Generation of deposition paths and quadrilateral meshes in Additive Manufacturing

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Abstract

In wire arc welding Additive Manufacturing (WAAM), filling paths have a strong influence on the deformation of fabricated part. Many researchers employ FEM to analyze the effects of different filling strategies. However, they mainly majored in regular simple path (e.g. line and circle).This paper presents the method to generate meshes in deposition region of complicated path which can be used in FEM. First, the contour offset path and skeleton path is introduced. Then, the deposition region of each path is created by offsetting the paths inward and outward. Afterwards, quadrilateral meshes are constructed within each region. Deposition region is approximated by meshes.

Keyword: deposition path, deposition region, quadrilateral meshes

Introduction

Additive Manufacturing (AM), or Rapid Prototyping (RP), has rapidly been developed in recent decades. Different from the traditional material subtract manufacturing method, it fabricates part layer by layer. In AM field, Wire and arc based Additive manufacturing has attracted more and more attention of researchers and institutions. Compared to AM with powder as feed stock material [Sing[1], Ding[2], Ding[3]] or laser as energy source [Ding[4]], the wire and arc AM has a lot of advantages, such as high material utilization, simple and inexpensive equipment and high production efficiency[Gu [5], Wang[6]].

The filling path plays an important role in AM process. It directly influences the geometric accuracy and mechanical property of fabricated part. There are two major basic filling patterns: raster scanning path and equal distance contour offset path [Ding D[7]]. Raster scanning path generation algorithm is very simple and efficient. But it scans in the same direction that would cause stress concentration leading to warping. Furthermore, the tool needs to cross the cavity frequently for part with holes. And the contour has a low accuracy because the raster path starts and ends in contour. Equal distance offset path generation algorithm iteratively offsets the outer contour of layer polygon by a fixed distance until filling the whole interior domain. This method change filling direction gradually (but still same in segment part) in each path which can decrease stress concentration. Contrast to raster path, the offset path is continuous in contour that it can improve the surface accuracy. However, the contour offset algorithm is very complex and time consuming. G.Q. Jin [8] combines the two type of path. In the contour, the contour offset path is adopted to ensure the accuracy, and the zigzag raster path with the best slope degree is employed in the interior to achieve minimum manufacture time. Y Yang [9] gets the contour offset path through the interior recognition and complex self-intersection and sharp corner treatment. DS Kim [10] generates contour offset path based on Voronoi Diagram which do not needs self-intersection treatment. Y.Ding [Ding [11]] mapped the revolved overhanging structures to a plane base and filled the contours by offsetting the medial axis until the whole contour is covered. This method initially provided a solution for AM building overhanging structures in 8-axis system.

Apart from the pattern of filling path, the deposition sequence determined by the paths also affects the part property in fabrication process. Sattari-Far I [12] studied the welding distortions in pipe-pipe joints of AISI stainless-steel type caused by different deposition sequence. A.H. Nickel [13] investigated two different deposition direction of raster pattern and two different deposition sequence of offset pattern. The FE analysis of four deposition sequence of multi-pass single-layer was performed by M P Mughal [14]. In the thermal analysis of welding process using FEM analysis software (e.g. ANSYS), the “birth and death” method is a key point because the activate order of elements represents the real deposition sequence. In many researches, only a few simple paths, such as segment, rectangle and circle, are considered and the activate order is decided manually. However, it is hard to do so for complex paths and elements.

Generation of deposition region

In production of complex thin wall parts, the wire arc welding additive manufacturing (WAAM) technology can substantially improve manufacturing efficiency. Contour offset paths, a common type of deposition path used in WAAM, are simple polygons derived from slice contours by inward offsetting. The method proposed in this study uses Voronoi diagram to create a contour offset path. For a given set of points and edges in a plane, a Voronoi diagram partitions the plane into regions, with each region including one point or one edge in its interior [Aurenhammer [15]]. These points and edges are called point sites or edge sites, and the regions are called Voronoi cells. For any point in a cell, its distance to the site associated with it is shorter than its distance to any other site. The boundaries of the Voronoi cells, i.e. the lines separating the regions, are referred to as Voronoi edges. For planar slice contours, sites are vertices and edges of polygons, and cell boundaries are made up of vertex angle bisectors, perpendiculars to edges at their endpoints, lines lying equidistant between parallel edges, and parabolas between points and segments. All line segments constituting the inner and outer contours offset within their own Voronoi cells and are joined to each other at their endpoints. This avoids dealing with contour intersections and self-intersections and thereby allows for efficient generation of a contour offset path based on Voronoi diagram. Figure 1 shows arbitrary slice contours. Figures 2 and 3 show the corresponding VD and contour offset path.

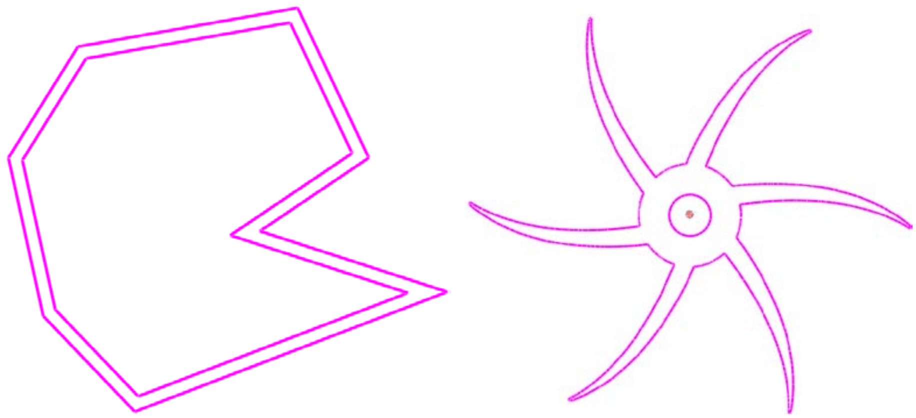

Fig.1. two slice contours

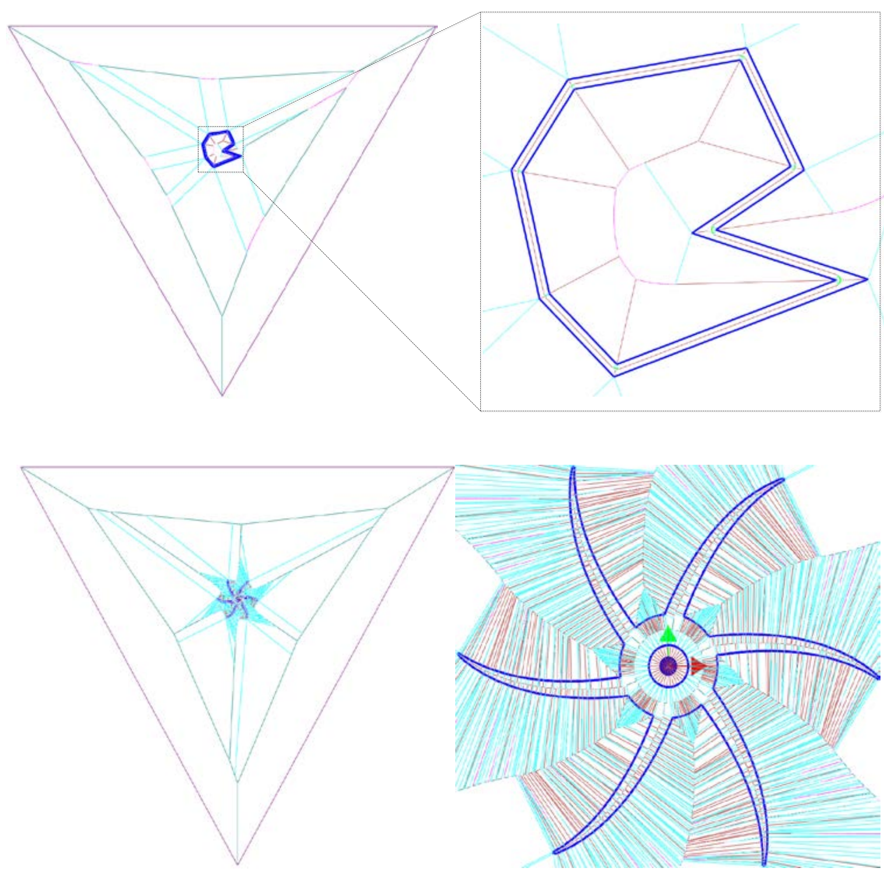

Fig.2. the Voronoi diagram of contours

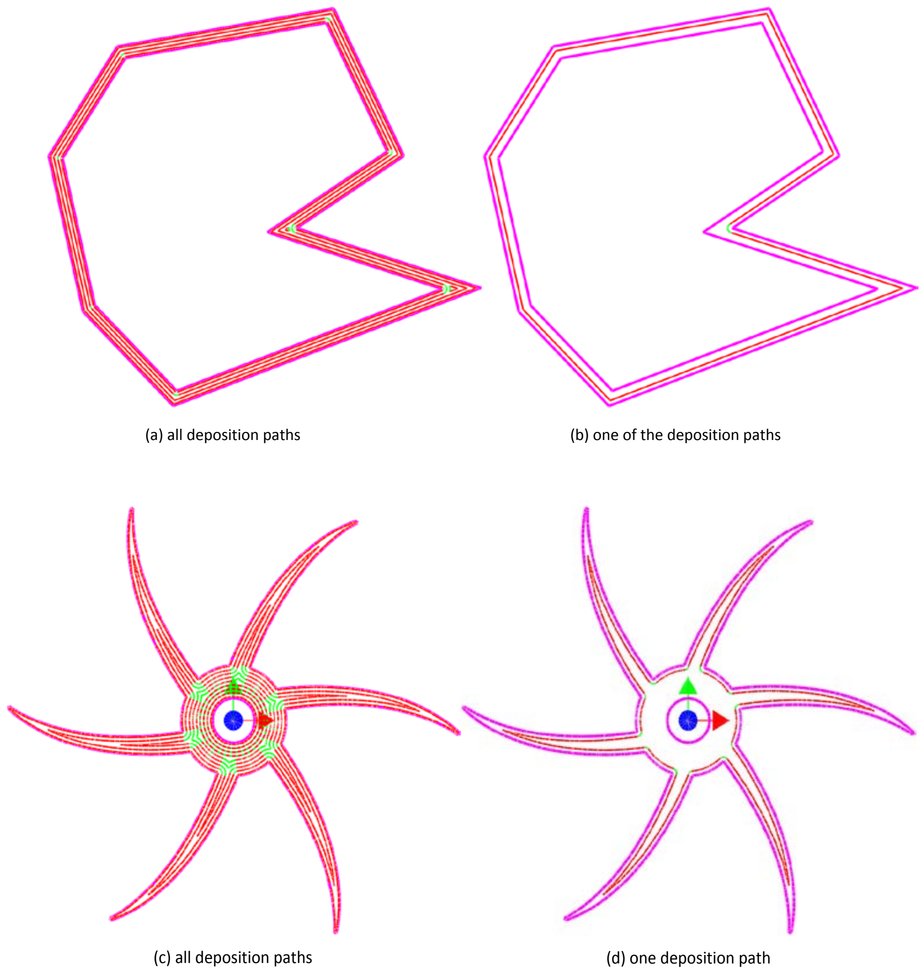

Fig.3. Deposition paths based on Voronoi diagram (purple outer polygons are slice contours, the red&yellow inner polygons are deposition paths)

In addition to contour offset path, skeleton is often extracted from VD as filling paths, especially for a part whose wall thickness is smaller than the width of a single weld bead. The skeleton is a part of the Voronoi diagram. The algorithm proposed in this study provide two types of skeletons: skeleton derived from a single contour (bisectors of the edges in one polygon) and the skeleton derived from different contours (bisectors of edges in two polygons), as shown in Figure 4.

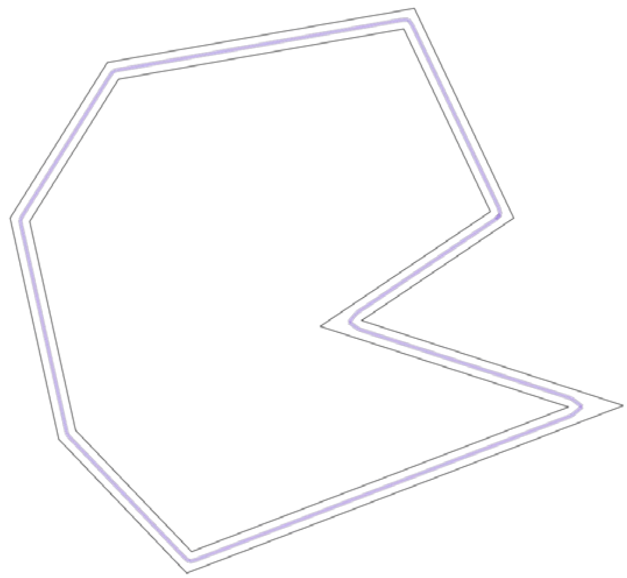

Fig.4. skeleton (medium purple) and contours (black)

In WAAM, filling paths determine the position and sequence of energy input and thus have a great influence on the deformation and stress state of fabricated part. The finite element method (FEM) is usually employed to analyze the distortion, temperature, and stress experienced a part during deposition. This method requires meshing of the real deposition region of the path. Deposition region refers to the ring-shaped region occupied by the material deposited from the melted wire. In this paper, a given deposition path is used as the input data, and the Voronoi algorithm is applied again to offset the path inward and outward separately, in the same manner as in the path generation process. Then two simple polygons are created as the outer and inner contours. The offset distance is half the effective width of a single deposition path, which depends on actual process parameters. Later, a bounding box is used to determine the inclusion relation between the outer and inner contours. The region enclosed by the two contours represents the effective deposition region. The vertices of the outer contour are ordered anti-clockwise, while those of the inner contour are ordered clockwise. Therefore, as the wire moves along the outer contour, the interior domain is on the left-hand side, while as the wire moves along the inner contour, the interior domain is on the right-hand side.

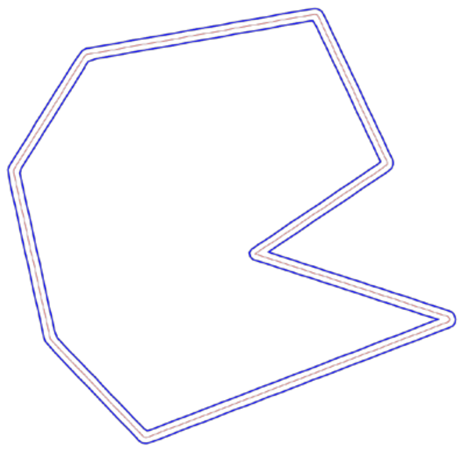

Fig.5. Path (red polygon) and its deposition region contours (purple polygons)

As described above, the deposition region of a single path is defined by two polygons whose shapes are similar to the path's. The size of cells within the deposition region can be modified by adjusting the lengths of line segments during discretization of the region. In the method proposed in this study, offset polygons (including paths and the contours defining the deposition region) are constructed from line segments and arcs based on VD. The size of cells can be adjusted by discretization of line segments and arcs and specific parameters can be input by users.

The proposed method does not directly discretize the deposition region. Instead, it discretizes the original path before offsetting so that discrete deposition contours can be naturally obtained after offsetting the path inward and outward. In addition, the arcs of the path need to be discretized into line segments. The purpose is to convert the path into a simpler polygon and thereby facilitate VD construction and path offsetting. Line segments can be discretized into several short segments with a given length or into a preset number of segments. Arcs can be discretized into segments with a given arc length or central angle. The vertices in the final discrete path are classified into three types: original vertices (0), points on line segments between their endpoints (1), and points on arcs between their endpoints (2). These vertices are denoted by V0, V1, or V2, with the integer identifiers (0, 1, and 2) indicating their attributes, i.e. types, as shown in the figure below.

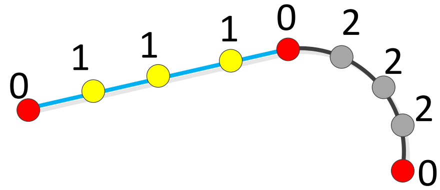

Fig.6. Types of points (0 - end points of line segment or arc, 1 - points in line segment, 2 - points in arc)

After discretization of line segments and arcs, the discrete points on line segments between their endpoints automatically offset, generating discrete points on the line segments constituting the deposition contours. Most of the discrete points on the inner contour are paired with those on the outer contour. Then any two pairs of points on the contours can form a quadrangle. The resulting discrete points on the offset contours have the same attributes as their source points on the original path. These points are denoted by V0 or V1.

In the VD offset method, an arc will be generated when a convex vertex of a polygon offsets outward or a concave vertex offsets inward. In this study, an offset arc can be generated by offsetting a vertex V0 or V2. An offset arc generated from a vertex V0 needs to be discretized; the length of the resulting segments depends on the discrete length or central angle of the arc. The two endpoints of the offset arc are designated V0 while other discrete points on it are designated V2. If an offset arc is derived from a vertex V2, it is just approximated by a line segment connecting its two endpoints, which are denoted by V2. As mentioned above, vertices V2 on the path are continuous and form arcs. Offsetting these arcs also produces arcs approximated by discrete segments. However, it is necessary to further discretize these arcs in order to obtain cells with desired sizes. Since these offset arcs are concentric with their source arcs on the path, the radius of each offset arc is its source arc's radius plus the corresponding offset distance. The further discretization is also based on a preset arc length or central angle

The discretization of original path enables automatic generation of discrete points on the contours during offsetting, thereby reducing the amount of calculation. Most quadrilateral cells in the mesh generated are obtained by combining triangles without complex calculation.

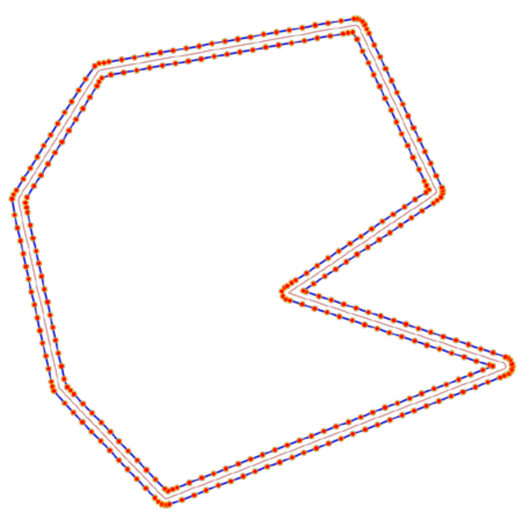

Fig.7. Discrete contours

Quadrilateral mesh in deposition region

This section describes how to generate a finite element mesh in the effective deposition region. A mesh normally comprises quadrangles, which are derived from triangles, and a small number of triangles. Based on the discrete polygons (offset contours), a Delaunay triangulation is constructed to mesh the polygons. The triangles in the triangulation share vertices with the polygons, as shown in the figure below.

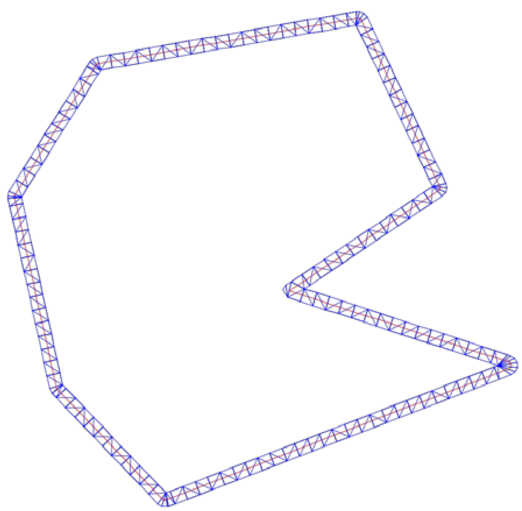

Fig.8. Triangle meshes

Based on attributes of vertices, the triangles in a triangle mesh can be divided into several types as follows:

(1) For a triangle having vertices V1, V1, and V1, it is classified as T0 if the three vertices lie on two contours; if they are distributed on the same contour, it is classified as T4;

(2) For a triangle having vertices V2, V2, and V2, it is classified as T1 if its vertices lie on two contours; if they are on the same contour, the triangle type is T5;

(3) For a triangle having vertices V0, V2, and V2, its type is T2 if its vertices are distributed on two contours; otherwise, its type is T6;

(4) Other triangles have their vertices coinciding with the vertices of the contours and link two line segments, or a line segment and an arc. These triangles are called link triangles and denoted by T3

Triangles T0, T1, T2, and T3 all have only two adjacent angles.

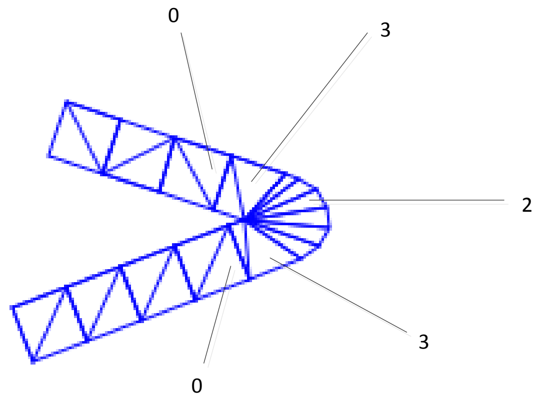

Fig.9. triangle types

Next, triangles can be combined into quadrangles using the method below:

(1) Randomly select a triangle with types T0, T1, and T2 as the start triangle. Then set the start triangle as _current and set quadrilateral index, _qidx, as 0;

(2) Traverse the adjacent triangles of _current, and store triangles T0, T1, T2, and T3 that have not been visited in the candidate triangle container, _candidates;

(3) If _candidates is empty, go to (8);

(4) If the attribute of _current is T2, set _current as degenerate quadrangle and store it in the mesh container. Then assign the quadrangle's index to corresponding triangles.Set the current triangle as the combine triangle and go to (7);

(5) Each candidate triangle can combine with _current into a quadrangle. Find the quadrangle whose interior angles have the minimum standard error and then set the corresponding candidate triangle as _combine;

(6) If the attribute of _combine is different from that of _current, go to (4); otherwise, store this quadrangle in the mesh container;

(7) Traverse the adjacent triangles of _ combine and set a triangle T0, T1, T2, or T3 that has not been visited as the new _current. After that, go to (2); and

(8) Traverse unhandled triangles and find its adjacent quadrilateral. If the quadrilateral is a triangle (degenerate), directly merge it with this degenerated quadrilateral. If it is real quadrilateral, split the quadrilateral into a quadrangle and a triangle and then combine this two triangle (unhandled one and split one).

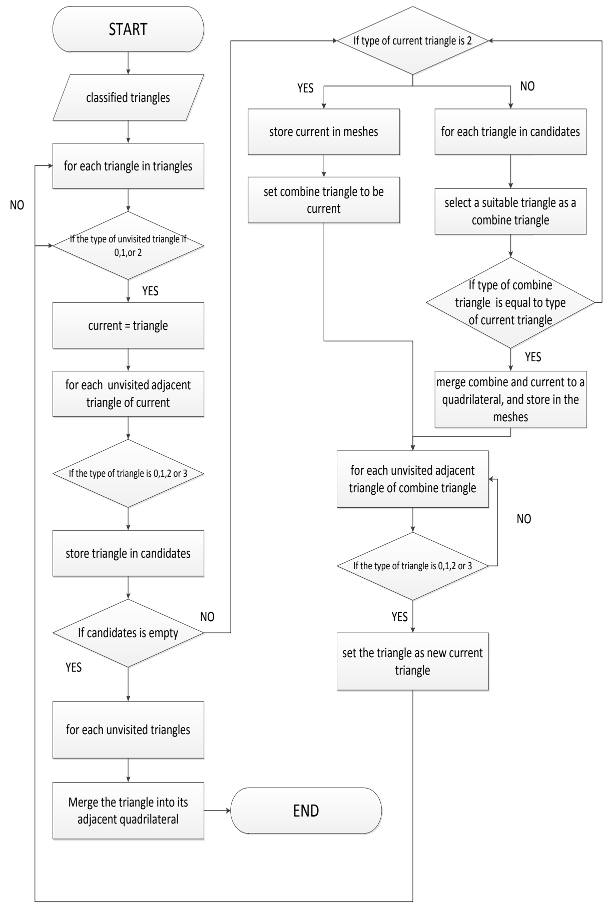

Fig.10. Flowchart of generating meshes

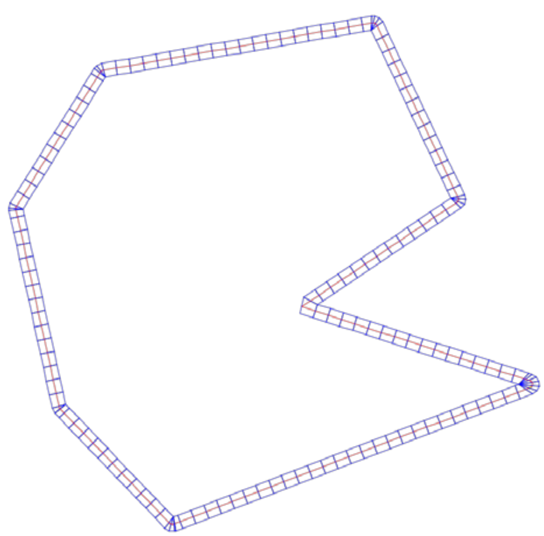

Fig.11. Quadrilateral meshes (blue) and path

At last, the mesh cells are ordered based on sequence of points in the path, in order to ensure that the sequence of the cells is consistent with the deposition sequence. Therefore, in the FEM analysis, the activation sequence of elements can be determined easily without any calculation.

Conclusion

In this study, the contour offset path and skeleton path are created for the fabrication of thin wall part using WAAM technology. On the purpose of learning the deformation and stress distribution of part caused by the deposition path, the method of meshing in the real deposition region is introduced. The meshes in the deposition region mainly consist of quadrilateral meshes and also there exists little triangles sometimes.

In the future work, the optimization of deposition path based on the FEM analysis is the primary aim.

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