

# Sectoral Path Planning for Selective Laser Melting of Workpieces with Variable-Thickness

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**Abstract.** Metal additive manufacturing demonstrates unique advantages in fabricating complex workpieces. However, if the wall of the workpiece is non-uniform, it is difficult to prevent the risk of cracking, especially for selective laser melting. In this paper, a sectoral scanning strategy for the workpiece with non-uniform wall thicknesses is proposed to address the challenges. Firstly, the thin and thick regions are partitioned automatically using medial axis transform and Otsu's algorithm; Secondly, transition regions are identified through a statistic method with the intention to optimize the stress distribution; At last, differentiated scanning paths are tailored for different regions. A path planning result for a non-uniform wall thickness component model is given to show the result the proposed methodology.

**Keywords:** Selective laser melting; Path planning; Region partition; Non-uniform wall thickness; Sectoral scanning.

## 1. Introduction

As a paradigm of digital manufacturing, metal additive manufacturing (AM) enables precise transformation from 3D models to physical parts through technologies including computer-aided design, precision motion control, and layer-wise fabrication [1,2]. Nevertheless, current research on workpieces with non-uniform wall thickness remains notably deficient, particularly in scan path planning, resulting in mechanical property inhomogeneity, deformation and even cracking. To address these issues, a sectoral path planning algorithm proposed in this paper.

## 2. Medial Axis Transform

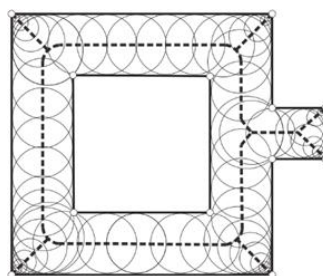


Fig. 1 The medial axis of a region bounded by two polygons.

The Medial Axis Transform (MAT), first introduced by Blum<sup>[3]</sup>, is a fundamental geometric descriptor as illustrated in Fig. 1., The medial axis is defined as the locus of centers of maximally inscribed spheres (or circles in 2D) within a geometric shape. This technique has been widely applied in various fields, including computer vision<sup>[4]</sup>, image processing<sup>[5]</sup>, and collision detection<sup>[6]</sup>. Current MAT computation methods can be broadly classified into two categories: (1) exact algorithms, such as domain decomposition approaches<sup>[7]</sup>; and (2) approximate algorithms, Constrained Delaunay Triangulation (CDT)- based method<sup>[8]</sup>.

In this paper, we employ a CDT-based method to generate more accurate MAT<sup>[9]</sup>. Firstly, the STL model is sliced to extract contours as shown in Fig. 2(a). Secondly, the contour is triangulated, and Steiner points are added to refine the mesh as shown in Fig. 2(b). Then, the triangles are

classified, and medial axis point is computed for each triangle. At last, the approximate MAT as shown in Fig. 2(c) is constructed by connecting the medial axis points according to the adjacency of the triangles.

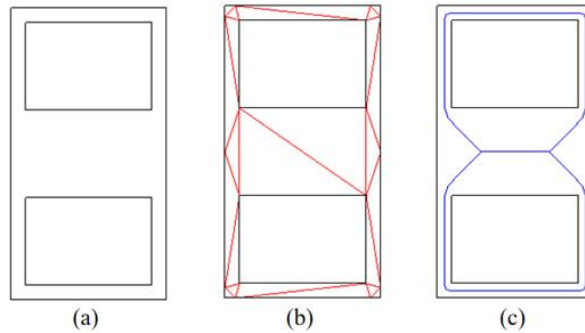


Fig. 2 Approximate medial axis of a region bounded by three polygons.

### 3. Partitioning Strategy

#### 3.1 Thin-Thick Region Segmentation

In order to segment the region bounded by several polygons into thin and thick regions automatically, we must determine a threshold for the thin and thick regions. In this paper, Ostu’s algorithm is employed to the threshold adaptively. Firstly, the medial axis is sampled to construct the thickness histogram of the region as shown in Fig. 3. Then, a threshold for the thin and thick regions can be determined using Ostu’s algorithm.

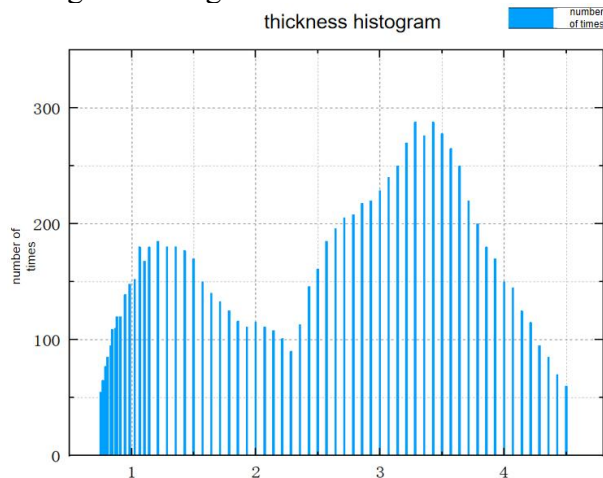


Fig. 3 Thickness histogram of the contour of a slice.

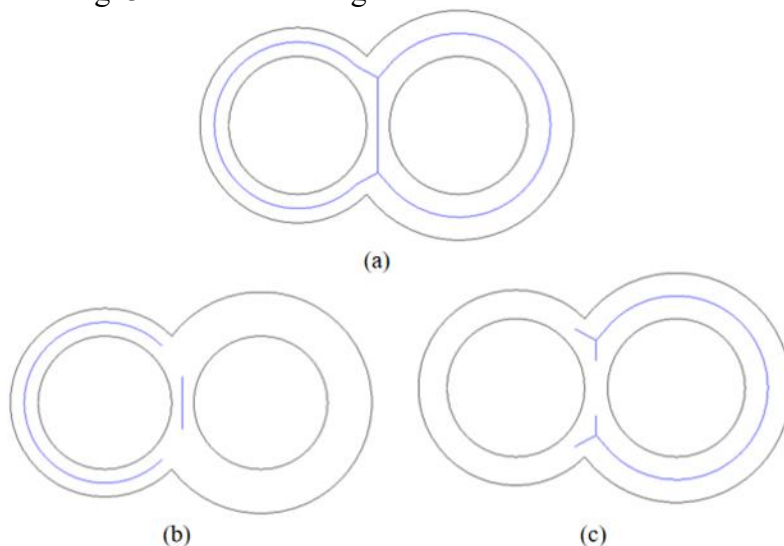


Fig. 4 Thin and thick region segmentation results

A segmentation result is shown in Fig.4. The medial axis of a region bounded by three polygons is shown in Fig. 4(a), and the medial axis is segmented into several parts with the threshold. The parts of the medial axis corresponding to the thin region is shown in Fig. 4(b), and the parts of the medial axis corresponding to the thick region is shown in Fig. 4 (c).

### 3.2 Transition Region Generation

The application of different scanning strategies in thin-wall and thick-wall regions may induce stress concentration at their interfaces. In this paper, a transition region is introduced between the thin and thick regions to minimize the adverse effect.

The transition region is generated using a region-growing method. The boundary points between the thin and thick parts of the medial axis are selected as seed points. Then, the region-growing method is applied on the segmented medial axis to generate a transition region.

Obviously, we can evaluate the variation of the local shape using the radius associating with the medial axis point. There are more significant local shape variations in a region with larger variance of the radius associating with the medial axis points vice versa.

Dual statistic tests are employed to terminate the transition region generation process, i.e. Levene's test for variance homogeneity ensuring shape consistency, followed by Wilcoxon rank-sum test for thickness uniformity verification.

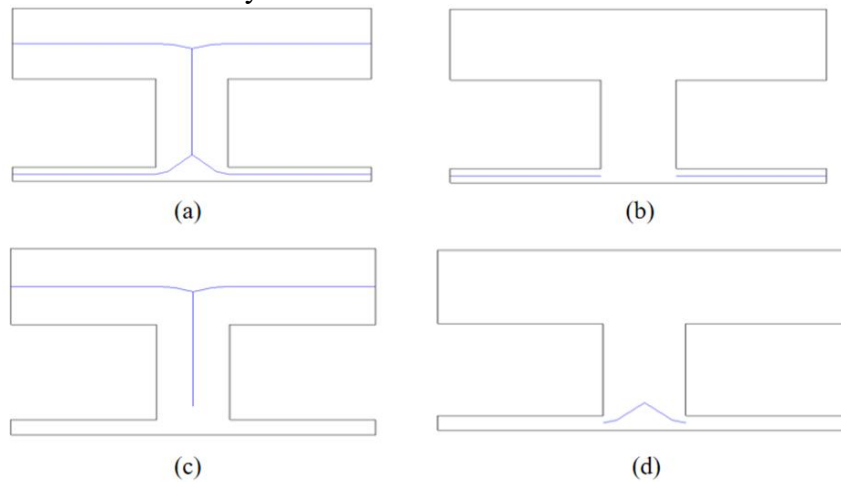


Fig. 5 The final medial axis segmentation result.

Given the non-normal distribution characteristics of the medial axis segment radius dataset, the median-centered Levene's test is adopted to verify variance homogeneity between adjacent segments. The test statistic is constructed as:

$$W = \frac{(N - k)}{(k - 1)} \cdot \frac{\sum_{j=1}^k n_j (\bar{D}_j - \bar{D})^2}{\sum_{j=1}^k \sum_{i=1}^{n_j} (D_{ji} - \bar{D}_j)^2} \quad \#(1)$$

where  $N$  is the total sample size,  $k$  is the number of groups,  $n_j$  is the sample size of the group  $j$ ,  $D_{ji}$  is the absolute deviation of the data of the group from the median, and  $\bar{D}_j$  is the mean deviation within the group. When the  $p$  value is greater than 0.05, it is considered that the adjacent sections have morphological consistency.

As a non-parametric test method, Wilcoxon rank sum test is formulated as:

$$W = \sum_{i=1}^{n_1} R(Y_{1i}) - \frac{n_1(n_1 + 1)}{2} \#(2)$$

where,  $R(Y_{1i})$  represents the rank of the  $Y_1$  sample in the merged sequence. By comparing the rank distribution of the two groups of axial radius data, the null hypothesis is accepted when the  $p > 0.05$ , and it was considered that there was no significant difference in the thickness distribution.

The final result is shown in Fig. 5. Given the medial axis shown in Fig. 5 (a), it is segment into parts corresponding to thin regions as shown in Fig. 5(b), and thick regions as shown in Fig. 5(c), and transition regions as shown in Fig. 5(d). After obtaining the three central axes, we draw the tangent points of the two contour edges at the boundary points of the buffer central axis segment with the central axis radius of that point. Then, by connecting the boundary points with the tangent points, the slice can be divided into three regions.

#### 4. Scanning Path

In this paper, a slice is decomposed into regions with thin and thick wall thickness, and transition regions. For the regions with thin and thick wall thickness, a sawtooth pattern is employed to generate the local, and a triangular mesh pattern is employed to generate the local path. Additionally, a contour path precisely following the whole boundaries of the slice is employed to improve the surface finish. A shortest path connecting all local paths and the contour path is generated at the end to get the path for the slice.

##### 4.1 Sawtooth Path

The sawtooth path utilizes short scan vectors and alternating scan directions to reduce residual stress.

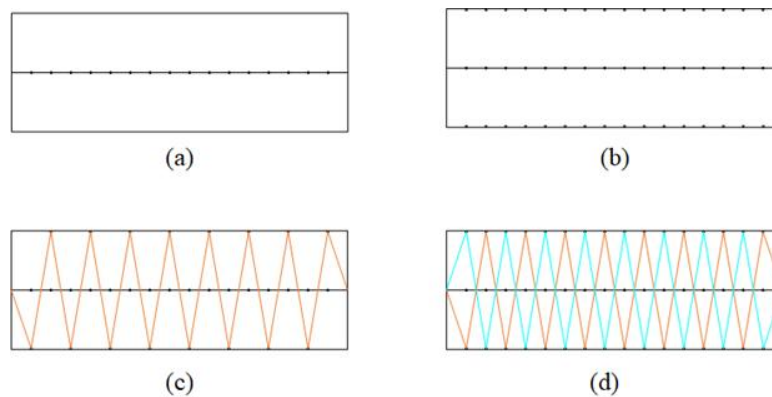


Fig. 6 Sawtooth path generation

As illustrated in Fig. 6, the sawtooth path generation involves three steps: (a) MAT generation as shown in Fig. 6(a), followed by (b) uniform distribution of sampling points along MAT segments at adjustable intervals, where perpendicular lines are constructed to intersect with the contour as path points as shown in Fig. 6(b). Then we can generate the path by alternatively connecting the peak and valley points to obtain either single-sawtooth path as shown in Fig. 6(c) or double-sawtooth path as shown in Fig. 6(d). For the region with thin wall thickness, single-sawtooth path is generated. For the region with thick wall thickness, double-sawtooth path is generated. Therefore, the slice is locally remelted to improve the density and reduce residual stress as well.

### 4.2 Triangular Mesh Path

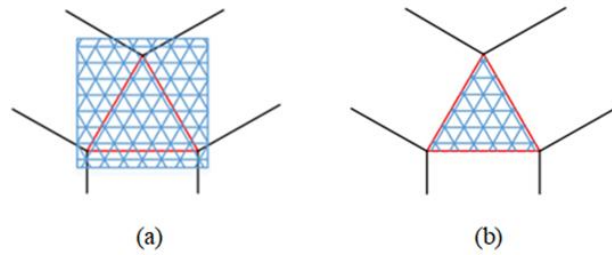
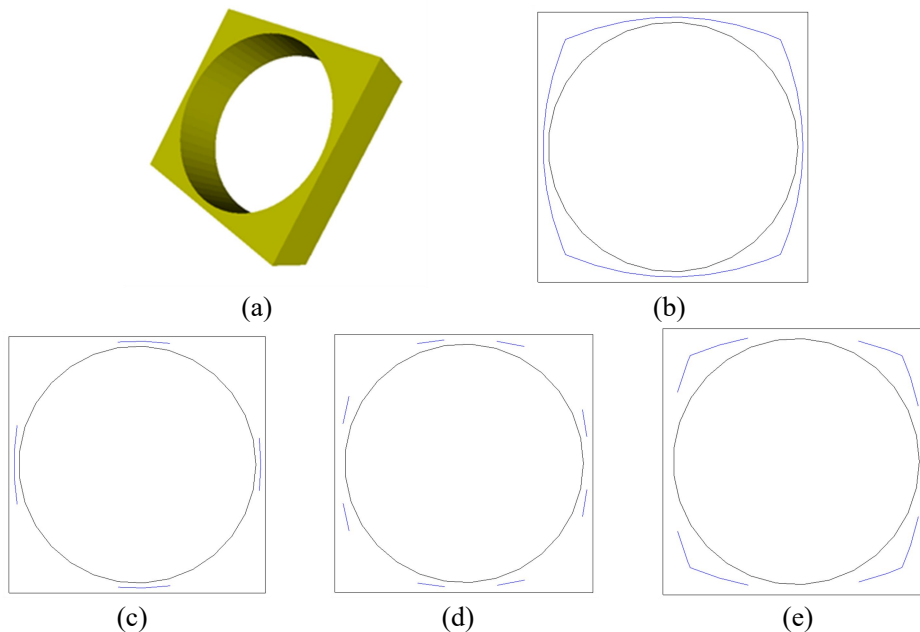


Fig. 7 Triangular mesh path generation

For the triangular mesh pattern, three scanning directions ( $0^\circ$ ,  $60^\circ$ , and  $120^\circ$ ) within the same layer are employed as shown in Fig. 7(a) to alleviate residual stress and improved the density. Firstly, a triangular mesh template that fully encloses the transition region is generated as shown in Fig. 7(a).; Secondly, the template is trimmed with the boundary of the transition region to obtain the local path as shown in Fig. 7(b)<sup>[10]</sup>.

### 4.3 Results

Taking the model with non-uniform wall thickness shown in Fig. 8(a) as an example, the process begins with slicing the 3D model, followed by computing an approximate medial axis as shown in Fig. 8(b). The medial axis is segmented into parts corresponding to thin regions (Fig. 8(c)), transition regions (Fig. 8(d)), and thick regions (Fig. 8(e)). Then, the slice can be divided into several regions according to the medial axis segmentation result as shown in Fig. 8(f). Region-specific path planning strategies are applied i.e. dual-sawtooth paths for thick regions, triangular mesh path for transition regions, and single-sawtooth paths for thin regions, and the result is shown in Fig. 8(g).



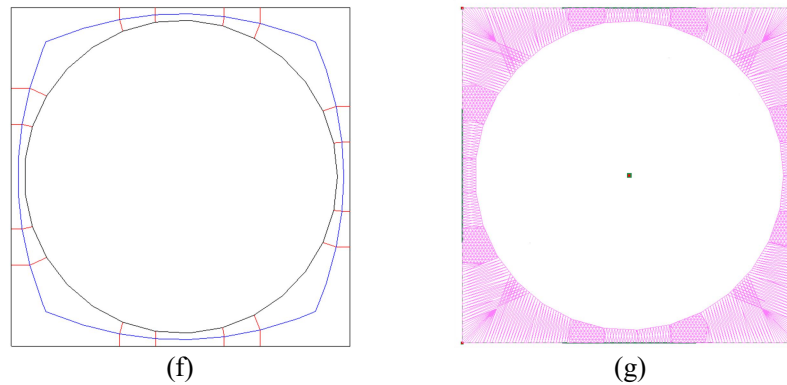


Fig. 8 Path generation

## 5. Summary

In this paper, a sectoral path planning method has been proposed for selective laser melting of workpieces with non-uniform thickness. The method employs Otsu's algorithm to segment thin/thick regions and a transition region is generated using the region-growing method. For different regions, paths with different patterns are generated with the intention to improve stress distribution, and suppressing mechanical property inhomogeneity and deformation as a result.

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