Direct Three-Dimensional Layer Metal Deposition

Jianzhong Ruan

Lie Tang

Frank W. Liou

Robert G. Landers

Department of Mechanical and Aerospace Engineering,
Missouri University of Science and Technology,
Rolla, MO 65409

Multi-axis slicing for solid freeform fabrication manufacturing processes can yield nonuniform thickness layers or three-dimensional (3D) layers. The traditional parallel layer construction approach to building such layers leads to the so-called staircase effect, which requires machining or other postprocessing to form the desired shape. This paper presents a direct 3D layer deposition approach that uses an empirical model to predict the layer thickness. 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 3D layers not only eliminates the staircase effect but also improves manufacturing efficiency by shortening the deposition and machining times. Simulation and experimental studies are conducted that demonstrate these advantages. Thus, the 3D deposition method is a beneficial addition to the traditional parallel deposition method.
[DOI: 10.1115/1.4002624]

Keywords: direct laser metal deposition, rapid prototyping

1 Introduction

Laser metal deposition (LMD) [1] is an important solid freeform fabrication (SFF) technology based on three-dimensional laser cladding. Similar to laser engineered net shaping (LENS) [2] and laser-based additive manufacturing (LBAM) [3], etc., LMD allows direct fabrication of functional metal parts from computer-aided design (CAD) solid models. Different from other laser metal deposition process, such as selective laser sintering (SLS) [4], the LMD-like processes are able to fabricate fully dense metal part directly from CAD models. Such technologies have been used to build thin structures since the processing forces are low. It can also be used to repair parts, thus reducing scrap and extending product service life.

Most metal rapid manufacturing systems involve a continuous supply of metallic material injected into a melt pool created by a localized energy source. The material melts and forms a melt pool that quickly solidifies. Parts are built layer by layer. The designed shape is typically approximated by a number of parallel layers. As a result, the so-called staircase effect is unavoidable, as illustrated in Fig. 1. For the LMD process, machining is performed after deposition 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 [5] or volumetric difference [6] between layers, attempts to minimize the staircase amount by determining the optimal layer thickness and slicing locations. However, these approaches are designed for fixed direction deposition processes and do not eliminate the staircase effect. The technique discussed in this paper seeks to eliminate the staircase effect by performing conformal shape deposition.

Multi-axis processing has been a recent focus of LMD, and various methods have been presented to meet the requirements for such a process. Most slicing approaches adopt the traditional parallel slicing approach and simply rotate the slicing direction 90 deg when an overhang structure occurs [7]. Although these methods provide a feasible solution, the staircase effect still remains. Furthermore, these methods cannot be applied to some cases since collision may occur when rotating the slicing direction 90 deg. For the part shown in Fig. 2(*a*), the building directions using the projection approach are illustrated in Fig. 2(*b*). Instead of turning the slicing direction 90 deg, the slicing direction is rotated as needed, as shown in Fig. 3. The slicing result generates a number of nonuniform thickness layers or 3D layers to fit the freeform shape, as shown in Fig. 2(*c*). In a 3D layer, the thickness varies at different locations.

This paper presents a study on directly depositing 3D layers by changing the layer thickness along the toolpath within one layer to fit the slicing result for the multi-axis slicing approach in this paper. An empirical model is developed to predict the layer thickness. The toolpath is generated based on the height change within a 3D layer. Instead of using a parallel toolpath scheme, the authors researched a nonparallel toolpath to directly form a 3D layer with a set of suitable deposition parameters along the toolpath.

This paper is organized as follows: In Sec. 2, the related work is summarized. The experimental setup is briefly discussed in Sec. 3. The deposition experiments and the empirical model construction are presented in Sec. 4. The nonparallel toolpath generation strategy is discussed in Sec. 5. A 3D layer deposition example and discussion are presented in Sec. 6. This paper is concluded in Sec. 7.

2 Related Work

As discussed above, in current LMD processes, the layer thickness within a single layer is constant. Most research in this area is focused on regulating laser power, mass flow rate, and laser scanning speed to maintain a constant deposition height [1,3]. This technique matches well with the traditional rapid prototyping (RP) slicing approach.

The multi-axis slicing approach studied by the authors utilizes the skeletonlike shape to guide the slicing procedure [8]. This slicing procedure uses either a 3D layer or a parallel layer, as needed. Following the slicing results, the deposition process fabricates a shape that is closer to the desired geometry. As the 3D layer is a critical issue in multi-axis slicing processes, directly fabricating 3D layers plays an important role in advancing multi-axis LMD processes.

Some studies have conducted research to directly build 3D layers using the LMD process or hybrid process, which integrates the LMD and machining processes in a single workstation. Hua [9] presented an approach to control the layer height by adjusting the laser power. This method uses the information gathered by two image cameras along the toolpath to determine the track height and change the laser power accordingly. A fuzzy control model is developed to vary the laser power and demonstrate the possibility of changing the deposition height within one track. However, this approach is direction dependent and is limited by the number of cameras mounted around the nozzle.

The authors developed a 3D layer construction approach by using a hybrid manufacturing system [10]. A 3D layer is formed by machining the extra material on a uniform thickness deposition layer. An overhang structure was built using this approach. Al-

Contributed by the Manufacturing Engineering Division of ASME for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received August 20, 2009; final manuscript received September 22, 2010; published online November 1, 2010. Assoc. Editor: Wei Li.

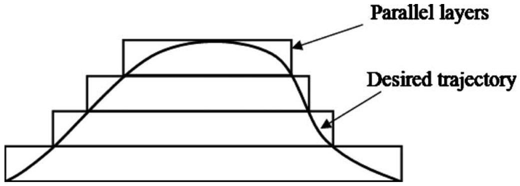

Fig. 1 Staircase effect of parallel layer deposition

though the hybrid manufacturing method can deliver a part built using 3D layers, the machined material is wasted. Thus, this method reduces overall efficiency.

Laser power, mass flow rate, and scanning speed are the three major process parameters affecting the LMD process [11]; therefore, different process parameters for the deposition can yield different heights. Some researchers have tried to develop an analytical model to predict the layer thickness given these process parameters. Pinkerton and Li [12] used energy and mass balance to predict the melt pool geometry. The results show that the difference between the experimental data and the predicted values is still relatively great. Due to the difficulty of finding a robust analytical model, an empirical model will be constructed in this study and will be used to perform a direct 3D layer metal deposition. Changing mass flow rate during the deposition involves recording the velocity profile in advance, accurately calculating the powder delivery system time constant, delay period, etc. Constantly varying the powder flow rate to change height is very challenging. Therefore, the mass flow is kept constant using the controller developed in Ref. [13].

3 Powder-Based LMD Process

The laser aided manufacturing process (LAMP), a hybrid manufacturing system integrating LMD and traditional machining processes, has been developed at Missouri University of Science and Technology (Missouri S&T). The LAMP system includes the following components:

- power source: Coherent Inc. (Santa Clara, CA), diode laser (model ISL-1000M)
- motion system: Fadal 3016L five-axis CNC machine
- powder delivery system: Bay State Surface Technologies (Wilmington, MA) (model 1200)
- cladding head: Precitec (Gaggenau, Germany) (model KG YC50) includes a coaxial nozzle and focusing lens

During deposition, the laser is focused to a small spot (approximately 2.5 mm in diameter) on the substrate by an optical system to achieve a high power density and to form a melt pool. The powder is heated while traveling through the laser beam and is injected into the melt pool where it is melted. When the laser moves away from the location, the melt pool solidifies. During this process, the laser interacts with the material (powder and substrate) and builds a shape. A powder flow control model for LAMP has been researched and developed at Missouri S&T to maintain a steady mass supply as needed [13]. This control system was adopted in this research to achieve consistent powder flow.

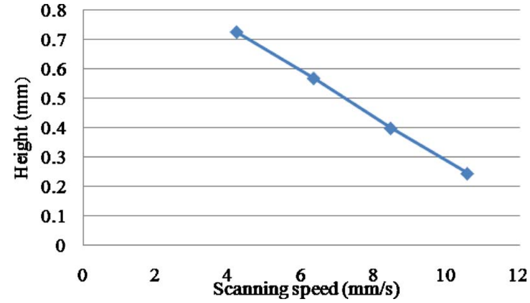

Fig. 3 Experiment result relating track height to scanning speed given a laser power of 850 W and a powder flow rate of 12 g/min

4 Empirical Model Construction

4.1 Experiment. The study presented in this paper describes the technique of directly depositing a 3D layer as well as toolpath planning. All three major process parameters can be adjusted to change the deposition result as previously discussed. However, changing the powder feed rate usually results in a delay, making it difficult to perform in-process control. Simply changing laser power without varying powder feed rate and laser scanning speed can only lead to a small change in layer height. Thus, in this research, laser scanning speed is selected as the process parameter to adjust in order to obtain a quick and efficient change in deposition height. To determine the layer height prediction model, a number of experiments were conducted on the LAMP system using different laser scanning speeds. Table 1 lists the experimental parameters. The material is H13 tool steel and the mean particle diameter is approximately 100 μm. A regression model is generated using the experimental results. The scanning speeds are 10 in./min (4.23 mm/s), 15 in./min (6.35 mm/s), 20 in./min (8.47 mm/s), and 25 in./min (10.58 mm/s). The range is selected based on previous deposition experiments. With a laser power of 850 W and a powder flow rate of 12 g/min, a sound deposition cannot be obtained when the laser scanning speed is over 30 in./min. When the laser scanning speed is below 5 in./min, too much powder is fed into the melt tool, which also leads to a poor deposition result.

4.2 Regression Model. A five-layer single track deposition experiment is performed for each laser scanning speed. The tracks are measured 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 3 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 and the prediction

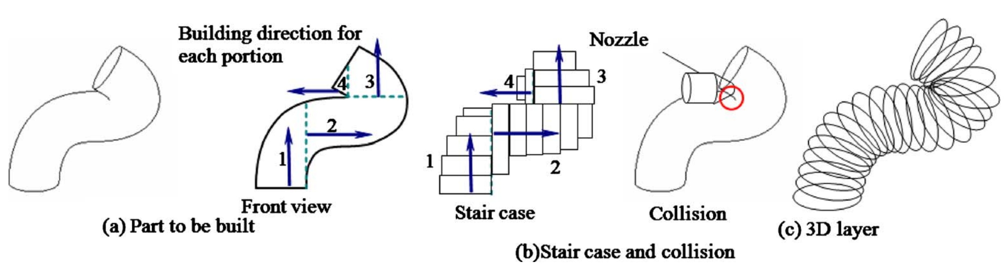

Fig. 2 Slicing example using traditional and 3D layer approaches

Table 1 Deposition parameters to construct empirical height model

Laser power (W)	Powder flow rate (g/min)	Laser spot size (mm)	Scanning speed (mm/s)
850	12	2.54	4.23, 6.35, 8.47, 10.58

error using this model is within 6.7%. This model will be used to predict the layer height when generating the toolpath and scanning speed profile to directly deposit 3D layers. This model is good for a single track deposition close to the substrate. The model is only valid for scanning speed from 4.23 mm/s to 10.58 mm/s.

5 Toolpath Generation and Deposition Parameter Selection

5.1 Toolpath Generation. The research presented in this paper focuses on 3D layer deposition of thin-wall structures. Typical thin-wall structures are built using one or two track deposition, as illustrated in Fig. 4. The toolpath generation task is to find the nonparallel track path for each layer. Assuming the maximum layer thickness that can be deposited is $L_{\max}$ and the minimum layer thickness that can be deposited is $L_{\min}$, the goal is to find suitable paths that minimize the processing time. The time required to finish the deposition is

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

where S_k is the kth toolpath segment length, v_k is the laser scanning speed at kth toolpath segment, and n is the number of toolpath segments. The goal of the designed toolpath is to minimize T. A freeform shape is shown in Fig. 5. The highest 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 part heights, respectively. The total number of deposition layers (L_n) to finish this shape is bounded by

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

The minimum number of layers is selected to minimize the deposition time. This strategy is performed to deposit the example shown in Fig. 5. The toolpath is generated by propagating the top curve to the surface on which the deposition is performed. The

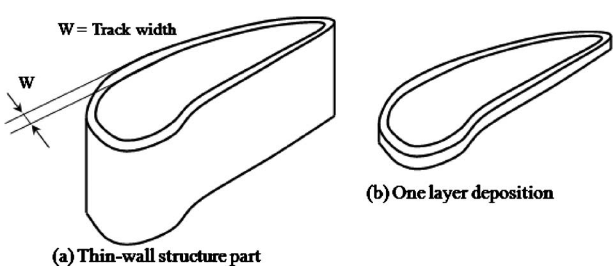

Fig. 4 Thin-wall structure example

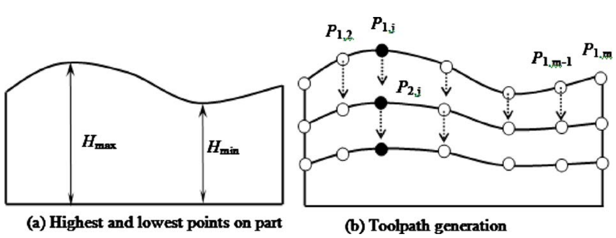

Fig. 5 Toolpath generation for 3D layer deposition

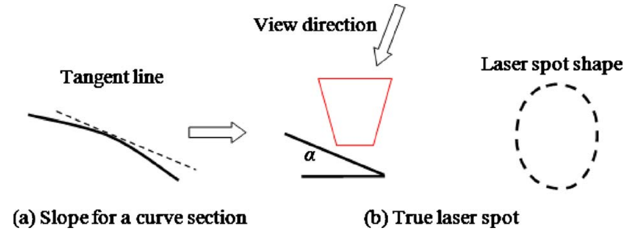

Fig. 6 Laser spot on curved surface

thickness of each layer is also changed to accommodate the curvature change in each path. The curve on top can be approximated using a number of points, as shown in Fig. 5(*b*). Let $P_{i,j}$ define the jth point on the ith curve from the top. For example, $P_{1,j}$ defines points on the top curve and $P_{n,i}$ define points on the bottom curve. Assuming the points on the top curve and the bottom curves have been identified, point $P_{i,j}$ is

$$P_{i,j} = P_{1,j} - [(P_{1,j} - P_{n,j}) \cdot j/L_n] \tag{4}$$

This method is different from a simple offset. In a simple offset approach, the distance between tracks on adjacent layers is the same. In the study discussed in this paper, the distance between points on adjacent layers is changed according to local geometry to reduce the curvature variation of each layer.

5.2 Parameter Selection. Once the toolpath is set, the deposition parameters are defined for each toolpath segment. As discussed above, the research presented in this paper only considers adjustments in laser scanning speed. The model describing the relationship between the layer height and the laser scanning speed is given in Eq. (1). The model is obtained from the experimental results of deposited tracks using toolpaths that are parallel to the substrate. As illustrated in Fig. 6, general toolpaths are 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 Fig. 6(*a*), the tangent of a point on a freeform surface can be determined. The small segment of the curve can be approximated by a short line with the same inclined angle α. The laser spot on the surface is not circular; instead, it is an ellipse. In this research, the laser power is uniform spatially. The power density is

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

where P is the laser power and A is the laser spot size area (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 unit time, the laser scanning speed is adjusted accordingly, assuming the laser power remains constant. Therefore, the laser scanning speed is

$$v_\alpha = v_d \cos(\alpha) \tag{7}$$

where v_d is the laser scanning speed used in Eq. (1) and v_α is the scanning speed for a slope with an inclined angle α. As the toolpath is composed of a number of piece wise segments, Eqs. (5)–(7) can be applied for each small segment.

6 Example and Discussion

6.1 Example. A circular part with a double sine curve is deposited to demonstrate the direct 3D layer deposition approach discussed in this paper. The radius r is 19.05 mm. The laser power is 850 W and the powder flow is 12 g/min. A total of 8 layers are deposited. The track profile of the double sine curve for each layer is

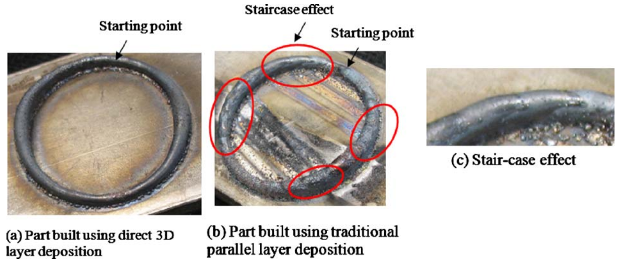

Fig. 7 Double sine curve part deposited using both approaches

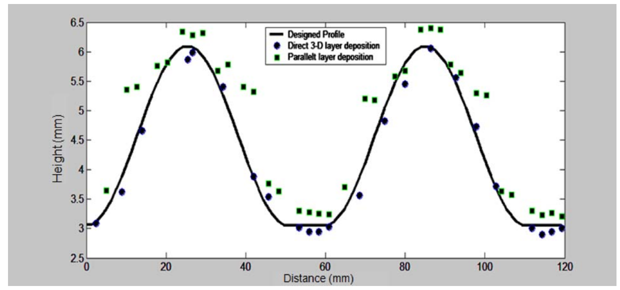

Fig. 9 Height of designed profile and deposition results using both approaches

$$H_i = 0.33 \cdot i \cdot [1 + \sin(1.5\pi + \varphi)] \tag{8}$$

where $i = 1, \ldots, 8$ and π is 3.1415926 rad or 180 deg, and φ is the phase of the wave. Figure 7(*a*) shows the part fabricated using the direct 3D layer deposition technique. The part shown in Fig. 7(*b*) is built using the traditional parallel layer deposition technique. The staircase effect is marked by circles. It clearly shows that the top surface of the part in Fig. 7(*a*) is much smoother than the top surface of the part shown in Fig. 7(*b*). The final desired profile is shown in Fig. 8(*a*). Figure 8(*b*) shows the toolpath for direct 3D layer deposition. The designed speed profile for the fourth track is shown in Fig. 8(*c*). Figure 9 shows the measured height of the two different depositions. It clearly shows the staircase effect in the deposited part using parallel layers. The time for the 3D layer deposition and the traditional approach to fabricate the part are 3.17 min and 4.84 min, respectively. For this example, the efficiency is improved by 34.5%. The surface roughness is the same as a typical meal deposition process and is between 90 μm and 120 μm. The powder waste rate is about 50–60%.

Figure 10 shows the height difference between the deposition and the target height using the two deposition approaches. The average error for the 3D layer deposition is 0.13 mm and the average error for the parallel layer deposition is 0.44 mm. For the parallel layer deposition, the greatest errors occur at the steps between layers. Usually, the error is the layer thickness. The 3D layer deposition technique produces a much smaller error due to its deposition strategy of following the desired shape. However, errors still exist due to the limitation of the deposition system such as inconsistencies in powder flow rate, inconsistent scanning speed, etc. The purpose of direct 3D layer deposition is to shorten the deposition time and to obtain better part quality. The example discussed above demonstrates these characteristics.

6.2 Discussion. As the total manufacturing time is the sum of the manufacturing time for each toolpath segment as described in Eq. (2), the two toolpath schemes are compared when depositing a simple nonuniform track. The track can be defined by an angle (α) and a length (L), as shown in Fig. 11. Given a relationship between deposition height and laser scanning speed $H = f(v)$, the table speed required to finish a defined height is

$$v = f^{-1}(H) \tag{9}$$

The height along the track is

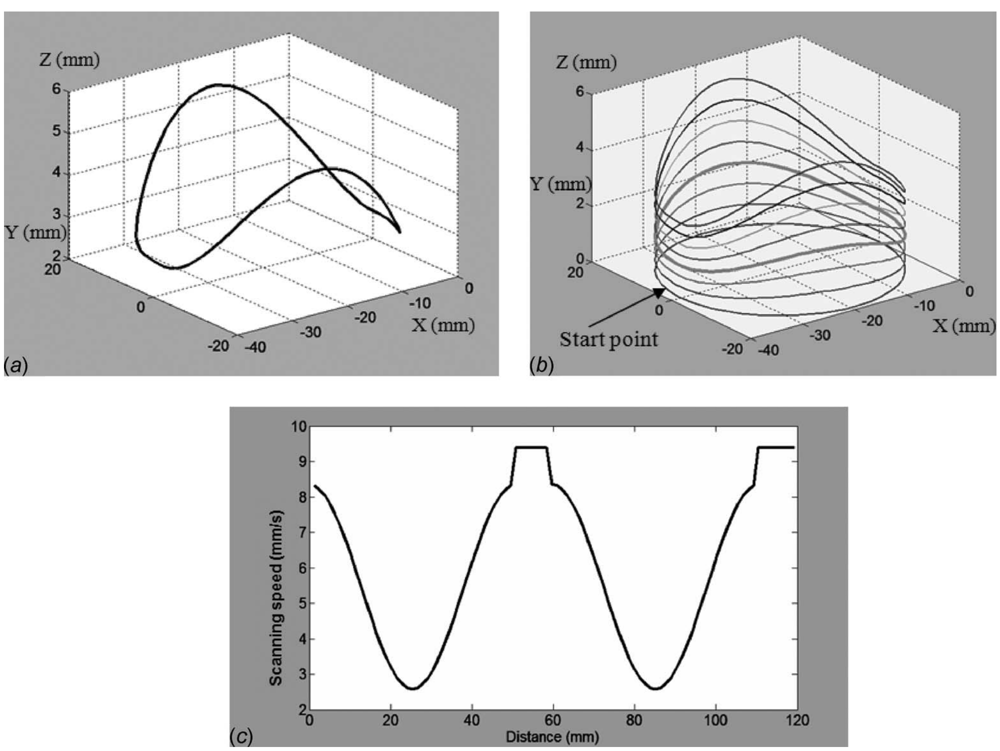

Fig. 8 Designed profile, toolpath, and laser scanning speed for a freeform shape: (*a*) designed profile, (*b*) toolpath for direct 3D layer deposition, and (*c*) defined scanning speed for fourth track

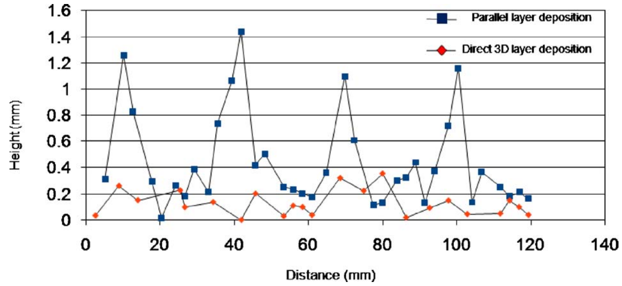

Fig. 10 Height difference between measured and target values for both deposition approaches

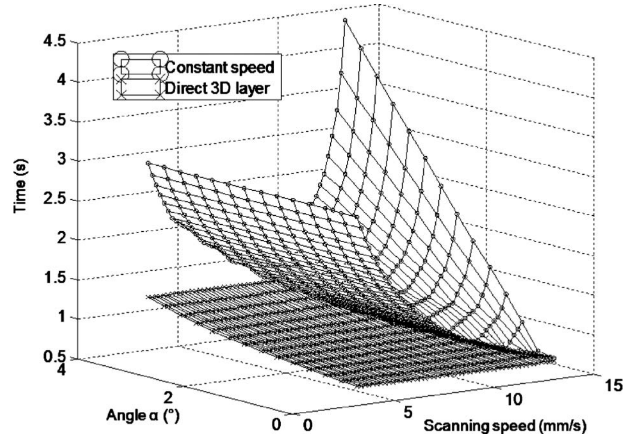

Fig. 12 Deposition time used by two deposition approaches for different cases

$$h = l\,\tan(\alpha) \tag{10}$$

The time to finish the track using 3D layer deposition technique described in Fig. 11 is

$$T = \int_0^L dl/f^{-1}(l\,\tan\,\alpha) \tag{11}$$

The time to finish the track shown in Fig. 11 using tradition parallel layer deposition technique is

$$T = \sum_{i=1}^{n} \frac{L-(i-1)\cdot f(v)/\tan(\alpha)}{v} \tag{12}$$

where v is the constant scanning speed and $n=[l\cdot\tan(\alpha)/f(v)]$. For parallel layer deposition, the fabrication time is a function of scanning speed (v). The faster the speed is, the less time is required to finish one layer. However, the deposition layer is also thinner, which means that possibly, more layers are needed to deposit the shape shown in Fig. 11. Figure 12 shows the relationship between deposition time and scanning speed using the two approaches. In this figure, the time required to finish the 3D layer deposition is independent of scanning speed. The track length is 10 mm. For a track with a greater height change (i.e., larger α), it is clearly shown that the direct 3D layer thickness technology is superior to the traditional parallel deposition technique. With a smaller angle, the advantage is not obvious since a faster scanning speed is used to perform the constant speed deposition and one layer deposition is sufficient; thus, less time is required to deposit the track using the traditional parallel layer deposition.

The example shown in this work has demonstrated the following advantages of the direct 3D deposition approach:

- The staircase effect can be substantially reduced.
- The deposition efficiency can be dramatically improved.

On the other hand, the 3D layer deposition technology is still a layered manufacturing technology that uses discrete layers to represent the geometry. The error due to the nature of layered manufacturing cannot be totally eliminated. For some cases, the 3D layer deposition technology has to be incorporated with the traditional layer deposition. For example, when the height change

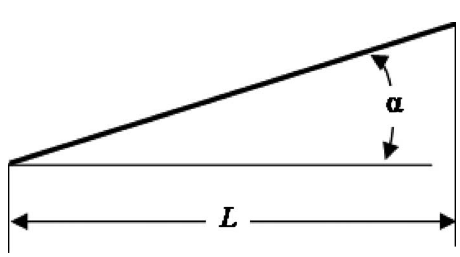

Fig. 11 Segment of a freeform curve toolpath

within one layer is greater than the deposition height range of a system, the traditional layer deposition will be applied to fabricate such geometry shape. The height prediction error is highly dependent on the deposition system. This paper is focused on the 3D layer slicing and deposition. The layer thickness control, which can be accomplished by a sensor or by using a machining operation [14], is out of the scope of this paper.

Compared to the traditional parallel slicing, the 3D slicing method is still a relatively new technology that requires a deposition parameter-height model. The slicing algorithm can be implemented automatically. However, an empirical model to predict the deposition height is constructed. With the development of metal deposition and the simulation tool, an accurate height prediction model can be obtained and the fully automated 3D slicing can be achieved. The 3D slicing technology brings unique features that make it superior to the traditional parallel slicing in the following scenarios:

- *The parts with top freeform surfaces:* For these parts, the 3D slicing can yield a better surface quality and shorten the fabrication time.
- *The gradually changed overhang structures:* For these geometry shapes, the 3D slicing method can overcome the overhang angle limitation and can provide a unique solution to fabricate these shapes with the metal deposition process.
- *Part with many slope surfaces:* For these shapes, 3D slicing method can totally remove the staircase effect, which dramatically improves the shape accuracy.

7 Summary, Conclusions, and Future Work

This paper presented an approach to directly deposit 3D layers in laser-based manufacturing processes. An empirical model is presented to predict the layer height as a function of the laser scanning speed for a single track deposited near the substrate. Using this model, the toolpath for the 3D layer deposition and scanning speed profile are generated. Nonparallel toolpath generation allows the deposition to follow the geometry of a part more precisely, as compared to parallel layer deposition. An experiment has shown that this approach has advantages over traditional parallel layer deposition in constructing freeform shapes. Direct 3D layer deposition is beneficial to multi-axis slicing/deposition. Using the direct 3D layer deposition technique enables freeform parts to be fabricated more accurately and more efficiently by eliminating the staircase effect and shortening the deposition time. Another advantage of the 3D layer deposition technique is that less material needs to be removed by finishing process thus, further decreasing fabrication time and extending tool life. Furthermore, direct 3D layer deposition enables multi-axis deposition systems to build complicated shapes, such as overhangs and free-form parts, more efficiently.

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

Acknowledgment

This research was supported by the National Science Foundation Grant Nos. DMI-9871185 and IIP-0637796 and a grant from the U.S. Air Force Research Laboratory Contract No. FA8650-04-C-5704. Support from Boeing Phantom Works, Product Innovation and Engineering, LLC, Spartan Light Metal Products Inc., Missouri S&T Intelligent Systems Center, and the Missouri S&T Manufacturing Engineering Program is also greatly appreciated.

References

[1] Choi, J., 2002, "Process and Properties Control in Laser Aided Direct Metal/Materials Deposition Process," Proceedings of IMECE, New Orleans, LA, Nov. 17–22, pp. 1–9.
[2] Griffith, M. L., Keicher, D. M., Atwood, C. L., Romero, J. A., Smegeresky, J. E., Harwell, L. D., and Greene, D. L., 1996, "Free Form Fabrication of Metallic Components Using Laser Engineered Net Shaping (LENS)," Solid Freeform Fabrication Symposium, Austin, TX, Aug. 12–14, pp. 125–131.
[3] Hu, D., Mei, H., and Kovacevic, R., 2001, "Closed Loop Control of 3D Laser Cladding Based on Infrared Sensing," Solid Freeform Fabrication Symposium, Austin, TX, Aug. 6–8, pp. 129–137.
[4] Agarwala, M., Bourell, D., Beaman, J., Marcus, H., and Barlow, J., 1995, "Direct Selective Laser Sintering of Metals," Rapid Prototyping J., **1**(1), pp. 26–36.
[5] Dolenc, A., and Mäkelä, I., 1994, "Slicing Procedures for Layered Manufacturing Techniques," CAD, **26**, pp. 119–126.
[6] 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," ASME J. Manuf. Sci. Eng., **125**, pp. 586–594.
[7] Singh, P., and Dutta, D., 2001, "Multi-Direction Slicing for Layered Manufacturing," ASME J. Comput. Inf. Sci. Eng., **1**, pp. 129–142.
[8] Ruan, J., Sparks, T., Panackal, A., Liou, F. W., Eiamsa-ard, K., Slatter, K., Chou, H., and Kinsella, M., 2007, "Automated Slicing for a Multiaxis Metal Deposition System," ASME J. Manuf. Sci. Eng., **129**, pp. 303–310.
[9] Hua, Y., 2004, "Adaptive Layer Process Control of Laser Aided Direct Metal/Material Deposition Process," Ph.D. thesis, Missouri University of Science and Technology, Rolla, MO.
[10] Ruan, J., Eiamsa-ard, K., and Liou, F. W., 2005, "Automatic Process Planning and Toolpath Generation of a Multi-Axis Hybrid Manufacturing System," J. Manuf. Process., **7**(1), pp. 57–68.
[11] Steen, W., 1998, *Laser Material Processing*, 2nd ed., Springer, New York.
[12] Pinkerton, A., and Li, L., 2004, "Modeling the Geometry of a Moving Laser Melt Pool and Deposition Track via Energy and Mass Balances," J. Phys. D: Appl. Phys., **37**, pp. 1885–1895.
[13] Tang, L., Ruan, J., Landers, R. G., and Liou, F. W., 2008, "Variable Powder Flow Rate Control in Laser Metal Deposition Processes," ASME J. Manuf. Sci. Eng., **130**(4), p. 041016.
[14] Tang, L., Ruan, J., Sparks, T. E., Landers, R. G., and Liou, F. W., 2009, "Layer-to-Layer Height Control of Laser Metal Deposition Processes," American Control Conference, St. Louis, MO, Jun. 10–12.