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A Method of Layer Height Control in Direct Laser Fabrication of 304L Stainless Steel (904)

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ABSTRACT

Direct Laser Fabrication is a blown powder laser deposition process capable of producing fully dense metallic parts by a layered manufacturing method. The process has applications in the fields of rapid manufacture and the repair or modification of existing metallic parts. However, a common problem encountered with this technique is the unwanted variation of layer height during the deposition process. This variation can lead to non-uniformity of the build and a deviation from required tolerances. Investigation of methods of delivery of powder to the laser-generated melt pool has resulted in a means of ensuring the deposition of consistent and controllable layer heights under a variety of process conditions. This paper describes how this is achieved while using an in house four port powder delivery nozzle. The process is demonstrated for the manufacture of 304L stainless steel samples and shows control of cumulative height errors in multilayer builds. In addition, the ability of the powder delivery system to deliver a near-constant layer height for different layer deposition parameters and to allow the generation of a variety of consistent layer heights for a single set of process parameters is illustrated.

1. INTRODUCTION

Direct Laser Fabrication (DLF) 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 concept of producing structures in this manner has been place since at least 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 DLF parts need some post-process machining to finish them to required tolerances.[2]

Rapid laser deposition processes such as DLF 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 DLF parts can exhibit desirable metallographic structures for some applications (such as directional solidification) and require less material and time to build, large-scale take up of this method of part generation in industry has been slow to materialise.

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 (1985)[5] and has been examined in greater detail by Vasinonta, Beuth and Griffiths (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 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.

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 combine to cause difficulty in maintaining a consistent clad bead profile for the purposes of building parts and especially for achieving a suitable aspect ratio for overlapping. 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. Since alterations of powder feed rate are subject to a lag response time at the workpiece it is difficult to use powder feed control as a means of dynamically correcting layer height. Therefore this paper has focused upon control of the powder delivery rate at the powder nozzle outlet. In short, the objectives of this work entailed a redesign of the powder delivery nozzle for the purposes of powder cloud shape control at its top surface in order to refine the powder cloud interface.

The desired effect upon the powder cloud is to refine the interface at its top surface such that there is an abrupt reduction in available powder in the vertical plane. This acts to limit the height to which the clad layer can build to an amount determined by the physical position of the top of the powder cloud. Whereas limited refinement of this interface can be achieved by simply increasing the fluidising gas velocity (and hence the particle velocity), any increase in particle velocity would result in a decrease in catchment efficiency due to increased ricochet of powder particles from the melt pool[5]. Therefore this work has concentrated on refining the top of the powder cloud while retaining low particle velocity. This has been achieved by using a relatively high-velocity coaxial gas stream to 'flatten' the top of the powder cloud as detailed later in this paper.

Controlling the height to which a clad layer is able to build in this manner has benefits beyond that of maintaining a specific layer height for a specific set of parameters. These include the ability to accurately produce different layer heights for the same set of parameters and to therefore also affect the degree of associated remelting, and also to allow unincorporated powder to be recovered which has not passed through the laser beam.

2. THE REDESIGNED POWDER FEED NOZZLE

The nozzle system designed to investigate the proposed control of the powder cloud shape appears below. A second iteration of a fixed 45 degree angle nozzle platform, it consists of four radially symmetric powder feed tubes on a toroidal track with the facility of two degrees of freedom for horizontal and vertical rotation of the powder feed tubes. A small-bore (2mm) gas nozzle coaxial with the laser beam is used to direct a turbulent gas flow at the area where powder streams emitted from the powder feed nozzles will intersect. The powder nozzle ring can be rotated upon a screw thread incorporated into the coaxial nozzle in order to vary the distance between powder streams intersect and coaxial nozzle exit.

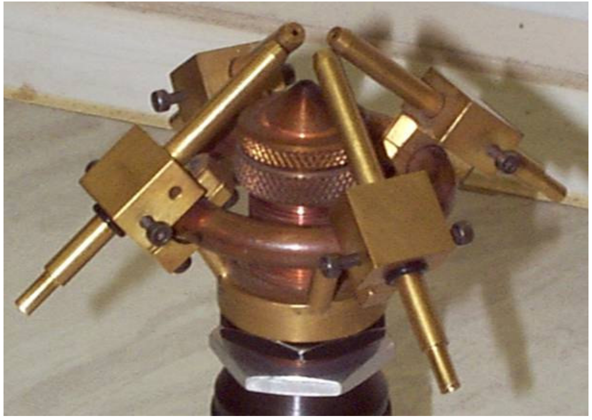


Fig. 1 The four port nozzle system

The earlier version of this system suffered from the effects of absorbed heat from the melt pool, causing warpage and hence misalignment of the powder feed nozzles. Hence, the system incorporates features to avoid this as follows:

(1) A skeletal structure to reduce convective heat incident upon the nozzle while obviating the need for water cooling.

(2) Main structures built of solid round copper bar to reduce incident absorption of reflected laser radiation.

(3) Toroidal powder nozzle support to allow symmetrical expansion in case of heating.

(4) Lateral and vertical adjustment for powder feed tubes allowing powder stream delivery angle variation in addition to allowing powder feed tubes to be accurately directed at the melt pool in case of structural warpage.

3. BASIS BEHIND REDESIGNED NOZZLE SYSTEM[9, 10]

The cladding nozzle can be split into two systems for the purpose of discussion. These are the powder feed tubes and the coaxial gas nozzle. The gas flow in a single powder feed nozzle will be discussed first, followed by the coaxial gas nozzle.

For each powder feed tube (neglecting the powder) using argon at a flow rate of 1 l/min and having a bore of 1.5mm, calculated average gas velocity = 9.43m/s. This results in a Reynolds number (Re) of approximately 1200 which is comfortably below the 2000 usually used as the limit for laminar flow. (At low values for the Reynolds number the roughness of the interior surfaces of the pipe is negligible and the pipe bore may be considered as smooth for fluid flow purposes.)[9]

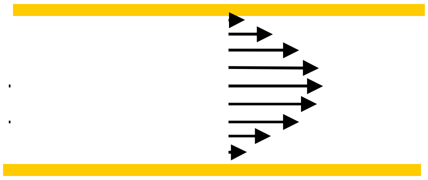


Fig. 2. Laminar flow streamlines

Therefore for typical cladding conditions (usually 0.25 to 1 l/min per powder feed tube in this work) the velocity components of the gas comply to that of laminar flow with those streamlines near the tube wall having a much lower velocity than those furthest away. In streamline flow the mean velocity of the gas corresponds to half that of the maximum velocity streamline at the pipe axis (corresponding to a parabolic velocity distribution with a static boundary layer at the pipe wall – fig.2, left)

At any angle other than the vertical the powder is not mixed homogeneously with the gas in the tube but rather tends towards the bottom wall under the action of gravity. In addition fluidisation of the powder causes larger particles to migrate towards the bottom surface of the tube due to stratification (a similar effect occurs in riverbeds where larger particles of gravel migrate below fine silt). Particles can also rotate in the gas stream, causing lighter particles to be lifted into the gas stream (the Magnus effect)[9]. This results in the powder mass distribution being skewed towards the bottom wall of the tube while the powder assist gas retains the parabolic velocity profile. The amount to which this non-uniformity of powder mass distribution takes place can be shown to be inversely proportional to the velocity of the gas flow transporting it i.e. at sufficiently high gas velocities the powder distribution would be uniform, even in horizontal pipes. Whereas powder particle velocity may be greater than that of the gas flow in the vertical section of the tube, it loses velocity by collisions with the tube wall as it deviates from the vertical.

As the powder-gas mix exits the tube the powder is flared less than the gas due to its higher momentum. However, unlike the gas, the powder is affected by the roughness of the interior of the pipe and is slowed by frictional effects and collisions.

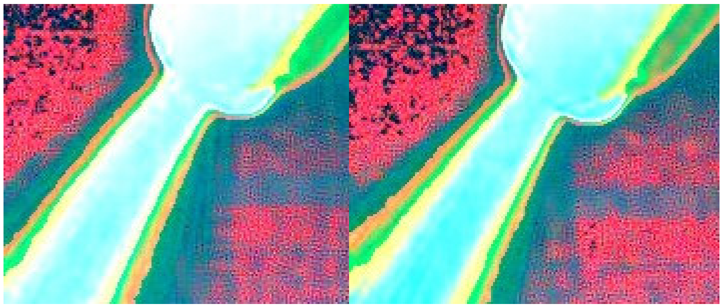


Fig.3 Two false colour images showing the powder stream exiting a 40° powder feed tube under flow rates of 3l/min (left) and 4l/min. The different colours indicate relative density of powder stream. It can be seen that the area of lower powder density at the top of the powder flow is greater than that at the base.

The coaxial gas nozzle, however, is under conditions of turbulent flow as the gas stream approaches the throat (Re >2000 at the nozzle exit for all argon flow rates over 1.24 l/min, hence tending to turbulent flow). This is due to the constriction of the coaxial nozzle bore as it approaches the throat of the nozzle causing a corresponding increase in gas velocity. Turbulent flow has a flatter velocity profile (corresponding to the ratio $v_{mean}/v_{max} = 0.82$) than streamline flow.

As the gas exits both powder feed and coaxial nozzles the difference in gas velocities compared to the stagnant surrounding gas causes the perimeter to the flow to be drawn into vortices, dissipating the excess kinetic energy. The emitted gas from the coaxial nozzle flares more than the gas from the powder feed tube because the velocity profile has been flattened by turbulent flow as it approaches the nozzle exit, and has also been affected by the roughness of the nozzle bore's exit.

In addition as the gas stream exits the mouth of the nozzles the lower ambient pressure causes the gas emitted from the pipe to expand according to the ideal gas law (PV^{γ}=constant where $\gamma = 1.667$ for argon). This expansion in volume causes a corresponding decrease in gas velocity, again more marked for the turbulent flow coaxial gas nozzle.

Therefore powder particles flaring from the top of the powder-gas mix have two relevant attributes. They are lighter particles than the bulk of the powder flow and they are travelling more slowly than the main powder stream. This means that they have a significantly lower momentum and can be redirected towards the mainstream powder flow using a downward-facing gas jet (the coaxial gas jet).

If the coaxial gas jet also has a conical divergent profile (as explained earlier) then the redirecting action will be greater at the top of the powder flow than at the base. This results in the powder cloud caused by the intersection of the four powder streams having the ability to be 'flattened' at the top by the action of the coaxial gas flow. A further effect of this redirection of the top of the powder streams is increased collimation of the powder streams below the intersection point.

This redirection of off-axis powder particles into the main powder stream results in a smaller powder 'penumbra' and allows the building of a clad layer whose height is controlled by the position of the top of the defined powder cloud which itself is in a fixed position relative to the powder feed nozzle. Hence raising or lowering the nozzle relative to the workpiece allows a clad layer of a consistent predetermined height to be laid down subject to minimum cladding conditions (i.e. that there is sufficient or greater power, interaction time and powder mass flow rate). This means that instead of the step height per layer being driven by the clad height, the clad layer height is driven by the input step height, subject to the step height being less than or equal to the unrestricted clad height.

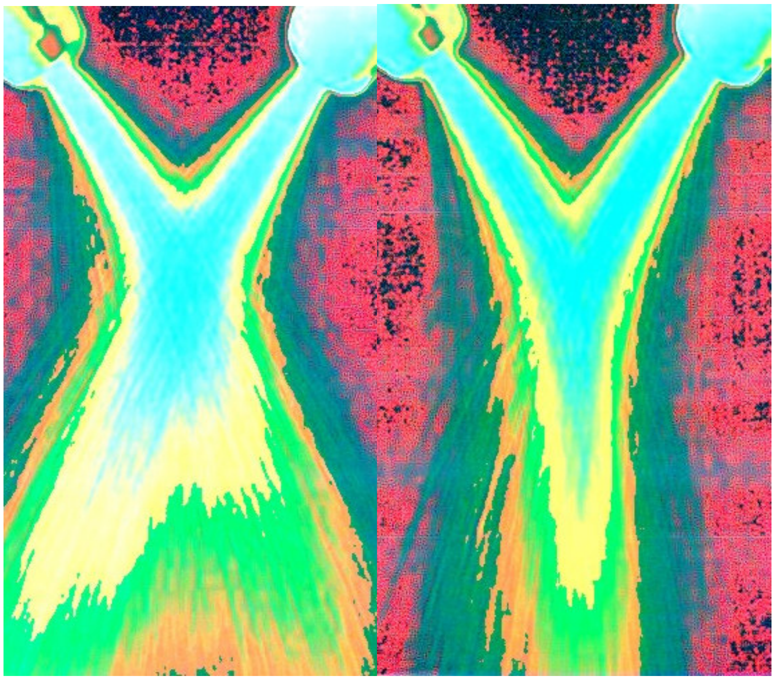


Fig.4 These two images show the effect of the use of a 12l/min gas flow through a 2mm coaxial gas nozzle situated 15mm above the intersection of the powder streams. It can be seen that the powder stream on the right has had the top 'penumbra' reduced and shows an increased vertical collimation below the intersection point of the streams

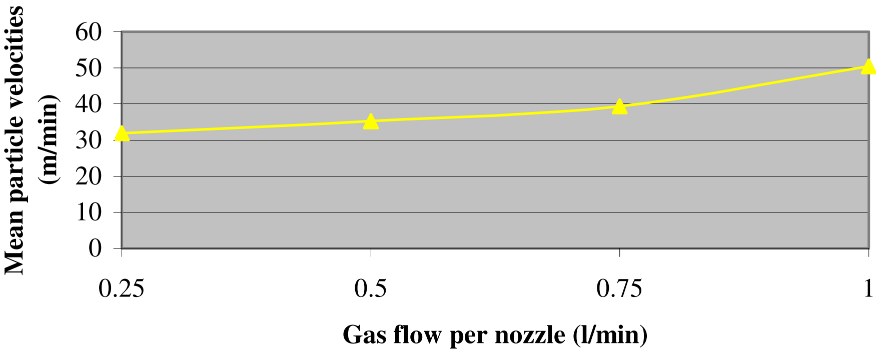
4. RESULTS OF USING THE MODIFIED NOZZLE SYSTEM

The effects of the new nozzle system were characterised for its control of layer height under different process conditions. The main process parameters which would normally affect a change in height of a single layer for a particular material are changes in process speed, powder flow rate and absorbed power[11, 12]. In addition, for continuous multilayer builds, the accumulation of heat within a build affects the height of a deposited layer, as does overlapping of clad tracks. Any variation of the clad layer height would be compounded during successive layers.

During the following sections the ability of the new nozzle system to restrict layer height under variations of the processing conditions listed above is tested.

In all of the following experiments the nozzle was used in the 45 degree configuration. Description of gas flow rates are abbreviated to (coaxial gas flow rate)-(powder gas flow rate) as follows; **10 l/min** coaxial gas flow coupled with **3 l/min** powder gas flow will be written as **10-3.** The associated mean particle velocities are shown in fig. 5 below.

Fig. 5. Mean particle velocities for applied fluidising gas flow rates



4.1 Effect of laser power variation on the height control system

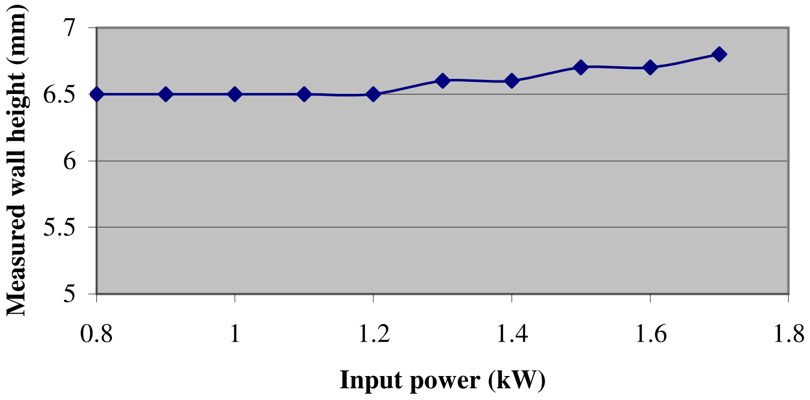
To obviate the effects of ricocheting of powder from the substrate surface on the control of layer height, investigation of the effects of power and powder variation on the clad height limitation effects of the new nozzle system were carried out on 10 layer builds. For each of these sets of experiments the process velocity was kept at 15mm/s and the nozzle was used with 10-4 flow rates.

Powder flow rate was kept at 8.27 g/min and a succession of 30mm long 12 layer wall samples were built with a laser spot size of 2.2mm. Samples were built at delivered powers of 0.8 to 1.7kW in 0.1kW increments with a step height of 0.5mm per layer. This step height was chosen in order to test the height limiting properties of the powder feed nozzle in that an unrestricted single layer was measured at 1mm high. The samples were then measured for build height and width of the built wall.

Fig.6 (below) shows variation in total wall height of 0.3mm over the power range chosen. (The total wall height is taller than the 5mm expected due to the nozzle not being positioned precisely such that the top of the powder cloud is coincident with the surface of the substrate for the initial clad layer.)

The largest height variation over the whole power range is therefore 4.4% for an increase in delivered power of 112.5%. This is a reasonable indicator that the powder nozzle has the ability to allow deeper melting with little related effect upon the height of the deposited layer. It would have been expected that a large increase in power would have resulted in an increase in layer height due to increased wetting of the layers allowing more powder to be incorporated, resulting in a correspondingly taller and wider wall. This has not been the case due to powder particles from the nozzle system ricocheting from the cooler sides of the wall if not incorporated into the melt pool. Therefore significant widening of the clad wall would only occur due to heat retention within the part. Since these are short walls the substrate acts as an adequate heat sink to prevent this from happening.

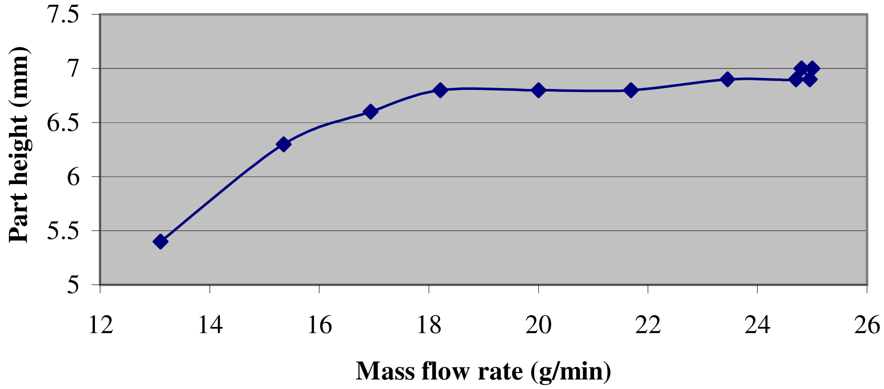
Fig.6 Build height against delivered power for 10 layer wall



4.2 Variation of powder mass flow rate against constant power for wall structures.

Varying the mass flow rate during cladding usually has a significant effect upon the clad layer height[13], hence the need for extremely accurate powder feeders. In order to investigate the effect of varying powder mass flow rate upon the height of a single 12 layer wall a series of walls were built with constant parameters of 1080W, 12-4 gas flow and 15mm/s process velocity. The step height was set at 0.5mm and powder flow was varied by means of increasing the screw feed rpm. A graph of the results appears in fig. 7 which shows an increase in part height up to a limit imposed by the physical position of the nozzle in relation to the melt pool corresponding to a mass flow rate of approximately 18g/min. At this point sufficient powder is available to build a clad layer of the required dimensions. The wall height is reasonably constant from this point in spite of the increase in mass flow rate through the nozzle system.

Fig.7 Part height against mass flow rate for restricted clad wall of 12 x 0.5mm layers



This is in accordance with the theory of operation of the new nozzle system which indicates that the clad bead will only build to a height defined by the top of the powder interaction zone and no higher due to lack of powder beyond that point. Increasing the mass flow rate beyond that point has little effect upon the deposited layer height due to excess powder ricocheting from the sides of the wall rather than being incorporated into the melt pool. The limit of the mass flow rate deliverable by the screw-feed powder feeder used here appears to be around 25g/min as is shown by the closely spaced points around this area. Increasing the screw feed rotation rate further had no effect on the powder mass flow rate available.

4.3 Single-pass square towers

A square tower $2^1/_2$D structure can be built in a continuous path by raising the step height by one quarter of the total layer height required per face. However, unlike cylindrical structures, the CNC table has to stop movement in one direction in order to produce the next vector path at right angles. This results in a dwell of the processing head and laser beam at each corner, usually resulting in a build-up at each corner on non height-restricting powder feed systems unless the laser power is ramped down to compensate[14,15]. The following structures are an example of square towers built in a single track with no power ramping or speed compensation employed and illustrate both the ability of the nozzle to control height variation at corners and the ability to produce different layer heights for the same set of process parameters by altering the step height alone.

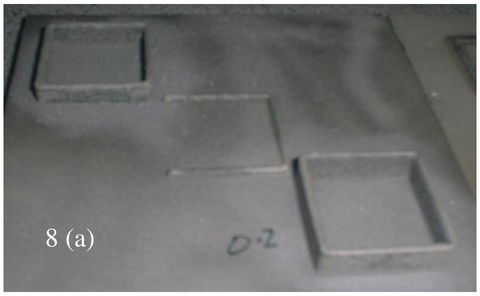
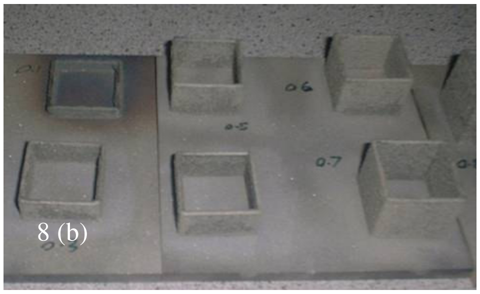
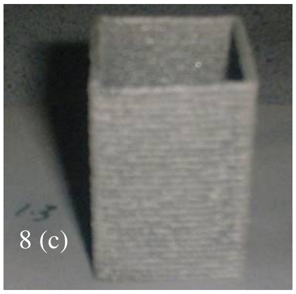


Fig.8 (a-d). Photograph 8(a) showing the first two 30 layer structures and a single first layer for purposes of assessing the initial nozzle position in relation to the substrate. This first layer is larger than the input step height due to the nozzle position being such that the top of the powder cloud is not coincident with the surface of the substrate. The total series consisted of using input step heights from 0.1 to 1.5mm in 0.1mm increments. Further examples along the run follow (anticlockwise from left: 8(b-d)) until height control failure at 1.5mm layer height





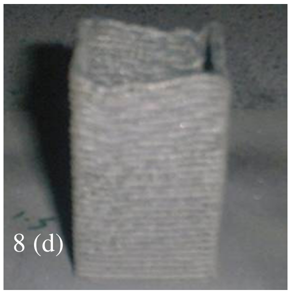
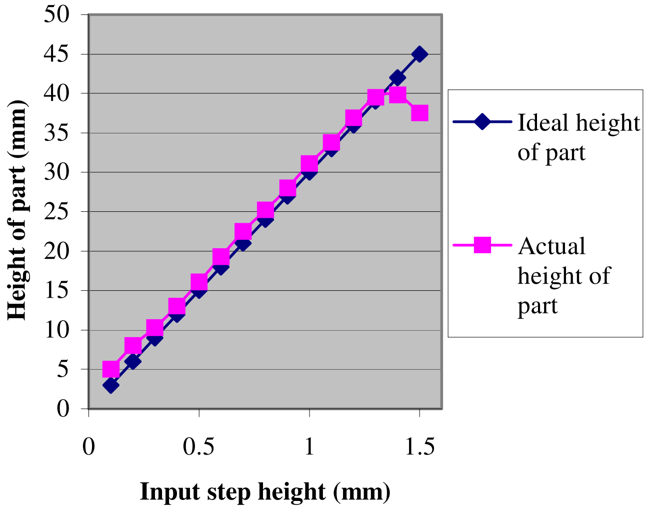


Fig. 9 Graph of part height compared to ideal



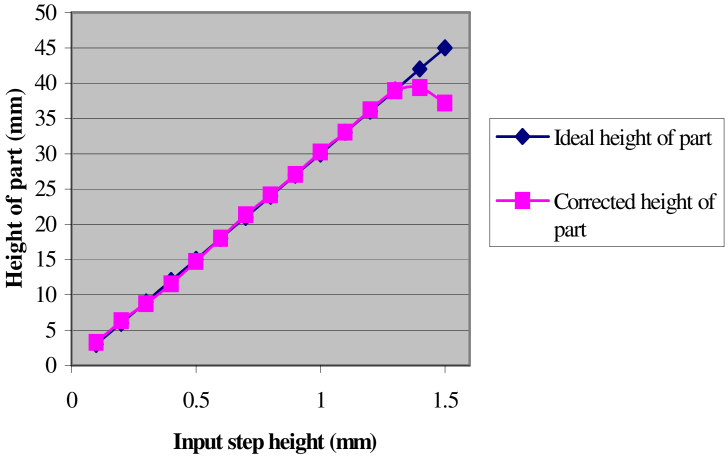
The height control of the build at the corners is entirely due to the powder cloud control previously described (there has been no compensatory input parameter control). In addition to height control of the clad layer at the corners, each of the samples has been built using exactly the same set of parameters excepting that the step height has been set differently in each case.

As is shown, the ability of the nozzle to control layer height (including at corners) continues up to 1.5mm step height where the effects of the step height being greater than the clad layer height appear in the form of a progressively unequal build. The 1.3mm step height sample adjacent to it is still exhibiting layer height control and clearly shows the helical build pattern used to generate the sample. The agreement of the input step height with actual height of build is shown in fig. 9. Part heights were measured at the terminal point of the clad which is at a corner and hence most likely to be affected by height variation. Fig. 9 shows that the actual height of the part tends towards agreement with the ideal height of the part except at step heights greater than 1.3mm. The variation in part height after 1.3mm layer height is due to the step height being more than the clad layer height as previously described. The variation at the beginning of the experimental run is due to the difficulty in placing the substrate surface coincident with the top of the powder cloud generated by the nozzle, which may not take place until more than one layer has been laid down. The table and associated graph in figs. 10 and 11 show the effect of accounting for an initial layer of 1.87mm by taking the difference between the expected initial layer height and the actual initial layer height and subtracting the result from the actual part height.

Fig.10 Compensation of part height allowing for nozzle offset error

Step height (mm)	Ideal height of part (mm)	Actual height of part (mm)	Contribution of initial layer of 1.87mm to height of part (mm)	Corrected height of part (mm)	Difference in corrected part height from ideal part height (mm)
0.1	3	5	1.77	3.23	0.23
0.2	6	8	1.67	6.33	0.33
0.3	9	10.3	1.57	8.73	-0.27
0.4	12	13	1.47	11.53	-0.47
0.5	15	16.1	1.37	14.73	-0.27
0.6	18	19.3	1.27	18.03	0.03
0.7	21	22.5	1.17	21.33	0.33
0.8	24	25.2	1.07	24.13	0.13
0.9	27	28	0.97	27.03	0.03
1	30	31.1	0.87	30.23	0.23
1.1	33	33.8	0.77	33.03	0.03
1.2	36	36.9	0.67	36.23	0.23
1.3	39	39.5	0.57	38.93	-0.07
1.4	42	39.8	0.47	39.33	-2.67
1.5	45	37.5	0.37	37.13	-7.87

Fig. 11 Graph of corrected part height compared to ideal



4.4 Overlapping of clad layers

Overlapping of clad layers during the course of a build can be separated into two cases. The first is that of limited overlapping in order to build a thicker wall and the second is where clad tracks cross over each other. The first case corresponds to the practice of laser surface cladding and can be accomplished with a suitable aspect ratio controllable with the new nozzle system by selecting a layer height of less than one fifth the width of the clad track to eliminate porosity or, as has also been noted, by promoting increased remelting between layers of a higher aspect ratio. The second case also relies upon accurate layer height control in order to prevent build-up of clad layer height at clad layer crossover points.

The following photograph (fig. 12) shows a part made in 304L which utilises both limited overlapping to create a thicker outer wall and total overlapping of clad layers where the inner double wall meets the outer wall

Fig.12 An example of overlapping layers height control

Partial overlapping of clad layers in order to build a thicker-walled part is necessary for all applications where the laser used has insufficient power density to build a layer of the required width. The requirement is to overlap parallel clad tracks such that no porosity appears between them[16]. In low dilution cladding it has been stated[17] that the aspect ratio of a clad layer being overlapped in this fashion should not be more than 5 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 height limiting effects of the new nozzle are adequate for controlling the aspect ratio of the clad layer as has been indicated in the preceding sections.

4.5 Thickening of clad walls due to heat retention

As a part is built the initial conduction of heat is through the substrate. For relatively thick substrates, there is a suitable heat sink which prevents excessive heat retention within the part. As the part continues to build the action of this heat sink is reduced by distance and heat conduction increasingly depends upon the local geometry of the part. An example of this is shown in the curved cylindrical section on the left. This part was built by building a cylinder on a rotating substrate such that the outer layers were taller than the inner ones. Though initially built as an example of dynamic layer height control using the new nozzle system it also shows the effect of heat retention upon

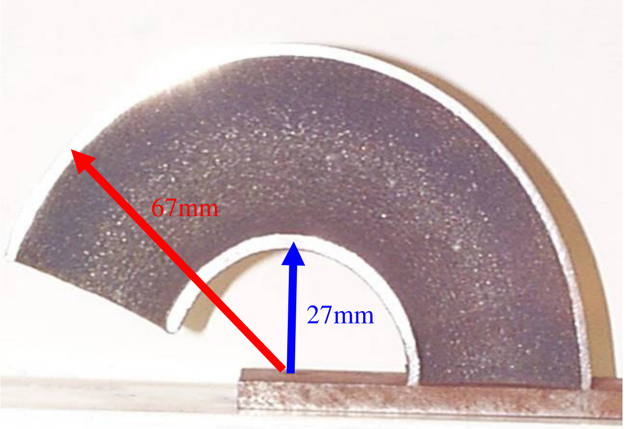


Fig.13 An example of constantly varying layer height control to produce an axially curved cylinder

clad width.

Examination of fig.13 shows that the inner circumferential clad wall shows an increase in thickness to a much greater degree than the outer one. From an initial wall width of 2.2mm on both the inner and the outer walls the widths increase to an equilibrium value of 2.9 and 2.3mm respectively as the base plate ceases to act as a major heat sink.

This increase in wall width is due to increased wetting as the temperature of the melt pool increases in line with excess retained heat[6].

5. CONCLUSION

This powder delivery process provides an independent method of controlling layer height by refining the top of the powder cloud at intersection. As a result, the deposited layer height can be controlled within limits for a range of applied parameters which would normally result in layer height variation. In addition the vertical collimation of the powder streams after intersection allows for the generation of thick layers while improving maximum catchment efficiency. Clad layer height control performed using this process is at the expense of powder catchment efficiency, though recovered powder is less likely to have passed through the laser beam and thus contains a lower proportion of oxidised particles.

The process has the benefit of being able to restrict deposited layer height to a high degree of accuracy without feedback mechanisms or specific software control and thus is of use in manufacturing parts where powder flow rates and delivered laser power are not highly consistent. As a result it reduces the necessary cost of associated equipment.

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