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Analysis of Laser Control Effects for Direct Metal Deposition Process

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As a promising and novel manufacturing technology, laser aided direct metal deposition (DMD) process produces near-net-shape functional metal parts directly from 3-D CAD models by repeating laser cladding layer by layer. The key of the build-up mechanism is the effective control of powder delivery and laser power to be irradiated into the melt-pool. A feedback control system using two sets of optical height sensors is designed for monitoring the melt-pool and real-time control of deposition dimension. With the feedback height control system, the dimensions of part can be controlled within designed tolerance maintaining real time control of each layer thickness. Clad nugget shapes reveal that the feedback control can affect the nugget size and morphology of microstructure. The pore/void level can be controlled by utilizing pulsed-mode laser and proper design of deposition tool-path. With the present configuration of the control system, it is believed that more innovation of the DMD process is possible to the deposition of layers in 3-D slice.

Key Words : Direct Metal Deposition, Laser Cladding, Feedback Control, Rapid Manufacturing, Porosity

1. Introduction

Laser aided direct metal deposition (DMD) is the process of laser cladding to make a metal component directly from a 3-D CAD model (Mazumder, 1996). Development of the DMD process has brought tremendous interest among the rapid prototyping industry as well as the tool industry (Mazumder, 2000). The remarkable improvement for rapid prototyping and tooling technology has fueled new product areas : functional metal prototypes and metal part production. The DMD process can be utilized in many promising fields such as net shaped solid metallic parts, functionally graded materials, cellular solids, in-situ alloying parts, and parts with conformal/internal features. An entirely new industry is being created, as many companies have introduced new systems that can build parts layer by layer with metal powders (Jee, 2002).

Though manifesting superiority and limitless potential have been heralded, a lot of work has to be done to perfect the process. The DMD process is still under development at universities, national laboratories and private institutions. The scientific challenge is to control the deposition dimension, microstructure, and mechanical properties. The control of those performances may be accomplished by controlling the melt-pool size and solidification time. However, the direct control of

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melt pool is almost impossible because of the factors such as powder catch rate and heat transfer rate. Proper solution has been sought by several researchers and one of them is to use feedback control system that controls the laser power and metal powder (Mazumder, 1999). In this paper, a control system is designed to increase the completeness of the DMD process. A feedback control system using optical height sensors is implemented to control laser power. A powder delivery system is also designed for the effective delivery of multiple powders. The system is evaluated with the deposition experiment of H13 tool steel. The effects of feedback controlled system are compared to those of uncontrolled system on dimensional characteristics and material defects such as porosity/void. Deposition height and surface roughness are analyzed as the characteristics of dimensional accuracy.

2. DMD Process and Control Issues

Laser aided DMD process is achieved with a laser system combined with a NC machine tool or laser-robot system. As shown in Fig. 1, the DMD system consists of four key technological components: laser cladding, CAD/CAM, numerical control of machine tool, and feedback control. In order to fabricate a part, a CAD model is generated using CAD/CAM system. After the model is sliced with uniform thickness, a machine tool path is generated based on the slice. The machine tool path is converted to a machine code with tool path and auxiliary functions, and then uploaded into a NC machine tool. Laser cladding is an additive manufacturing process that a laser generates a melt-pool on the substrate material while a second material is injected into that melt-pool. Layered manufacturing is achieved by this cladding line-by-line and layer-by-layer until an entire component is built up.

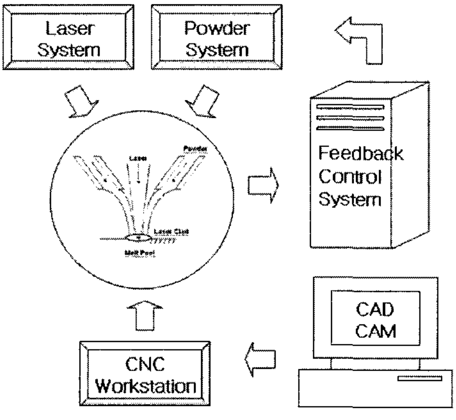


Fig. 1 Components of DMD system

Technical difficulties to implement cladding process are how precisely to control the geometric dimensions and material properties. In an ideal deposition case, the surface flatness may be kept in uniform. However, in a real process, irregular powdered material flow and laser power fluctuation often result in undesirable deposition. It has been reported that excessive surface irregularity during the process could cause undesirable defects in the interface between layers after deposition (Mazumder, 1997; 1999; Choi, 2001; Koch, 2000). Close control of dimension results in substantial savings in post-process machining cost for surface finish. Substantial cost reduction is possible, if desired properties can be achieved through process control and minimizing post-process heat treatment.

For laser aided DMD process, there are five major process parameters: laser power, laser beam diameter, powder mass flow rate, traverse speed, and laser beam path width (%overlap). The uniform deposition height as well as deposition integrity may be obtained by controlling these five parameters. Proper solution has been sought by several researchers during recent years. One of the proposed methods is to use feedback control system that controls the specific energy and amount of mass to be delivered (Mazumder, 1999; Koch, 2000). The basic function of feedback control system is to limit the maximum height of metal deposition. An example fabricating a part which has an overlapping deposition path shows the advantage of height control (Mazumder, 1999). Comparing two samples which are deposited with and without height control, excess cladding build-up occurs in a sample without control system. Another example is the staircase effect of the hemisphere shaped part (Mazumder, 1999). When the deposition thickness is uniform, the staircase effect is inevitable due to the step-wise build-up scheme. The geometric inaccuracies from the staircase effect may be solved using adaptive thickness deposition with feedback control system and an adaptive slice algorithm (Kulkarni, 1996).

Another problem to obtain deposition integrity is to control the metal powder stream. The part scale level, such as micro-, meso-, or macro-scale, is always a big issue when fabrication is concerned. One of the biggest challenges to the DMD process is how small the part can be built, and it is mainly determined by the size of metal powder. It is planned that the new generation of diode pumped solid state (DPSS) laser could provide as small as 25 μm diameter of focused laser beam quality (Marabella, 1996). In general sense, the size of melt-pool is same as the size of laser beam. In order to melt and solidify delivered metal powder inside the melt pool, the size of metal powder should at least be one half of the melt pool size based on previous research (Choi, 1994). The flow control of tiny metal powder which may be less than 10 μm is a tough task since it flows randomly due to buoyancy effect. Powder flow problems such as unexpected impasse and sticking due to electrostatics may be caused. Now it may bring the issues of establishing effective powder delivery method. In addition, DMD process requires the precise and effective delivery of multiple powders to deposit hybrid materials in same part. One advantage of the DMD process over traditional methods is the fabrication of functionally graded materials. That means the mixture of different powders may be delivered into melt pool, continuously changing volume fraction of particles line-by-line or layer-by-layer. Flawless mixing of multiple powders and effective powder delivery into melt pool are needed to improve the DMD process.

3. Design of Control System

3.1 Feedback control system

As shown in Fig. 2, the feedback control system consists of height sensing unit and feedback signal processing unit. For on-line observation of the melt-pool, a CCD camera connected to a monitor is used. An optical photo-sensor is developed for the height sensing. Two or three-sensor system may be chosen to neutralize the effect of tool path direction (Mazumder, 1999). The optical sensor should be calibrated based on the desired image of melt-pool, and consequently it keeps from triggering any signals as long as the current layer thickness is retained equal to the slicing height position.

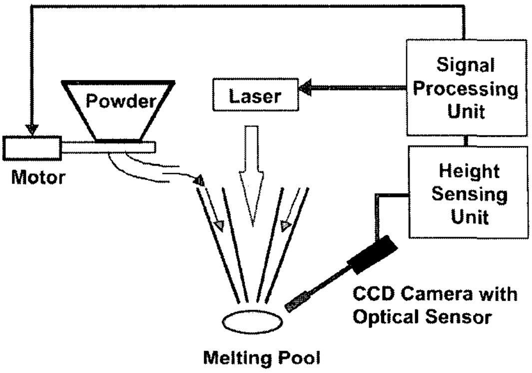


Fig. 2 Concepts for feedback control

Due to the possible instability of laser power and powder mass flow captured into the melt-pool, the deposited track may result in over- or under-deposition. Under-deposition needs to be compensated through the appropriate pattern design. It may be corrected by the algorithm of repeating tool path on the same layer during the process. However, over-deposition is a critical problem in the process. If over-deposited, the excessive thickness should be removed by extra removing process. The main idea of the feedback control is to provide adaptive control capability that laser power is reduced as quickly as possible when over-deposition is detected. The image of melt pool is sent onto an optical photo sensor. The image position on the sensor reflects the height change of the melt pool on the deposited surface. The detected image from melt-pool is evaluated at height sensing unit. When the height of the current melt pool is higher than desired position, the sensor catches the image of the melt pool. Then, a proper signal is sent out to signal processing unit and laser power controller. The signal processing unit may also send a signal to the powder delivery system.

3.2 Control diagram

Figure 3 is the schematic diagram of the control system. The overall DMD process is monitored and controlled by personal computer (PC). Using LabVIEW® software, a control unit is developed to control the whole process intelligently. The controller is connected to the deposition process planning unit to control NC machine tool. Process planning includes the information of tool path as well as auxiliary functions of equipments such as laser shutter, powder feeding motors, mixer motor, powder-delivering gas, and shielding gas. The process parameters such as laser power, powder mass flow rate, process speed, and process tool path are generated based on the adaptive slicing information of the 3-D CAD model. The functions and parameters are programmed in machine codes, so that the controls of laser power, powder feeding, and tool path are synchronized.

The PC controller calculates the necessary voltage signals for laser power generator and DC motors based on layer thickness and powder mass fraction information. The analog voltage signal from the PC controller is sent to laser power controller and DC motor servo controller through two data acquisition (DAQ) boards. DAQ1 and DAQ2 are designed as an analog output board and a multi-function board respectively. The signal processing unit is a circuit which is designed to enable real-time controls without time delay. Receiving a detection signal from the optical height sensor system, the signal processing unit determines necessary output signal of instant power-off for laser power controller. The power-off time varies depending upon pulse repetition rate and duty cycle of the reference pulse input signal. The signal processing unit also sends output signals to the PC controller to control laser power magnitude and serve motor speed. The PC controller evaluates the signal from the signal processing unit and sends the voltage signal to laser and motor controller for the control of laser power magnitude and powder flow.

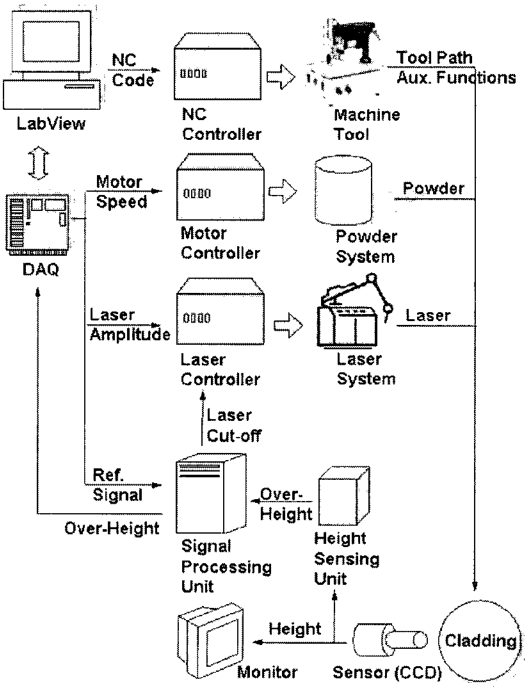


Fig. 3 Schematic diagram of control system

3.3 Feedback control response

Comprehensive tests were performed to evaluate the system. The frequency and duty cycle of the signal were set to 20 Hz and 95% respectively. Fig. 4 shows the actual laser power variation under feedback control during one layer deposition. The deposition tool-path of each layer starts with a contour (the first peak in the plot) path followed by inside pocketing path, then another contour path and so on. Laser beam is cut off between contour and pocketing tool-path for a short time allowing the worktable to reach the preset traverse speed. The dynamics of laser power reflect the effect of feedback control, and in general, the frequency of laser power change is lower than that of the laser pulse (60 Hz) as shown in Fig. 5. Averaged laser power (voltage) considering the feedback control is measured as shown in Fig. 4.

Figure 5 also shows how the sensor signal works on the laser pulse (60 Hz, 95% duty cycle), and the high pulse of the sensor implies that optical detector observes over-deposition of layer thick-

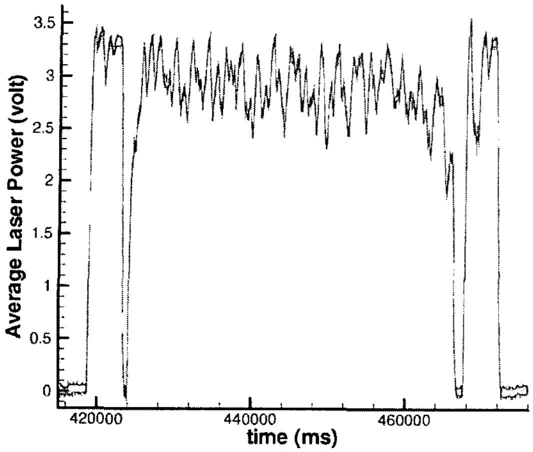


Fig. 4 Effects of feedback control on the laser power

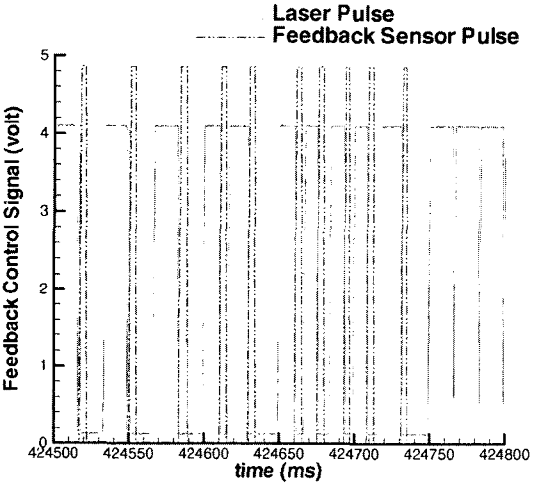


Fig. 5 Feedback sensor signal and resulting laser pulse

ness. The duration of the optical sensor pulse is usually less than 5 ms. The laser pulse is triggered down instantly as the sensor pulse (front edge) is up, thereby the real time control is accomplished.

3.4 Powder delivery system

A powder delivery system is designed to mix multiple powders and deliver uniform mass flow. As shown in Fig. 6, the system consists of three powder containers, a powder blender, a concentric nozzle assembly, and delivery gas inlets. Each powder container has a dimpled-shaft delivery system and a motor assembly of miniature DC motor, reduction gear head, and tachometer. The motor is driven by the servo-controller, so that speed of the motor can be controlled by a signal from the feedback control system. Using the motor control, the powder mixing and the mass flow rate can be precisely controlled and stabilized.

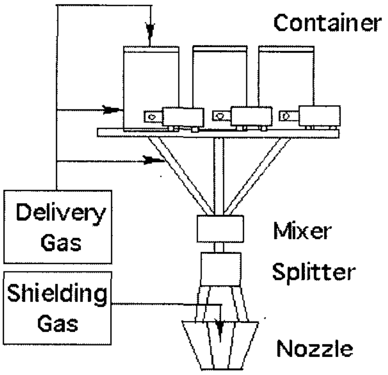


Fig. 6 Multiple powder delivery system with mixing capability

Powders are designed to be delivered with a delivery gas. In order to make powder flow regular, delivery gas, argon is provided in three ways. Delivery gas also prevents from the blocking of the spindle in container, which may occur by leaked powder. Powder blender mixes powders delivered from different hoppers with the operation of mixing equipment. Powder can be delivered from blender to the melt pool using either a side-delivery device or a concentric nozzle. Side-delivery nozzle has an advantage to provide high volume deposition. However, the concentric nozzle enables precise control of powder delivery and provides equal deposition rates in any direction. Therefore, the concentric nozzle is adapted for the system. To prevent oxidation, the shielding system is designed to supply adequate amount of gas to drive away the ambient air without causing excessive disturbance at the melt pool. Helium gas is used as a shielding gas since helium gas has higher ionization potential than argon gas. It produces plasma with lower electron density at the laser-substrate interaction point (Steen, 1998). The powder flow stream from concentric nozzle to melt pool tends to be spread out. In order to improve the powder catch efficiency into the melt pool, the standoff distance between nozzle and melt pool should be optimized.

A test was carried out to evaluate the performance of powder delivery system. When the powders are delivered at motor speed 15 rpm without delivery gas, the maximum variation of the mass flow rate is measured about 5%. It is believed that the variation comes from the uneven dimple size on the spindle and can be reduced if it is finely fabricated. It is also observed that there is a little leakage from both ends of the spindle. However, the leakage rate is reduced, as the motor speed gets higher. With the increase of motor speed, the variation of powder mass flow rate decreases to the level of 1%. As aforementioned, the spindle may be blocked by leaked powder if the feeder runs without powder delivery gas. In order to provide stable performance and to seal both ends of the spindle, an inert gas needs to be provided and the amount of the delivery gas should be well controlled.

Since the powder mass flow rate is varied as the motor speed is controlled, the motor speed needs to be calibrated to the powder mass flow rate. Fig. 7 shows test data of powder mass flow rate with delivery gas. As the motor speed is controlled and stabilized by the LabVIEW® and motor controller, precise linear relationship is provided between control voltage and powder mass flow rate. Although many other factors such as nozzle geometry, humidity, standoff distance, shielding gas pressure and melt pool size may affect the powder catch efficiency, the test shows that the powder delivery system works effectively.

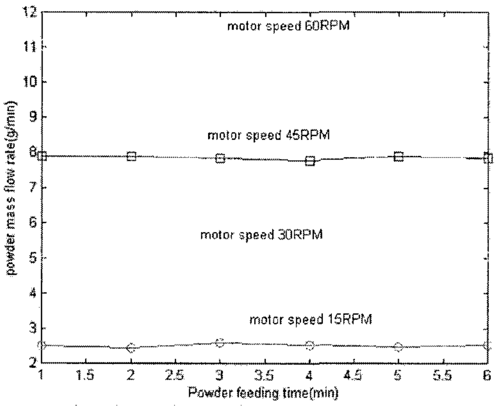


Fig. 7 Mass flow rates of the powder feeder (powder : H13, powder mesh size : 100/325)

4. Experimental Procedure

An experiment was executed to evaluate the control effects of the feedback system. Fig. 8 shows the experimental setup used in this investigation. Process conditions are listed in Table 1. AISI H13 tool steel was used in this study, since it is a choice of materials for the die and mold making industry. The chromium hot-working steel is widely used because of its combination of softening resistance and toughness (Roberts, 1998). The powder of H13 tool steel (Delcrome6552) is obtained from Stellite® Coatings with normal working hardness of 40 to 55 HRc and average standard mesh size of 100. The powders are dried by heating them at 200℃ in an oven furnace with a steady argon flow for about 8 hours, and then cooled slowly to room temperature. The deposition samples are fabricated to have the dimensions

Table 1 Process conditions

Material	H13
Laser Power	660 W
Layer Thickness	0.254 mm
Powder Mass Flow Rate	5.5 g/min
Traverse Speed	19.05 mm/sec
Path Overlap	50%
Delivery gas rate	10 ft^3/hr
Shielding gas rate	20 ft^3/hr

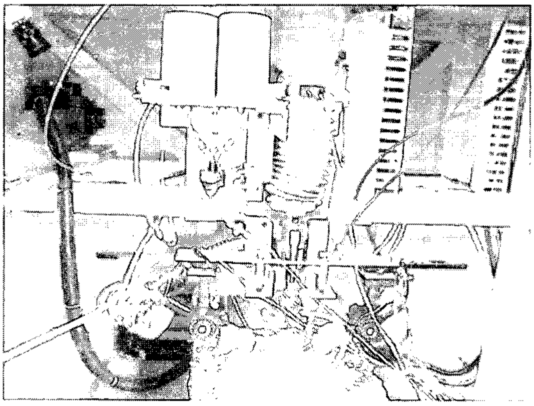


Fig. 8 Experimental setup

of 20.32 mm, 20.32 mm, and 5.08 mm in length, width, and height respectively. The substrate material is 9.53 mm thick AISI 1018 steel with polished surface. A 1.75 kW [cw/pulsed (7.5 kW)] CO_2 laser system with F7 focusing head assembly is used to produce a defocused 1.0 mm diameter beam with a Gaussian power distribution (TEM 00). Laser pulse is generated with 60 Hz frequency and 95% duty cycle. The feedback control system is activated only for the control of laser cut-off time at this experiment. The deposition tool path of each layer starts with a contour path followed by inside pocketing path. To examine the effects of feedback control, four different pocketing patterns were selected as shown in Fig. 9. The deposition direction x means the direction along the line between two optical sensors. Fig. 10 shows a deposited sample with zigzag_xy pattern.

The measured performances are actual layer thickness and surface roughness for the characteristics of dimensional accuracy. Porosity and void are measured for the material defects. For the thickness measurement, twenty layers were built-up and actual thickness per layer was calculated after being divided by the number of layers. For surface roughness measurement, a surface profiler, PocketSurf III, was used. Before the measurement, samples are cleaned with wire brush to remove partially melted powder and oxidation. Multiple measurements are made and the values are averaged. An optical microscope (Nikon EPIPHOT 200) along with image analysis software, Scion Image, was used to measure the porosity/void ratio.

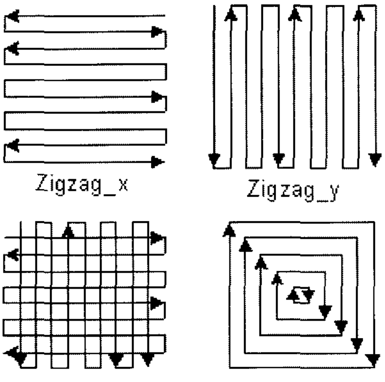
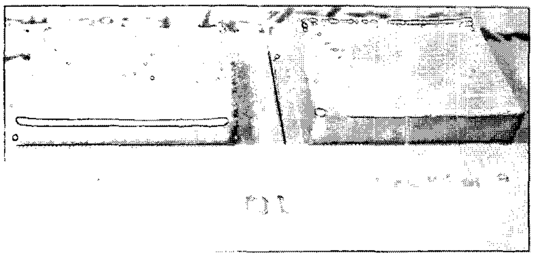


Fig. 9 Deposition tool path patterns



(a) With control (b) Without control

Fig. 10 Deposition sample with zigzag xy pattern

5. Dimensional Characteristics

In the vertical direction, the layer thickness of one deposition was set as 0.254 mm. The optical sensor was designed to have the resolution of 0.0254 mm and maximum controllable over-height as 0.508 mm. The ideal height of 20 layers is 5.08 mm. Fig. 11 shows measured sample heights which are the dimension in vertical direction. In every deposition patterns, feedback controlled deposition process shows the superior dimensional accuracy than uncontrolled process. With the control system, the pattern, zigzag_y has the smallest thickness error of 0.25 mm. It means that the side view of the sensor is more efficient for the control than the front or back view. The pattern, zigzag_xy shows the most reduction of errors, from 2.13 mm to 0.38 mm. It means the control system was activated for the most period in the pattern, zigzag_xy. Fig. 12 shows the average laser cut-off time rate. High cut-off rate means frequent interruption of laser power. Recurrent interruption may result in the partially melted powder and consequently end up with bad material characteristics like pore/void. From the previous experiments, the DMD process may produce good samples when the cut-off time is less than 30%. Even though the feedback control system improves the dimensional accuracy, the selection of adequate laser power and powder flow rate is also important for the material characteristics. The horizontal dimension of deposited layers was also measured. Though the height feedback

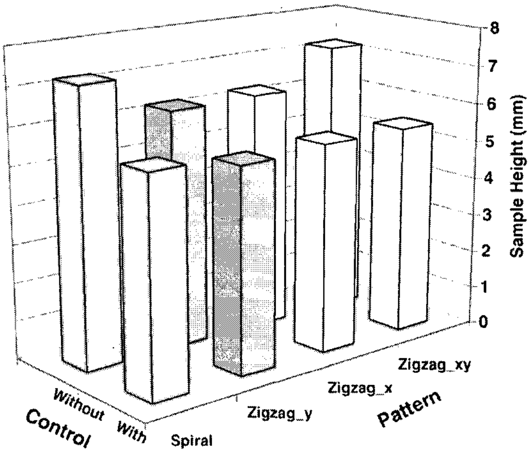


Fig. 11 Measured heights of samples

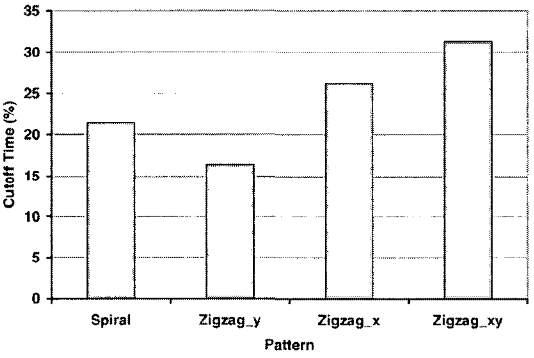


Fig. 12 Average laser cut-off times

control system attempts no direct control on the horizontal direction, it may influence on the width of clad deposition. The measured data showed no hint of the effect of feedback control on the dimension in horizontal direction. The deposition patterns also made no significant difference.

Figure 13 shows a typical single laser clad showing surface roughness. The surface profile shows two distinctive features ; one for the transient region and another for the steady state. Fig. 14 shows the measured average surface roughness (Ra) of the top surface across the clad direction. Independent from laser control, surface roughness is in the range of 5-6 μm except for the pattern, zigzag_xy. The average surface roughness on the vertical walls is in the range of 3-4 μm. The measured results show that the feedback control has little effect on the surface roughness. Moreover, since the final parts may need the finish machining depending on the surface texture requirement, the roughness property may be negligible. However, the surface roughness may suffer in the case

(a) Transient profile

(b) Steady state profile

Fig. 13 Typical laser clad showing surface roughness (cross sectioning by clad direction)

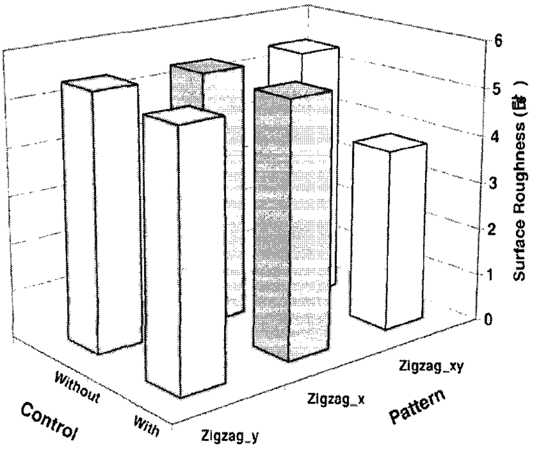
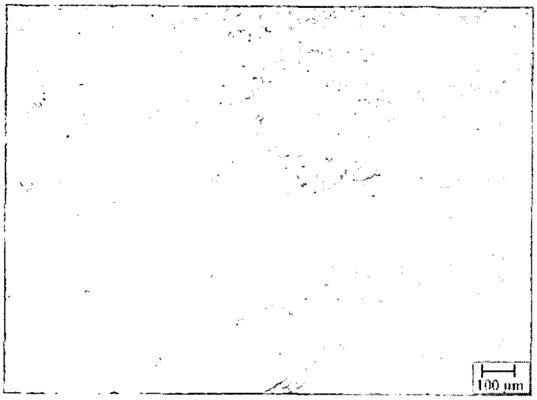


Fig. 14 Average surface roughness

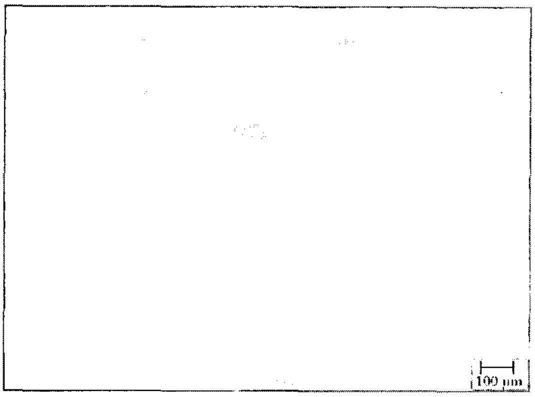
where there are too many feedback controls observed. This means that the average laser power is further reduced and thereby the surface profile may be locally lowered.

6. Porosity/Void

To observe the porosity/void in the samples, optical micrographs (50X) are taken. Fig. 15 shows the shapes for samples with Zigzag_x deposition pattern. Fig. 15(a) is taken from the sample with feedback control on ; meanwhile Fig. 15(b) is from the sample without feedback control. The deposition shape in Fig. 15(a) shows the effect of feedback control, which causes irregular deposition nugget sizes between the paths (50% overlap). Fig. 16 shows two forms of defects, porosity and void. From the micrographs in Fig. 16(a) the spherical-shape pores appear mostly in the clad nugget. They show up randomly in the deposited samples. The size of pores is usually less than 100 μm. The formation mechanism of the porosity is still not clear. It is believed that the formation of the pores should be related with the dynamics of melt-pool (Matsunawa, 2001). The other defect, like irregular shaped voids, is caused by insufficient laser fluency. It is found that they are mostly located along the clad boundary as shown in Fig. 16(b). If the feedback control works very frequently, this defect (void) will be likely formed more than the porosity. A series of micrographs are taken for each sample to survey the whole area of the sample cross-section. Then, the micrographs are analyzed by imaging software (Scion Image) to get the total area of the pores/voids, and then pore/void ratio is calculated and averaged. Fig. 17 shows that the deposition patterns affect the porosity/void ratio, and

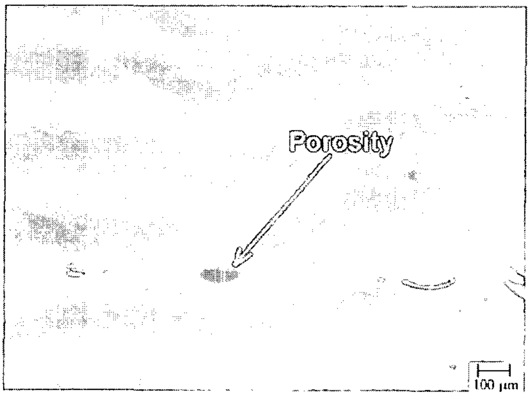


(a) Sample with feedback control

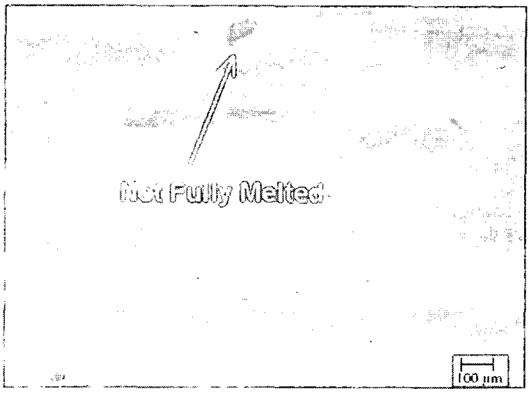


(b) Sample without feedback control

Fig. 15 *Deposition shape in zigzag_x pattern*



(a) Porosity



(b) Void (not fully melted)

Fig. 16 *Defects in the deposited samples*

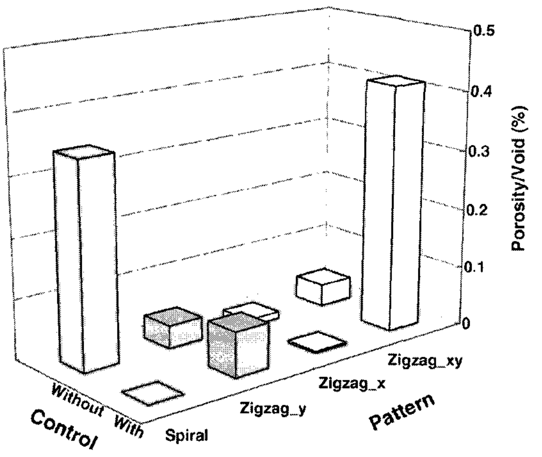


Fig. 17 Porosity/void ratio

it is observed that Zigzag_xy pattern often produces poor quality samples. The average laser cut-off time in Fig. 12 also shows that as the cut-off time is small, the process with the feedback control may produce good samples with fewer defects. It can be explained that the clad melt-pool may not penetrate down the intersection of the clad track due to sharp edge on the irregular surface caused by alteration of clad direction. The void may be formed at the intersection of each clad track. In case of other three patterns, the feedback control should not be responsible to cause the porosity defects. However, as stated above the feedback control may result in the partially melted powder. If too much feedback control occurs and results in too much interruption of laser power, the sample quality may be suffered.

5. Conclusions

A feedback control system was introduced for laser aided DMD Process. A powder delivery system was also designed for the effective delivery of multiple powders. An optical height sensing system with two sets of sensors was used for monitoring the melt-pool and real-time control of deposition dimension. The feedback control enhanced the dimensional accuracy, however, had little effect on the surface roughness. With the feedback height control system, the dimensions of part can be controlled within designed tolerance maintaining real time control of each layer thickness. Clad nugget shapes reveal that the feedback control can affect the nugget size and morphology of microstructure. The pore/void level can be controlled utilizing pulsed-mode laser, and also the level can be well suppressed by proper design of deposition tool-path. Depending on the selection of deposition tool-path patterns, the level of porosity/void may be increased due to irregular surfaces caused by clad track. Zigzag_xy tool-path is the case, though it shows the most increase of dimensional accuracy. With this control system, it is believed that more innovation of the DMD process is possible. The process is not just bounded to deposit layers in 2.5-D slice but expanded to deposit layers in 3-D slice. Further research effort is requested on 3-D adaptive slicing algorithm and feedback control of the process on five-axis CNC machine.

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