09 Aug 2000

Process Modeling, Monitoring and Control of Laser Metal Forming

N. Munjuluri

Sanjeev Agarwal
Missouri University of Science and Technology, sanjeev@mst.edu

Frank W. Liou
Missouri University of Science and Technology, liou@mst.edu

Recommended Citation

N. Munjuluri et al., "Process Modeling, Monitoring and Control of Laser Metal Forming," *Proceedings of the 11th Annual Solid Freeform Fabrication Symposium (2000, Austin, TX)*, pp. 235-242, University of Texas at Austin, Aug 2000.

PROCESS MODELING, MONITORING AND CONTROL OF LASER METAL FORMING

N. Munjuluri*, S. Agarwal+ and F.W. Liou*

*Department of Mechanical and Aerospace Engineering and Engineering Mechanics
+Department of Electrical and Computer Engineering
University of Missouri – Rolla, Rolla, MO 65409

Abstract

Laser Metal Forming (LMF) process is one of the prominent Rapid Prototyping (RP) process that can be used to develop functional and fully dense metal parts. This paper addresses process modeling, monitoring and control of a laser metal forming system currently under development at Laser Aided Manufacturing Processes (LAMP) laboratory at University of Missouri–Rolla. This LMF system is based on a 2.5kW Nd:YAG laser as energy source and integrates five axis metal deposition and five axis machining. The current paper is aimed at characterization of effects of operating parameters such as traverse speed, mass flow-rate and laser power on the LMF process. A low cost monitoring system is being developed using off the shelf sensors like infrared temperature sensor, near infrared CCD camera and laser displacement sensor to measure the process index parameters. A closed loop control structure has been simulated for online control of the LMF process.

Introduction

In today's competitive world, the critical factors for success are product quality, time to market and cost. A faster development cycle requires the production of a highly accurate model directly from the CAD data. Rapid prototyping (RP) technologies offer a viable solution for this purpose. RP technology was commercially introduced in 1987 with stereolithography apparatus (SLA). Currently many commercial RP systems such as selective laser sintering (SLS), laminated object manufacturing (LOM), fused deposition modelling (FDM), solid ground curing (SGC) are available. However all these systems can only fabricate geometrically identical parts and not functional parts. Some progress has been made to use these RP techniques for the rapid manufacture of functional parts such as mold cavities and investment and vacuum-castings. Along with these commercial efforts, lot of research has been going on to design and develop rapid manufacturing processes to directly fabricate functional metal parts. One of the techniques that's been widely developed by several of these research groups is the direct metal layered manufacturing.

In Layered Manufacturing, solid model of the part is built layer-by-layer using material delivery or a curing system capable of tracing out the layer. Yevko et al. [1] classified these methods into two groups, depending on the techniques as conventional welding-based processes and laser-based powder spraying processes. Dickens et al. [2] introduced 3D welding based on the technology of MIG welding process. In this method, a robot-mounted MIG torch is used to build the part via layer-by-layer welding. The accuracy of this process has been reported in the literature at about ± 0.5 mm. Hartmann et al [3] introduced this layer-by-layer fabrication method where the part is built by deposoiting layers composed of primary and a support structure material. Deposition of layers is carried out using variety of techniques such as thermal spraying, welding and microcasting. Five axis machining is used to shape the layers and shot-peened to control the residual stresses. The support structure is removed by etching when the building process is completed.

Some of the previous efforts in laser-based powder-spraying process include, the Directed-light Fabrication by Mah [4], Laser-engineered Net Shaping by Griffith et al [5] Aluminium Powder Spraying by Koch and Mazumder [6], Laser Surface Cladding by Murphy et al [7] and Direct Manufacturing of Metallic Parts by Konig et al. [8]. Most of these rapid metal-forming systems are capable of producing fully dense metal parts that have mechanical properties comparable to those produced by conventional methods. However most of these systems suffer from two common drawbacks, staircase effects and limited 3-D geometries. One potential solution to these problems is to integrate deposition process and conventional machining process, which eliminates Staircase effect and helps in manufacturing complex 3-D geometric parts without the need of support material. The newly established Laser Aided Manufacturing Processes (LAMP) laboratory at University of Missouri–Rolla is conducting research towards the development of a layered manufacturing system by integrating five axis direct metal deposition and five axis machining using high power Nd:YAG laser as energy source. Further details of the system are reported elsewhere in this proceeding. The aim of this paper is to develop closed control architecture for intelligent process control of Laser Metal Forming system. The various parameters in laser metal forming process and the relationships between them are discussed. A control algorithm structure has been designed to implement a closed loop control for processes when process model is partially known and is potentially changing continuously albeit slowly.

Process Parameters

Process parameters describe the processes variables that influence the performance measure for the process and determine the quality of the part produced by Laser Metal Forming process (LMF). For the current discussion, primary performance measure considered is the deposition rate (C), which defines the rate of deposition measured as the volume the part built in unit time. Thus the aim will be to maximize the deposition rate in LMF process. More elaborate performance measures (such as that incorporating (powder catchment efficiency η_m) are possible but are not considered for the current development. In the following we enumerate some of the most important parameters that directly affect the rate of deposition and some other parameters which affect the quality of the parts.

Laser Power (P): Laser power defines the amount of energy input to the process. Bonding between the two layers cannot be achieved if the amount of laser power is too low. Moreover, if it is too high, excessive melting of the deposited layer and thermal stresses may occur.

Powder flowrate (M): Powder flowrate in LMF process is defined as the mass of powder flow in a unit time, usually expressed in g/s or g/min. The flow-rate decides the amount of metal impinging on to melt pool. Not all the powder fed to the process can be caught for building the part. The ratio of powders used for deposition to the total powder flowrate is defined as the powder catchment efficiency (η_m). Catchment efficiency may depend on many factors. For the current development a constant η_m is assumed.

Traverse speed (V): Traverse speed defines the relative speed in the direction of deposition between the prototype and the laser and is measured in mm/s. Traverse speed can be easily defined in terms of the feed rate of the positioning system (CNC).

Beam Spot Size (D): The laser beam diameter at the laser material interaction surface is defined as spot size and can be easily defined in terms of the standoff distance. Typically the standoff distance is chosen for a required spot size and powder flow characteristics and is kept constant throughout the process.

Clad Bead Geometry: A typical cross-section of the bead produced in LMF process is shown in Figure 1. The geometry of the bead is defined in terms of the bead width (W), bead height (H) and aspect ratio (A).

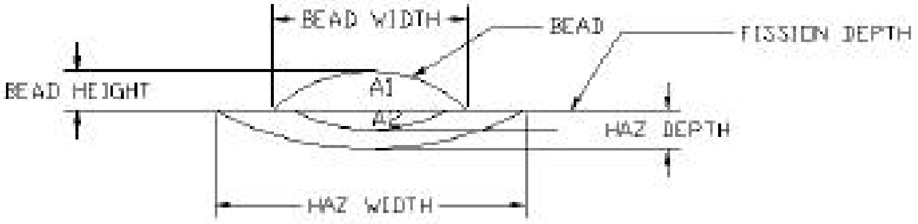

Figure 1. Typical cross – section of single bead

The aspect ratio of the bead is defined as:

$$A = W / H \tag{1}$$

Dilution (Di) and fusion depth : Dilution in LMF process was defined as,

$$Di = \frac{A2}{A1 + A2} \tag{2}$$

where, A1 and A2 are the cross section area as shown in Figure 1. Monitoring of dilution is necessary to achieve a good fusion bond between the layers.

Degree of overlap (j) and overlap index (i): Degree of overlap is defined as the ratio of the part of bead overlapped with overall bead width. Sometimes an overlap index is used which is defined as:

$$i = 1 - j \tag{3}$$

In LMF process constant bead width and constant overlap degree is required so that uniform layer thickness can be maintained.

Empirical Relationships for Process Parameters

Steen [9] pioneered the modeling of laser material processing. Later on many theoretical models were developed to understand the relationship between various parameters involved in laser material interaction. Weerasinghe [10,11] developed a three dimensional finite difference heat transfer model to obtain clad bead dimensions resulting from a given set of operating and process parameters. Chande et al. [12,13] developed a two dimensional heat and mass transfer model which includes the effect of mass transportation for powder injection based laser material processing. Mazumder et al. [14] developed another one dimensional model for laser material interaction which considered both energy transport and mass transport at a non-equilibrium rate. However, because of the various assumptions, these theoretical models cannot be used for process control. Therefore, empirical models of the process based on extensive experimental work by Weerasinghe [11], Steen et al. [15] and Takeda et al. [16] are used in this paper.

Bead width: The bead width (W) is linearly related to the traverse speed for constant laser power:

$$W = D' (1 - bV) \tag{4}$$

where, V is the traverse speed (mm/s), `b’ and D’ are the system constants which are obtained experimentally. D’ is closely related to the beam spot diameter D.

Bead height: The bead height (H) can be defined as a function of powder flowrate and traverse speed as:

$$H = aM/V \qquad (5)$$

Where, M is the powder flowrate (g/s) and `a' is a system constant obtained experimentally.

Layer thickness: The following statistical relationship can be used to relate layer thickness (h) as a function of bead clad height (H) and overlap factor (i):

$$h = -1.8\, H \ln(i) \qquad (6)$$

Dilution: The following constraint on the maximum and minimum laser power are defined from experimental and theoretical calculations in order avoiding excess dilution:

$$P/(DM) \leq K_m \qquad (7)$$
$$P/M \geq K_{min} \qquad (8)$$

where, K_m and K_{min} are the process constants.

Interrun porosities: The degree of overlap and aspect ratio of the single track affect the interrun porosity for the defocused beam. Experiments have shown [15] that if the following conditions constraints ensure good quality with minimal interrun porosity:

$$A \geq 5 \qquad (9)$$
$$i \geq 0.3 \qquad (10)$$

Open-loop Optimization

Typically the process planning for LMF system gives geometry and the thickness of the layer to be deposited. The aim of the control system is to reliably deposit this layer of the material. Thus the open-loop optimization problem can be stated as: Given layer thickness h, find the best values of operating parameters, i.e. the traverse speed (V), powder flowrate (M), and laser power (P), so that a layer of acceptable quality can be deposited. The problem can be expressed mathematically as: Maximize

$$C = iWV \qquad (11)$$

Subject to the following constraints:

$$P/M \geq K_{min} \qquad (12a)$$
$$P/(DM) \leq K_m \qquad (12b)$$
$$A = W/H \geq 5 \qquad (12c)$$
$$0.25 \leq i \leq 0.5 \qquad (12d)$$
$$P_{min} \leq P \leq P_{max} \qquad (12e)$$
$$V_{min} \leq V \leq V_{max} \qquad (12f)$$
$$M_{min} \leq M \leq M_{max} \qquad (12g)$$

One the process constants, a, b, c, dm, K_m and K_{min} are obtained from experimental analysis, process parameter values of V, M and P can be obtained by solving the above optimization problem for any desired layer thickness. Figures 2-5 show the open-loop optimal traverse speed, powder flow-rate, laser power, and resultant deposition rate as a function of the layer thickness. The values of the process constants used here are same as reported in [15]. These operating parameters can be saved in the form of lookup tables, which can be used to preset the open-loop process parameters for desired layer thickness.

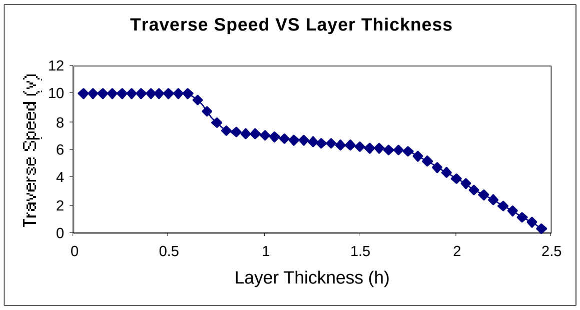

Figure 2. Traverse speed vs layer thickness

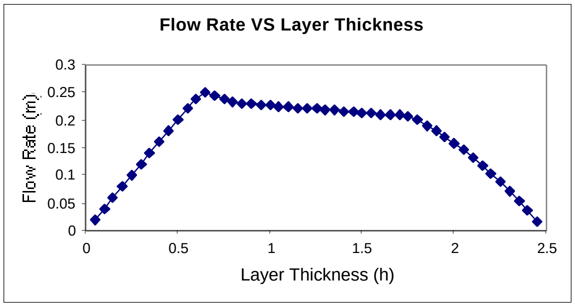

Figure 3. Flow rate vs layer thickness

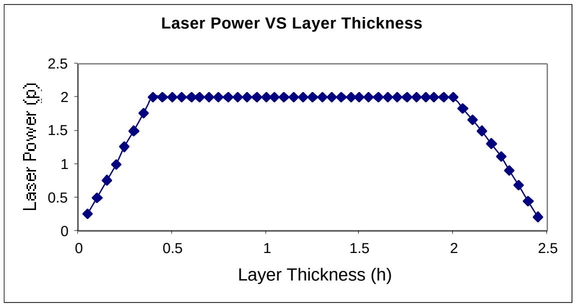

Figure 4. Laser power vs layer thickness

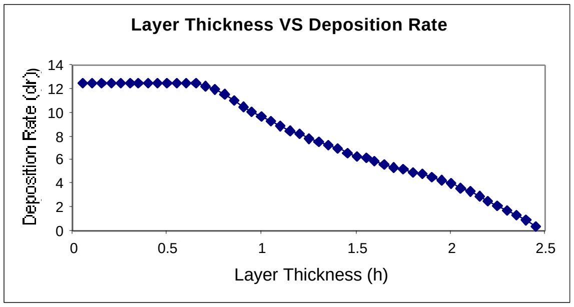

Figure 5. Deposition rate vs layer thickness

Closed Loop Process Control

A careful selection and presetting of the process parameters, based on the optimization technique described in the previous chapter is insufficient due to the inherent uncertainty of the LMF process. For example, as the process proceeds the substrate temperature may increase, which in turn affects the system constants. Thus the operating parameters should be changed in order to ensure the quality of the parts. We propose to implement a closed loop control system based on monitoring of the bead width, bead height and melt pool temperature during the ongoing process and correspondingly adjust the process parameters in order to achieve desired performance.

The function of the closed loop control module being developed is to coordinate functioning of various components of the Laser Metal Forming system at optimum operating conditions to achieve the desired product quality. Since the system is multi-variable and non-linear and there is no dynamic model of the process, many existing control techniques cannot be used for feedback control. Therefore a feedback control system using a rule based approach that can negate the process uncertainty is implemented. Let us assume that the desired bead width, bead height and dilution are $W=W_r$, $H=H_r$, $Di=Di_r$ respectively. Due to the disturbance such as the increase in substrate temperature, the achieved values are different from these desired parameters. The error function in such a case can be defined as:

$$\delta W = Wr - W[\,k\,] \qquad (13a)$$
$$\delta H = Hr - H[\,k\,] \qquad (13b)$$
$$\delta Di = Dir - Di[\,k\,] \qquad (13c)$$

where W[k], H[k] and Di[k] are the measured values at iteration k and δW, δH , δDi are the errors correponding to the desired parameters W, H and Di respectively.

From the empirical relationships between the process parameters, it can be seen that the bead width can be varied by the change in traverse speed, bead height can be varied by corresponding change in either powder flow rate or traverse speed and dilution can be varied by change in either laser power or powder flow rate. Moreover, since the influence of powder flow on bead width and the traverse speed on dilution is negligible a feedback control law can be designed as:

$$V[k+1] = V[k] - K_v \,\delta W \qquad (14a)$$
$$M[k+1] = M[k] + K_m V[k] \,\delta H \qquad (14b)$$
$$P[k+1] = P[k] + K_p \,\delta Di[k] \qquad (14c)$$

where, V[k + 1], M[k + 1], P[k + 1] are the new operating parameters that are used for the deposition of next segment. The three variables introduced in the control law are bead width control gain, $Kv > 0$, bead height control gain, $Km > 0$, and dilution control gain, $Kp > 0$. Figures 6-10 show the bead height, bead width, traverse speed, flow rate and laser power over time for two different starting parameters values. The first set show the results with 10mm/sec as traverse speed, 0.2 g/sec as flow rate and 2KW of laser power as preset value while the second set had preset values of 4mm/sec as traverse speed, 0.4 g/sec as flow rate and 1.6KW of laser power. In both the cases the desired parameters are 3mm bead width, 0.7 mm bead height and dilution of 0.1. The results demonstrated that in both the cases, convergence was achieved and the final operating parameters are same as desired.

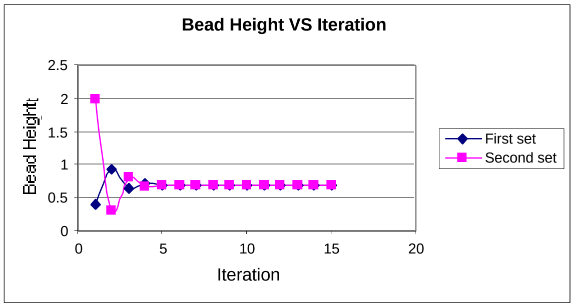

Figure 6. Bead width vs iteration

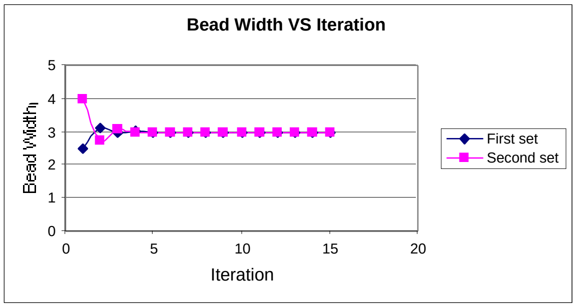

Figure 7. Bead height vs iteration

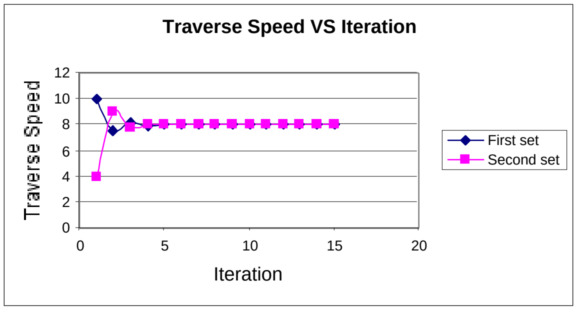

Figure 8. Traverse speed vs iteration

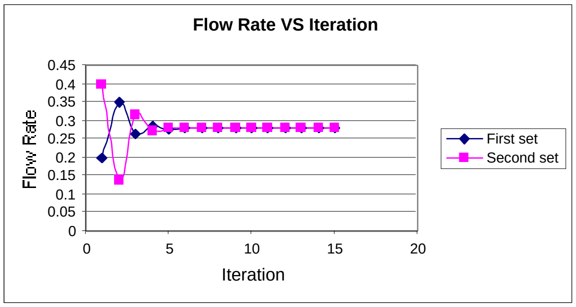

Figure 9. Flow rate vs iteration

In the above algorithm it can be seen that the selection of control gains play an important role in process control. Either too high or too low can delay the system convergence rate or even lead to the instability of the closed loop control system. Figure 11 shows the laser power for different selection of the control gain. An adaptive gain selection has been implemented based on golden section rule.

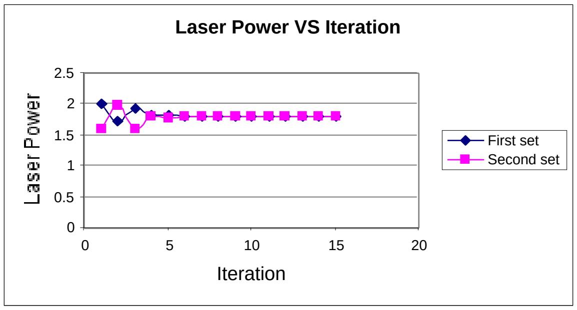

Figure 10. Laser power vs iteration

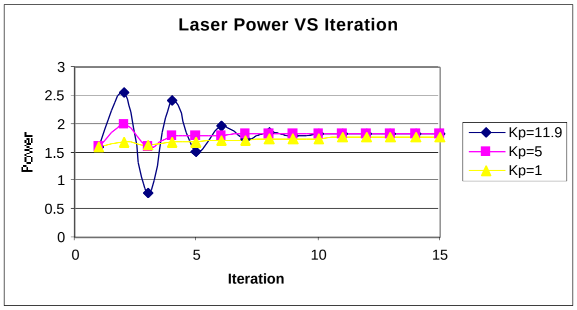

Figure 11. Laser power vs iteration

The simulations in Figures 6-10 show the effectiveness of the control law to achieve the desired performance (bead width, bead height and dilution) when the process is inaccurately modeled and hence the preset values of laser power, powder flow-rate and traverse speed are inaccurate. Figure 12-15 shows the closed loop control results in the presence of system variation due to increase in substrate temperature. Results for open-loop, fixed gain closed-loop and adaptive gain closed-loop control are shown. As can be seen closed-loop control architecture is effective in the process control of the LMF process.

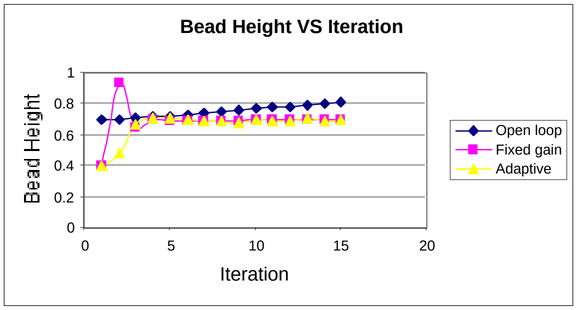

Figure 12. Bead height vs iteration

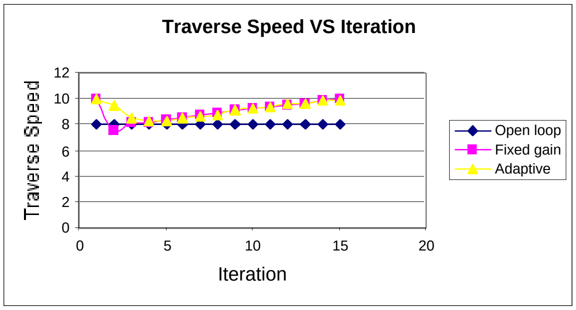

Figure 13. Traverse speed vs iteration

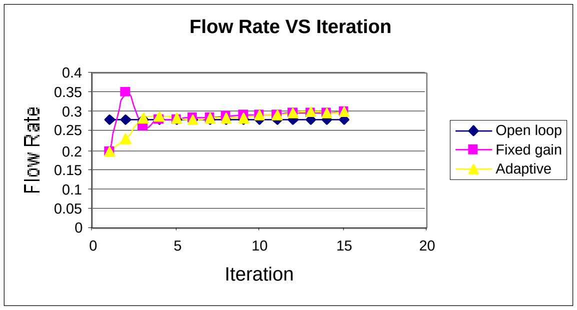

Figure 14. Flow rate vs iteration

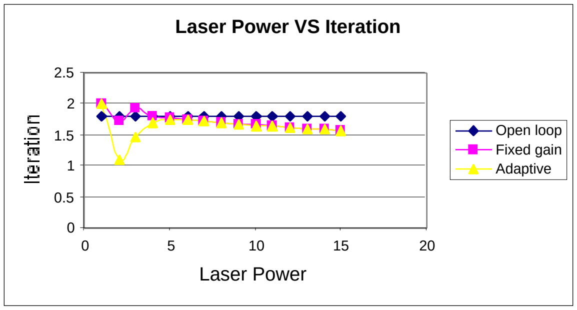

Figure 15. Laser power vs iteration

From the closed loop control architecture that has been discussed in previous section it can be understood that the parameters that are to be monitored continuously are bead width, bead height and dilution. Bead width can be measured on-line using an IR/visual image sensor. Bead height (or deposited layer height) can be potentially measured using laser displacement sensor. However, there is no off-the-shelf sensor for on-line measurement of dilution. Li et al [17] have proposed a dual frequency electromagnetic sensor for non-contact dilution calculation. However, the technique is not used widely. For the current research, we propose to model the control law based on melt pool temperature, which can be easily measured using two-color IR temperature sensor.

Conclusions

This paper reported some preliminary simulation results in order to address the problem of control of laser metal forming system being developed at Laser Aided Material Processing Laboratory at University of Missouri – Rolla. In this work, the parameters that influence the performance of the process are studied. Based on the empirical relationships reported earlier in the literature, architecture for on-line closed loop process control has been designed and simulated. The simulated results demonstrated the robustness and stability of the controller in the presence of unknown model dynamics and changing process parameters. The current modeling is based on the measurement of dilution. However since on-line measurement of dilution is difficult, an alternative control law based on bead height, bead width and melt pool temperature will be developed and implemented.

Acknowledgements

This research was supported by the National Science Foundation Grant Number DMI-9871185, Missouri Research Board, and a grant from the Missouri Department of Economic Development through the MRTC grant. Their support is appreciated.

References

[1] Yevkov V., Park C.B., Zak G., Coyle T.W. and Benhabib B., Cladding Formation in Laser-beam Fusion of Metal Powder. *Rapid Prototyping Journal,* Vol 4, no 4, 168-184 (1998).

[2] Dickens P.M., Pridham M.S., Cobb R.C. and Gibson I., 3D welding. *Proceedings of the First European Conference on Rapid Prototyping,* Nottingham, 81-4 (1992).

[3] Hartmann K., Krishhan R., Merz R., Neplotnik G., Prinz F.B., Shultz L., Terk M. and Weiss L.E., Robot-assisted shape deposition manufacturing. *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, Vol 4, IEEE, SanDiego, CA, 2890-5 (1994).

[4] Mah R., Directed light fabrication. *Advanced Materials and Processes*, Vol 151 no 3, 31-3 (1997).

[5] Griffith M.L., Keicher D.M., Atwood, C.L., Romero J.A., Smugeresky J.E., Harwell L.D. and Greene D.L., Free form fabrication of metallic components using laser engineered net shaping (LENS). *Solid Freeform Fabrication Conference Proceedings*, Austin, TX, 125-31 (1996).

[6] Koch J.L. and Mazumder J., Rapid prototyping by laser cladding. *Proceedings of International Conference on Applications of Lasers and Electro-Optics (ICALEO)*, Orlando, FL, 556-65 (1993).

[7] Murphy M.L., Steen W.M. and Lee C., The rapid manufacture of metallic components by laser surface cladding. *Laser Assisted Net Shape Engineering, Proceedings of the LANE'94,* Vol 2, October, Erlangen, 803-14 (1994).

[8] König W., Celiker T. and Song Y.-A., Process development for direct manufacturing of metallic parts. *Laser Assisted Net Shape Engineering, Proceedings of the LANE'94*, Vol 2, October, Erlangen, 785-92 (1994).

[9] Steen W.M., Laser chemical vapor deposition. *Ph.D. Thesis*, *Imperial* College,
London University (1976).

[10] Weerasinghe V.M., Computer simulation model for laser cladding. *Conference Proceedings of Transport Phenomena in Material Processing,* Vol 10, ASME, Nov (1983).

[11] Weerasinghe V.M., Laser cladding of flat plates. *Ph.D. Thesis*, Imperial College,
London University (1988).

[12] Chande T. and Mazumder J., Two-dimensional transient model for mass transport in
laser surface alloying. *Journal of Applied Physics,* Vol 57, March 2226-2232 (1985).

[13] Chande T. and Mazumder J., Composition control in laser surface alloying. *Metallurgical Transaction,* Vol 14b, June 181-190 (1983)

[14] Mazumder J. and Kar A., Solid solubility in laser cladding. *Journal of Metals,* Feb 18-23 (1987).

[15] Steen W.M., Weerasinghe V.M. and Monson P., Some aspects of formation of laser clad tracks. *Proceedings of SPIE Conference,* Innsbruck, Austria, Vol 650, April 226-234 (1986).

[16] Takeda and Steen W.Mstudy of mechanisms and parametric relationships of blown powder laser cladding. *Internal Report (Unpublished),* Imperial College (1986).

[17] Li and Steen W. Mstudy of mechanisms and parametric relationships of blown powder laser cladding. *Internal Report (Unpublished),* Imperial College (1986).