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A Smooth Toolpath Generation Method for Laser Metal Deposition

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Abstract

Laser metal deposition (LMD), also known as direct metal deposition (DMD) or laser engineered net shaping (LENS), which uses a laser beam to form a melt pool on a metallic substrate, into which powder or wire is fed. The conventional contour and zigzag toolpath pattern for LMD are discontinuous at turn points or corner points. The discontinuous toolpath causes uneven deposition, which brings height variation and porosity problems. This paper aims to develop a smooth toolpath generation method for LMD to improve the deposition quality. A parametric curve equation based on trigonometric functions is derived and built. It can be used for arbitrary smooth connections or transitions in toolpath planning and provide constant feedrate for deposition. The proposed method was applied to a patch deposition experiment and a component repair experiment with Ti-6Al-4V powder. The experimental results show that the smooth toolpath can noticeably improve the dimensional accuracy and surface roughness and reduce porosity.

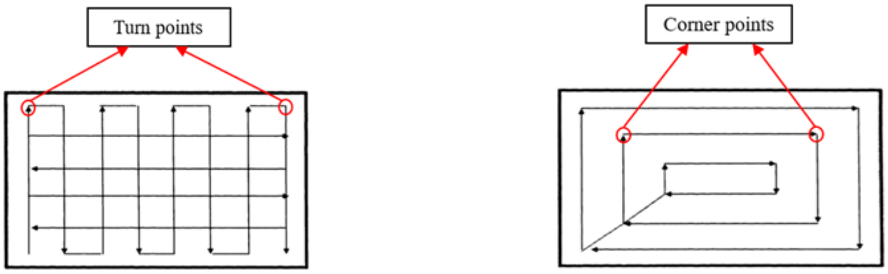
Keywords: Laser metal deposition; Toolpath generation; Additive manufacturing.

1. Introduction

Additive manufacturing (AM) is defined by ASTM F42 Technical Committee as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. Traditional manufacturing processes require analysis of the part geometry to determine the order in which different features can be fabricated and if tools and fixtures may be needed. In contrast, AM technology significantly simplified the process of producing complex 3D objects directly from CAD data and needs only some basic understanding of how the AM machine works, the materials that are used to build the part, and dimensional details [2]. Directed energy deposition (DED) is an additive manufacturing process in which focused thermal energy (e.g., laser, electron beam, or plasma arc) is used to fuse materials by melting as they are being deposited [1]. Laser metal deposition (LMD), also known as direct metal deposition (DMD), direct laser deposition (DLD), laser engineered net shaping (LENS) or laser cladding, is a laser based DED process which uses a laser beam to form a melt pool on a metallic substrate, into which powder or wire is fed [3].The applications of the LMD process include the fabrication of complex geometry parts without support structures such as thin-walled structures and overhauling parts; Functionally graded material (FGM) [4] parts with multiple powder hoppers with different materials; repairing for high value components like turbine blades, engine combustion chambers, and etc.

For the AM process to be widely accepted by the industry, the ability of predictable, repeatable, consistent, uniform fabrication is critical. The building process-structure-property relationships modeled and integrated with CAD/E/M tools for each material and process are needed. The quality of material produced by AM is closely related to the topology and fairness of deposition paths. A poorly planned path often results in voids or gaps between adjacent passes or layers [5]. Commonly, there are two main toolpath planning strategies in AM technology: the zigzag toolpath pattern and contour offsetting toolpath pattern [6], as shown in Fig.1. There is discontinuity both in the zigzag path pattern and the contour offsetting path pattern, and it may cause overfilling at turn points and uneven surface during deposition [7]. Due to the discontinuity of the zigzag path pattern and contour offsetting path pattern, the nozzle undergoes acceleration and deceleration at the turning points (i.e., decelerate the nozzle to zero speed at the turn point and accelerate to the predefined speed from the turn point). As Fig. 2 shows, the feedrate change at a turn point or corner point is correlated with the angle between adjacent path segments with the assumption that keep the constant federate value. The change of the vector feedrate f is $2f*\sin(\alpha/2)$, where f is the feedrate, and α is the angle between the current path segment and the extension of the previous segment. Therefore, the non-smooth path pattern may cause overfilling or vibration at the turn points or the corner points from the beginning of the acceleration process to the end of the deceleration process. For repair, it may also cause uneven surface and porosities at the boundary between deposited area and base material [8, 9]. The discontinuity problem that also exists in pocketing milling, especially for high-speed machining (HSM), was discussed in the papers [10-12]. Arc or bi-arc segments were used to connect or transit the zigzag toolpath or contour-offsetting path for pocking milling. However, arc segments might not be robust enough for arbitrary toolpath connection or transition in AM toolpath planning.

This paper aims to develop a smooth toolpath generation method for LMD to improve the deposition quality. In order to improve the evenness of adjacent passes or layers, the focus of this work is to find a general solution to realize any kinds of connection or transition for 2D/3D deposition toolpaths and get an entire smooth toolpath.



(a) Zigzag toolpath pattern (b) Contour offsetting toolpath pattern

Fig. 1: Two main toolpath planning strategies in AM

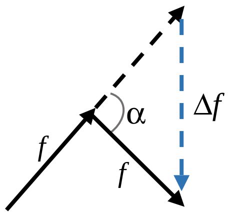


Fig.2: Feedrate change at turning/corner points

2. Smooth toolpath generation method

This section will firstly discuss and define the discontinuous problem in toolpath planning of AM and then derive a general solution according to the problem definition. Smooth toolpath examples will be given by applying the proposed method.

2.1 Problem definition and solution

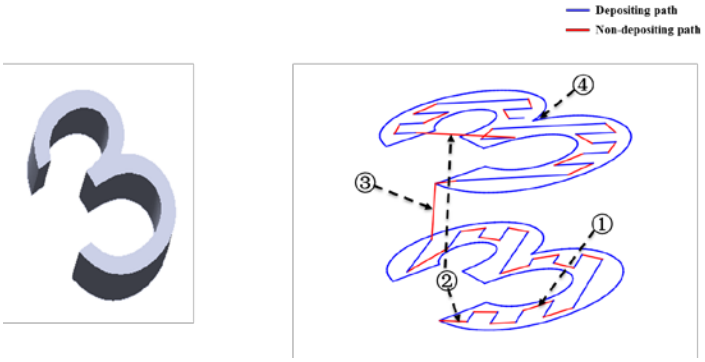
The discontinuous problem happens in the turn points or corner points in the toolpath planning. Because the zigzag toolpath pattern and the contour offsetting toolpath pattern are two main toolpath planning strategies, an example of an outside contour toolpath with an inner zigzag toolpath example shown in Fig. 3 is presented to analyze different types of connection or transition that need to be dealt with. As shown in Fig. 3 (a), there is a 3D model of the number ‘3’ with several corner points at the contour. Conventional contour and zigzag toolpaths are generated according to the slice of the 3D model. As shown in Fig. 3 (b), there are four types of connections or transition discussed as follows:

(1) Connection between zigzag toolpath as shown at position ①. Turn points existed from depositing path to non-depositing path and vice versa. Linear connection makes the zigzag toolpath discontinuous.

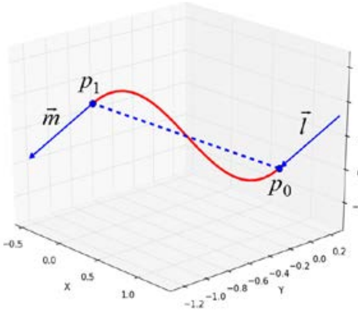
(2) Connection of toolpath elements as shown at position ②. It is usually impossible to fill up a layer with only one piece of zigzag toolpath or contour toolpath when handling complex shapes. After the generation of sub-paths, these sub-paths need to be connected or contour toolpaths need to be connected with zigzag paths.

(3) Connection of adjacent layers as shown at position ③. When finished with the current layer manufacturing, the nozzle needs to be moved to the next layer.

(4) Transition of corner points for contour toolpath as shown at position ④. Corner points happen in the non-smooth contour toolpath; it needs a smooth transition to avoid discontinuous problems.



(a) 3D model (b) Contour toolpath and zigzag toolpath for AM



(c) General definition

Fig.3: Problem definition of discontinuous toolpath in AM

As Fig. 3 (c) shows, the connection or transition problem can be generally defined as building a curve instead of linear connection to connect arbitrary start point p_0 with travel direction $\vec{l}$ and end point p_1 with travel direction $\vec{m}$. The curve also should share common tangent direction with travel direction $\vec{l}$, $\vec{m}$ at the joint points p_0, p_1. When $p_0 \neq p_1$, it is connection problem; otherwise, it is transition problem. A parametric curve equation described in Eq. (1) is derived and built based on three trigonometric functions and three vectors to provide a general solution for smooth connection or transition.

$$\vec{s}(t) = \vec{p} + f(t) * \vec{u} + g(t) * \vec{v} + l(t) * \vec{w} \tag{1}$$

where $\vec{p}$ is the start point p_0; the parameter of the curve is $t \in [0, \pi/2]$; the three trigonometric functions are $f(t) = \sin(t)$, $g(t) = 1 - \cos(t)$, $l(t) = (1 - \cos(2t))/2$; the three vectors are $\vec{u} = r * \vec{l}$, $\vec{v} = r * \vec{m}$, $\vec{w} = p_1 - p_0 - r * \vec{l} - r * \vec{m}$; and r is the scale coefficient to control the size of the curve. There are four main properties of this parametric curve equation:

(1) The parametric equation satisfies the problem definition: when $t = 0$, $\vec{s}(0) = p_0$ and $\vec{s}\,'(0) = \vec{l}$; when $t = \pi/2$, $\vec{s}(\pi/2) = p_1$, $\vec{s}\,'(\pi/2) = \vec{m}$.

(2) The parametric curve is C^n continuous and meets with the depositing toolpath with C^1 continuity [13].

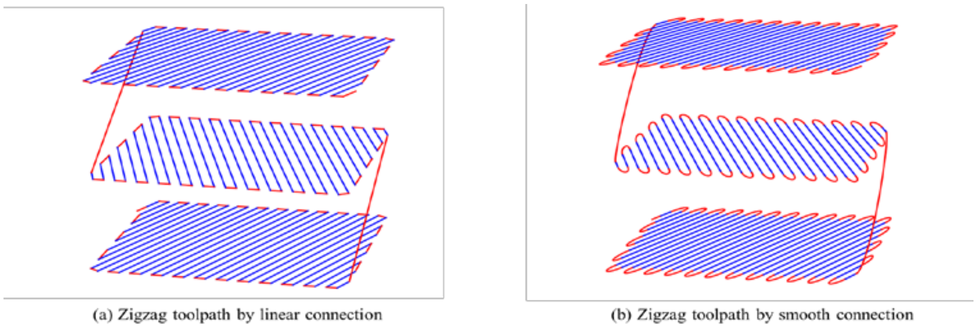
(3) When scale parameter r is 0, the curve equation becomes a linear equation.

(4) When $p_0 \neq p_1$, it is connection curve; when $p_0 = p_1$, it is transition curve.

Mathematically, the connection or transition of a conventional toolpath is C^0 continuous. The parametric curve generated by Eq. (1) has infinite derivatives, which is C^n continuous and meets with the depositing toolpath at the joint point with C^1 continuity. As discussed before, the feedrate change at a turn point or a corner point depends on the angle between adjacent path segments in the conventional zigzag toolpath or contour toolpath. Using the smooth curve, the angle between adjacent path segments at a turn point or a corner point is close to zero after interpolation. Therefore, the smooth toolpath offers a constant speed for the depositing toolpath. The scale parameter r in the three vectors of Eq. (1) can control the size of the curve, which can potentially provide adaptive idle time for each single path during the deposition. The parametric curve is a robust, flexible, and efficient solution for arbitrary 2D/3D toolpath connection or transition.

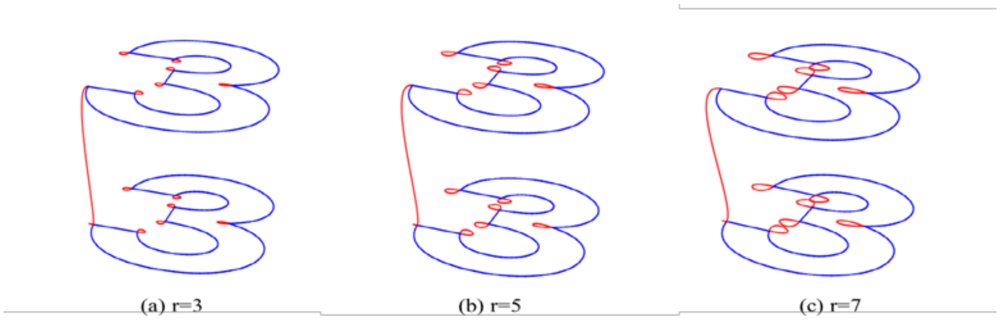
2.2 Smooth toolpath examples

This subsection gives smooth toolpath examples generated by the proposed method. A smooth zigzag toolpath example is generated for a patch deposition as shown in Fig. 4 (b), compared with a conventional non-smooth toolpath as shown in Fig. 4 (a). A smooth curve is adopted to connect each single path in each layer and adjacent layers (the blue line represents the depositing toolpath and the red line represents the non-depositing toolpath). The raster direction of adjacent layers changed to get interlaced zigzag toolpath and to shorten the travel time from current layer to the next layer. A smooth transition toolpath example for contour toolpath is shown in Fig. 5. Smooth transitions for corner points and smooth connections between connective layers are obtained using the proposed smooth toolpath generation method. Different transition curve sizes are defined corresponding to the different scale coefficients described in Fig. 5 (a), (b), and (c). The smooth toolpath generation method is also applied to optimize the toolpath generation for a component repair. As shown in Fig. 6 (a), there is a hole defect in the component. The defect area is scanned to get point cloud as described in Fig. 6 (b). Then, the convex hull algorithm is used to obtain the slices and the toolpath, which includes the outside contour toolpath and the inside zigzag toolpath can be generated by the raster toolpath generation method [8]. Fig. 6 (c) shows the optimized toolpath by smooth connection and transition.


(a) Zigzag toolpath by linear connection

(b) Zigzag toolpath by smooth connection

Fig. 4: Smooth toolpath pattern for laser metal deposition


(a) r=3

(b) r=5

(c) r=7

Fig. 5: Contour toolpaths by smooth transition with different curve size

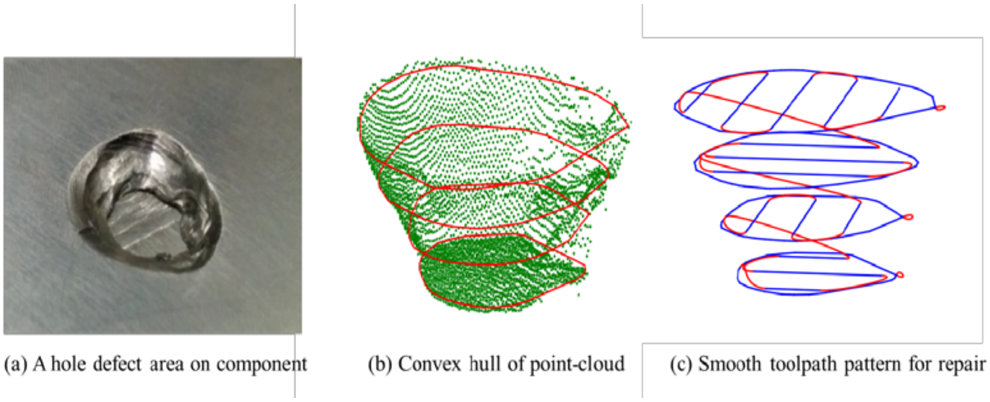

(a) A hole defect area on component (b) Convex hull of point-cloud (c) Smooth toolpath pattern for repair

Fig. 6: Optimized toolpath using smooth toolpath generation for repair

3. Simulations and Experiments

Deposition experiments were implemented at Missouri S&T laser-aided manufacturing process (LAMP) lab using the LMD system, which consists of an argon-purged chamber, a 1 kW Nd-YAG fiber laser, a side nozzle powder feeder, and 3-axis numerical control work table. Fig. 7 shows the experimental set-up of the LAMP LMD system.

A patch deposition experiment using Ti-6Al-4V powder was implemented to demonstrate the difference using the smooth zigzag toolpath and the non-smooth zigzag toolpath described in Fig. 4. The metal powder used for this experiment is Ti-6Al-4V alloy with a size distribution of -60 +120 mesh. It has a chemical composition of 6.33% aluminum, 4.1% vanadium, 0.17% iron, 0.19% oxygen, and the remainder is titanium. The parameters for the patch deposition are shown in Table 1 and the parameters are chosen according to previous deposition tests. As shown in Fig. 8, the deposition experimental results demonstrate that the surface roughness and dimensional evenness is noticeably improved using the smooth zigzag toolpath compared with the non-smooth zigzag toolpath. During the deposition, the toolpath come out for non-depositing movement (instead of moving along the deposited edge) and then come in for depositing movement. It avoids add more powders to the melt pool on the edge. The smooth parametric curve provides smooth transition from the depositing path to the non-depositing path. In other words, it provides constant deposition feedrate for the depositing toolpath to reduce the height variation causes from feedrate change. Another experiment using smooth toolpath is for component repair, hybrid manufacturing process which integrates LMD process with CNC machining process is adopted to repair a hole defect. As Fig.9 (a) shows, there is a hole defect on a Ti-6Al-4V component. After scanning, the deposition toolpath is generated and described in Fig. 6 (c). Fig. 9 (b) shows the deposition result after filling the defect area, and Fig. 9 (c) shows the result after machining and polishing. The repair experiment results show that there are no obvious porosities inside the deposition area or at the boundary between base material and deposition material using the optimized toolpath.

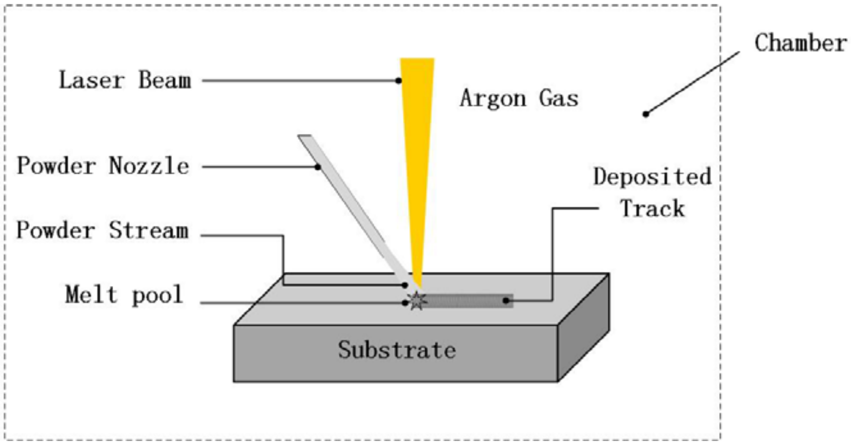


Fig. 7: Schematic of the MST-LAMP LMD system

Parameter	**Value**
Power feed rate	20 g/min
Traverse speed	600 mm/min
Deposition power	1.0 kw
Layer thickness	0.15 mm
Track width	2.0 mm
Overlap	0.5

Table 1: Parameters for patch deposition

(a) Deposition with non-smooth zigzag toolpath (b) Deposition with smooth zigzag toolpath

Fig. 8: Experimental results by smooth toolpath generation for laser metal deposition

(a) A hole defect on component (b) After deposition (c) After machining and polishing

Fig. 9: Repair experimental results

Parameter	Value
Power feed rate	20 g/min
Traverse speed	1000 mm/min
Preheat power	0.7 kw
Deposition power	1.0 kw
Layer thickness	0.035 mm
Track width	2.0 mm
Overlap	0.5

Table 2: Parameters for repair experiment

4. Conclusion

In this paper, a smooth toolpath generation method is proposed for laser metal deposition. A parametric curve equation based on trigonometric functions is built to provide general solution for smooth connection or transition. Compared with arc or bi-arc solution, the parametric curve solution in this paper is a robust, flexible, and efficient solution for arbitrary 2D/3D toolpath connection or transition. It provides constant feedrate for depositing toolpath. Meanwhile, the scale coefficient of the curve also makes the curve size controllable. Experiments were implemented for a patch deposition experiment and a component repair experiment with Ti-6Al-4V metal powder. The experimental results show that the smooth toolpath pattern can noticeably reduce porosity and improve the dimensional accuracy and surface roughness for laser metal deposition.

Acknowledgments

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