Direct 3D Layer Metal Deposition

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Abstract

Multi-axis slicing for solid freeform fabrication (SFF) manufacturing processes can yield non-uniform thickness layers, or 3D layers. Using the traditional parallel layer construction approach to build such a layer leads to a staircase which requires machining or other post processing to form the desired shape. This paper presents a direct 3D layer deposition approach. This approach uses an empirical model to predict the layer thickness based on experimental data. The toolpath between layers is not parallel; instead, it follows the final shape of the designed geometry and the distance between the toolpath in the adjacent layers varies at different locations. Directly depositing a 3D layer not only eliminates the staircase effect, but also improves the manufacturing efficiency by shortening the deposition and machining times. Experiments are conducted that demonstrate these advantages**.** Thus, the 3D deposition method is a beneficial addition to the traditional parallel deposition method.

Introduction

Laser Metal Deposition (LMD) is an important Solid Freeform Fabrication (SFF) technology based on three–dimensional laser cladding [1]. Such a technology allows direct fabrication of functional metal parts directly from CAD solid models. Thus, such a process can be used to build thin structures since the processing forces are low. It can also be used to repair parts, which reduces scrap and extends product service life.

Most metal rapid manufacturing systems involve a continuous supply of metallic materials injected into a melt pool created by a localized energy source. The material is melted and forms a melt pool which quickly solidifies. Parts are built to completion layer by layer, from bottom to top. The designed shape is typically approximated by a number of parallel layers. As a result, the "staircase" effect is unavoidable as shown in Figure 1. For the LMD process, machining is performed on the deposited part in order to obtain the desired dimensions. Unfortunately, this operation increases the overall production time. Research on the slicing procedure or path planning, such as controlling cusp height [2] or volumetric difference [3] between layers, attempts to minimize the amount of the staircase by finding the optimal layer thickness and the slicing locations.

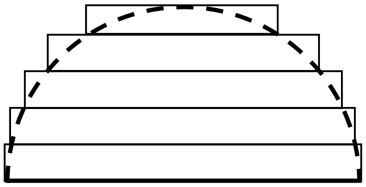
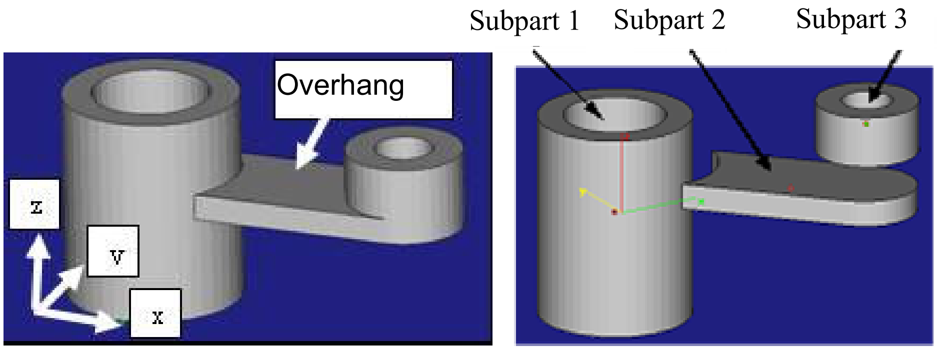


Figure 1. Stair case effect

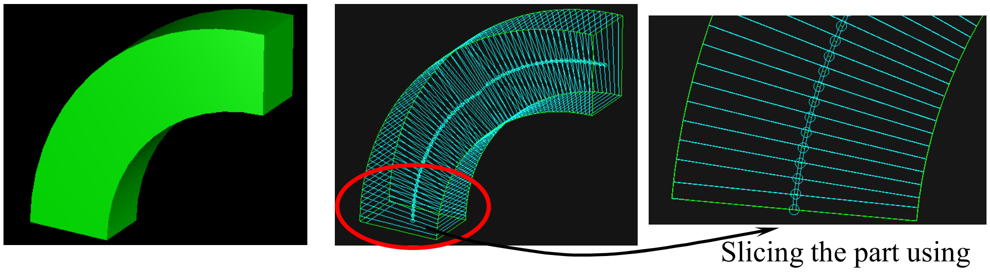
The multi-axis process has been the recent focus of LMD and various methods have been presented to meet the requirements for such a process. For example, to fabricate a metal part using deposition technology, one major issue is to build an overhang structure as shown in Figure 2(a),.A multi-axis process is needed so that the part can be built in three phases with different build directions and orientations. The part is decomposed into three subparts, one for each build direction as shown in Figure 2 (b), and the build sequence is subpart1, subpart2, and subpart3. The build directions for subparts are along the z-axis, x-axis, and z-axis, respectively. When parallel layers are deposited for complex shapes, the stair case effect always occurs. On the other hand, it is ideal to build the part by following the change of the shape. In order to achieve the objective, the deposition direction is changed to follow the geometry shape and the rotation capability in the deposition system can be fully utilized. The multi-axis slicing approach studied by the authors utilizes the skeleton-like shape to guide the slicing procedure [4]. This slicing procedure uses a 3D and parallel layers as needed. Figure 3 shows the slicing result of an overhang example



(a) A part with overhang to be built using metal deposition technology.

(b) The part needs to be decomposed into three subparts to be built.

Figure 2. An overhang example to be built by multi-axis LMD process



Slicing the part using 3D layers

(a) Solid model

(b) Multi-axis slicing

Figure 3. Overhang example

Unlike uniform thickness in the parallel layers, the thickness in 3D layers varies from location to location. Using a hybrid deposition/removal approach can achieve this objective as shown in Figure 4. However, this method involves two processes and is not efficient since manufacturing time is extended and some of the deposited material is removed.

Direct depositing a 3D layer is an ideal approach to form such a shape. This paper presents a direct 3D layer deposition technique with a focus on the thin-wall structure applications using a powder based metal deposition process.


(a) Deposit (b) Side milling to form the shape (c) Final overhang

Figure 4. The hybrid approach to build a 3D layer

Direct 3D Layer Deposition Planning

Laser power, mass flow rate and scanning speed are the three major parameters in LMD processes [5]. Some researchers have tried to develop an analytical model to predict the layer thickness. Pinkerton *et al.* [6] uses energy and mass balance to predict the melt pool geometry. The results show the difference between the experimental data and the predicted value is still relatively great. Due to the difficulty of finding a robust analytical model, an empirical model is built in this research and its prediction result is used to perform direct 3D metal deposition. As complicated as it is to change all majoring parameters to adjust the deposition height, the empirical model is very useful in finding the relationship between the deposition height and the major parameters. In order to simplify the situation, the laser scanning speed is adjusted in this study, while the laser power and powder flow rate are held constant.

Empirical Model Construction

The power, mass flow rate and travel speed are the major factors impacting the deposition height; therefore, different parameters for the deposition can yield different heights. Changing mass flow rate during the deposition involves recording the velocity profile in advance, accurately calculating the time constant, etc., which may lead to an imprecise variations. Therefore, the mass flow is kept constant using the controller developed by the authors. The study presented in this paper describes the technique of directly depositing a 3D layer as well as toolpath planning; thus, only the travel speed is varied during the deposition in order to simplify the problem.

To determine the model to predict layer height, a number of experiments were conducted using the Laser Aided Manufacturing Process (LAMP) system at Missouri S&T using and laser scanning speeds. Table 1 lists the important experimental parameters. The material is H13 tool steel. A regression model is generated using the experiment results.

Table 1. Deposition Parameters

Laser Power	Powder flow rate	Laser spot size	Speed (mm/s)	Height (mm)
850W	12 g/min	2.54 mm	4.23, 6.35, 8.47, 10.58	18.3, 14.7, 10.9, 6.35

A 5-layer single track deposition is performed for each laser scanning speed. The results are scanned using a 3D laser scanner (NEXTENGINE Desktop 3D scanner, Model 2020i) to determine the height. The height is obtained by averaging the data over the track. Figure 5 shows the result. The following empirical model is constructed.

$$H = 1.044 - 0.0735v \tag{1}$$

where H is the layer height (mm) and v is the scanning speed (mm/s)

The correlation coefficient is 0.9989. The error of the prediction using this model is within 6.7%. This model will be used to predict the layer height when generating the toolpath and speed profile to directly deposit a 3D layer. This model is valid for a single track deposition close to the substrate with a speed between 3.5mm/s to 12mm/s.

Toolpath Generation and Parameter Selection

Toolpath Generation

The research presented in this paper is focused on 3D layer deposition of thin-wall structures. A typical thin-wall structure is built using one or two track deposition, as illustrated in Figure 5; thus, the toolpath generation task is to find the nonparallel track path for each layer. Assuming that the maximum layer thickness which can be deposited is $L_{\max}$ and the minimum layer thickness is $L_{\min}$, the goal is to find the suitable paths which require the least amount of time to finish. The entire time to finish the deposition can be expressed.

$$T = \sum_{k=1}^{n} \frac{S_k}{V_k} \tag{2}$$

where S_k is the k$^{\text{th}}$ toolpath segment and speed V_k is the average laser scanning speed at segment S_k. The parameter T is entire time to finish the toolpath. The goal of the designed. toolpath is to minimize T. A free-form shape is shown in Figure 6. The highest point and lowest points are found by checking the distance between the top and the bottom boundaries. Let H_{max} and H_{min} be defined as the maximum and minimum heights, respectively. To eliminate the staircase effect, the toolpath has to follow the final shape of the part. For the case in Figure 6, the last toolpath is boundary C. The total number of deposition layers to finish this shape is bounded by

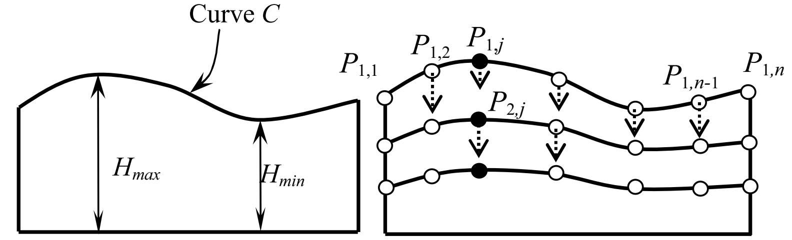
$$\left[{H_{\max}}/{L_{\max}} \right] + 1 \le n \le \left[{H_{\max}}/{L_{\min}} \right] + 1 \tag{3}$$

Let us assume that the minimum number of layers is selected to deposit the example shown in Figure 6. The curve on top can be approximated using a number of points as shown in Figure 6 (b). Let $P_{1,j}$ define the highest point on the top curve. The corresponding point $P_{2,j}$ next to $P_{1,j}$ along the deposition path is defined as

$$P_{i-1,j} = P_{i,j} - (H_{\max} / n) \bullet -\vec{D} \tag{4}$$

where $\overrightarrow{-D_z}$ is a unit vector along the negative Z direction.

For an arbitrary point on the curve, the same approach is applied; thus, the toolpath is defined from the top to the bottom. However, this method is different from a simple offset. Equal distances between each corresponding point on the adjacent paths avoid the rapid change in layer thickness within one layer.



(a) Highest and lowest distances (b) Toolpath generation

Figure 6. Toolpath generation for 3D layer deposition

Speed Selection

Once the toolpath is determined deposition parameters are defined for each toolpath segment. As discussed above, the research presented in this paper only considers adjusting the laser scanning speed. The model describing the layer height and the laser scanning speed are presented in Table 1 and Eq. 1, respectively. The model is obtained from the experimental results of deposited tracks using toolpaths that are parallel to the substrate. The toolpath is not parallel to the substrate, therefore, directly applying the model cannot provide correct layer height prediction. The slope of the toolpath has to be considered.

As shown in Figure 7 (a), the tangent of a point on a freeform surface can be determined. The small segment of the curve can be approximated by piece wise short lines with the same inclined angle α. The laser spot on the surface is not circular but instead it is an ellipse. Power density is

$$P_d = P / A \tag{5}$$

where P is the laser power and A is the area of the laser spot size (mm^2).

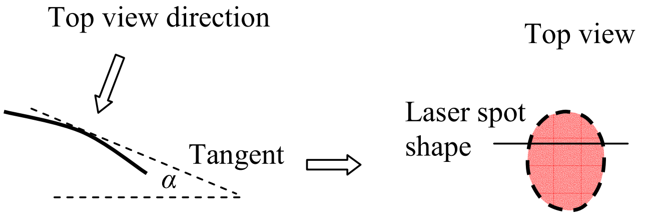
For a slope with an inclined angle α, the power density is

$$P_\alpha = P_d \cos\alpha \tag{6}$$

In order to maintain the same power density per time, the laser scanning speed is adjusted accordingly, assuming that the laser power is kept the same. Therefore the laser scanning speed is

$$V_\alpha = V_d \cos\alpha \tag{7}$$

where V_d is the laser scanning speed used in the model of Eq 1. and V_α is the speed for the slope with an inclined angle α.



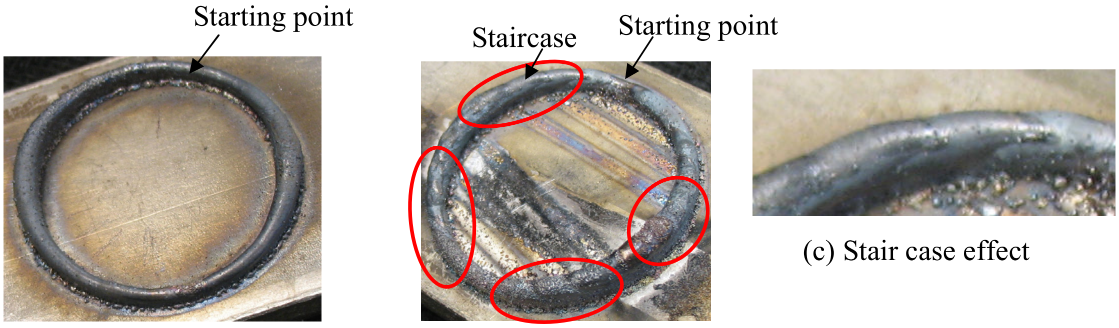
(a) Slope for a curved section

(b) Laser spot is changed

Figure 7. Laser spot on curve surface

Example

A circular part with a double sine curve has been deposited to demonstrate the direct 3D layer deposition approach discussed in this paper. Figure 8 (a) shows the part fabricated using the direct 3D layer deposition technique. The part shown in Figure 8(b) is built using the traditional parallel layer deposition technique. The staircase effect is marked by red circles. It clearly shows the top surface of the part in Figure 8(a) is much smoother than the top surface of the part shown in Figure 8(b). The final desired profile is shown in Figure 9 (a). Figure 9 (b) shows the toolpath for direct 3D layer deposition. The designed speed profile for the fourth track is shown in Figure 9(c). Figure 10 shows the measured height of two different depositions. It clearly shows the staircase effect in the deposited part using the parallel layers. The time for 3D layer deposition and the traditional approach to fabricate the example part is 3.17 min and 4.84 min, respectively. For this example, the efficiency is improved to 34.5% due the shorter toolpath.

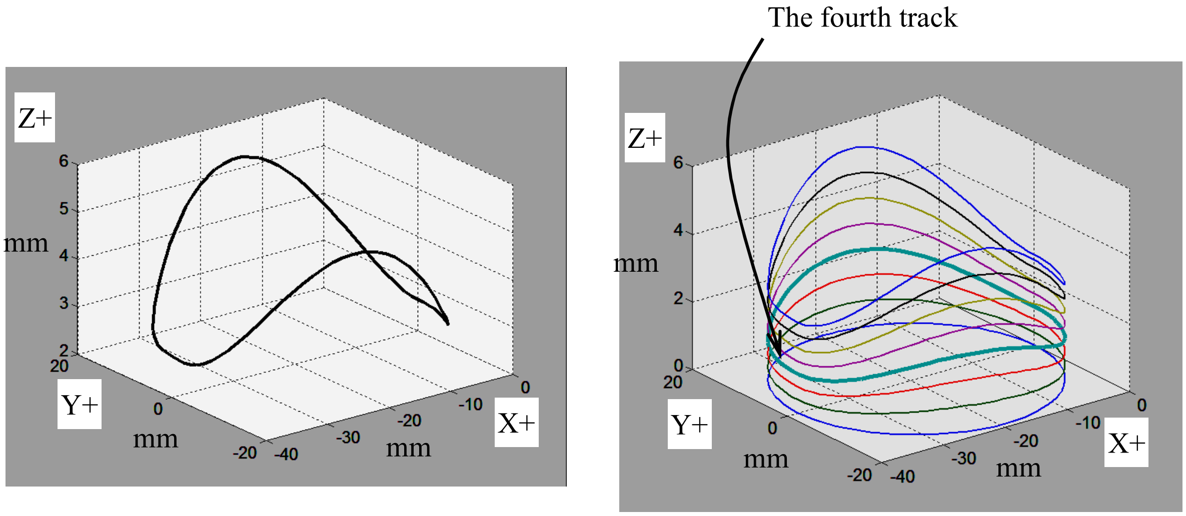


(a) Part built using direct 3D layer deposition

(b) Part built using traditional parallel layer deposition

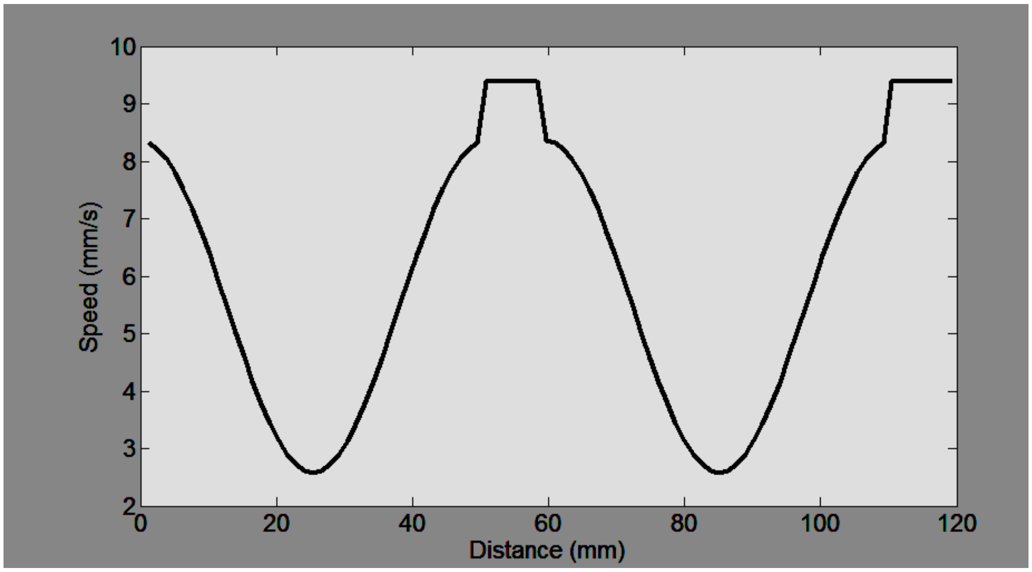
(c) Stair case effect

Figure 8. Double sine curve part deposited using both approaches



(a) Designed profile

(b) Toolpath for direct 3D layer deposition



(c) Defined laser scanning speed for the fourth track

Figure 9. Designed profile, toolpath and laser scanning speed for the part

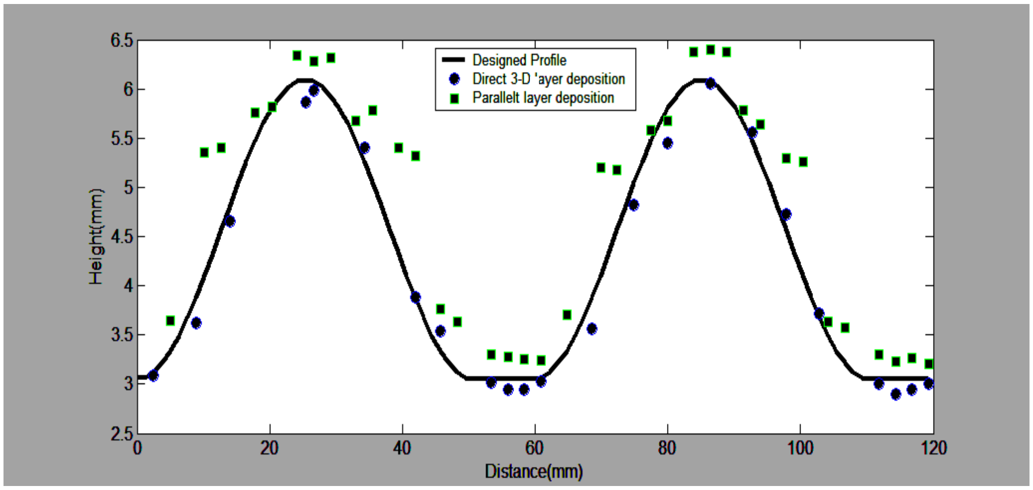


Figure 10. Height of designed profile and the deposition result using both approaches

The example shown in this work has demonstrated the efficiency and other advantages of this approach, which are summarized below:

- The staircase effect can be substantially reduced by depositing a 3D layer.
- The deposition efficiency can be dramatically improved by finding the optimal combination of speed and deposition height.

Direct 3D layer deposition is superior to traditional parallel layer deposition in fabricating freeform features. This technique yields a better final shape of the deposition. In addition, direct 3D layer deposition leads to a better deposition rate, thus, improving the overall efficiency by saving the deposition time as well. However traditional parallel layer deposition is still a great addition to the approach discussed in this paper.

Summary and Conclusions

This paper discusses an approach to directly deposit a 3D layer. An empirical model is presented to predict the layer height as a function of the laser scanning speed. Using this model, the toolpath for the 3D layer deposition and laser scanning speed profile are generated. Non-parallel toolpath generation allows the deposition to follow the geometry of a part more precisely, as compared to parallel deposition. An experiment has shown this approach has advantages over the traditional parallel layer deposition in constructing free-form shapes. The direct 3D layer deposition is beneficial to the multi-axis slicing/deposition. Using the direct 3D layer deposition technique enables the freeform part to be fabricated more accurately and more efficiently by eliminating the staircase effect and shortening the deposition and machining times. Furthermore, direct 3D layer deposition enables multi-axis deposition system to build complicated shapes such as overhangs and freeform parts more efficiently.

Currently, direct 3D layer deposition has been performed for single track (i.e. thin-wall) features. In the future, the research will be expanded to include 3D features. The effect of overlap and the track width will be incorporated in a future model and toolpath planning. Additionally, laser power adjustment can be an important tool in implementing 3D layer deposition. This will also be included in future work.

Acknowledgments

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Reference

[1] , J., 2002, "Process and Properties Control in Laser Aided Direct Metal/Materials Deposition Process", *Proceedings of IMECE*, New Orleans, Louisiana, November 17–22, pp. 1–9

[2] Dolenc, A. and Mäkelä, I., 1994, "Slicing procedures for layered manufacturing techniques," *CAD*, Vol. 26, Feb., pp.119-126.

[3] Yang, Y.; Fuh, J.Y.H.; Loh, H. T. and Wong, Y. S., 2003, "A volumetric difference-based adaptive slicing and deposition method for layered manufacturing", *Journal of Manufacturing and Science,* Vol.125, pp.586-594.

[4] Ruan, J.; Eiamsa-ard, K. and Liou F.W., 2005, "Automatic Process Planning and Toolpath Generation of A Multi-Axis Hybrid Manufacturing System," *SME Journal of Manufacturing Processes*, Vol.7, No.1, pp.57~68.

[5] Steen, W.., 1998, "Laser Material Processing", 2nd Ed., Springer

[6] Pinkerton, A. and Li, L., 2004, "Modelling the Geometry of a Moving Laser Melt Pool and Deposition Track via Energy and Mass Balances", *Journal of Physics D: Applied Physics*, Vol. 37, pp.1885-1895.