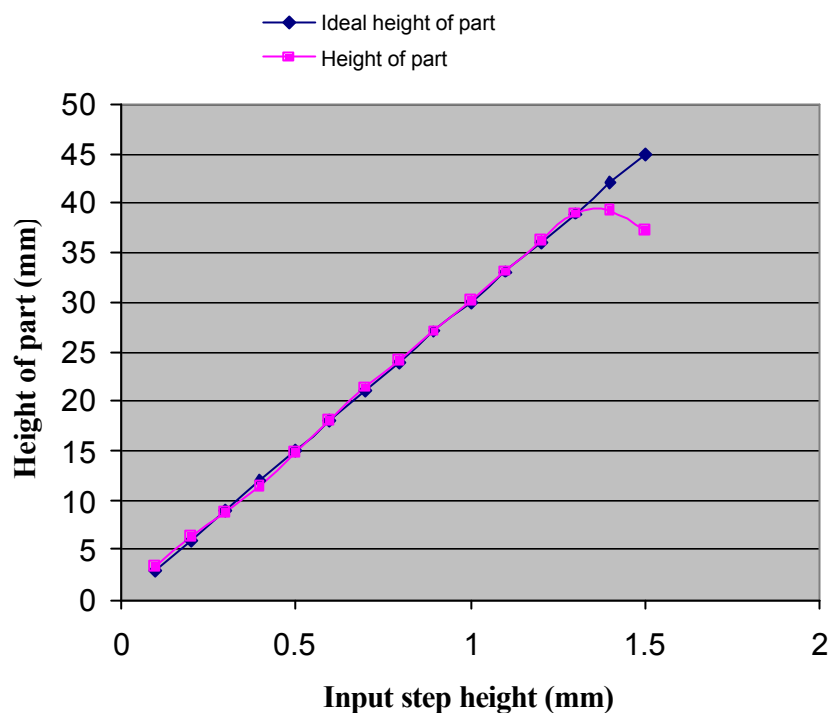

Fig.5 Actual height of deposited structures against desired height over a range of layer heights. (The falloff in part height beyond 1.3mm step height is due to the programmed step height being more than the possible clad layer height.)

4. Control of layer height on surfaces with raised or recessed features

One of the major uses for laser deposition is in the modification of existing parts which may need an extra feature added for purposes of strength, wear resistance, extra attachment points or repair/reinforcement. The surface to be modified may have raised or recessed features which would normally require surface profiling carried out in order to allow program modifications to be made. A specimen example of parts which would fall into this category appears in the series below (Fig. 6a-d). In Fig. 6a an irregular surface is shown that would normally require modelling to adjust the deposition parameters accordingly within the program, or a highly responsive feedback system. This surface has step, semicircular and angled cutouts to a depth of 3.5mm. Utilizing the layer height control process detailed in the previous section the deposition process for a simple wall is carried out such that the first layer is built corresponding to the lowest point on the irregular surface (Fig. 6b). Deposition is not carried out on surfaces higher than this until the gradual raising of the nozzle brings them into the defined area of the powder cloud. Fig. 6d shows the repaired surface which has been machined. No cracks or gaps are evident.
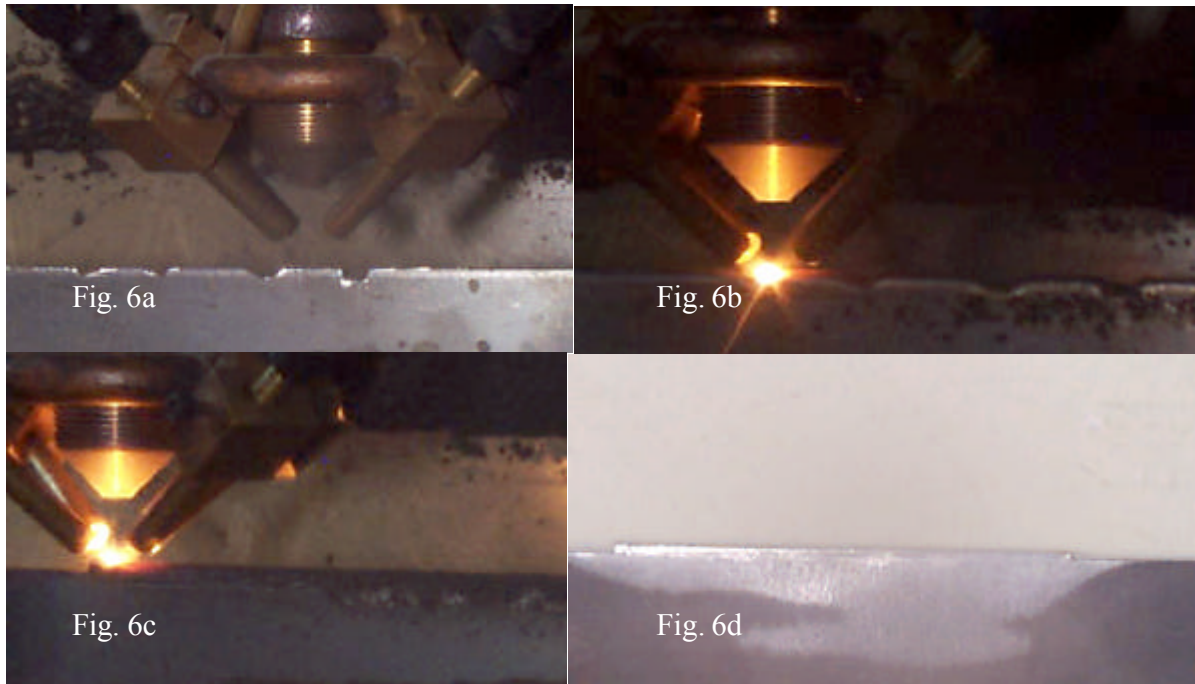
Fig. 6 a-d. Stages in repair of an uneven substrate surface.

5. Incorporation of new components.

One of the interesting features of being able to deposit structures upon irregular surfaces in this manner is the ability to incorporate small components into the part being built or modified. Fig.7
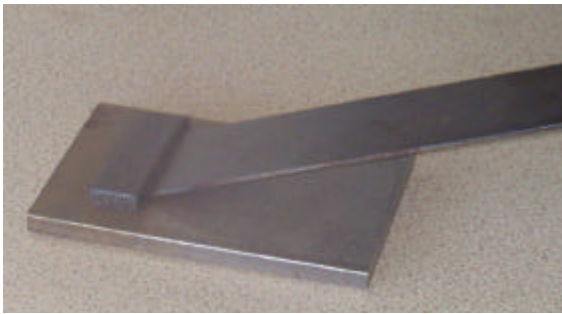

Fig 7. Laser formed part incorporated into deposited billet.

shows a structure built at Liverpool where a stock mild steel strip has been incorporated into a deposited billet. This strip has a thickness comparable with the laser beam spot size and as a result has been laser formed (i.e. bent using the temperature gradient mechanism) at the same time. The degree of layer height control has been sufficient to account for this forming process to be accommodated within the build process. A further example of this incorporation process currently being investigated at Liverpool is the incorporation of cooling channels into a deposited or pre-existing part by simply building over pre-shaped metal piping rather than programming voids in the structure. Advantages to this are that the cooling channels incorporated in this manner are smooth on the inside without any generated layer discontinuities in the channel wall, and thus can utilize higher fluid flow velocities without generation of cavitation within the coolant fluid. A further use proposed is in the generation of quasi-hollow structures by building parts around pre-manufactured hollow pre-forms, thereby avoiding the conditions conducive to crack propagation under cyclic stresses noted by Capshaw [2] .

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6. Retained heat and microstructure effects

Controlling the deposited layer height in the manner described causes deeper remelting of previous layers than would be the case for unrestricted layer deposition or power feedback layer height control methods. This results in lower cooling rates and increased coarsening of the as-deposited microstructure. The increase in volume of the substrate (or previous layer) melt pool due to layer height restriction can be illustrated by comparison with the energy balance model from Steen[13] shown in equation (1)

$$\eta_w P_{laser} = (\rho Shvw + \rho z_m vw)[C_p\, T_m + L_m + f'L_v] + \; T_m wk\left(\sqrt{\frac{vD_b}{4a}}\right) \quad (1)$$

Volume of unit layer deposited

Volume of melt pool generated in substrate

Energy conducted away through the material

where $\eta_w P_{laser}$ represents the energy coupled into the workpiece
ρ = density of material
S = shape factor of clad layer
h = height of clad layer
v = process velocity
w = width of clad layer
z_m = melt pool depth
C_p = specific heat of material
T_m = melting temp of material
L_m = latent heat of melting of material
$f'L_v$ = fraction of material vaporized
a = thermal diffusivity
D_b = beam diameter
K = thermal conductivity

If layer height restriction is taken into account equation (1) may be altered as follows for increase in melt pool depth:

$$\eta P = (Sh_r\, \rho vw + (z_m + (h_o - h_r\,))\rho vw)[C_p\, T_m + L_m + f'L_v] + T_m wk\left(\sqrt{\frac{vD_b}{4a}}\right) \quad (2)$$

where h_o = unrestricted layer height

h_r = restricted layer height

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Restricting the amount of material being deposited per layer will raise the temperature and hence the volume of the melt pool as heat accumulates in the build (compared to an 'unrestricted' layer height). Fig. 8 illustrates this effect. This part was built by building a cylinder on a rotating substrate such that the outer layers were taller than the inner ones. This allowed a build where reheating frequency, velocity and power were constant.
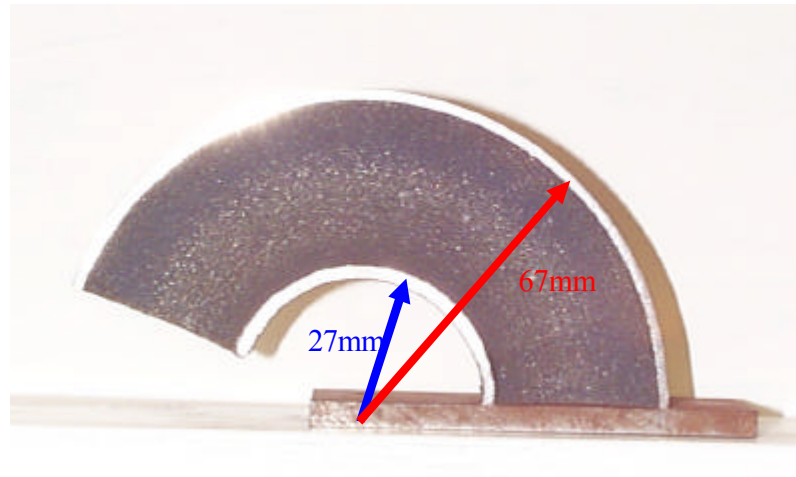

Fig 8. Axially curved DLD cylinder (sectioned)

Examination of Fig.8 shows that the inner (27mm radius) clad wall with a layer height of 0.32mm increases in thickness to a much greater degree than the outer one with layer height of 0.8mm. From an initial wall width of 2.2mm on both the inner and the outer walls the widths increase to an equilibrium value of 2.9mm and 2.3mm respectively. This shows the expected increase in meltpool volume due to heat retention between passes but also illustrates the ability of the layer height restriction process to cope with excess laser power. A pyrometer is planned for incorporation into the system to provide data on melt pool temperatures. This data could be used to reduce laser power when appropriate to compensate for excessive melt pool temperatures.

This method of layer height restriction also appears to be useful in building structures with overlapping or crossed layers. The requirement for area surface cladding or solid fills is to overlap parallel clad tracks such that no porosity appears between them. In low dilution cladding it has been stated [11] that the aspect ratio of a clad layer being overlapped in this fashion should not be more than 5 [12] and that it should not overlap the previous layer by more than 70%. If higher dilution is permissible the aspect ratio can be increased in proportion [5]. The clad layer height limiting effects of the process described are adequate for controlling the aspect ratio of the clad layer.

The following micrographs (Fig 9) show the effect of clad height limiting on partially overlapping layers. Using the same process parameters it has been possible to change the aspect ratio in the clad layers from 5 in the 0.4mm step height case to 3.33 in the 0.6mm case. In each case the overlap has been 50%, the process velocity has been 15mm/s and the powder mass flow rate has been 9.4g/min. The laser power was 1 kW with a 2mm spot size using a 190mm focal length lens.
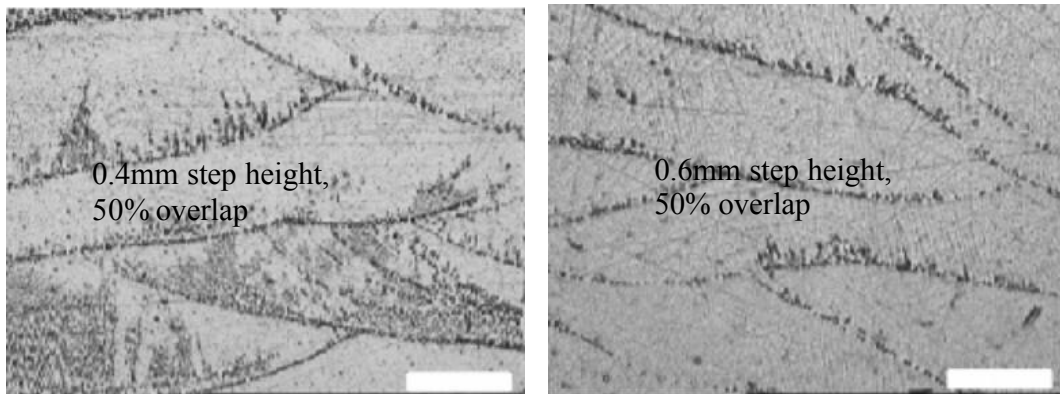
Fig 9 Micrographs of midsection of thick wall built with partially overlapping clad layers (bar size 200 μm)

The 0.4mm step height sample shows a coarser microstructure compared to the 0.6mm step height sample that has been the feature of increased clad layer height restriction referred. Dendrites in the 0.4 mm step height sample are thicker and the interlayer banding is more pronounced. Pores are not evident in either sample, indicating that dilution was sufficient to avoid their formation.

One point with regards to producing thick walls or billets with partially overlapping layers is that the heat retained in local areas of the part is a function of the processing path, therefore careful selection of the overlap pattern is necessary to prevent some areas of the part cooling more slowly than others, with the resultant effects upon microstructure. In addition, if the part gets hot enough over a large enough area, convective gas currents will disturb the powder cloud geometry of the nozzle, resulting in reduction in clad height limiting effectiveness [9].

7.Conclusions

The layer height restriction process described appears to be able to cope with surface irregularities up to 3.5mm peak-to-trough measurement independently of any height-control feedback system or part-specific programming. This is in addition to preventing cumulative height errors due to process parameter variation or retained heat in the built part. The increased melt pool temperature associated with such restriction, however, can result in increased wetting and/or coarser microstructures. The proposed inclusion of a feedback power control based on melt pool temperature is anticipated to reduce these undesirable effects.

8.References

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