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# Optimization of tool-path generation for material extrusion-based additive manufacturing technology☆

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**Abstract**

In this study, we propose a tool-path generation approach for material extrusion-based additive manufacturing (AM) that considers the machining efficiency and fabrication precision, which are inherent drawbacks of general AM techniques compared with conventional manufacturing methods. The proposed approach aims to tackle the generation of direction-parallel tool-paths for the interior filling of simple connected areas, which comprises three main steps: (1) determining the inclination of reference lines; (2) generating and grouping tool-path segments into individual sub-paths; and (3) linking sub-paths based on specific requirements. These three modules interact to affect the efficiency and precision of AM significantly. In order to find an optimal inclination, we first analyze the impacts on the fabrication efficiency and manufacturing accuracy with different inclinations. A comparatively accurate building time model is developed subsequently to obtain the optimal tool-path inclination, but without compromising the machining precision, based on the analysis of a geometrical accuracy model. The proposed approach employs different inclinations in distinct layers according to specific manufacturing scenarios and technological requirements. After determining the reference lines, the tool-path segments are selected and grouped based on some characteristics (e.g., the number of intersections between reference lines and boundaries) to make up individual sub-paths, which are then connected to a zigzag-shaped path with short line segment connections. In the module for sub-path linking, some strategies are introduced to decrease the number of useless tool-paths, i.e., uncut paths, which could jeopardize the manufacturing quality by frequently turning the print head on and off. In addition, parametric curves are used to link the final sub-paths to avoid deceleration/acceleration processes in the end/starting parts of the sub-paths. The proposed approach has been used in practice to generate tool-paths for a wide range of models and the results verify its effectiveness and obvious advantages.


*Keywords:* Additive manufacturing; Inclination determination; Sub-path linking; Tool-path generation

## 1. Introduction

Additive manufacturing (AM) is a material additive process, which is fundamentally different from conventional subtractive manufacturing processes [1]. AM fabricates a physical object from a CAD model layer by layer, which is more convenient and rapid than other manufacturing approaches. Recently, a wide variety of AM technology applications have emerged in diverse fields, such as architecture, biomedical engineering, and product development [2]. Given its advantages in terms of time and cost savings, AM technology is expected to be an important industry in the near future.

In general, AM technology is characterized by its high efficiency due to the reduction of a product's development period. However, the manufacturing process is not as rapid as desired because of the layer-based fabricating procedure. Thus, building a complex part usually requires several hours, which is unacceptable in most current manufacturing scenarios. Han [3] noted that reducing the building time is now an important issue that affects the development of AM technology. A wide range of deposition strategies has been proposed by many researchers to increase the manufacturing speed. From adaptive slicing to post-processing, an inherent weakness of AM technology that these methods

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cannot avoid is that this technique is essentially a start–stop process, which deposits layers sequentially [4]. In addition, the transition between patches in each layer can degrade the building efficiency greatly and this has also attracted much attention. These issues are obvious and serious in some specific AM technologies based on material extrusion.

To further enhance the effectiveness and efficiency, tool-path planning has gradually become a major feature of process planning for AM technology. A desirable deposition tool-path could improve the precision, surface quality, and strength of prototypes, but it may also reduce the building time and forming material requirements [5]. In general, two main tool-path planning strategies are employed in AM technology: contour-parallel paths and direction-parallel paths [6]. A contour-parallel tool-path employs successive offsets of the boundary curves as tool-path elements, where each successive offset can be obtained using a classical Voronoi diagram approach, whereas a direction-parallel tool-path contains a large number of line segments, which are parallel to a specified inclination. These two strategies have distinct characteristics in terms of the deposition quality and efficiency [7]. Although the contour-parallel tool-path has been studied using various algorithms for several years, the most common tool-path strategy employed in current research is the direction-parallel path because of its practical advantages in terms of easy visualization and high-speed machining [8].

Two key issues in tool-path planning for material extrusion-based AM technology are the boundary filling strategy and tool sequencing strategy [9]. The boundary filling strategy mainly addresses the problems of filling up a patch of internal area continuously without halting the manufacturing process, which has been studied widely in various fields of AM as well as conventional milling manufacturing. The tool sequencing strategy represents the connection of sub-paths in an appropriate order. The fabrication efficiency is the main consideration when determining the sequences of sub-paths because distinct sequencing strategies result in different lengths for the final tool-path to jump from the end of one sub-path to the starting point of another sub-path. Because the time required to execute each jump is almost proportional to the jump distance, minimizing the jump distance is the objective when optimizing the sequencing strategy [10]. In the present study, we focus on tool-path generation in AM technology based on material extrusion, where we aim to obtain the desirable fabrication efficiency and satisfactory precision.

Few studies have addressed the reduction of the process time in AM technology from the perspective of tool-path optimization. Because the tool-path strategy is closely associated with the fabrication quality, most initial research into tool-paths was restricted to issues related to the manufacturing quality. Han et al. [3] proposed a deposition planning approach based on a grouping and mapping algorithm. First, they analyzed the causes of overfilling and underfilling during fused deposition manufacturing (FDM) and they tried to alleviate their occurrence by optimizing the tool-path. Kao et al. [11] presented a shape optimization algorithm, which was implemented to allow high-quality spiral deposition paths to be produced based on its skeleton. Yang et al. [12] introduced an equidistant path generation algorithm to improve the fabrication efficiency and surface quality. Later, Yang [5] and Wah [10] transformed tool-path optimization in AM technology into a classical NP-complete problem and they employed a genetic algorithm to obtain a solution. Jin [13] proposed a mixed tool-path generation algorithm that generated contour tool-paths along the boundary and the offset curves of each sliced layer were used to preserve the geometrical accuracy, where the zigzag tool-paths of the internal area of the layer were employed to simplify the computing processes and to speed up fabrication. However, they did not provide details of how to connect each of the path segments, which we address in the present study.

Tool-path planning for AM is an essential but complex issue, which fundamentally affects the fabrication quality and efficiency. To plan the tool-path effectively and scientifically, we propose a tool-path optimization method that generates more reasonable and appropriate tool-paths for material extrusion-based AM technologies in different scenarios. This method is characterized by a full consideration of the forming quality and deposition efficiency, according to the specific requirements when addressing distinct problems, rather than considering one feature alone. Three main stages are involved in the proposed tool-path generation approach: determining the inclination, generating the tool-path for each sub-region, and connecting the individual sub-paths. This process is illustrated in Fig. 1. The proposed tool-path planning method can be adjusted adaptively to different fabrication requirements and it can improve the deposition quality by employing parametric curves to connect sub-paths, in contrast to previous approaches.

## 2. Related work

### 2.1. Generation of tool-paths in AM

The tool-path required for material extrusion in AM is a predefined trajectory along which the nozzle is driven to deposit fabrication material and to form the surface layer by layer. Because the deposition quality features (e.g., surface roughness, dimensional accuracy, and part strength) are influenced by the tool-path, as well as some other processing parameters, many efforts have been made to optimize tool-path planning. In fact, the tool-path planning process in material extrusion-based AM is similar to that of conventional milling in pocket areas. Therefore, various types of tool-path patterns from milling can be introduced into AM, such as zigzags, contours, spirals, and some other filling patterns.

At present, contour-parallel-based and direction-parallel-based filling strategies are mainly employed in AM, which have their own advantages and disadvantages. The contour-parallel tool-path comprises a series of contours, which run parallel to the boundaries of the two-dimensional cross-sections yielded by slicing [14], thus this type of fabrication accuracy is greater and more satisfactory. However, its main problem is the implementation of the offset algorithm, which is computationally expensive and complex. The shapes of the boundaries tend to be comparatively complex in AM, especially with multi-cavity structures. Furthermore, in some circumstances, contour-parallel-based tool-paths may yield more uncut tool-paths, which have negative

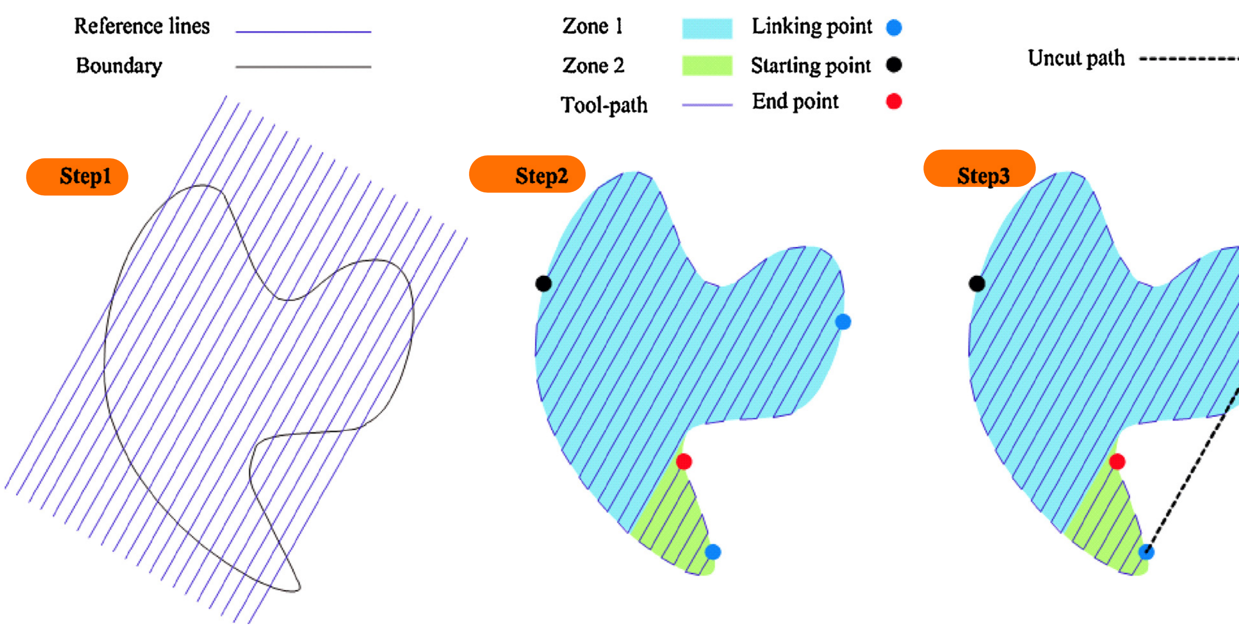


Fig. 1. Scheme showing the method used for direction-parallel tool-path generation.

effects on the fabrication efficiency and accuracy due to the nozzle head turning on and off frequently. This problem is illustrated in Fig. 2. By contrast, direction-parallel paths contain many path segments, which correspond to back and forth motion in a fixed direction within the boundary that needs to be filled up in the interior region. This approach is obviously simple and fast to implement, but at the expense of fabrication precision. In order to exploit the merits of these two approaches, it is suggested that contour-parallel filling can be used for the boundaries to achieve smooth surfaces whereas direction-parallel filling could be used for the interior regions to obtain the requisite part strength, as well as acceptable machining efficiency. A previous study [13] described the used of a fitting algorithm to establish the NURBS-based contour curve on the boundaries initially, before generating the control points of the offset contour curves to determine the relevant tool-paths along the boundary. The interior area of the model was fabricated subsequently using the direction-parallel tool-path.

### 2.2. Direction-parallel tool-paths

The direction-parallel tool-path is one of the most common tool-paths employed in current AM techniques. This method fills an area line-by-line in a specified direction [15]. After determining the inclination of the reference lines, a series of line segments (along the predefined inclination) connected with small turn

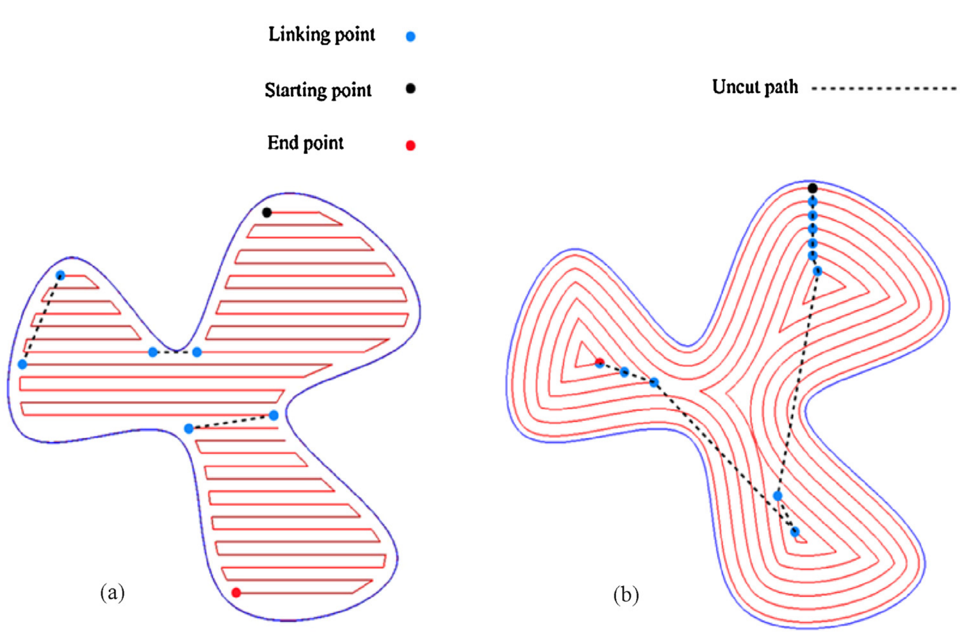


Fig. 2. Comparison of different tool-path generation strategies.

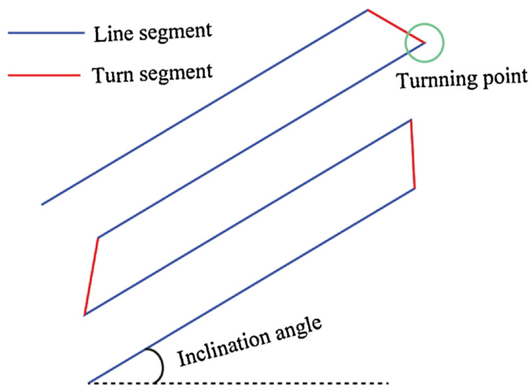


Fig. 3. Illustration showing a direction-parallel tool-path.

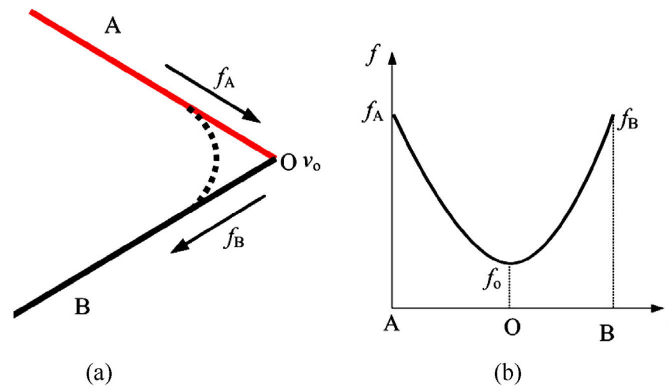


Fig. 4. Scheme showing are al tool-path and the feed rate profile at the turning point.

segments are generated as the tool-paths (Fig. 3). This method is easy to implement, but there are many unresolved problems. In particular, it is often impossible to fabricate a simple connected area continuously without turning off the nozzle, which is common when fabricating complex models with hollow structures inside. This issue is also common in conventional milling, but the effect on AM is more severe due to the control of the nozzle. In Fig. 2(a), the dotted line represents the connection between each individual sub-path. In addition, the presence of vast numbers of small turn segments in the tool-paths can degrade the fabrication quality and efficiency to some extent. Sharp corners require a comparatively slow speed, thereby leading to deceleration and acceleration processes when traveling around corners, and the quality is degraded as a consequence. Another problem with direction-parallel tool-paths is warping of the forming material because the tool-path is in the same direction in a specific layer, although this can be alleviated by the contour-parallel tool-path.

### 2.3. Evaluation of tool-path planning

Reducing the fabrication time has been a major aim since AM emerged as an important technology in the machining field. Several studies have addressed this issue. For example, Han et al. [1] developed a build-time analysis model for an FDM process. In their method, several parameters were identified that could be used to speed up the build time, including the layer thickness, road width, table speed, and repositioning distance. Despite a lack of universality, this method is useful for increasing the fabrication efficiency. Jin [13] also presented a build-time model for contour-parallel and direction-parallel tool-paths. Based on their model, adaptive algorithms were designed to address the different geometrical characteristics of product models and to achieve the minimum build time. However, they simply analyzed the relationship between the build time, slope degree, and the lengths of segments. They presented a simple comparative analysis of different slope degrees, but they did not provide detailed explanations of the decisions to use these parameters. Thus, an analytical method for determining the optimal parameters is required to speed up the building process.

In addition, it is not reasonable to expect that the theoretical machining time will be proportional to the total length of the path segments because this ignores the effects of acceleration and deceleration during processing. Thus, when filling a direction-parallel tool-path that comprises many small path segments, the average feedrate of the nozzle is substantially lower than the desired value because the nozzle must accelerate and decelerate while moving along the tool-paths. In order to determine the appropriate processing parameters to achieve a satisfactory machining efficiency, an effective and accurate build-time model is required to estimate the actual machining time and to compare the machining efficiency with different types of tool-paths. If the effects of acceleration and deceleration are considered, the major factor that determines the fabrication speed is the number of corners in the junctions between individual path segments. The speed of the nozzle must decrease in corners to satisfy the dynamic limitations of machine tools and the precision requirements. In corners, the actual filling tool-path must blend smoothly from the first segment to the next segment according to predefined acceleration/deceleration parameters. The real tool-path and the corresponding feedrate in a corner are shown in Fig. 4.

Apart from the machining efficiency, corners can also degrade the fabrication quality because of the acceleration/deceleration processes that occur around corners and their geometrical characteristics. The variation in speed near corners may affect the cross section of the deposited material, which has detrimental effects on the smoothness of the surface. Furthermore, the features of material extrusion-based AM technology mean that some areas near corners may be deposited with the material twice, which is known as overfilling, whereas other areas are unfilled, which is known as underfilling. This problem is illustrated in Fig. 5. It is easy to conclude that the numbers of overfilled and underfilled areas will increase as the angle between two adjacent path segments decreases. Furthermore, the fabrication quality is satisfied more fully if the path segments are longer with fewer corners. Because the overfilling and underfilling conditions in one layer are similar to those in the two adjacent layers, these effects can be accumulated to further degrade the quality, thus tool-path planning should consider this issue and try to avoid excessive numbers of corners.

In general, to obtain the optimal tool-path for material extrusion in AM, we should aim to satisfy the following three objectives during tool-path planning: (1) balancing the

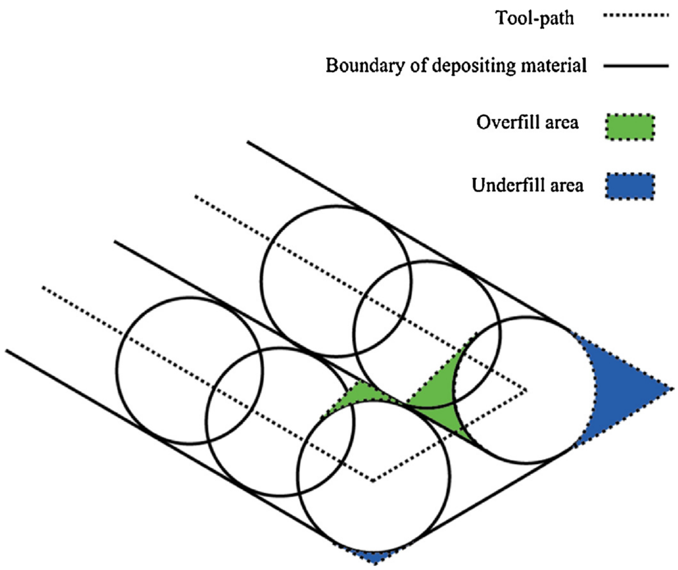


Fig. 5. Deposition scheme at corners.

fabrication quality and machining efficiency to obtain the optimal inclination; (2) minimizing the number of sub-paths to reduce the number of times that the nozzle is turned on and off; and (3) determining an appropriate order of sub-paths to minimize the idling time on the uncut path.

## 3. Optimal tool-path generation method for AM

In the present study, the contour-parallel tool-path is employed to deposit the boundaries to obtain a smooth surface, whereas the interior part confined by the offsets of the boundaries is deposited using the direction-parallel tool-path because of its high efficiency and simple implementation. The generation of contour-parallel tool-paths has been studied for years, where its complexity and difficulty are determined mainly by the implementation of the offset algorithm, especially for complex structures. Thus, no further optimization can be performed to enhance the machining efficiency and increase the deposition quality. By contrast, the direction-parallel tool-path strategy used for interior filling requires further research because of its variability and flexibility. Two essential factors that merit comprehensive consideration during direction-parallel tool-path planning are as follows:

(1) Inclination angle of the reference lines. This is the angle between the reference line and the $x$ axis, which can be rotated in a range of [0°, 180°]. Different inclination angles can change the total tool-path length, build time, number of tool-path elements, etc.
(2) Linking tool-path elements. In general, it is impossible to fill up a layer with only one piece of a direction-parallel tool-path when handling complex shapes. Thus, after generating the sub-paths, these sub-paths are linked to obtain a satisfactory machining efficiency by minimizing the idling time on the linking paths.

Previous studies [16–19] have investigated the effects of these two factors. However, Jin et al. [16] simply considered the total tool-path length and ignored some other important parameters, such as the minimum uncut paths in the linking sub-paths. The algorithms proposed by Held and Tang [17,18] were well suited to conventional pocket milling, but they could not address the tool-path planning issues that affect AM because they ignored the effects of the nozzle, material, etc. [20]. Therefore, we propose an approach for finding the optimal inclination, which may differ according to the specific machining requirements. Furthermore, this approach optimizes the linking strategy between sub-paths, while balancing the airtime minimization and quality obtained.

### 3.1. Determination of the inclination

The inclination of the direction-parallel tool-path may depend on various factors. Before providing a detailed description of the proposed approach, we first introduce some parameters that need to be considered when planning the tool-path. The total tool-path length, including the linking paths between sub-paths, is generally considered to be positively correlated with the build time. However, due the presence of many short segments, the nozzle speed has to be decreased in practice to avoid large machining error at the corners. Thus, the average speed is lower than the expected speed. In addition, the filling path will deviate from the desired path if the nozzle speed does not decrease to zero at the corners. Therefore, minimizing the number of corners can improve the machining productivity by maximizing the average length of the tool-path elements and allowing a constant velocity to be maintained. The number of linking path must be minimized because the nozzle needs to halt the deposition process on these paths.

#### 3.1.1. Efficiency priority-based strategy

In order to evaluate the machining efficiency in a quantitative manner, an effective machining time model is required. Because the feedrate varies along the path, the feedrate profile needs to consider acceleration and deceleration during processing. Acceleration and deceleration occur due to the existence of corners in the tool-path. The feedrate at a corner is correlated with the angle between the adjacent path segments, where it is assumed that the feedrate value does not change at a turning point. The change in the vector feedrate $\Delta f$ is $2f^{*}\sin(\alpha/2)$, where $f$ is the feedrate at the corner and $\alpha$ is the angle between the current line segment and the extension of the previous segment, as shown in Fig. 6. It is easy to conclude that a corner with a smaller angle can yield a slower feedrate at the corner because of the greater change in the direction of the feedrate. To obtain a continuous feedrate profile, a look-ahead function is required to determine the feedrate profile, thereby avoiding rapid deceleration, which is detrimental to machine tools [21]. In the look-ahead module, the feedrates at the corners are determined in advance according to the dynamical properties and geometrical characteristics. Next, the feedrate profile is generated based on the predetermined feedrate at the corners and the acceleration/deceleration strategy. A tool-path and its feedrate profile are illustrated in Fig. 7. It is clear that short

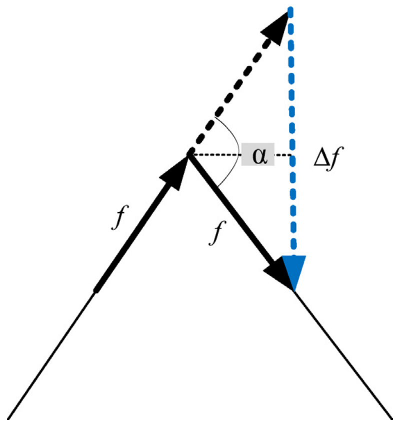


Fig. 6. Feed rate change at corners.

path segments require more frequent deceleration/deceleration processes, which decrease the machining efficiency markedly.

Two basic types of tool-path are employed in interior filling: depositing paths and un-depositing paths. The latter connects individual depositing paths on one layer, and the connecting strategy is discussed in the next section. When analyzing the build time, we simply connect the sub-paths by assuming that the length is zero, which means that the feedrate at the end of the previous sub-path and the starting point of the next sub-path is the maximum (this can be satisfied using some of the methods described in Section 3.1.2). The inclination is determined based on the efficiency priority as follows. According to the feedrate profile, we can determine the machining time for some specific inclinations initially. For example, the inclination changes incrementally by 10° from 0° to 180°, and thus 19 sampling points can be used to interpolate a curve to obtain a

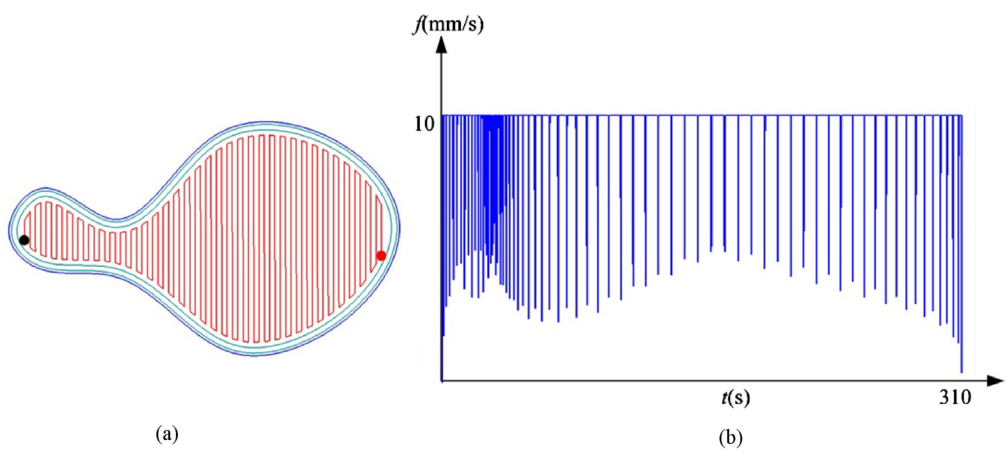


Fig. 7. Tool-path and its feed rate profile.

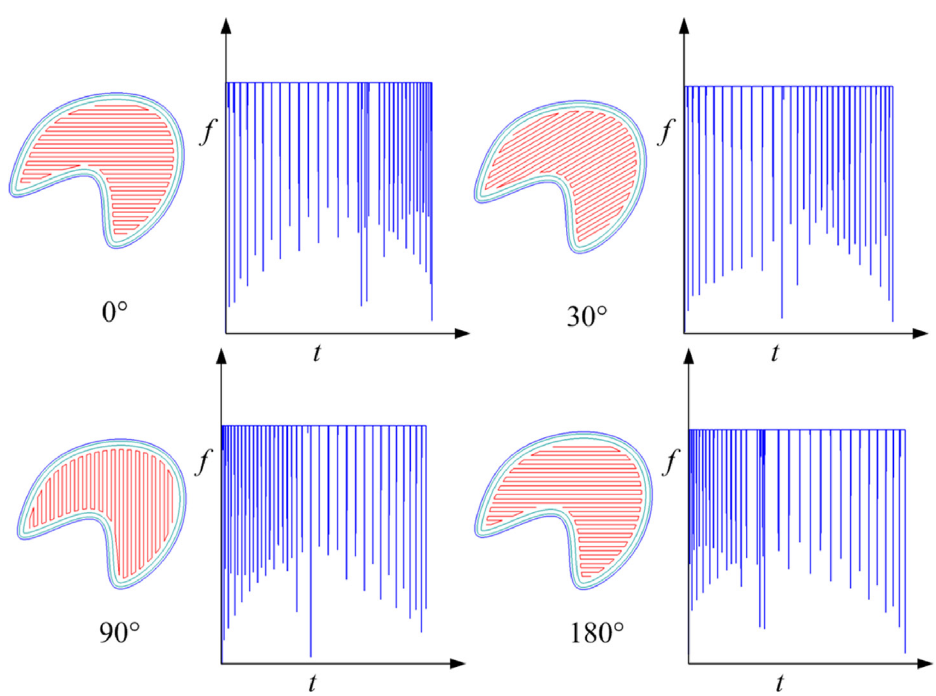


Fig. 8. Tool-paths and feed rate profiles with different inclinations.

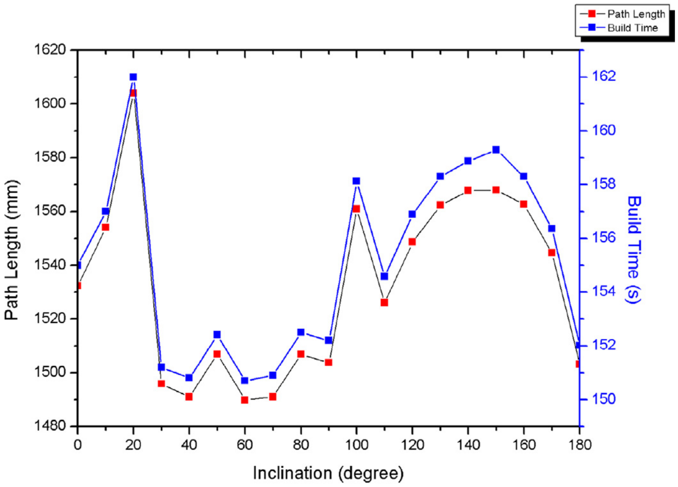


Fig. 9. Length of the tool-path and the build time with different inclinations.

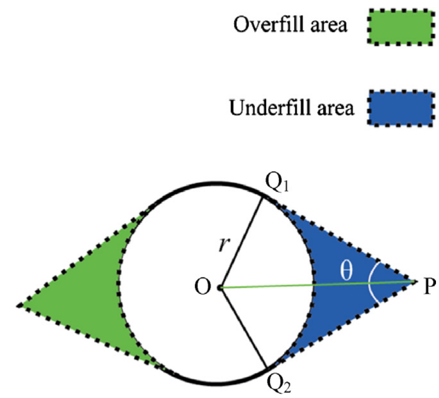


Fig. 10. Deposition scheme at a corner.

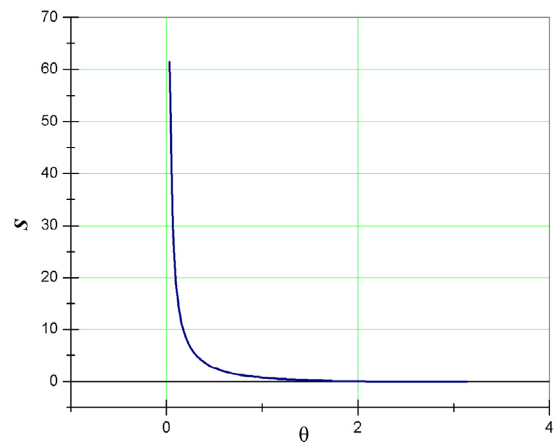


Fig. 11. Correlation between overfilled/underfilled areas and the inclination.

suitable inclination for a satisfactory machining efficiency. This can be demonstrated by a simple example. We employ a cross section obtained from a bone to analyze the process used to find the optimal inclination based on the efficiency priority. Different direction-parallel tool-paths and their feedrate profiles can be obtained based on different inclination degrees, as shown in Fig. 8 (e.g., 0°, 30°, 90°, or 180°). After the path length and the build time are obtained, these data are used to interpolate a curve, as shown in Fig. 9. It is easy to obtain the optimal inclination from the graph, i.e., about 60°.

### 3.1.2. Quality priority-based strategy

Similarly, to evaluate the deposition quality in an effective manner, it is necessary to establish an appropriate accuracy analysis model to find the optimal inclination. Based on the analysis in Section 2.3, the fluctuation in the feedrate can cause unevenness in the deposited material and the surface formed may be rough. Furthermore, the corners will degrade the fabrication quality due to the presence of overfilled and underfilled areas, as shown in Fig. 5. This is one of the critical issues that affect direction-parallel-based tool-path planning because of the large number of corners. As shown in Fig. 5, the overfilled area at the corner is equal to the underfilled area, which is correlated with the angle between two adjacent path segments. This is illustrated in Fig. 10. The overfilled region and the underfilled region at a corner have the same area according to the geometrical symmetry. This area can be obtained by subtracting a sector from two right-angled triangles. Thus, the area is obtained using Eqs. (1) and (2):

$$S_{\text{underfill}} = S_{\text{overfill}} = S_{\Delta OPQ_1} + S_{\Delta OPQ_2} - S_{\text{sector}OQ_1Q_2} \tag{1}$$

$$S_{\text{underfill}} = S_{\text{overfill}} = r^2 \cot\frac{\theta}{2} - \left(\frac{\pi-\theta}{2\pi}\pi r_2\right) = r^2\left(\cot\frac{\theta}{2} + \frac{\theta}{2} - \frac{\pi}{2}\right), \tag{2}$$

where $r$ is half of the path width and $\theta$ is the angle between two adjacent path segments. From Eq. (2), we can determine the correlation between the area $S$ and the angle $\theta$ by plotting a graph, as shown in Fig. 11. It is clear that smaller angles will lead to larger overfilled/underfilled areas, whereas the overfilled/underfilled areas tend to be acceptable as the angle becomes larger. The fabrication quality is affected by the overfilled/underfilled areas, which are determined by the inclination angle, to some extent. Therefore, the optimization target is to decrease the number of sharp corners during tool-path planning. According to the analysis above, the overfilled/underfilled areas should be minimized to obtain a satisfactory fabrication quality. In the present study, the process employed to obtain the optimal inclination and to achieve a high quality result is similar to that based on the efficiency priority. The underfilled/overfilled areas with different inclination angles can be obtained using Eq. (2). The optimal inclination based on the quality priority is determined from the interpolated curve using several sampling points. This can also be illustrated by a simple example. The cross section is obtained from a figure and the sampling points are determined based on incrementing the inclination angle from 0° to 180°. Several tool-paths with different inclinations are shown in Fig. 12. In addition to the overfilled/underfilled areas, the number of corners in the tool-path is also illustrated in Fig. 13. According to the graph, the number of corners decreases gradually to a minimum as the inclination varies from 0° to 90°. Next, the number increases to its maximum, which is similar to that at 0°. By contrast, the overfilled/underfilled areas fluctuate noticeably as the

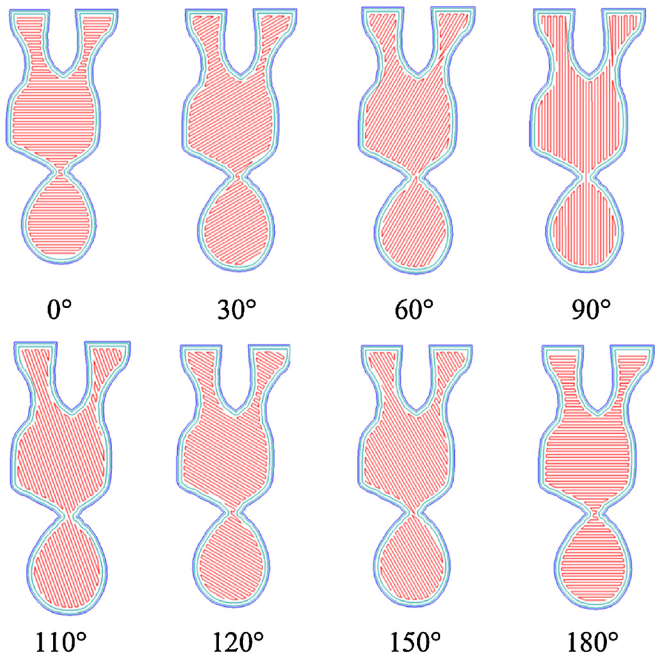


Fig. 12. Tool-paths with different inclinations.

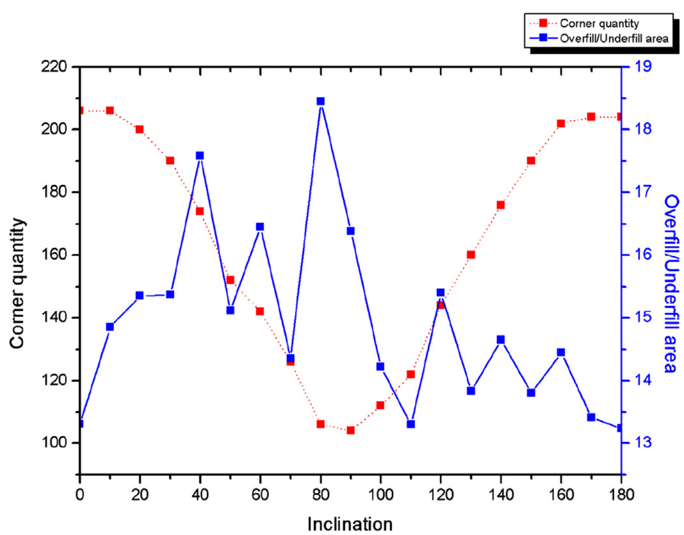


Fig. 13. Corner quantity and overfilled/underfilled areas with different inclinations.

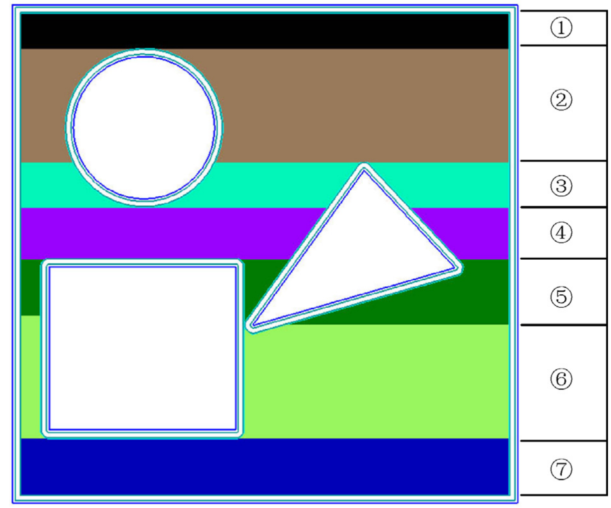


Fig. 14. First partition based on the number of intersections.

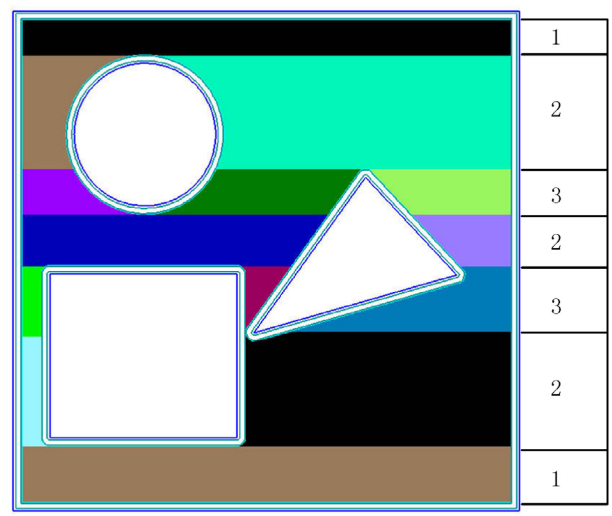


Fig. 15. Further partitions based on the number of intersections.

inclination varies. It is clear that the optimal inclination based on quality is around 110°.

### 3.2. Linking individual sub-paths

After determining the inclination based on different priorities, the sub-regions are generated according to the number of intersection points between sweeping lines and offset boundaries. As shown in Fig. 14, a simple connected area is divided roughly into seven parts. Next, each part is divided further into individual connected areas based on the number of partitions in each part. As shown in Fig. 15, the first part is simply one connected area, and thus it is an individual sub-region, whereas the second part is divided into two sub-regions. By this analogy, the whole area is divided into 14 sub-regions for further tool-path generation.

It is undesirable to generate tool-paths for each separate sub-region because some can be connected mutually without compromising the fabrication quality. Furthermore, the connections between some sub-regions can avoid turning the nozzle head on and off frequently, which helps to improve the fabrication quality. Each sub-region has four potential starting points (i.e., the first two endpoints and the last two sweeping lines), thus these four points all need to be considered when determining whether two sub-regions satisfy the conditions for connection.

In order to assess whether two points in two distinct sub-regions satisfy the conditions rapidly and accurately, all of the potential starting points are sorted and grouped in advance. First, all of the offset boundaries, including the exterior and interior boundaries, are numbered as shown in Fig. 16. A structure is built to contain the information for the four potential points in one sub-region, as shown in Fig. 17(b). The order of these four potential starting points is determined as follows. *PointOne* is the starting

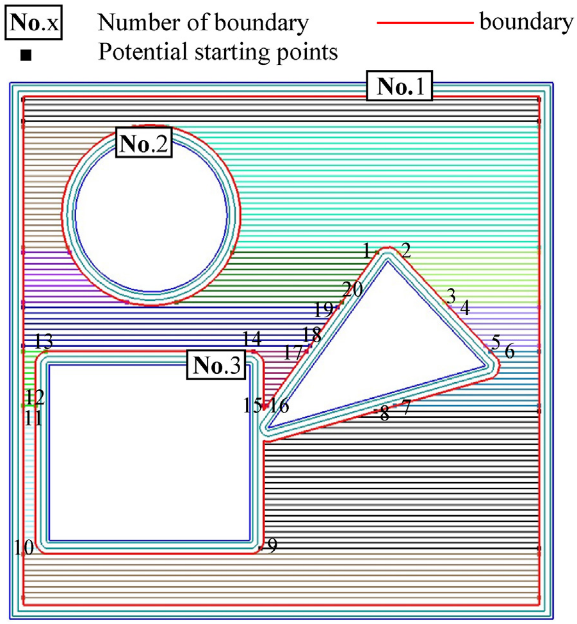


Fig. 16. Procedure used to connect adjacent segments.

point of the first sweeping line and *PointTwo* is the end point of this sweeping line. If the number of sweeping lines is even in this sub-region, *PointThr* is the starting point of the last sweeping line and *PointFour* is the end point of this sweeping line. By contrast, if the number of sweeping lines is odd, *PointThr* and *PointFour* exchange their positions. Thus, if *PointOne* is the starting point of the path in this sub-region, then *PointThr* is the end point, and vice versa. If *PointTwo* is the starting point of the path in this sub-region, then *PointFour* is the end point, and vice versa. At the same time, the information for each potential point is represented by a structure, as shown in Fig. 17(a). In addition to the coordinates of this point, *BoundaryIndex* represents the index of the boundary that contains this point. *PointIndex* is the index of this point on the boundary, which is determined according to its position on the boundary. The indices of all the potential starting points on one boundary increment in a clockwise manner. If we use boundary No. 3 in Fig. 16 as an example, there are 20 potential starting points on this boundary

```
typedef struct tagPotentialPoint
{
    double x,y,z;       //coordinates of the point
    int BoundaryIndex;  //index of the boundary which contains this point
    int PointIndex;     //index of this point on the boundary
} PotentialPoint;
```

(a) Structure of potential starting points

```
typedef struct tagSubPathPoints
{
    PotentialPoint PointOne;  //The first point
    PotentialPoint PointTwo;  //The second point
    PotentialPoint PointThr;  //The third pint
    PotentialPoint PointFour; //The fourth point
} SubPathPoints;
```

(b) Structure of sub-paths including four potential starting points

```
typedef vector<SubPathPoints> SubPathPointsArray;
```

(c) Array of sub-paths in one cross section

Fig. 17. Some definitions for the connecting stage.

and their indices are ordered in a clockwise manner. Thus, only two potential starting points with adjacent indices can be connected.

A flowchart showing the connection process is illustrated as Fig. 18. The input for this process comprises all the sub-regions stored in *m_originalSubPathPointsArray*, whereas the output comprises the processed sub-paths stored in *m_ConnectedSubPathPointsArray*. In general, the number of elements in *m_ConnectedSubPathPointsArray* is smaller than that in *m_originalSubPathPointsArray* because of the connections between some sub-regions. Initially, the output array is initialized for the following stages. The first sub-region in the inputting array is removed to add a temporary sub-path variable *tmp_SubPathPoints* and its *PointOne* is treated as the starting point. Next, the first sub-region is deleted from the original array. According to the starting point of the first sub-region, its end point (*tmp_endpoint*) can be obtained for the following searching step. Provided that *m_originalSubPathPointsArray* has elements, the search operation is performed to find a connectable point (*tmp_ConnectablePoint*). Three criteria determine the candidate connectable points: the first is that the distance between *tmp_endpoint* and *tmp_ConnectablePoint* in the direction perpendicular to the sweeping lines is *m_width*, which is the distance between two adjacent sweeping lines; the second is that these two points are in the same boundary, which means they have the same *BoundaryIndex*; and the third is that the gap between their *PointIndex* is one, which denotes that they are adjacent intersection points on the same boundary (or one of them is the first and the other is the last *PointIndex* in that boundary). If there is a connectable point, *tmp_endpoint* and *tmp_ConnectablePoint* are connected, and the latter is added to *tmp_SubPathPoints*. Assuming that *tmp_ConnectablePoint* is on the *m_originalSubPathPointsArray*[i], the starting point of *m_originalSubPathPointsArray*[i] is *tmp_ConnectablePoint*. Next, *m_originalSubPathPointsArray*[i] is added to *tmp_SubPathPoints* before deleting it from *m_originalSubPathPointsArray*. The next step is to obtain the end point *tmp_endpoint* and to enter the next loop. By contrast, if there is not a connectable point in the original array, *tmp_SubPathPoints* is added to the output array, and the next step is to initialize the *tmp_SubPathPoints* and to enter the next loop. The connecting process is terminated if the original array is empty.

After the connecting process, some of the sub-regions are mutually connected, as shown in Fig. 19. The number of sub-paths is decreased from 14 to 5. However, an alternative optimization methodology can minimize the number of sub-paths after the processes above. As shown in Fig. 19, when we remove the first element each time, we treat *PointOne* as the starting point of this sub-region. However, some issues may occur due to this process. For example, the sub-path $C_1C_2$ should be added to sub-path $D_1D_2$ but it is not added due to the inappropriate choice of the starting point. If the starting point of $C_1C_2$ is changed to another end of the first line segment, this sub-path can be connected to $D_1D_2$, with fewer uncut paths. Therefore, after the first connecting process, some sub-paths can also be connected to other sub-paths, which helps to minimize the uncut

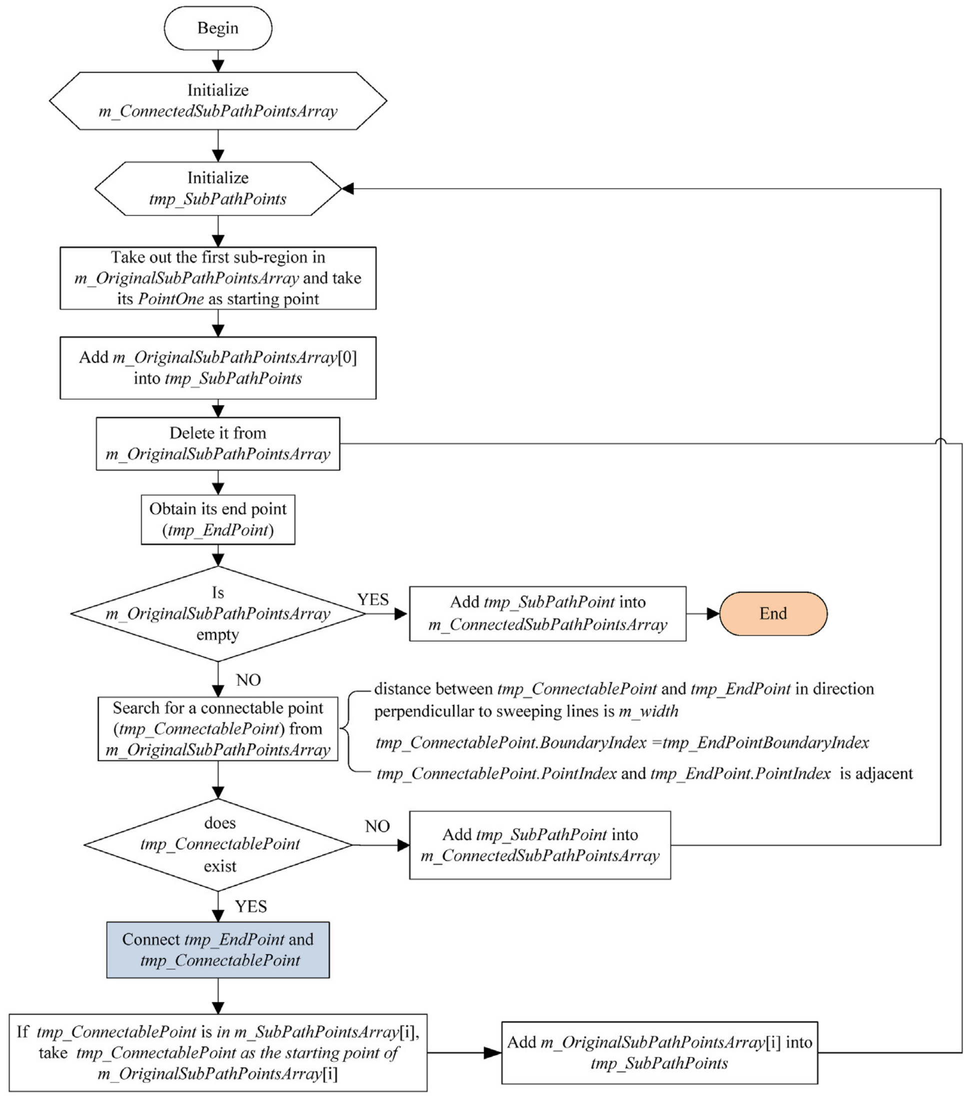


Fig. 18. Flowchart of the process used to connect adjacent connectable sub-paths.

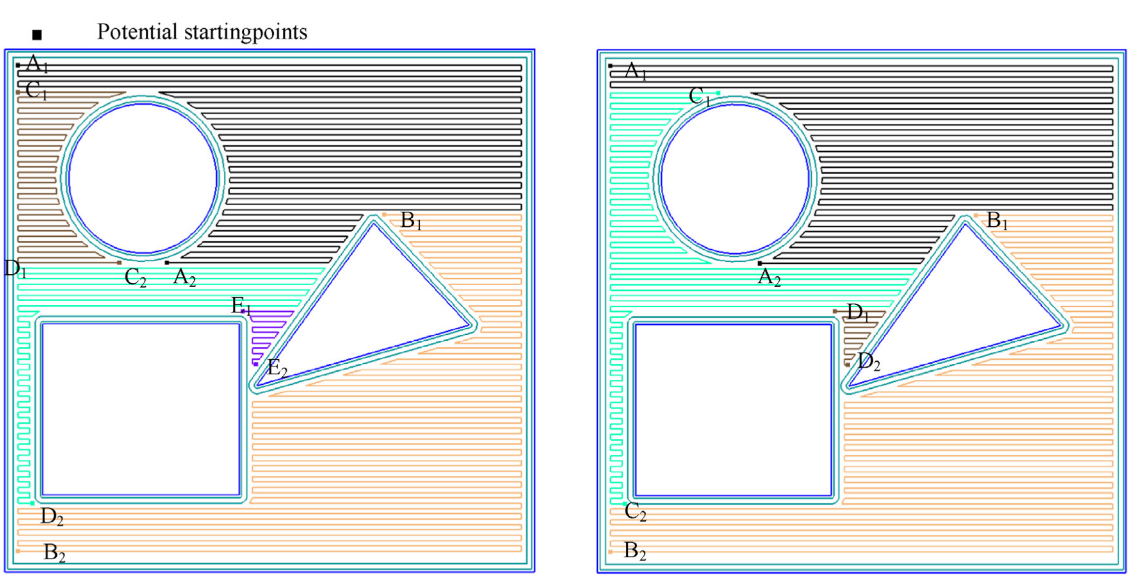


Fig. 19. Tool-path after connecting adjacent processes.

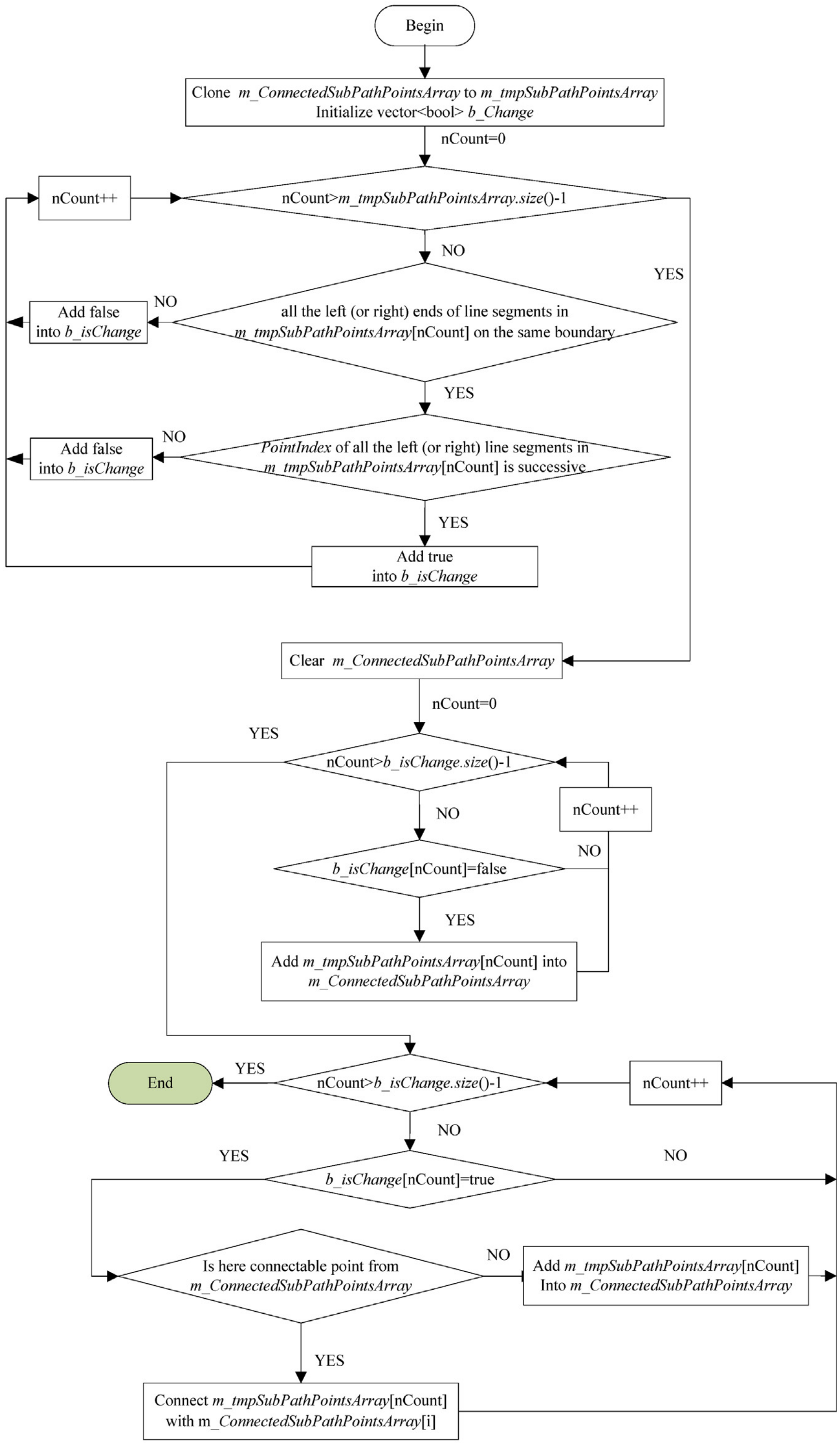


Fig. 20. Flowchart showing the process used to reconnect some connectable sub-paths.

paths when changing their starting points. A flowchart illustrating this process is shown in Fig. 20. The aim of this process is to find some connectable sub-paths and to connect them by changing their starting points. However, not all of the sub-paths can change their starting points to another end of the sweeping lines after the first connecting process. Specifically, sub-paths $A_1A_2$, $B_1B_2$, and $D_1D_2$ in Fig. 19 cannot change their starting points because some of the connections made in the first connecting process would be broken. Thus, we find that only the sub-path that satisfies the following conditions can change its starting point. First, all the left ends of the line segments have the same *BoundaryIndex*, which means that they are on the same

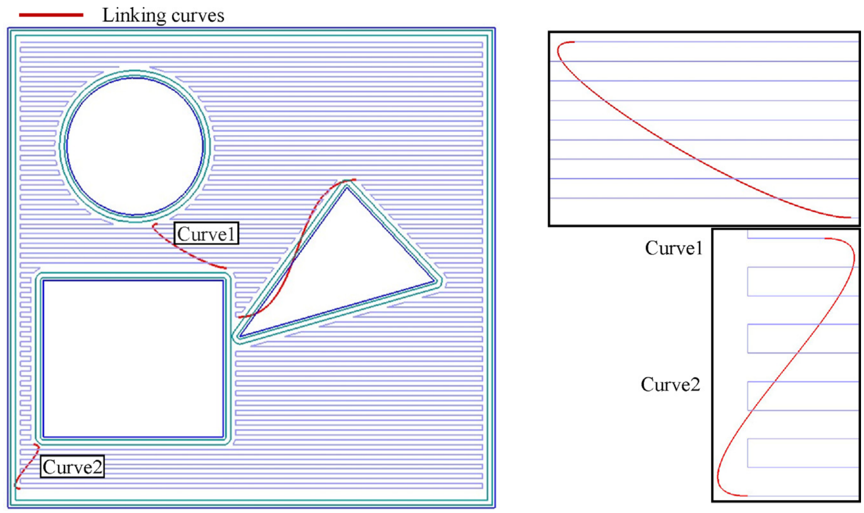


Fig. 21. Tool-path after reconnecting a process.

boundary, and all the right ends of the line segments should satisfy the same requirement; and second, the *PointIndex* of all the left (or right) ends is successive. Clearly, not all of the sub-paths that can change their starting points can be connected to other sub-paths. The sub-path $E_1E_2$ can obviously change its starting point but there are no other appropriate sub-paths with potential starting points that can be connected with $E_1E_2$. After the reconnecting process, the number of sub-paths is decreased by connecting the sub-paths $C_1C_2$ and $D_1D_2$, while changing the starting point of sub-path $C_1C_2$.

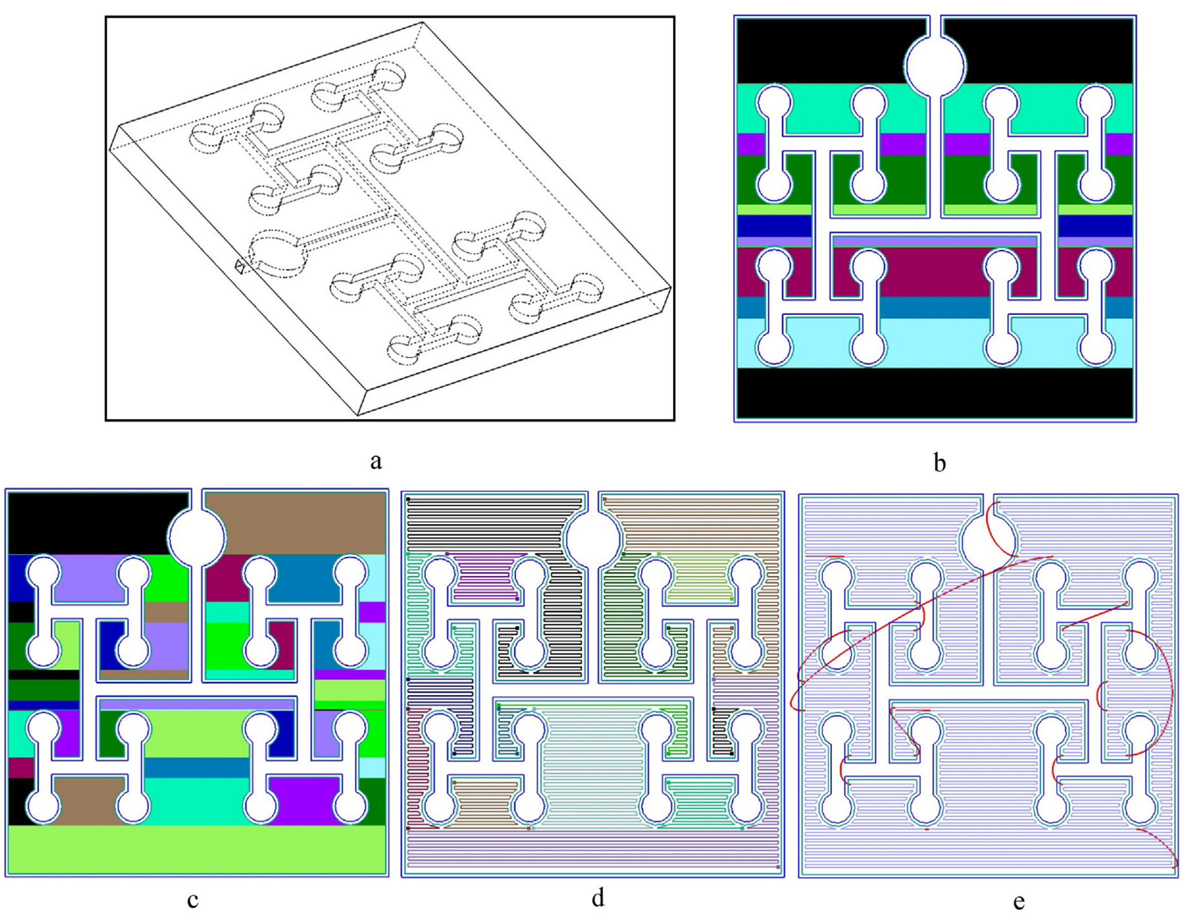


Fig. 22. Tool-path generation for a microfluidic channel: (a) model of a microfluidic channel, (b) first partition, (c) further partitions, (d) generation of sub-paths, and (e) linking sub-paths.

After the above operation on the sub-paths, no other optimization method is required to decrease the number of sub-paths. The final step is to connect these remaining sub-paths with uncut paths. The aim of this step is to minimize the length of the uncut paths. This problem can be described as follows: the printing head needs to travel to each of all the starting points once and only once, by starting from any point and halting at the last potential starting point. This is similar to the Traveling Salesman Problem (TSP), but it cannot be solved by algorithms that are suitable for TSP due to the difference in the starting point and terminal point when traveling one sub-path. Thus, in the present study, a greedy algorithm is used to determine the fabrication sequence for the sub-paths. At each stage, when determining the next sub-path, the nearest potential starting point from the terminal point of the current filling sub-path is selected from among all the untraveled sub-paths. Although this greedy algorithm can only obtain a locally optimal choice at each stage with the aim of finding a global optimum, it is acceptable in situations where the number of elements is not huge. The sequence of sub-paths after applying the greedy algorithm is: $A_1 \rightarrow A_2 \rightarrow D_1 \rightarrow D_2 \rightarrow B_1 \rightarrow B_2 \rightarrow C_2 \rightarrow C_1$.

If these sub-paths are mutually connected with lines based on the order determined, as found in many current methods, the corners between sub-paths and uncut paths would degrade the fabrication quality because of acceleration/deceleration near the corners. Thus, a type of spline parametric curve is used to connect the sub-paths. The two ends of the spline are set as tangents to the line segments of two sub-paths, which means that the feedrate does not need to decrease at these two ends, thereby avoiding acceleration and deceleration at these locations. The final tool-path is as shown in Fig. 21. When the number of uncut paths is quite large, this connecting approach can significantly improve the depositing quality.

## 4. Case study and discussion

Two models are employed in this study to validate the effectiveness of the proposed tool-path generation strategy for material extrusion in AM technology. The first fabrication model is a simple microfluidic channel, which is used commonly in a lab-on-a-chip [22]. Due to its micro-scale and the complex structure of its interior, only a few methods are suitable for producing such 3D microfluidic channels. AM is a recommended approach for producing this type of structure. The structure of the microfluidic channel is shown in Fig. 22(a). The length, width, and height of this model are 60 mm, 60 mm, and 5 mm, respectively. Its cross section is used to illustrate the tool-path generation process. According to each step, after determining the inclination angle (0°) and the appropriate gap between each tool-path (0.5 mm), the tool-path is generated step by step, as shown in Fig. 22(b–e). Due to its complex interior structure, 15 sub-paths need to be connected by parametric curves. The total length of the tool-path for the layer shown is 4433.075 mm and the build time for all the direction-parallel paths is 181.776 s, with a maximum feedrate of 50 mm/s and an acceleration of 100 mm/s$^2$ based on the feedrate profile shown in Fig. 23. In this example, the inclination angle is selected based on the quality priority, thus the overfilled and underfilled areas are less than those with other inclination angles. In addition, the number of sub-paths is decreased to minimize the uncut paths. All of the sub-paths are connected with spline curves one by one, using a greedy algorithm to determine the orders.

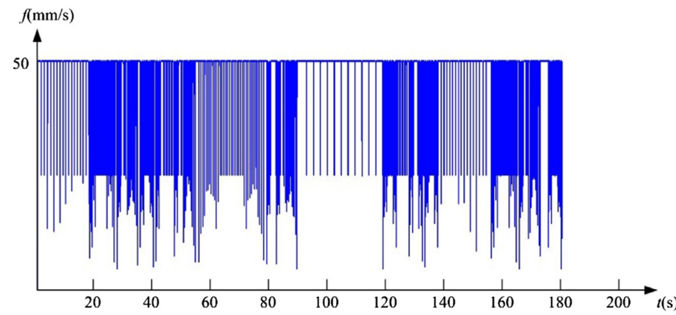


Fig. 23. Feedrate profile for a layer in the microfluidic channel model.

The second model is a human ear model, which is critical in the medical industry, as shown in Fig. 24. The length, width, and height of this model's bounding box are 56.897 mm, 32.557 mm, and 16.829 mm, respectively. The slicing thickness is 0.25 mm and the gap between the individual line segments during tool-path generation is 0.3 mm. The critical step when fabricating this model is determining the inclination angle. The 10th and 55th layers are used as examples to illustrate the determination of the inclination angle. When the efficiency priority is employed,

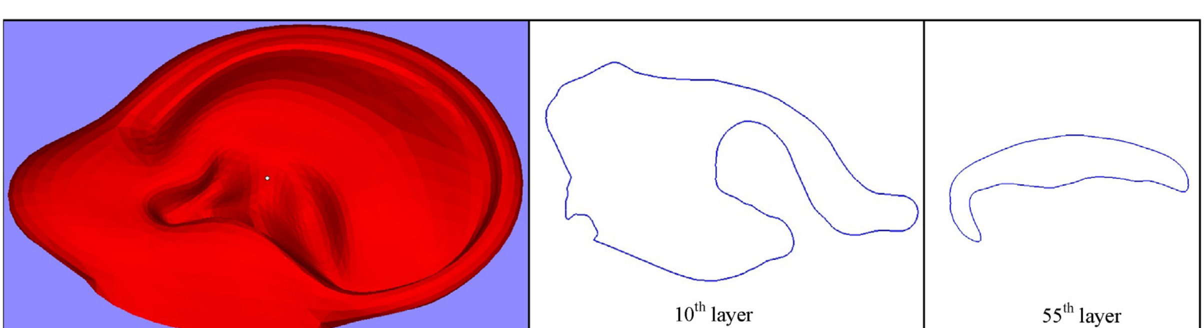


Fig. 24. Ear model analysis.

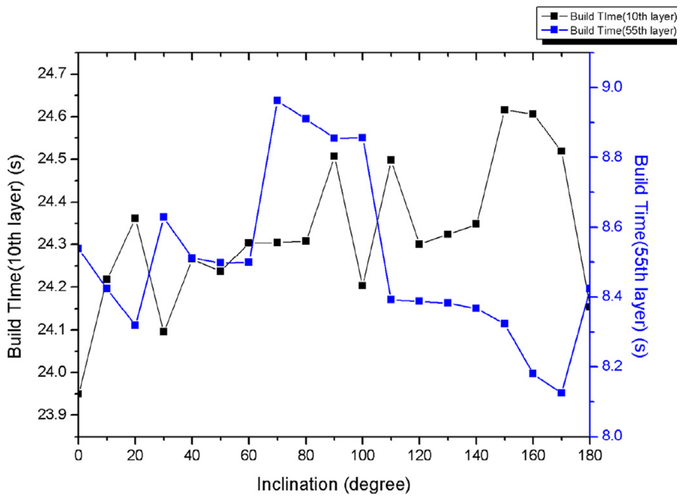


Fig. 25. Correlations between the build time and inclination for the10th and 55th layers.

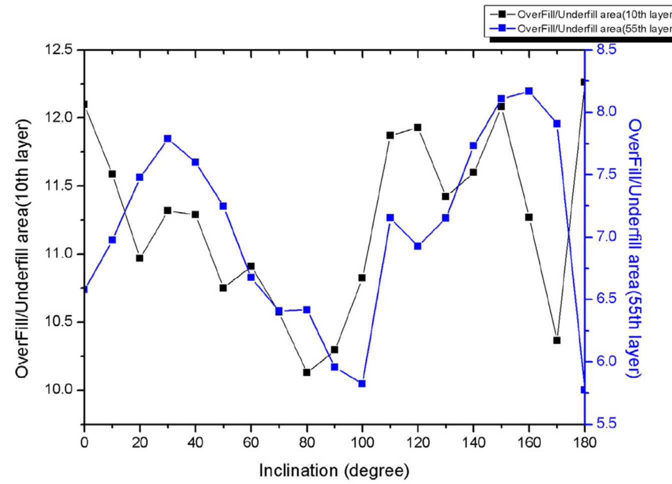


Fig. 26. Correlations between the overfilled/underfilled areas and the inclination for the10th and 55th layers.

the inclination angles of the reference lines in each layer are determined based on the minimum build time. Graphs showing the correlations between the build time and different inclination angles are presented in Fig. 25. The optimal inclination angles for the 10th and 55th layers are 0° and 170°, respectively, based on the efficiency priority. In general, the difference between the maximum build time and the minimum build time is about 1 s, thus the build time for this ear model can be decreased by more than 1 min. Similarly, Fig. 26 shows the relationship between overfilled/underfilled areas and different inclinations, where the optimal inclinations for the angles of the 10th and 55th layers are 80° and 180°, respectively, based on the quality priority. The corresponding tool-paths with the optimal inclinations are shown in Figs. 27 and 28, respectively.

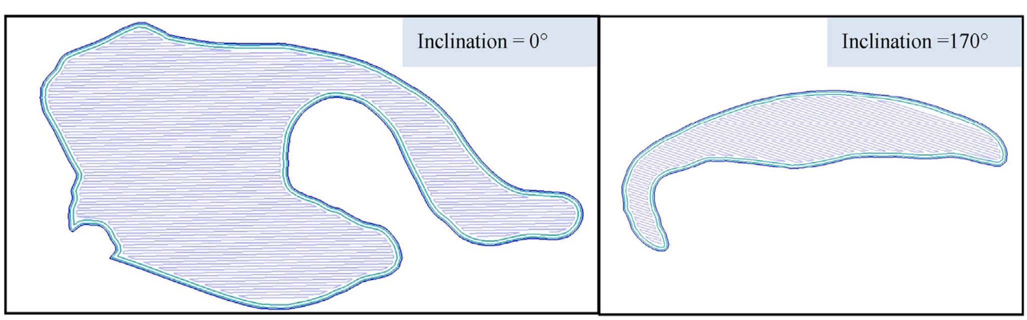


Fig. 27. Optimal inclinations for the10th and 55th layer based on the efficiency priority.

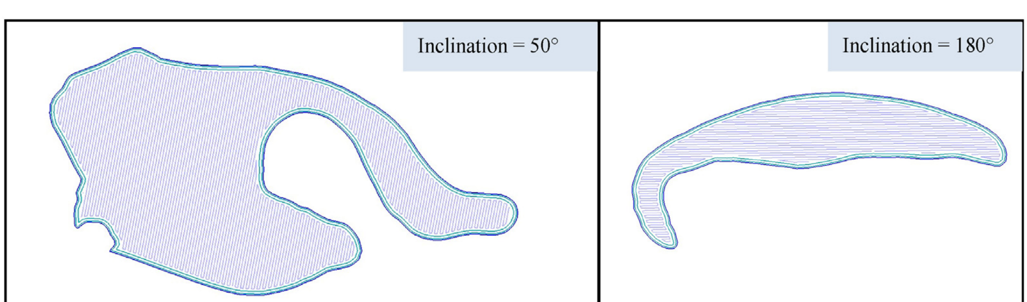


Fig. 28. Optimal inclinations for the10th and 55th layers based on the quality priority.

## 5. Conclusions and future work

To address the two key issues that affect AM (i.e., low efficiency and poor fabrication quality), we propose a tool-path generation approach for this promising industry, especially for material extrusion-based AM technology. This approach is mainly used to generate the direction-parallel tool-paths based on distinct priorities with different requirements. The major features of our approach are as follows:

(1) Three main stages are required to generate direction-parallel tool-paths for material extrusion-based AM: determining the inclination, generating the tool-path for each sub-region, and connecting individual sub-paths. Several optimization methods are employed in the first and third stages to improve the fabrication efficiency and to obtain an acceptable level of surface roughness.
(2) When determining the inclination angle, different priorities can be employed in various circumstances. To ensure a comparatively accurate build time, we establish a build time model that integrates the deceleration/acceleration stages to obtain the feedrate profile. In addition, the overfilled/underfilled areas in the corners are used to measure the machining quality. The proposed method for determining the inclination in each layer can adapt the priority according to different requirements.
(3) Our proposed strategy for linking sub-paths can obtain the minimum number of sub-paths. The initial partition principle is based on the number of intersections between the sweeping lines and boundaries. Next, the connectable sub-paths are selected and connected to each other. Finally, a greedy algorithm is used to determine the sequence of sub-paths, which are subsequently linked with parametric curves to avoid producing corners between sub-paths and uncut paths.
(4) Two models are used to demonstrate the effectiveness of the proposed approach. The tool-path generated with the proposed method can obtain a satisfactory machining efficiency or improve the fabrication accuracy.

A problem with our proposed tool-path generation methodology for material extrusion-AM is the use of a greedy algorithm to link the sub-paths. Using a greedy algorithm, we can only obtain locally optimal solutions when determining the sequence of sub-paths because the next sub-path is selected based simply on the end-point of the current sub-path without considering all of the previous sub-paths. After the choice has been made, it is treated as the optimal decision and the selected sub-paths are eliminated. Thus, the selections made by the greedy algorithm are never reconsidered even if we find that the previous choices might not be the best. Therefore, these characteristics of the greedy algorithm mean that it cannot obtain the most optimal results. In our future research, we will investigate other novel strategies for linking sub-paths, especially for complex connected regions.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.addma.2014.08.004.

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