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2-D path planning for direct laser deposition process

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2-D PATH PLANNING FOR DIRECT LASER DEPOSITION PROCESS

by

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ABSTRACT

The zigzag and offset path have been the two most popular path patterns for tool movement in machining process. Different from the traditional machining processes, the quality of parts produced by the metal deposition process is much more dependent upon the choice of deposition paths. Due to the nature of the metal deposition processes, various tool path patterns not only change the efficiency but also affect the deposition height, a critical quality for metal deposition process. This thesis presents the research conducted on calculating zigzag pattern to improve efficiency by minimizing the idle path. The deposition height is highly dependent on the laser scanning speed. The thesis also discussed the deposition offset pattern calculation to reduce the height variation by adjusting the tool-path to achieve a constant scanning speed. The results show the improvement on both efficiency and height.

ACKNOWLEDGMENTS

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1. INTRODUCTION

Since its appearance in 80s of last century, Layered Manufacturing (LM) technology, also known as Rapid Prototyping (RP) has given industry an approach to achieve the goal of providing products with a shorter development time and a lower cost. It involves successively adding raw material, in layers, to create a solid part directly from a CAD model instead of removing material as in the traditional subtractive manufacturing processes such as machining. LM processes fabricate a physical part in an additive fashion, layer by layer. The metal rapid prototyping process is a potential technique that can produce fully functional parts directly from a CAD system and eliminate the need for an intermediate step. Among LM processes, direct laser deposition process is capable to fabricate fully dense metal parts directly from the CAD model. It is an additive process wherein a laser energy source is used to melt metal powder or wire on to a substrate. Such a process has drawn interest from aerospace, heavy machinery and other industries.

Due to its complexity, such a process requires an automatic planning system to drive. Automatic deposition path planning is a critical component in the planning system. Path planning is a fundamental process planning task, which affects the final part's quality and building time. Path planning is defined as the process of generation of the sequence of paths that the nozzle or laser must follow in order to fill the part and any required support structures. The current common practice is to use commercial available machining CAD/CAM package or other specific planning systems to generate 2-D deposition path. However, the results obtained from these planning systems cannot meet all needs for metal deposition processes. Material additive process features are needed to be considered when generating deposition path. The typical 2-D path patterns are raster pattern which is also called zigzag path (Figure 1.1) and spiral-like pattern also called the offset path (Figure 1.2). Each of them has its own advantages and can be used to generate deposition path of a layer. Systems built on this principle include LENS [1], DMD [2]. Layer quality is reflected by the difference between the designed part and the built part, i.e. the amount of excess (overfilled) or insufficient (under-filled) material deposited, assuming that the part is well designed.

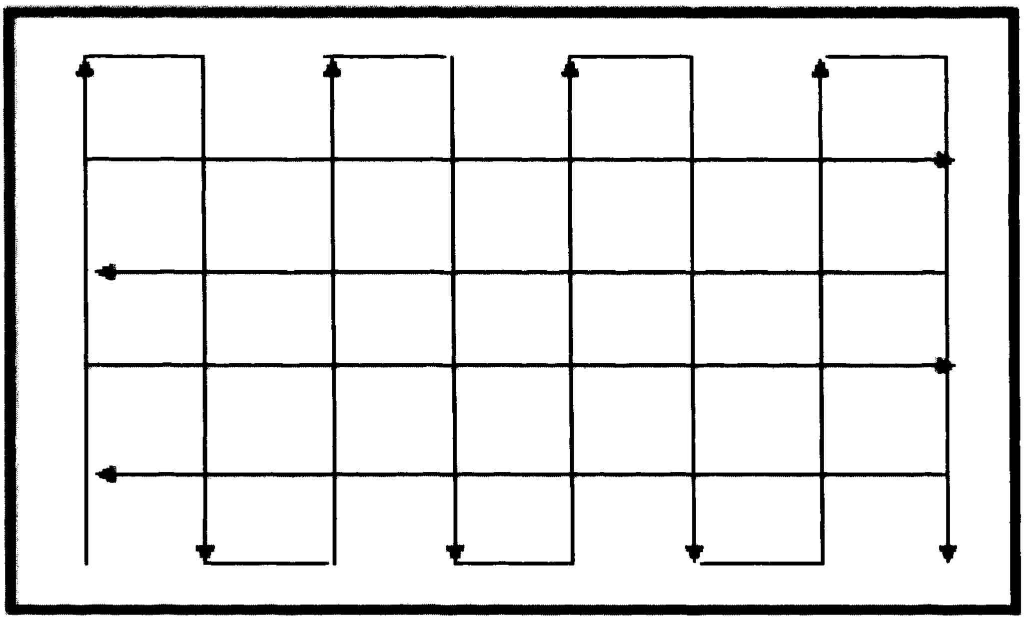

Figure 1.1 Zigzag Path

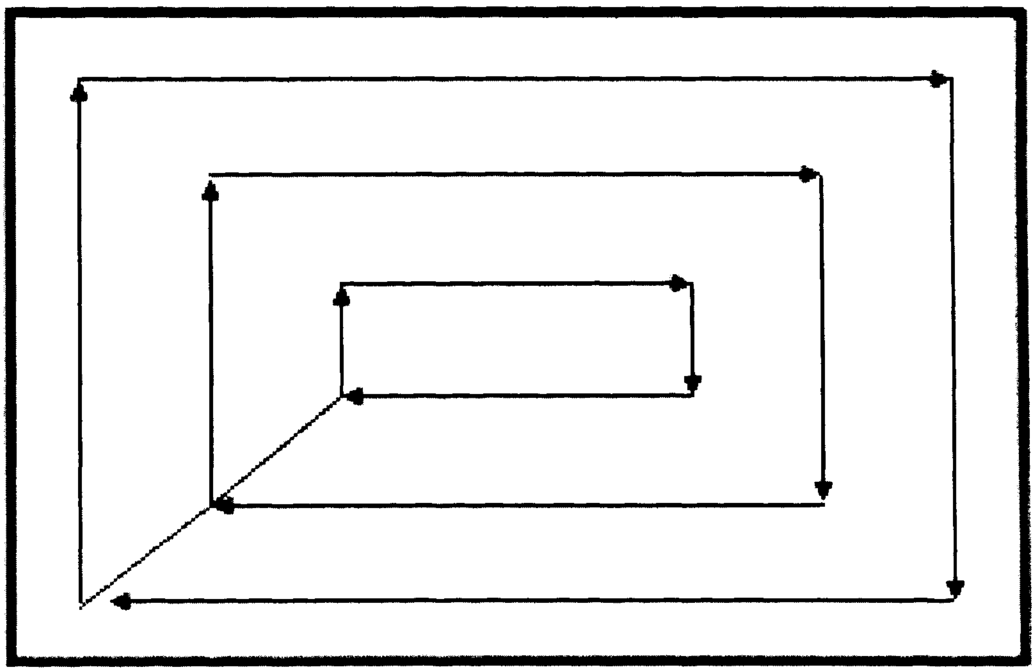

Figure 1.2 Offset Path

The condition of overfills (bumps or excess material) and under-fills (gaps or voids) in a layer is considered as layer evenness, which is majorly determined by tool-path. This research presents the study of the usage of different 2-D deposition tool-path patterns.

Zigzag Pattern: In the Zigzag pattern, the nozzle tip moves back and forth parallel to the referenced directions. When the tip moves back and forth the laser is turned on and off repeatedly in order to control the material deposition. Because, if the zigzag path is continuous then there will be overfills at the turn points. However, to control the overfilling one solution is to control the speed of the nozzle. 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. When the nozzle is decelerating and comes to a stop the laser is turned off. Similarly, when the nozzle starts accelerating the laser is turned on. So, the zigzag path is discontinuous at turning points. Thus, the tool-path represented at the turns and also at the jumps from one region to the other, to cover the entire area of the layer, is called the non-depositing tool-path. An efficient tool-path should have a lesser ratio of the non-depositing to the depositing tool-path. In this research, the zigzag path is optimized in order to improve the efficiency by reducing the idle or non-deposition path.

Offset Pattern: In an offset pattern, offset segments for the geometry boundaries are generated and used as a guide for the nozzle to move along (Figure 1.3). The recursive-offset approach posts several problems. First, offsetting a single closed curve could result in multiple disconnected paths. This problem is often solved by lifting the tool, moving it across to the next starting point, and starting the next path. Second, paths generated this way do not guarantee to completely fill a desired 2D region. Because when there exist a sharp corner, portions of the offset curves are trimmed to ensure the desired offset distance. The deposition process can be considered as a constant-radius disk being swept along the computed path. Without appropriate overlapping, it leaves gaps between consecutive curves due to the greater-than-radius distance from the trimmed points to the corner (Figure 1.4). Thus, to handle the corners appropriate overlapping is to be considered.

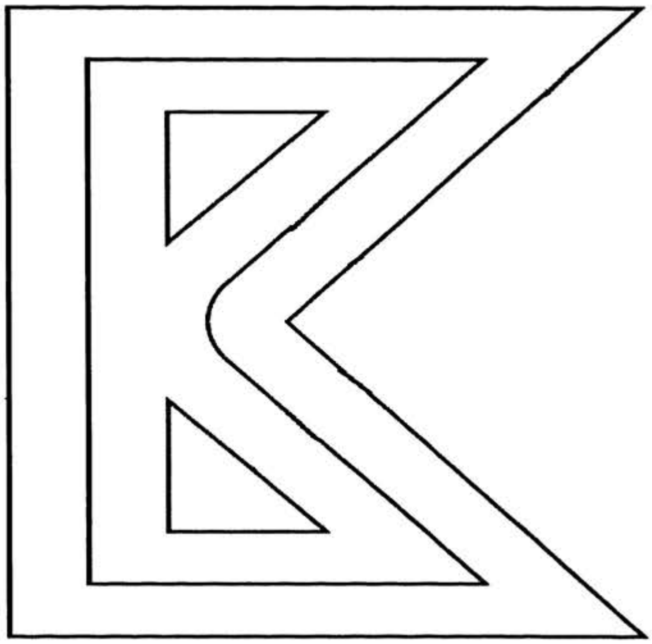

Figure 1.3 Offset Path Generated for the Machine Deposition

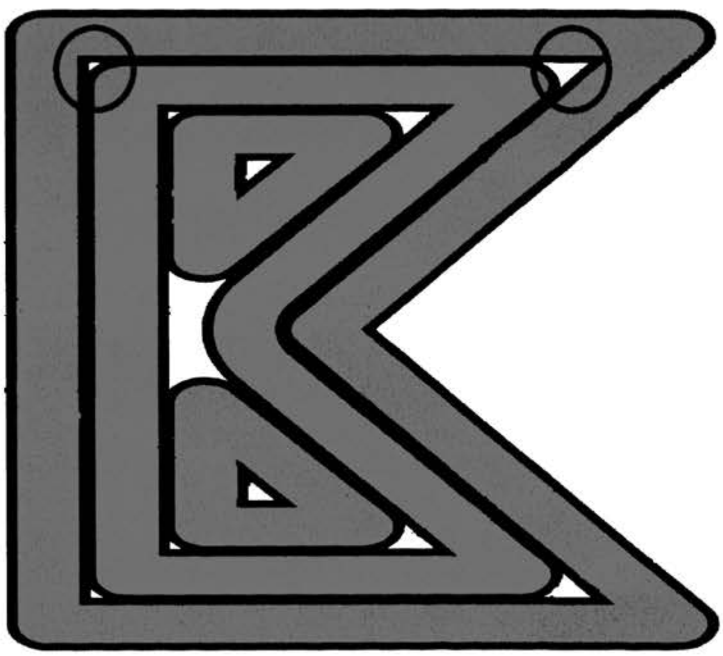

Figure 1.4 Offset Path Deposited without Overlap between the Consecutive Paths due to which the Gaps are Created

Although there is an overlap between the offset curves, the small angled sharp corners are not yet covered. In this research, a solution to handle the sharp corners is being studied. Different from the machining process, the deposition height is highly determined by the scanning speed given a constant laser power and material feeding rate. Using this characteristic, the offset path is generated and optimized to minimize the variation of the scanning speed to maintain the deposition height estimation.

2. RELATED WORK

In layered manufacturing, the quality of the parts is still very much dependent upon the shape of the deposition paths [3], especially for direct metal deposition processes. Even though the deposition path patterns have been studied for a long time, including raster path, contour offsetting paths and spiral-like offsetting paths etc, there are still some problems or assumptions associated with different algorithms.

In the zigzag pattern, the tip of the nozzle is moved back and forth parallel to referenced directions. The common zigzag pattern technique is to scan in the direction parallel to the longest side of the geometry results in the shortest deposition path. However, the angles of the zigzag paths are still the source of localized build errors which cause the unevenness aligned with the direction of paths in the build [3]. A zigzag pattern which is based on the optimal inclination of the tool and the tool path elements in the specific inclination and connecting the tool path elements to form a shortest path in the milling process is explained [4], illustrated in Figure 2.

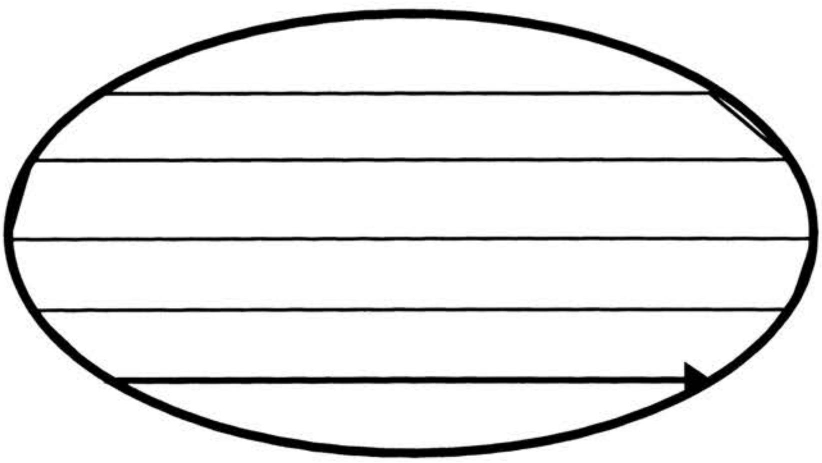

Figure 2.1 0° Inclination: Five Tool-Path Elements

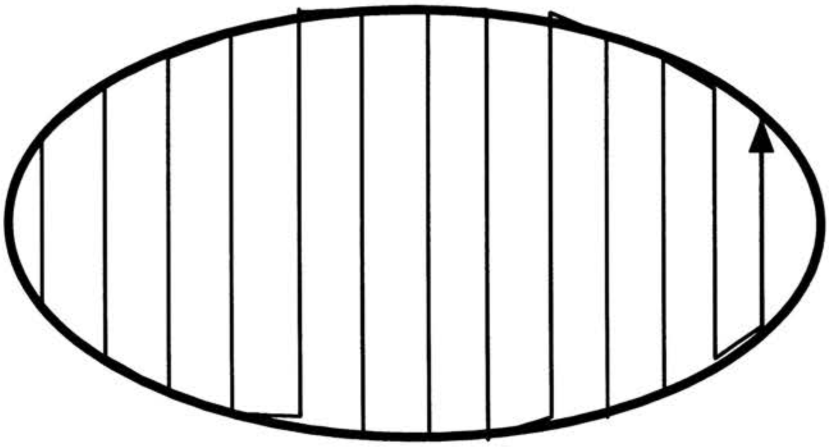

Figure 2.2 90^o Inclination: Thirteen Tool-Path Elements

In an offset pattern, offset segments of the geometry boundaries are generated and used as a guide for the nozzle to move along. By tracing the offset paths, residual stress could be relieved before tracing the next adjacent edges. Therefore, stress-induced warping is reduced. This pattern includes pair-wise offset, pixel-based offset, Voronoi approaches and spiral-like offset. However, these approaches usually have some problems such as detecting the intersection of offset edges and removing invalid loops [5~7] and being computationally intensive [8] and numerically stable [9, 10]. Based on the work performed by Kao and Prinz [3], spiral offset paths are typically preferred for producing isotropic deposits. In [11], a modified approach to generate offsetting edges is introduced. This algorithm divides the deposition layer into some unconnected regions for which the offsetting paths will be generated for every single region component. Apparently, this method has more power to handle some complicated arbitrary shapes, especially those with inner loops. On the other hand, these tool-path generation methods do not consider the path effect on the scanning speed. The fabrication resolution can be improved by adjusting the power level [12]. Adjusting the offset tool-path to achieve a constant cutting force has been studied by Wang et al. [13]. Both of them have considered the effect of power and tool-path on the results. A similar concept has been developed for metal deposition process to reduce the variation of the deposition height.

In this research, a zigzag path generation is developed based on the hierarchy structures of a shape. A shape is divided into several sub-areas which are formed as a hierarchy graph structure. For offset pattern generation, the deposition height model is developed and relationship between the path and scanning speed model is used to optimize deposition path.

3. POWDER-BASED LASER METAL DEPOSITION PROCESS

Lasers have a tremendous impact in manufacturing industries. With laser innovations, the world is now experiencing the use of optical energy in a wide range of applications from material processing to Rapid Prototyping (RP). The use of lasers, in conjunction with metal powder, is one of the latest extensions to rapid prototyping, which had earlier involved plastic parts exclusively. Rapid prototyping using lasers has enabled the fabrication of complex, near–net shape functional metal parts directly from a CAD model at a low cost and offers faster turnaround. Currently this technology is implemented under a variety of names such as Direct Light Fabrication (DLF), Laser Metal Forming (LMF), Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Selective Laser Cladding (SLC), etc. Though the system description and specifications of each of these vary, they all rely on the same principle of part fabrication, i.e. layer by layer deposition [15].

A general description of the method of fabricating a part involves utilizing a laser to melt metal powder injected by a nozzle and laying down clad tracks via a positioning system having a controlled motion as shown in the Figure 3.1. In some cases the lasers may be directed along a defined path and tracks are laid down on a stationary table. To control the deposition process it is necessary to understand the process system mechanics for which relations among various parameters need to be studied. The optimization of the process requires the measurements and control of parameters such as the powder feed rate, process speed, melt pool temperature and melt pool quality [15]. The applications of the powder based laser deposition process are Surface restoration on damaged areas, Repair or fabrication of components, Surface coating, Fabrication of dissimilar materials etc.

Usually, a laser powder-based metal deposition process consists of a high power laser, powder delivery system, cladding nozzle, and motion control. In a typical laser powder-based metal deposition process, metal powders, injected into the laser focal zone, are melted and then re-solidify into fully dense metal in the wake of the moving molten pool created by the laser beam as shown in the Figure 3.2. Successive layers are then stacked to produce the entire component volume of fused metal representing the desired CAD model.

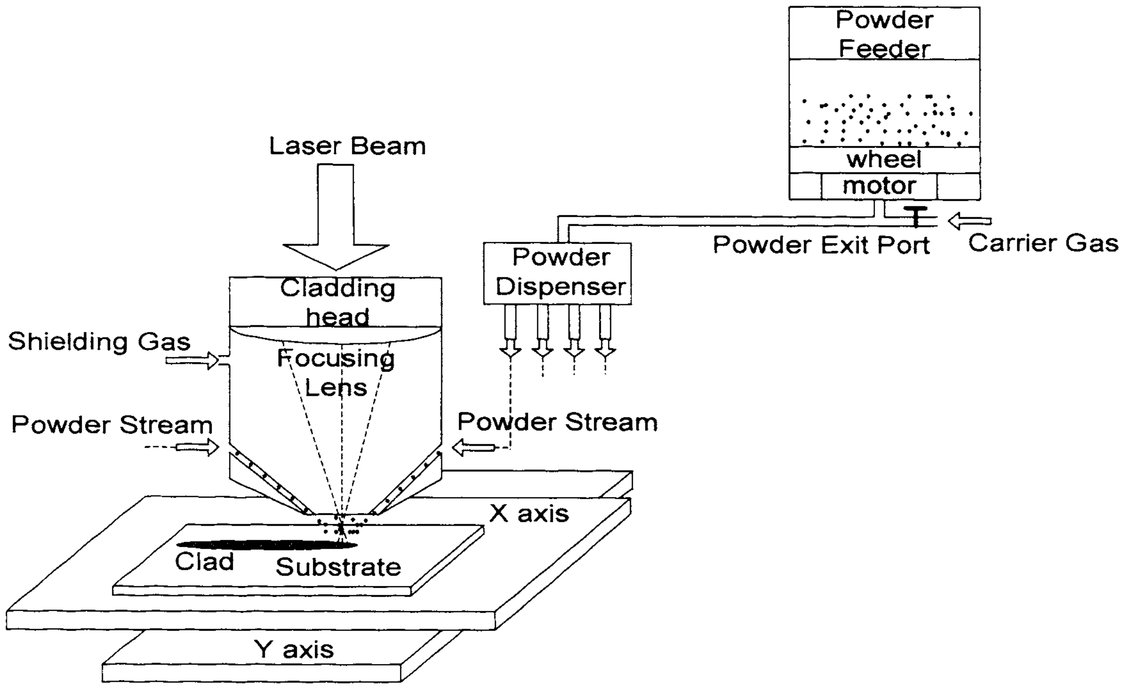

Figure 3.1 Powder-Based Laser Metal Deposition Process Setup

In this research, this process is used for the repair or fabrication of the machine parts. Different than other rapid prototyping processes, the laser powder-based metal deposition process will have the overlap between each track when the metal is deposited. As shown in the Figure 1.4, the deposition tracks will have gaps created if there is no overlap between each track. As the laser powder-based metal deposition process handles this problem, the gaps between the deposition tracks are eliminated. Some unmelted powder during one track deposition is melted when the laser scans the neighboring area and this effect may cause the uneven layer height deposition. To investigate this effect, experiments have been run using different laser scanning patterns in the Laser Aided Manufacturing Process (LAMP) lab at Missouri University of Science and Technology (Missouri S&T). LAMP's process is a multi-axis hybrid manufacturing process which can directly produce functional parts with machining accuracy [11]. The diode laser in the LAMP lab is used in this research to achieve better energy efficiency.

Figure 3.2 LAMP Deposition Process using the Laser Beam

4. 2-D PATH PLANNING

2-D deposition pattern and strategy study has been investigated and the zigzag and offset pattern are selected for each sub-region based on geometric shape [14]. The two different tool-path generations are discussed below.

4.1 2-D ZIGZAG PATH PLANNING

A typical zigzag path consists of a number of parallel segments. The path travel direction and connection determines the efficiency. Path orientation determines the entire path length. In laser deposition process, the "idle" or non-working path should be as short as possible due to the energy consumption and potential material waste. Path connection determines the length of "idle" paths; thus, the tool-path orientation and path connection are two critical techniques in generating zigzag path.

4.1.1 The Tool-path Direction Determination: Illustrated in Figure 2.1 and Figure 2.2, it can be observed that the tool-path with an inclination of 90^{o} is having more number of non-depositing track paths compared to the one with 0^{o} inclination. Also the total length of the tool-path for the 90^{o} inclination is longer than the tool-path of 0^{o} inclination. In this research, the bounding box concept is used to select the inclination direction for zigzag path instead of using the longest edge of a 2-D shape. The ratio of the longer edge to shorter edge of the bounding box is different, as shown in Figure 4.1 and Figure 4.2. This concept is used to determine the inclination direction. In this research, the bounding box with the largest ratio is used to generate zigzag path. In order to find the bounding box with the largest ratio for a 2-D shape, the shape is rotated and the bounding box at each orientation is obtained. For each step compare the ratio of the longer edge to the shorter edge of the newly generated bounding box. If the ratio is larger compared to the previous bounding box then consider the current one. This process is continued. Finally, the bounding box with the largest ratio among all is selected and the inclination direction for the zigzag path is determined. The inclination direction is the direction of the longest edge of the largest ratio bounding box.

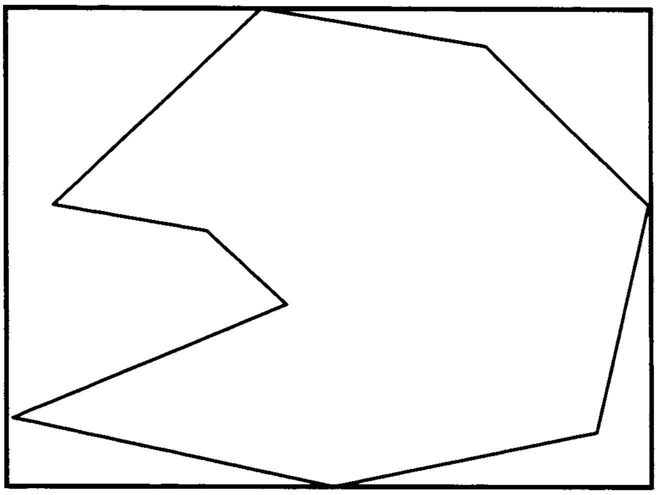

Figure 4.1 Bounding box with Large Ratio

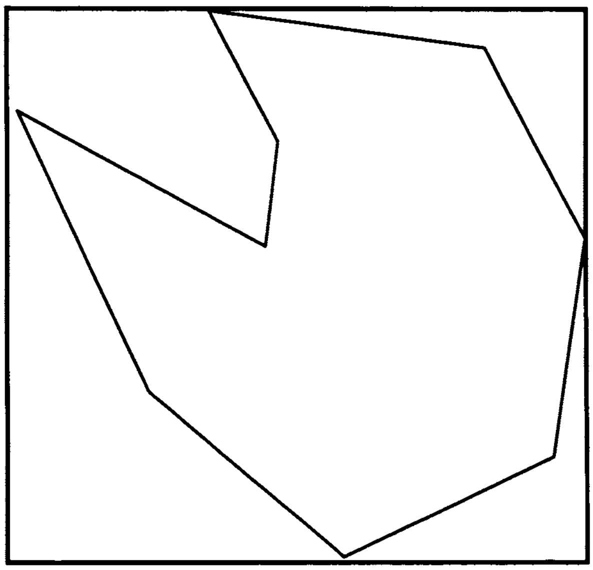

Figure 4.2 Bounding box with Smaller Ratio

4.1.2 Graph structure construction: Once the zigzag path orientation is determined, a series of parallel paths can be generated. Connecting these paths has many different ways which results in the difference in efficiency. A hierarchy graph is designed for zigzag paths and is used as guide for path connection, illustrated in Figure 4.3. Such a hierarchy structure is formed while generating the zigzag path as shown in Figure 4.4.

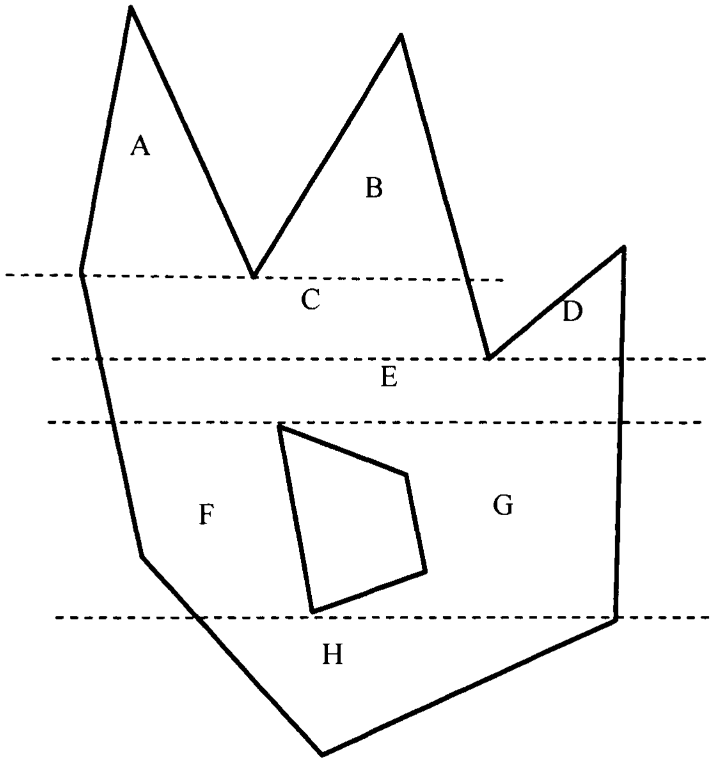

Figure 4.3 Zigzag Path Regions

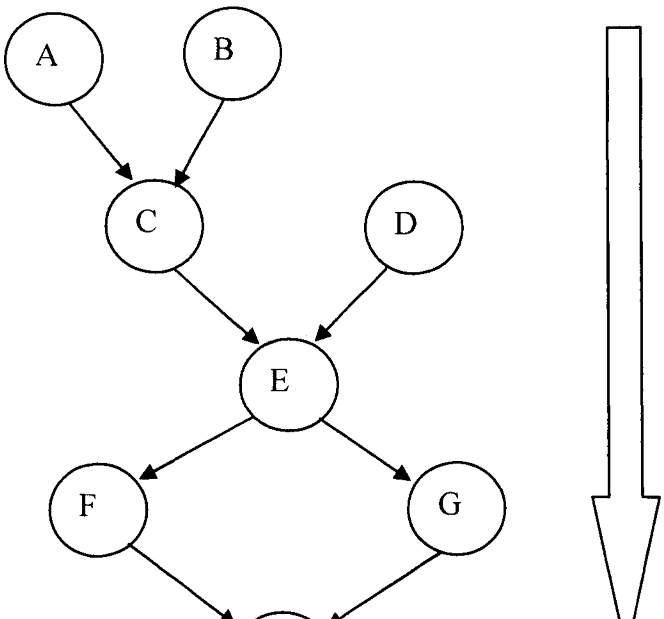

Figure 4.4 Hierarchy Graph Structure

When the first parallel is obtained, node (s) is (are) created for each segment. Each node contains a series of parallel segments, as shown in Figure 4.5. When topological relationship changes, the current node is complete and another new node is created to record the newly generated tool-path. A "parent-child" relationship is formed between these two nodes, as shown in Figure 4.6.

The hierarchy graph not only defines the different areas (regions) of a 2-D shape following the zigzag orientation but also defines the path connection sequences, as shown in Figure 4.7. The graph is complete when all the regions are connected, as shown in Figure 4.8. In this hierarchy graph, the level is assigned to each node. The parents of the same child are assigned as the same level.

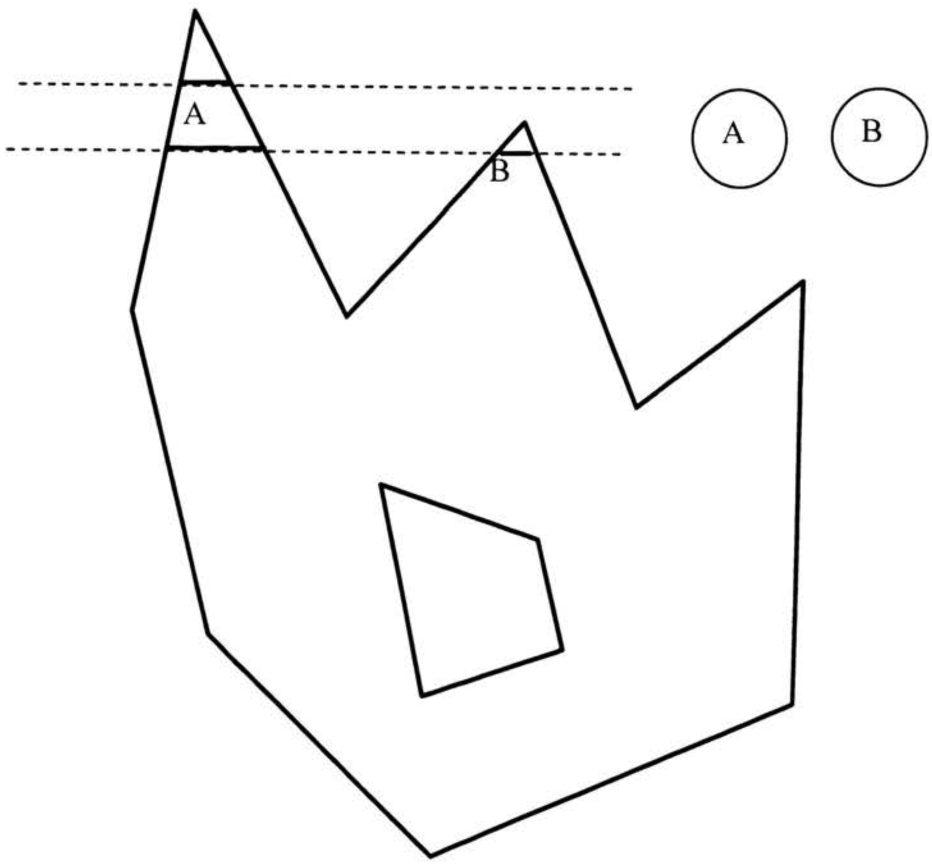

Figure 4.5 First two nodes are A and B

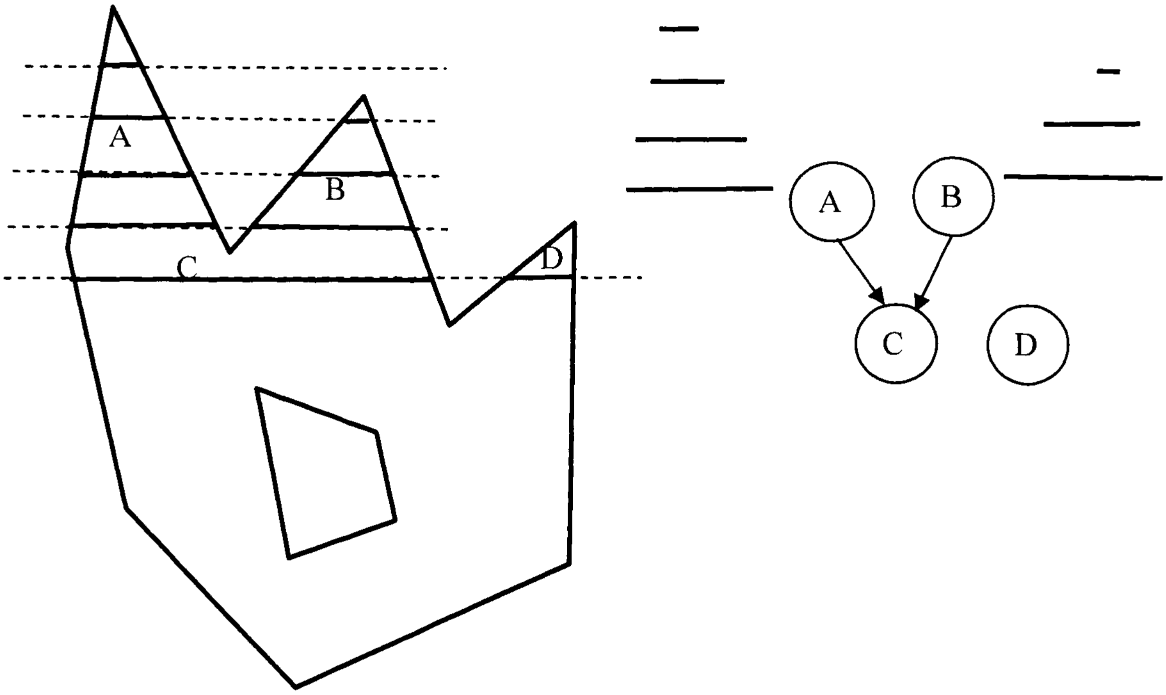

Figure 4.6 Nodes A and B are complete due to the topological change. Nodes C and D are created. Nodes A and B are parents of Node C

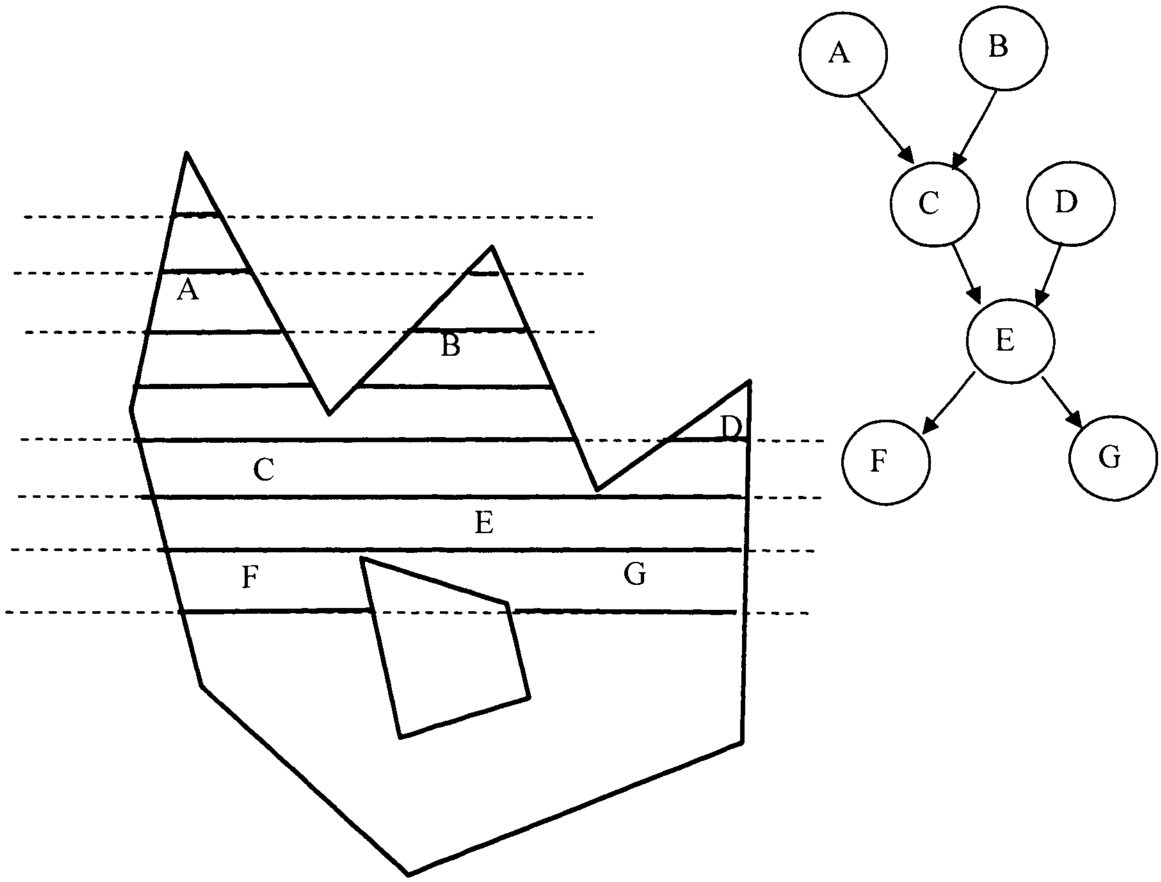

Figure 4.7 The Graph is Continuously Formed

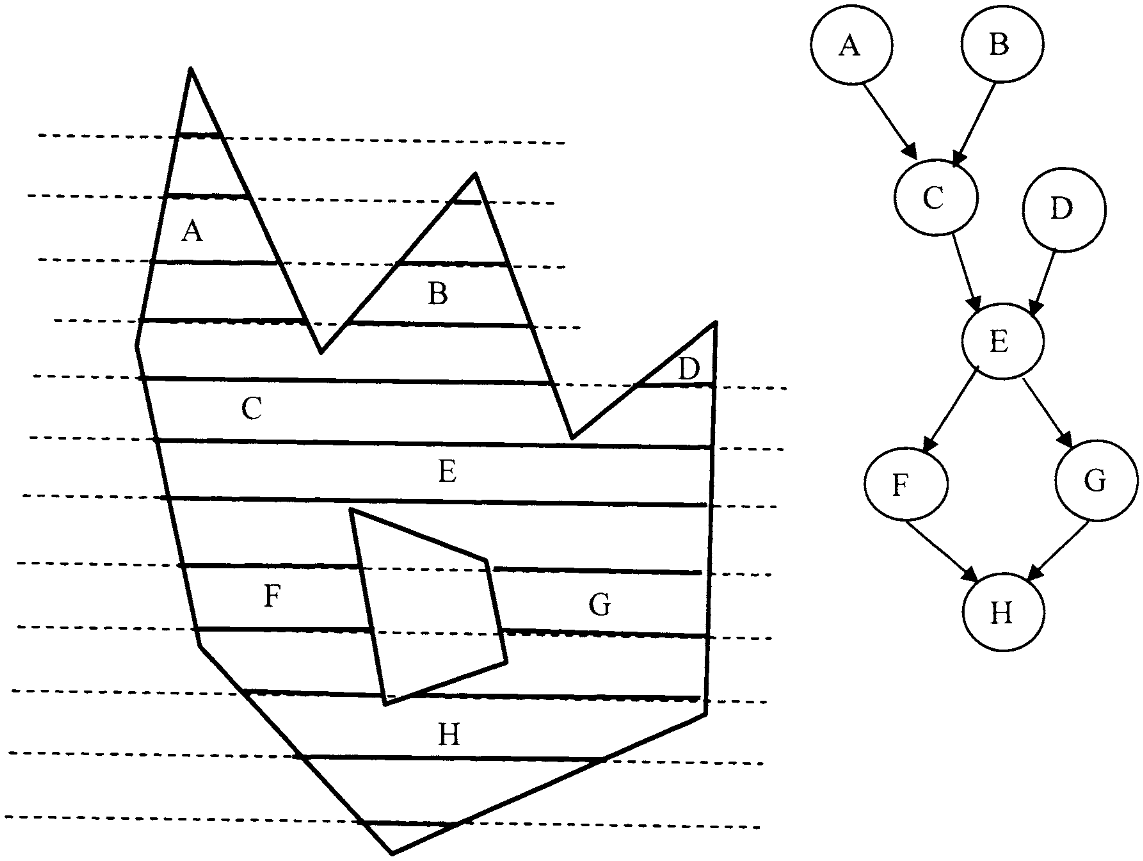

Figure 4.8 Final Graph

In order to avoid unnecessary "back and forth" movement, the left top point is taken as the starting points. It is very clear that the sequence A (Figure 4.9) is more efficient than the sequence B (Figure 4.10) since the "jump" between node A and D is longer. The bounding box is represented as 'BB', the tool-path orientation is given by $\overrightarrow{DP}$. The starting point of the tool-path is selected based on the bounding box (BB) and is represented using 'TP'. The *Getintersection* function will output the deposition tracks of the layer. The intersection point of this deposition track is represented using 'IP'. The graph is represented using 'NG'. The zigzag path generation method is summarized below:

Input *(2D Shape S, Zigzag Path Interval t)*

Output: *Zigzag path*

Begin

GetBoundingBox (S) → *BB*

GetPathOrientation (BB) $\rightarrow \overrightarrow{DP}$

GetTopLocation(BB) $\rightarrow$ *TP*

GetIntersectionPoint $\rightarrow$ *IP*

GetIntersection(TP, S)

While *(no more intersection)*

  If *(First Intersection)*

    CreateNode $\rightarrow$ *NodeList*

  Else

   If *(Topological relationship changes)*

     EndCurrentNode

     PutCurrentNodeIntoGraph $\rightarrow$ *NG*

     CreateNode $\rightarrow$ *NodeList*

   Else

     PutPathIntoNode

   End

  End

  ComputeNextIntersectionPoint (t, $\overrightarrow{DP}$*)*

EndWhile

Do breath Search in NG

OutputZigZagPath

End

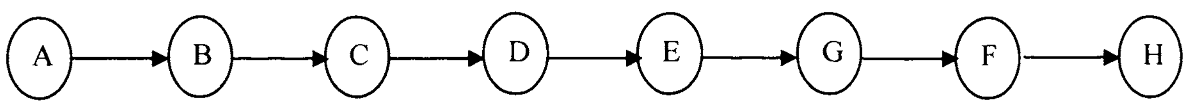

Figure 4.9 Zigzag Path Travel Sequence A

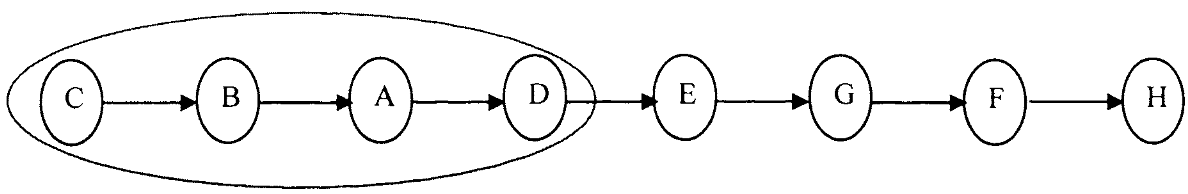

Figure 4.10 Zigzag Path Travel Sequence B

4.1.3 Graph Data Structure: A graph consists of a number of data items, each of which is called a vertex. Any vertex may be connected to any other, and these connections are called edges [16]. The following Figure 4.11 shows a graph in which the vertices are numbered from 1 to 5. The edges represent the connection between these numbered nodes. Two vertices in a graph are adjacent if they form an edge. The graph in the Figure 4.11 has bidirectional edges. There is no specific direction mentioned from one vertex to the other. The connection can be in either ways. Such kinds of graphs are called the undirected graphs. An undirected graph is connected if, for any pair of vertices, there is a path between them. The graph in the figure is connected.

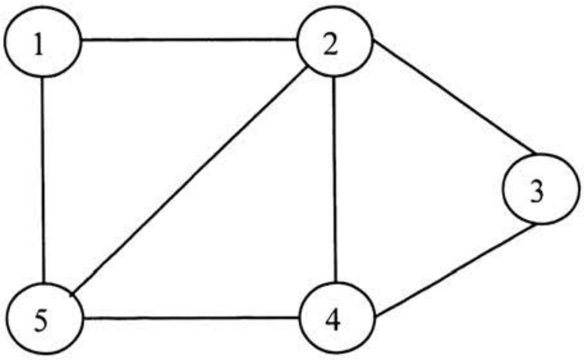

Figure 4.11 Undirected Connected graph

While graphs are a very common data structure used in a wide array of different problems, there is no built-in graph data structure. Part of the reason is because an efficient implementation of a Graph class depends on a number of factors specific to the problem at hand. For example, graphs are typically modeled in either one of two ways:

- As an adjacency matrix
- As an adjacency list

These two techniques differ in how the nodes and edges of the graph are maintained internally by the Graph class.

Adjacency Matrix: A two-dimensional Boolean matrix, in which the rows and columns represent source and destination vertices and entries in the matrix indicate whether an edge exists between the vertices associated with that row and column [17]. Operations with a graph represented by an adjacency matrix are faster. However, if a graph is large such a big matrix to represent a graph can't be used, so collection of adjacency lists is used, which is more compact. Using adjacency lists is preferable, when a graph is sparse, i.e. $|E|$ is much less than $|V|^2$, but if $|E|$ is close to $|V|^2$, choose adjacency matrix, because in any case O ($|V|^2$) memory is used. Here E is the number of edges and V is the number of vertices.

Adjacency list: An adjacency list is implemented as an array of lists, with one list of destination nodes for each source node [17]. The main idea of this way is storing a linked list of adjacent vertices for each vertex. For a graph with a sparse adjacency matrix an adjacency list representation of the graph occupies less space, because it does not use any space to represent edges that are not present. The adjacency list for the graph in Figure 4.11 is shown below in the Figure 4.12

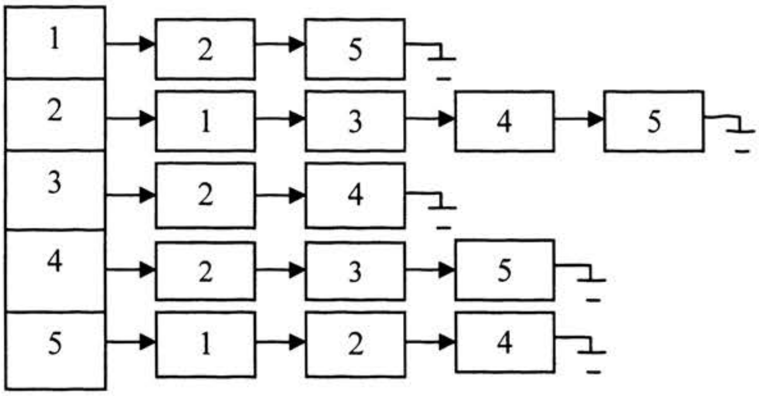

Figure 4.12 Adjacency List Representation of the Graph

The graph data structure used to store the zigzag path in this research also uses the adjacency list representation. The disadvantage of the adjacency list representation is that for storing the edges the vertex information is replicated. For example, in the Figure 4.12 the vertex 1 has an edge with vertex 2. Here the linked list of the vertex 1 has stored the vertex 2 as an edge by replicating it. Also the linked list of the vertex 2 stored vertex 1 as an edge by replicating it. So, in order to reduce the memory wastage for replicating the vertex information, the edges used in the zigzag graph structure has no data field. It uses two pointers one to point the vertex which forms the edge and the other to connect to the next set of edges for the respective vertex. Here, instead of replicating the vertex information the pointer points back to the vertex which has to be replicated. So, the memory used for the data field is reduced by using a pointer which uses fixed memory space of 4 bytes in a 32-bit system. If the data field occupies less than 4 bytes then this method will not be effective. However, if the data field occupies more than 4 bytes then this method is helpful. In the graph structure used in storing the zigzag path, the data field of the nodes of the graph has linked list which stores the sub-area/region information of the slice. So, this method saves a huge memory in this case as it will not replicate the linked list in the edge information.

The graph data structure used in the zigzag path planning has the vertex information represented as a Node. The fields in the Node class are represented in the Figure 4.13. The edge between the nodes is represented by using the Edge class. The fields in the Edge class do not have the data field. Instead 'n_next' pointer is created which points back to the node which makes the edge. The Edge class fields are shown in the Figure 4.14.

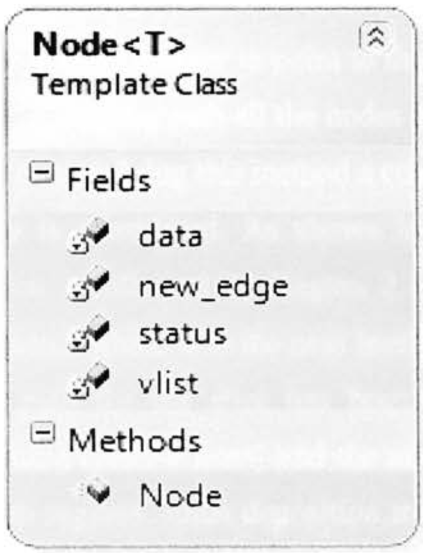

Figure 4.13 Fields and Methods of the Node class

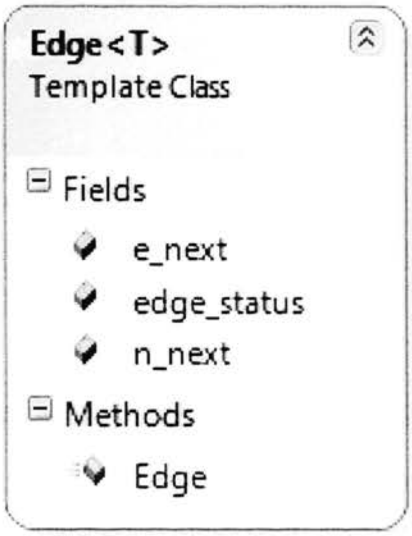

Figure 4.14 Fields and Methods of the Node class

The graph structure using the adjacency list representation is shown below in the Figure 4.15. Each node in the array of nodes is pointed to by a linked list of edge information. In normal graph data structure the edge type is also same as the node type. However, in this case the edge is a different class and the node is a different class. The edge does not store the node information. Instead, uses a pointer to point to the node whose information is to be stored. To obtain the optimal zigzag path all the nodes in the graph should be covered once by the shortest path. While applying this method a condition that the sub-regions are to be covered breadth wise is considered. As shown in Figure 4.18 the regions are covered breadth-wise. Region 1 followed by Region 2 which is in the same level is covered before going to Region 3 which is in the next level.

Initially the zigzag path for the slice has been computed using the shortest distance between the depositing (yellow lines) and the non-depositing (red lines) paths. The layer is not divided into regions. Each deposition track is stored in the linked list with its starting and ending points (Figure 4.16). With respect to the starting point of the deposition path, each of the next tracks is selected based on the shortest distance from the current deposition track to the remaining tracks which are not yet connected.

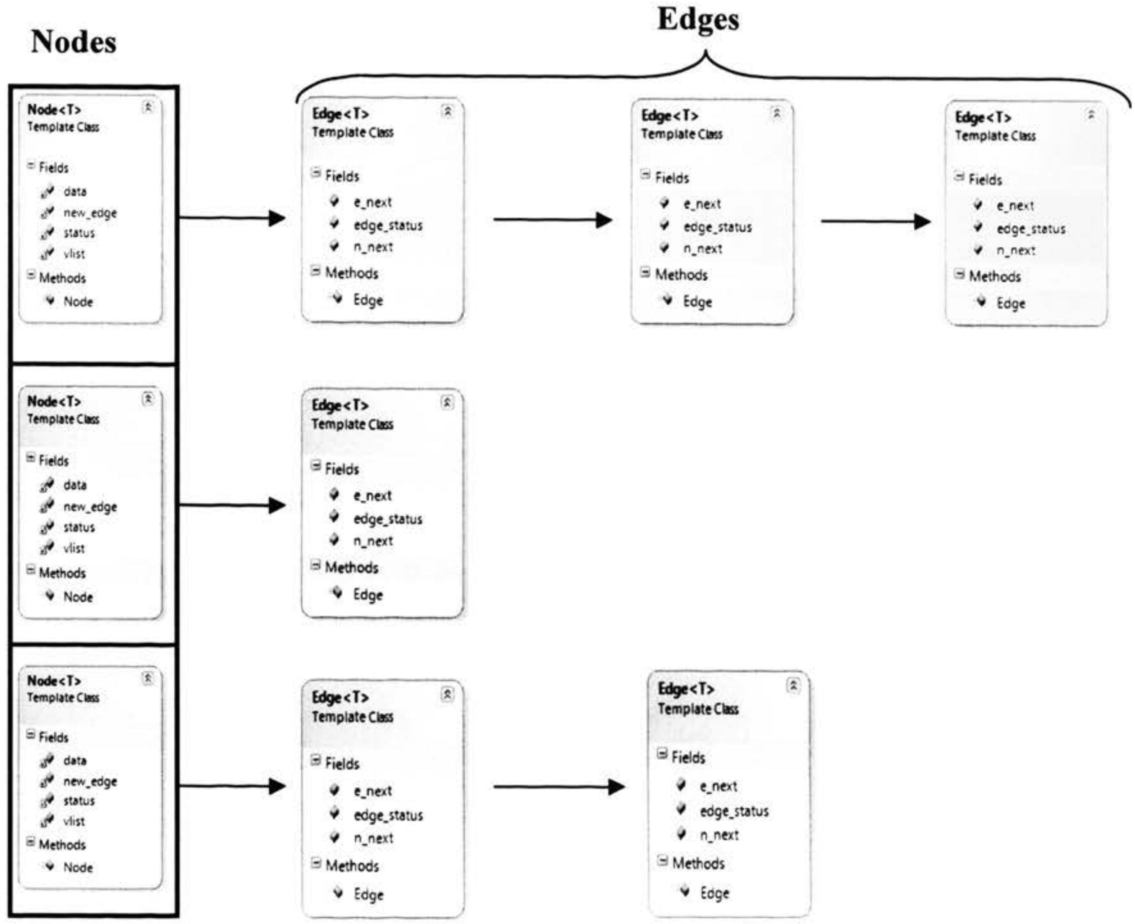

Figure 4.15 Graph Structure for the Zigzag Path Planning using Adjacency List Representation

This process is continued until all the deposition tracks are covered (Figure 4.17). The path obtained using this method has many unnecessary back and forth jumps. The circled region in the Figure 4.17 is covered by making an unnecessary jump. So, to avoid these jumps the algorithm mentioned in the section 4.1.2 is implemented. In this algorithm the slice is divided into sub-regions as shown in the Figure 4.18. For example, the sub-regions in the Figure 4.18 are numbered 1 to 5 with each sub-region separated by purple line. Now these sub-sections are stored as nodes in the graph and the shortest path which will cover all the sub-regions is computed as shown in the Figure 4.18.

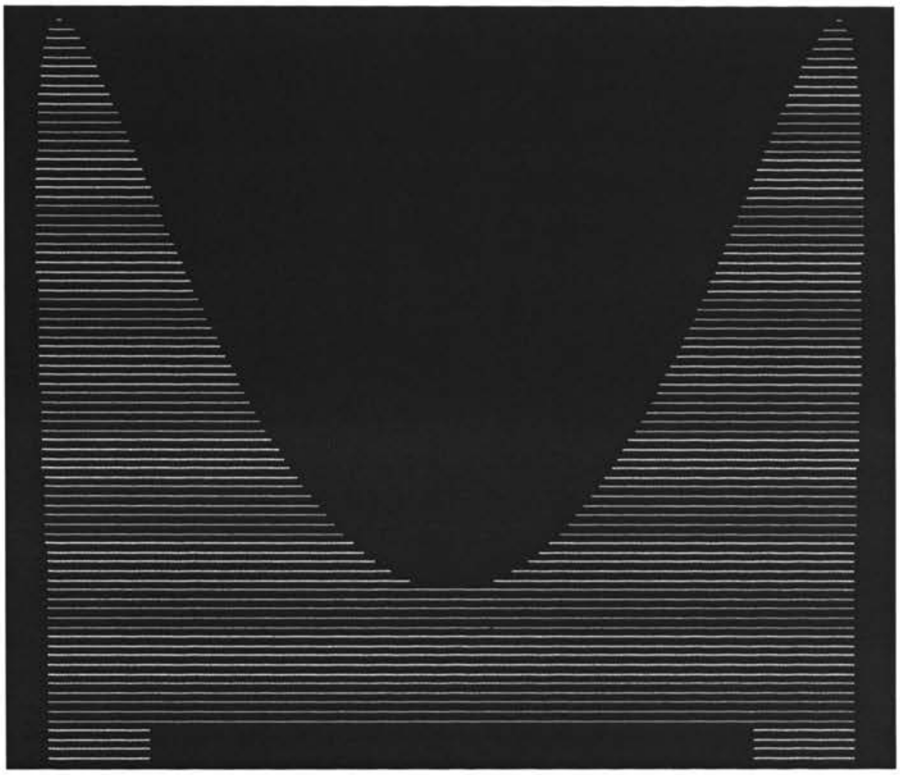

Figure 4.16 The Deposition Tracks before Zigzag Path is Generated

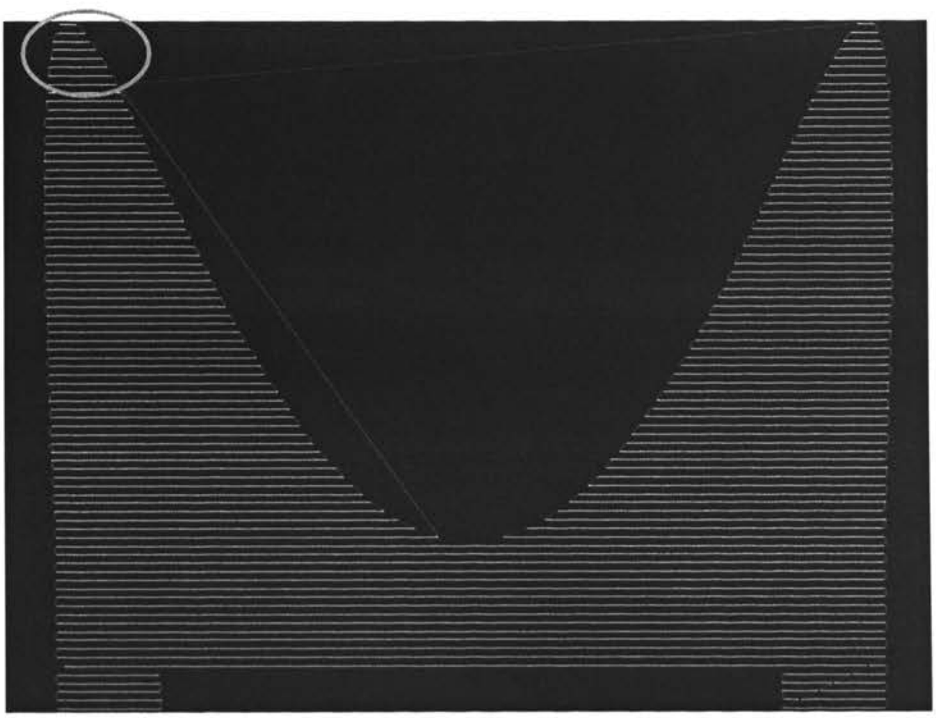

Figure 4.17 Zigzag Path having Unnecessary Jump to Cover the Circled Area

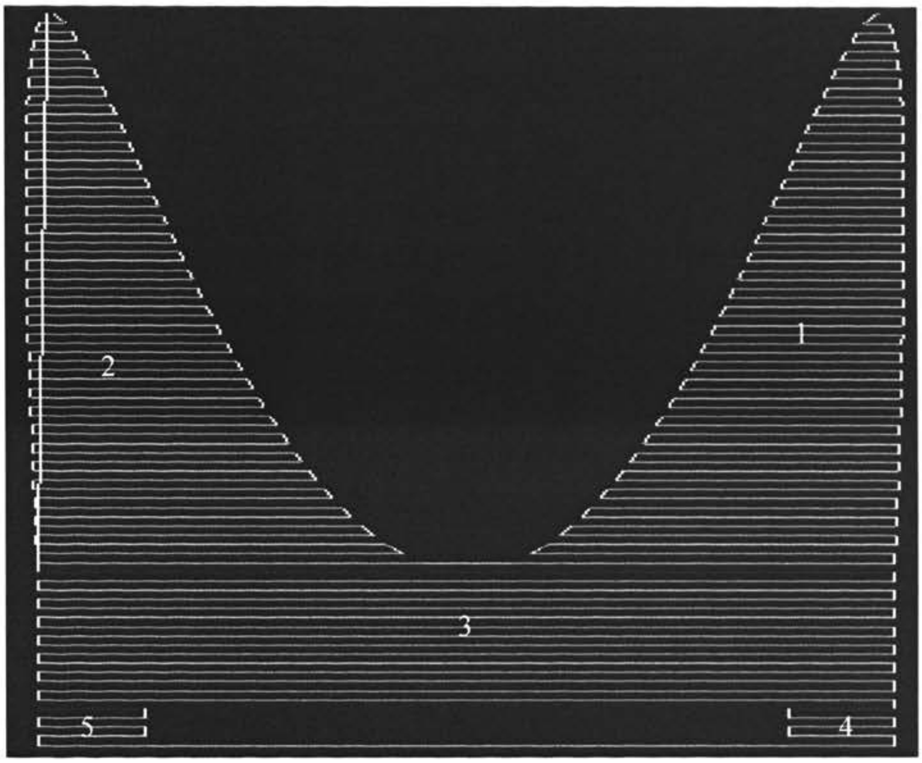

Figure 4.18 Zigzag Path with Reduced Number of Jumps

4.2 OFFSET TOOL-PATH GENERATION

The offset tool-path for machining processes has been researched widely. Simple offset or contour tool-path has been common practice in industry for a while. Although such path pattern has been used to generate tool-path for metal deposition process, the character of material additive process is still not fully incorporated into tool-path generation. For example, the different overlap of tool path does not change the final machined shape for a regular machining process. However, the different overlaps in the tool-path for a laser metal deposition process have huge impact on layer height. The research on offset tool-path generation in this thesis is to maintain the deposition height by varying the speed.

4.2.1 Characters of the Metal Deposition Process:

Deposition height vs. laser scanning speed: The deposition height is determined by the scanning speed with constant laser power and material (or powder) feed rate.

Figure 4.19 shows the relationship between the deposition height and scanning speed. The height is the average of 5-layer single track deposition. The experiment is performed using LAMP system at Missouri S&T. The tracks are measured using a 3D laser scanner (NEXTENGINE Desktop 3D scanner, Model 2020i). Therefore, changing the scanning speed is able to vary the deposition height.

Deposition bead shape: The ideal shape of a deposition bead is a cap as shown in Figure 4.20. However, due to the heat transfer phenomena, the center of the laser spot always has the highest temperature. For most of the materials, the deposition bead is a bell-like shape as shown in Figure 4.21. The height profile can be modeled as,

$$H_r = f(r),\ r \leq R \quad (1)$$

where R is the radius of laser spot.

An empirical model can be constructed for different materials with different laser scanning speed

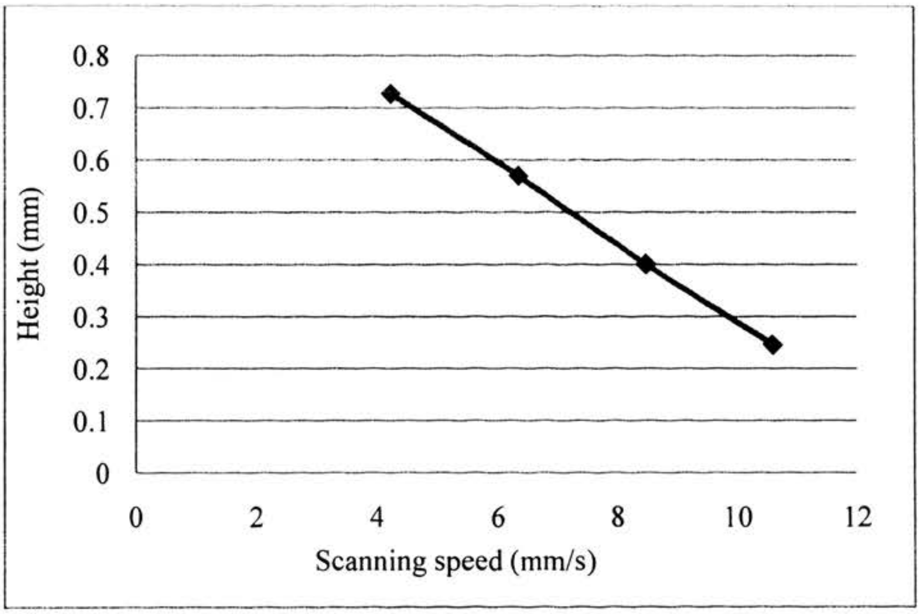

Figure 4.19 Experiment Result Relating to Track Height and Scanning speed given Laser Power of 850W and a Powder Flow Rate of 12gpm

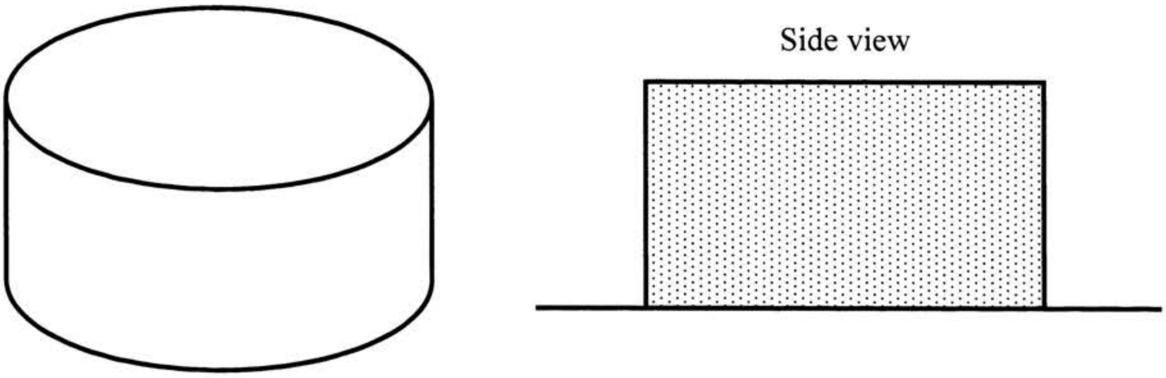

Figure 4.20 Ideal Deposition Bead Shape

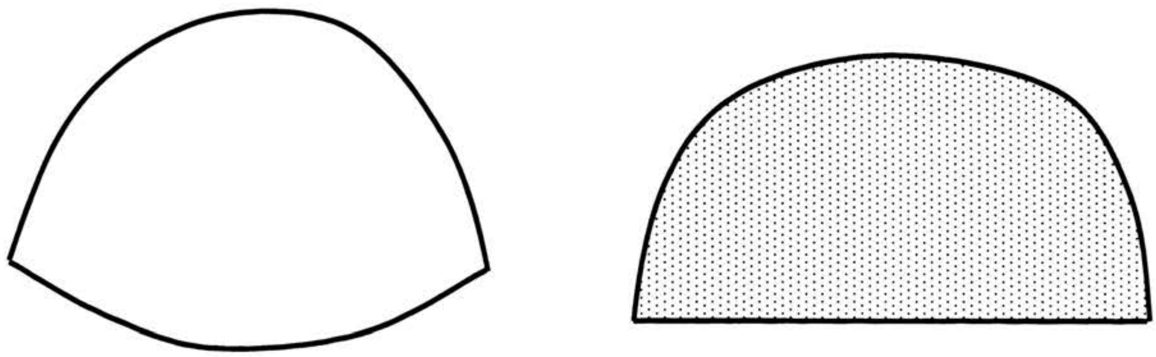

Figure 4.21 Realistic Bell Shape for a Deposition Bead

Overlap effect: The overlap of the tool-path in the machining process is to guarantee that the machining tool covers the entire area to be machined. In laser metal deposition process, the overlap also serves another purpose. The cross section of a deposition track for most metal materials is also bell-like; thus the overlap between tracks also helps to maintain the height. It is obvious that a small overlap leads to less deposition and a large overlap can lead to over deposition. The deposition P of any location can be given by

$$H_p = \sum_{i=1}^{n} \alpha_i f(r_i) \tag{2}$$

where α_i is an empirical coefficient for different metal materials. There are n deposition locations nearby location P with a distance less than the laser spot or bead size. This model considers the add-on effect of the material additive process.

4.2.2 Realistic Speed Profile: In typical process planning, a nominal speed is used for entire deposition path. However, due to dynamics of each axis, each axis has to accelerate or decelerate while changing the travel direction; thus, the machine cannot maintain an ideal constant speed. For Fadal CNC machine used in LAMP system, it is observed that the speed is dropped dramatically (more than 90%) when make a sharp angle turn (angle less than 20°). Figure 4.22 shows a speed profile for a circle. The speed variation is about 35%. The speed variation is lowered to 5% when a polygon approximated circle is used. Based on these observations, the strategy of offset path adjustment is to use polygon segments to remove the sharp angle.

4.2.3 Tool-path Adjustment Approach:

Sharp angle identification and processing: Assuming a B-Spline or a polygon model in the input geometry, the sharp angle point can be identified by tracing the angle between the edges. In this offset adjustment process, the tool-path along the boundary is not changed in order to maintain the required shape; thus the adjustment takes place on the path next to the boundary

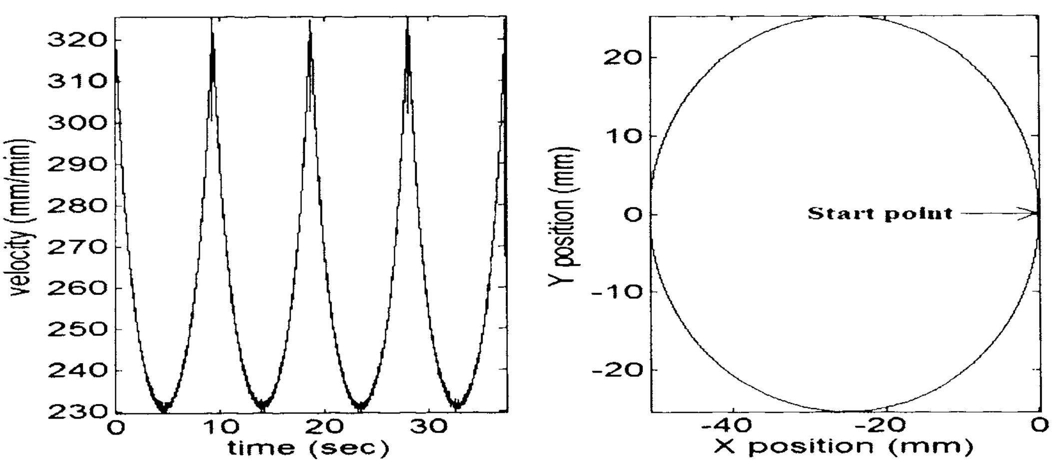

Figure 4.22 The Speed Profile of FADAL 3016L for a Circle

Let $\vec{P}$ be the point at a sharp angle on the offset path and $\overrightarrow{P_O}$ is the corresponding point on the outer path, shown in Figure 4.23. In order to adjust the tool-path and remove the sharp angle, it is obvious that the point $\vec{P}$ should move along the direction $\overrightarrow{P_O P}$ shown in Figure 4.24. However, the moving direction is $\overrightarrow{PP_O}$ for the concave vertex shown in Figure 4.25. $\overrightarrow{P_O P}$ or $\overrightarrow{PP_O}$ is along with bisector line. Moving $\vec{P}$ along this direction can have the equal impact on the neighboring path since the points on the bisector line have equal distance to both edges which form the angle. The first guessing point is given by

$$\overrightarrow{P_N} = \vec{P} + \vec{L} * a * T \quad (3)$$

where T is the track width, α is a coefficient for track width and $0.25 < a < 0.5$. a is determined by the sharpness of the angle. The sharper the angle, the greater α is. The resultant direction obtained after the dot product of $\vec{P}$ and $\overrightarrow{P_O}$ is given by $\vec{L}$

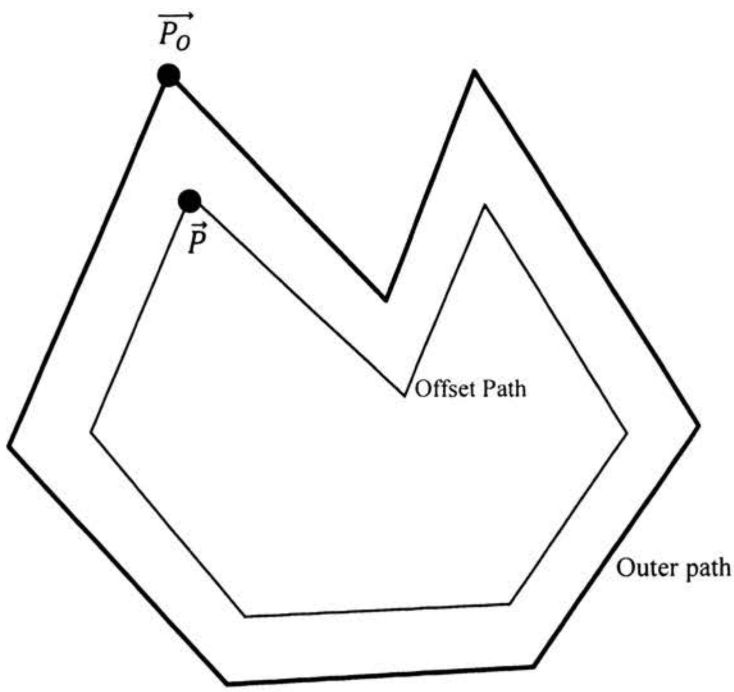

Figure 4.23 Vertex at a Sharp Angle

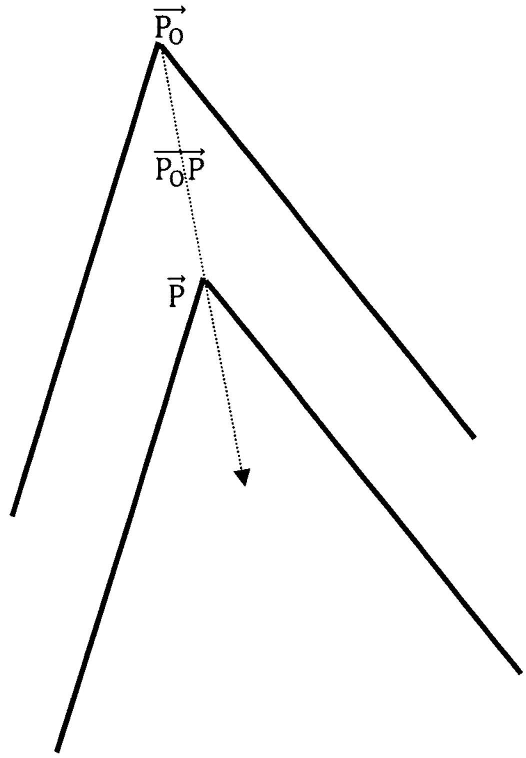

Figure 4.24 Convex Vertex Moving Direction

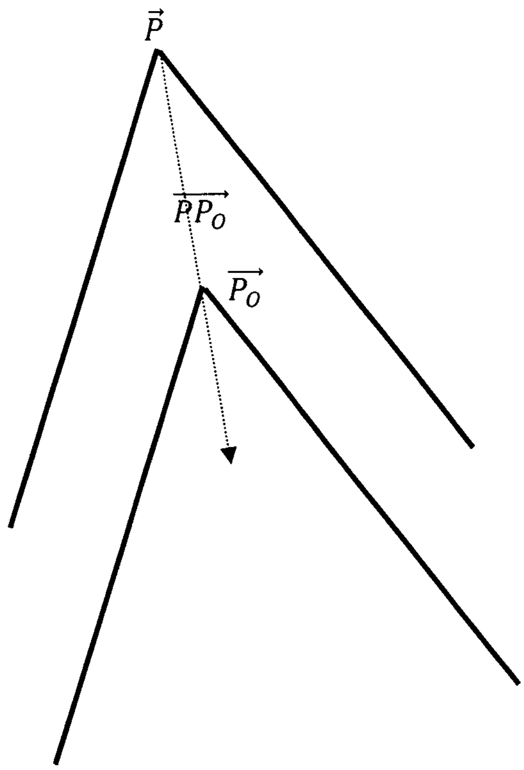

Figure 4.25 Concave Vertex Moving Direction

When a new point $\overrightarrow{P_N}$ is created as shown in Figure 4.26, the edges which are around the vertex $\vec{P}$ are checked. The following procedures for convex vertex are applied:

1. Find the vertices of the edge.
2. Identify points along the edges of the angle so that the length of vectors which they form with $\overrightarrow{P_O}$ are just longer than $\overrightarrow{P_O P}$. In Figure 11, $\overrightarrow{S_{N1}}$, $\overrightarrow{S_{N2}}$ are created points.
3. Form the new edges $\overrightarrow{S_{N1}P}$, $\overrightarrow{S_{N2}P}$ and put them into edges list and remove the un-needed edges, edge E_2, E_3 are removed.

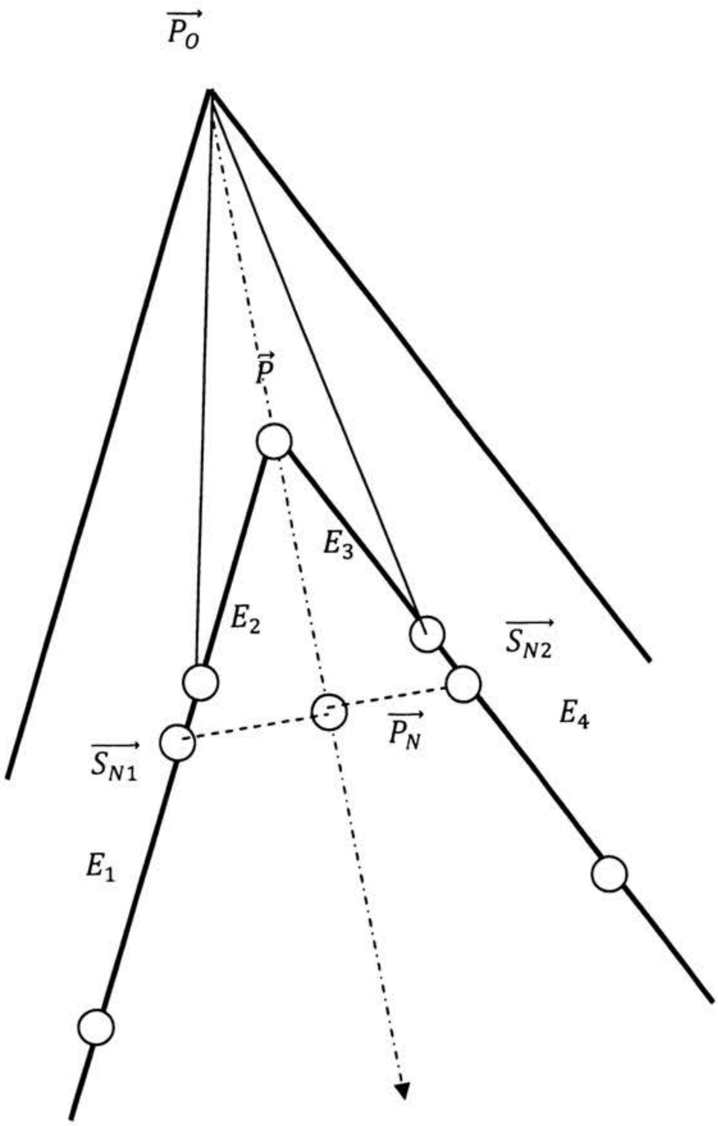

Figure 4.26 The New Point Identification

Void fill path: The other issue is that some void appears when the tool-path adjustment is performed. As shown in Figure 4.27, the void occurs in the center area. An extra path is created to fill the gap which is given by:

$$\vec{S} = \vec{P} + \vec{L} * \left(\frac{b}{\sin(\alpha/2)} + 1\right) * T \tag{4}$$

$$\vec{E} = \overrightarrow{P_N} - \vec{L} * T \tag{5}$$

where $\vec{S}$ and $\vec{E}$ are the vertices of the edge, α is the angle at the corresponding point at the outer path. b is a coefficient for overlap effect.

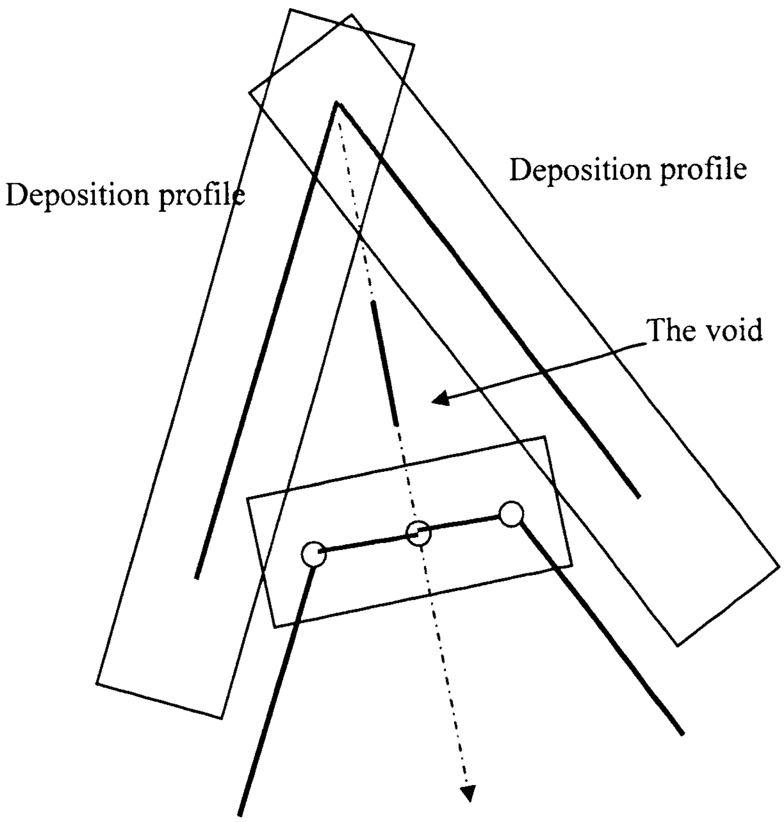

Figure 4.27 The Void Created After Tool-Path Adjustment

5. EXAMPLES

The presented algorithm has been implemented in VC++ using OpenCascade geometry kernel. Figure 5.1 shows a zigzag path example. The total deposition length is 327.0 mm and the length of idle path is 40.8mm so the efficiency is 88.9%. A random orientation is selected to generate the path and the efficiency is dropped to less than 80%. Figure 5.2 shows the similar example with hole. However, the efficiency is dropped to 80% as the idle path has to jump over holes. The proposed work can generate efficient tool-path for most cases. However, it is also found that this approach does not obtain the most efficient path for very few cases. The reasons for this issue can be:

- The bounding box with the greatest ratio is not found due to search accuracy.
- The breath searching for the hierarchy structure does not yield the best solution.

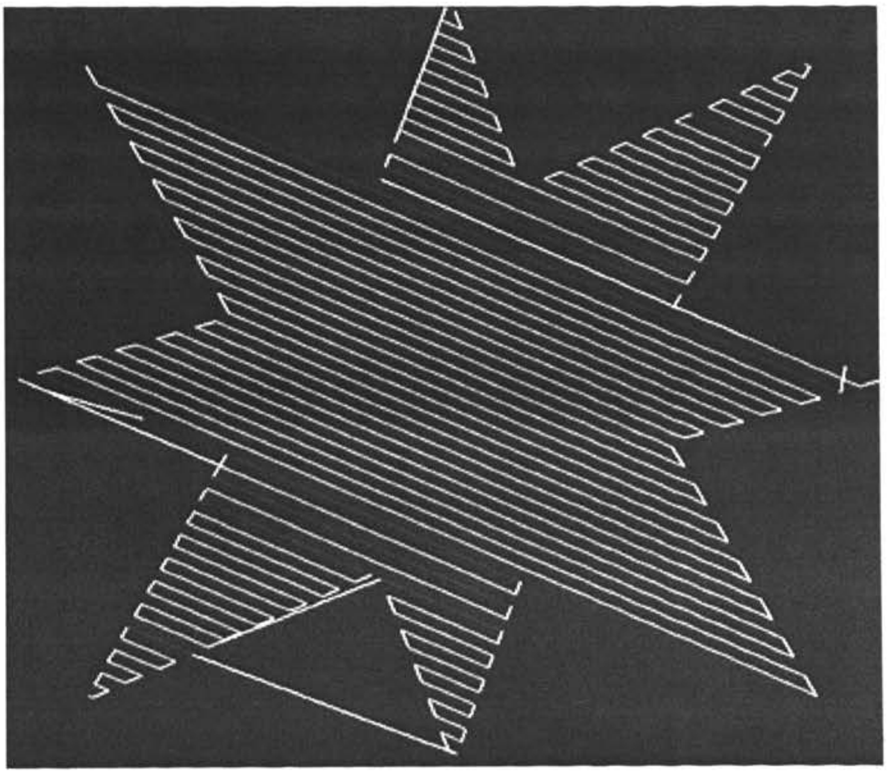

Figure 5.1 Zigzag Path Generated for a Star

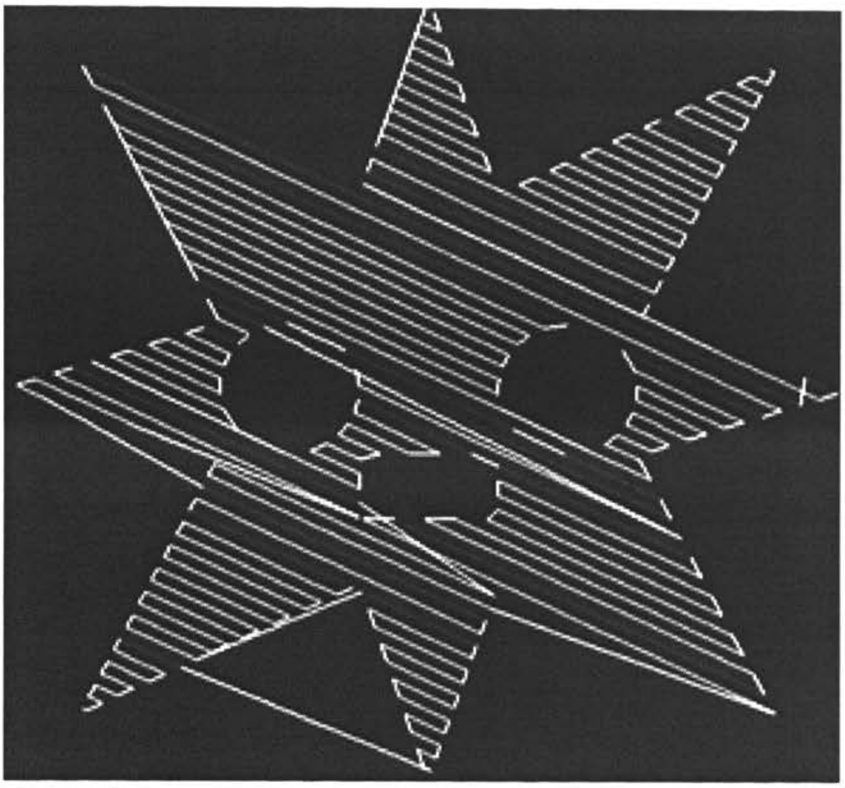

Figure 5.2 Zigzag Path Generated for a Star with Holes

The offset path generated in Figure 5.3 shows multiple disconnected regions. The number of disconnected regions increases as the number of holes increase. Figure 5.3 and Figure 5.4 are two different examples which have multiple holes and the offset path generated has multiple disconnected regions. This problem is solved by lifting the tool, moving it across to the next starting point, and starting the next path. Thus, the deposition for the disconnected regions is handled.

For the offset deposition tool-path generation with holes using OpenCascade, an algorithm has been used. The OpenCascade handles only the tool-path generation for a closed outer wire. If the layer has holes in it the offset tool-path cannot be generated directly. As the tool-path is generated at each offset, a check is performed if the offset tool-path intersects with any of the set of holes of that layer. If there is an intersection then a cut operation is performed and the newly obtained tool-path is used to perform next offset. Else if there is no intersection then perform offset on the original tool-path itself. Using this algorithm, the offset tool-path for a layer with holes is generated. Figure 5.3 and Figure 5.4 show two examples for the offset tool-path generation with holes.

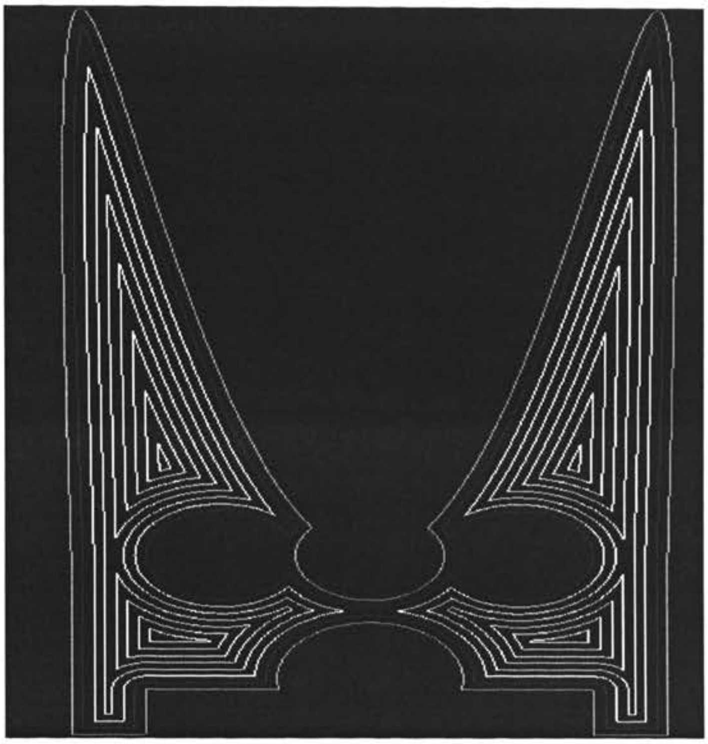

Figure 5.3 Offset Path for a Complex Shape with Holes

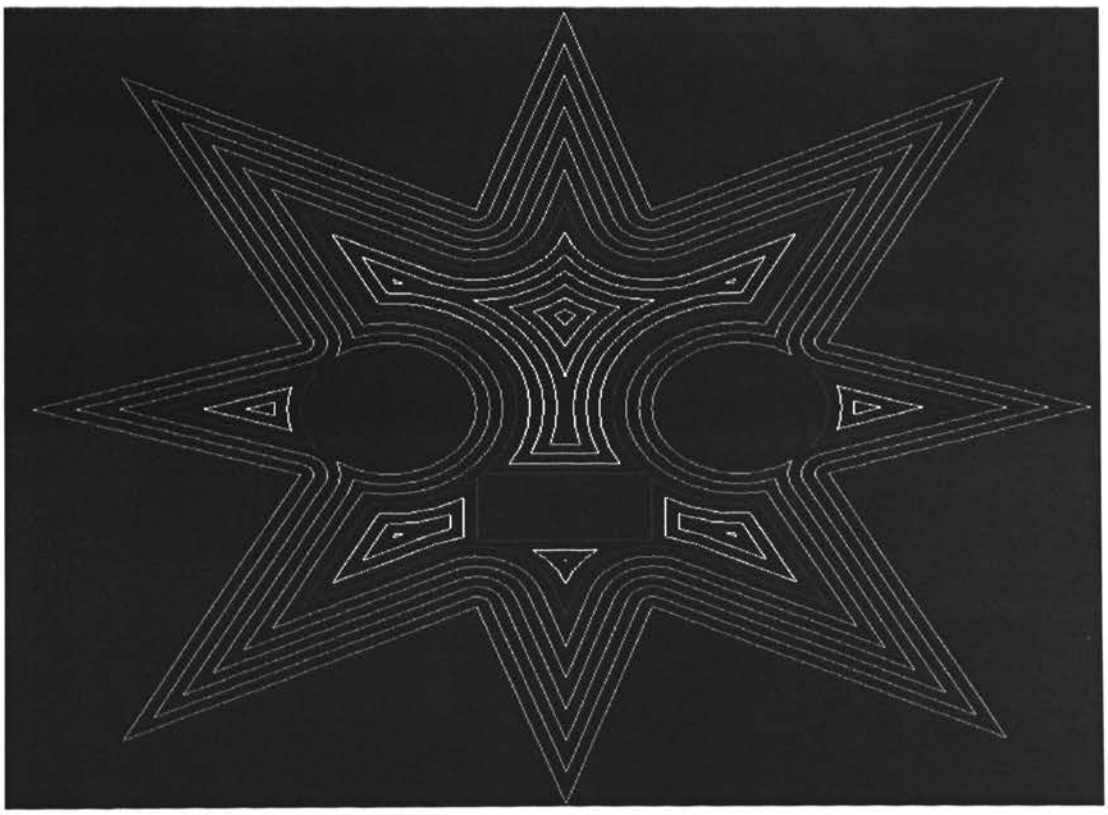

Figure 5.4 Offset Path for a Star with Holes

After the offset tool-path is generated by handling various cases, the offset tool-path adjustment at the sharp corners is to be handled. When the material is deposited along the generated tool-path then the sharp corners of the layer have under-fills as the offset distance is not maintained constant at these points. The sharp corner is handled only if the angle at the corner is less than 90°. If the angle is more than 90° then the offset distance is maintained the same at the corners as well.

In the research presented in this thesis, the sharp angle is defined as less than 90°. In Figure 5.5, an offset path without adjustment is shown. No sharp angle in this shape is found thus no adjustment is made. Figure 5.6 shows an offset example which has sharp corners and which are to be handled. The offset tool-path is adjusted using the sharp corner handling and void fill method. Figure 5.7 shows an offset example with an adjustment. It is clearly shown that all sharp angles (greater than 90°) are removed. On the other hand, the offset path adjustment is only based on angle analysis and does not consider the overlap effect in the close path situation as shown in Figure 5.7.

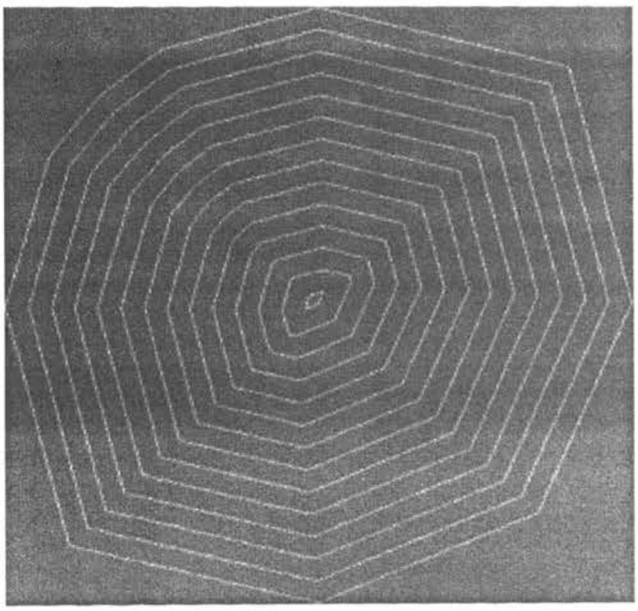

Figure 5.5 An Offset Example without Path Adjustment

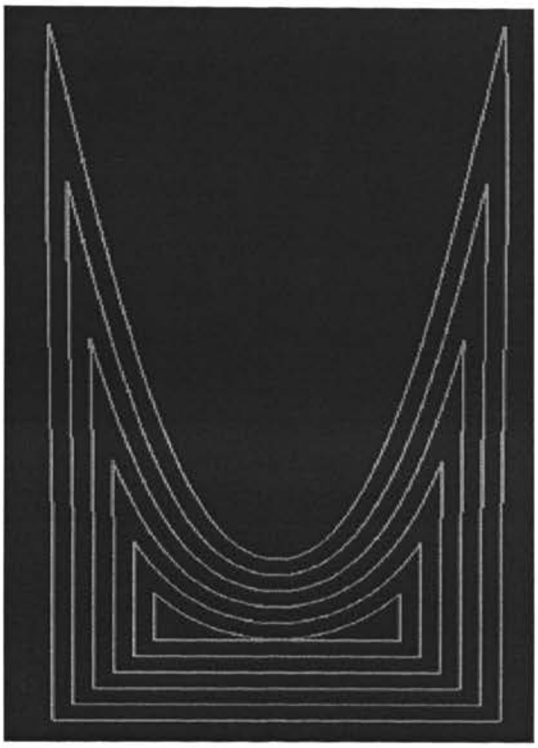

Figure 5.6 Offset Example before Path Adjustment

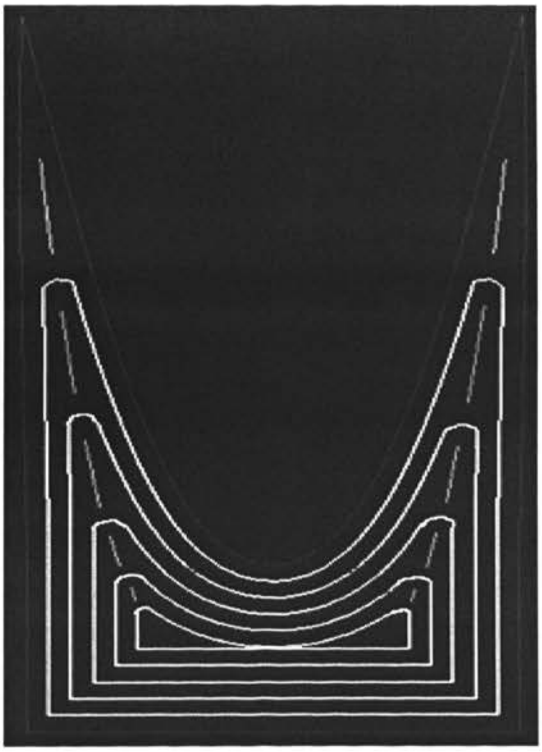

Figure 5.7 Offset Example after Path Adjustment

6. CONCLUSION

In this thesis, various tool-path generations for the power based laser metal deposition process are studied. The most commonly used tool-path patterns for the deposition process are the zigzag tool-path and the offset tool-path. In this thesis, approaches to generate the zigzag tool-path and offset tool-path are presented.

Firstly, the zigzag path is generated by using the shortest distance method. Comparison between this method and the method using the bounding box and hierarchy graph structure for zigzag tool-path generation process is done. The bounding box of the layer with the greatest ratio of its longest edge to its shortest edge is considered. The direction of the longest edge of the bounding box defines the deposition path and the direction of the shortest edge defines the "idle" or connecting path direction. The efficiency of the zigzag tool-path is measured based on the ratio between the non-depositing and the depositing tracks. A hierarchy graph structure has been used to sort the parallel paths and generate an efficient sequence to avoid "waste" travel time. The bounding box with the greatest ratio and hierarchy graph structure is very helpful in finding an efficient way to connect the zigzag path. For most cases, the approach is suitable to find an efficient solution. The advantages of using this approach are listed below:

- Reduce the overall travel time by shortening the non-deposition track length
- Improve the material usage by reducing the waste on the non-deposition track

Secondly, the offset path is generated by handling different cases like the offset tool-path generation with holes in the layer. The offset path with holes has multiple disconnected regions. The number of disconnected regions increases as the number of holes increase. This problem is solved by lifting the tool, moving it across to the next starting point, and starting the next path. Thus, the deposition for the disconnected regions is handled. The deposition on the offset tool-path generated had gaps between the tracks. To handle this, an offset tool-path adjustment based on overlap and speed profile is studied. The overlap between the tracks will reduce the gaps created and the speed of the tool helps to control the amount of material deposition. However, the gaps created at the sharp angles were not handled by the overlap. The offset distance at the sharp angles is greater than the desired offset distance. Thus, when the material is deposited there are under-fills at the shape angles. To overcome the problem due to the sharp angles in the geometry causing inconsistency in the speed, a void fill method based on overlap and bead profile is studied. The advantages of this approach are:

- Material is deposited based on the speed profile which reduces the overfills
- Under-fills at the sharp angles is handled
- Total strength of the deposition part increases as the overfills and under-fills are handled

In the future, the matrix-based offset path can be studied to fully utilize the deposition profile. However, such an approach is very time consuming. Therefore, a quick offset path generation for layers will be needed. Mapping an offset path to different layers could provide a solution.

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