A New Feature in an Extrusion Based LM Process - Adaptive Roadwidth

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1. Abstract

For extrusion based LM processes, a computational based adaptive roadwidth algorithm have been developed which further reduces (if not eliminate) all voids and defects. Toolpath equations are written in terms of roadwidth, vector path offset, sub-perimeter offset, and vector angles. The program computes all contours and vector paths to fill a layer, the location and size of all voids/defects, and makes comparison with the acceptable void limits. Based on this information, the adaptive roadwidth for the vector paths are then created to minimize the voids and defects. This new feature is added to the existing in-house multi-material LM CAD software.

2. Background

Currently, at Rutgers University, under an Office of Navy Research (ONR) funded MURI program [1], a CAD based intelligent multi-material LM software system has been developed. One of the most important modules in it is the intelligent toolpath generation software [2]. This paper discusses a new intelligent feature of the software: adaptive roadwidth toolpath generation algorithm and its results. This is achievable by using one nozzle jet with multiple roadwidth during the building process.

There is another “adaptive” algorithm existing called adaptive slicing [3]. It is for different stage in LM CAD process, slicing stage, comparing to adaptive roadwidth, which is for toolpath generation stage after the object is sliced. In adaptive slicing, the slice thickness varies at different layers of the object to achieve user-specified quality for the accuracy of object surfaces and having least building time [3].

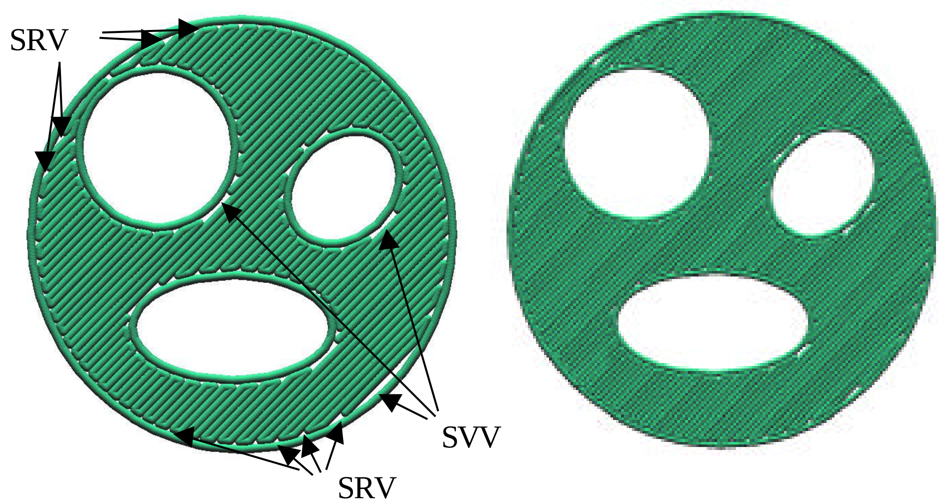
Adaptive roadwidth is to achieve void free and having least building time for each layer of the object. It is for the internal quality of the object.

3. Motivation

The multi-material CAD for the intelligent Layered Manufacturing System generates toolpath data file to fabricate multi-material functional parts using FDMC hardware [4]**.** Voids in a part are the main concern for the part quality. The objective of this study is to develop a void free toolpath generation algorithm and software for the multi-material LM process. At last year SFF symposium [2], toolpath generation software was presented. This software creates toolpath for complicated geometry shape parts and has intelligent features designed for better machine control and part quality. By altering toolpath parameter values and using intelligent features, part quality was improved. Several multi-material parts are designed, simulated and fabricated [5]. Constant roadwidth toolpath was used in this work.

To improve the part quality further, void types within a layer of a part are analyzed. Normally, void exists only under boundaries if vector offset is negative. There are three kinds of void exist on layers of part: Sub-perimeter vector-direction void (SVV), Sub-perimeter road-turn void (SRV) and Irregular void (IV).

- SVV is sub-perimeter and on the vector direction. It's predictable, and the void size can be calculated (see figure 1).
- SRV is sub-perimeter and between two adjacent road turns. It's predictable. The void size can be calculated (see figure 1).
- IV is because of irregular behaviors of machine or material flow. This kind of voids is unpredictable, and CAD software cannot account for it.



(a) Roadwidth: 15 mil (b) Roadwidth: 20 mil

Figure 1: A Hollowed Surface with Constant Roadwidth

To eliminate these voids, two different approaches are developed. SVV usually occurs at the beginnings or ends of the path. The occurrence of these voids is equal to two time of the number of boundaries. This requires a special treatment [6], and it is not included here due to space limitation. SRV usually occurs between the boundary and the road turns along the path. Computationally it is a function of roadwidth. This implies that as roadwidth decreases, the void size reduces significantly.

Issues with Constant Roadwidth Toolpath

When roadwidth and all other parameters are fixed, SRV size varies along the boundary. When the intersection angle between vector road & perimeter is 90º, the SRV size is minimum. When the angle is closer to 0º, the SRV size is maximum. At certain roadwidth, some locations are already SRV free, but others still have unacceptable SRV (Fig 1a). To reduce the void sizes, the constant roadwidth is reduced everywhere (Fig 1b). At SRV free locations in Fig 1a, there is no need to reduce the roadwidth. But in Fig 1b, the SRV still exists after roadwidth reduction.

In addition, the constant reduction in roadwidth increases the part building time. At the same time, number of road turns, number of accelerations and decelerations are increased. It will also increase the possibility of machine errors. For these reasons, it becomes apparent to develop toolpath that has adaptive roadwidth feature.

Objectives of Adaptive Roadwidth

The goal of adaptive roadwidth is to eliminate voids and has least building time for the part. As stated above, constant roadwidth has drawbacks in eliminating SRV. By calculating the SRV free roadwidth for all SRV locations, adaptive roadwidth can eliminate SRV on the need basis. As to the building time, if uniform large roadwidth is used, building time will be short, but there will be a large number of unacceptable voids on that layer. If uniform fine roadwidth is used, the number of voids is less, but building time will increase. The adaptive roadwidth algorithm only decreases roadwidth at locations whose void size is larger than the requirement, so that it has both least building time while keeping SRV free.

4. Method

There are four steps in adaptive roadwidth toolpath generation that is explained in the following section.

Toolpath Generation with Constant Roadwidth & Contour Sub-division

Toolpath with constant roadwidth is generated using our software [2]. The toolpath for each layer has least number of continuous paths. Each continuous path forms a closed convex contour (Fig 2b). In each contour, there are SRV path locations and void free path locations. The next step is to sub-divide each contour into Void Contours (VC) and original roadwidth contours (Fig 2c) based on void size calculation.

Void Size Calculation & Void Contour Identification

Void size is predictable at all specific locations. The void size parameters are boundary roadwidth, sub-boundary offset, vector roadwidth and vector offset. Based on the vector path, the two neighbor turning point (P_0 P_1 in Fig 3) coordinates are known the type of voids is dependent on the two turning points and void size parameters. These are void cases (Fig 3).

SRV Void Cases

In the 1st void case, the two turning points centered at P_0 & P_1 are close enough to have an overlap. The void size in this case is usually small, but may still be unacceptable. In the 2nd void case, the two turning points are away from each other so that there is no overlap. The void size in this case is larger than the 1st case. In the 3rd void case, the distance between two turning points is so far away that portion of void area is outside of rectangular $P_0\ P_0'P_1'P_1$. The void size in case 3 is the largest.

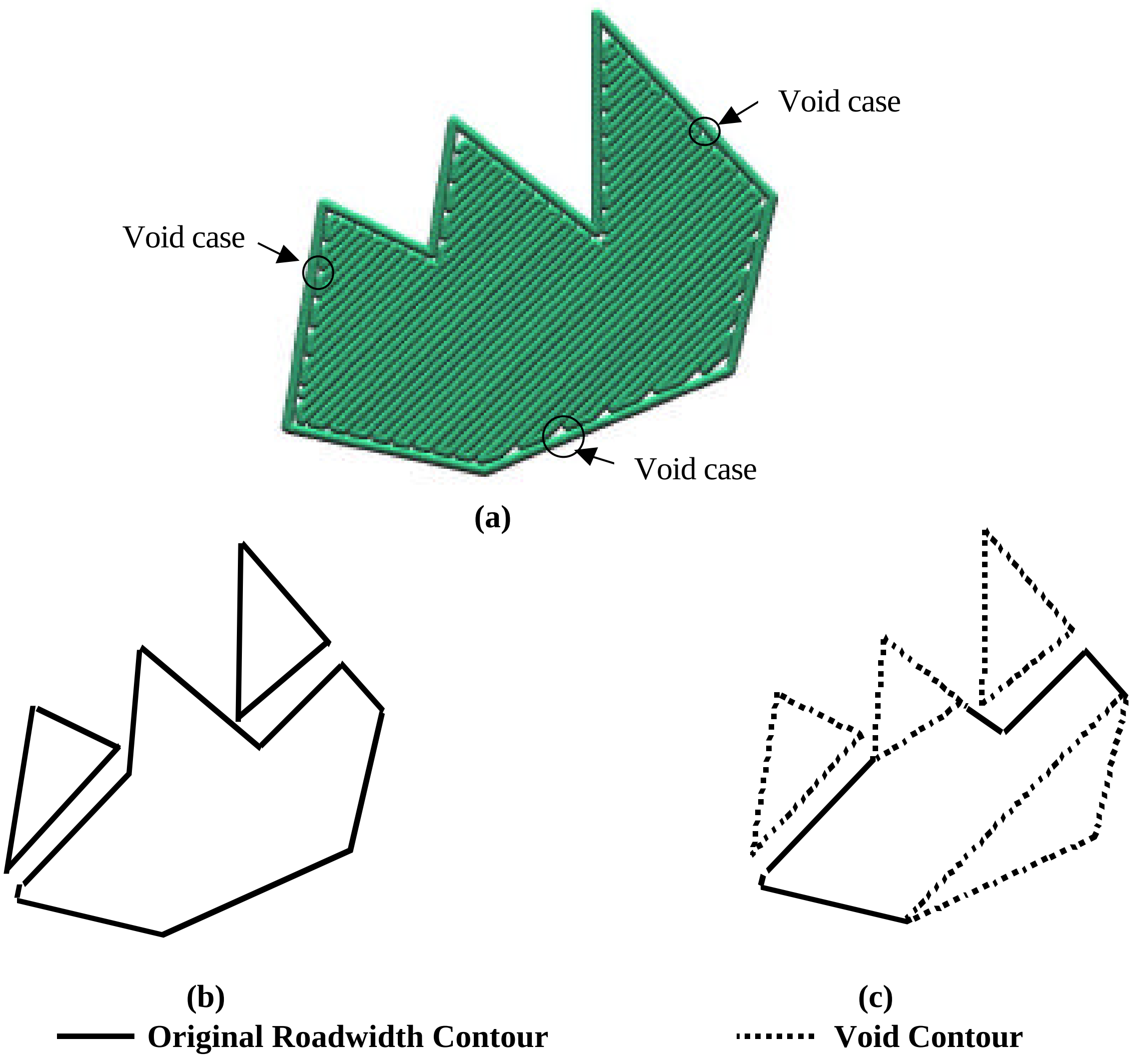


Figure 2: Void Contour Identification

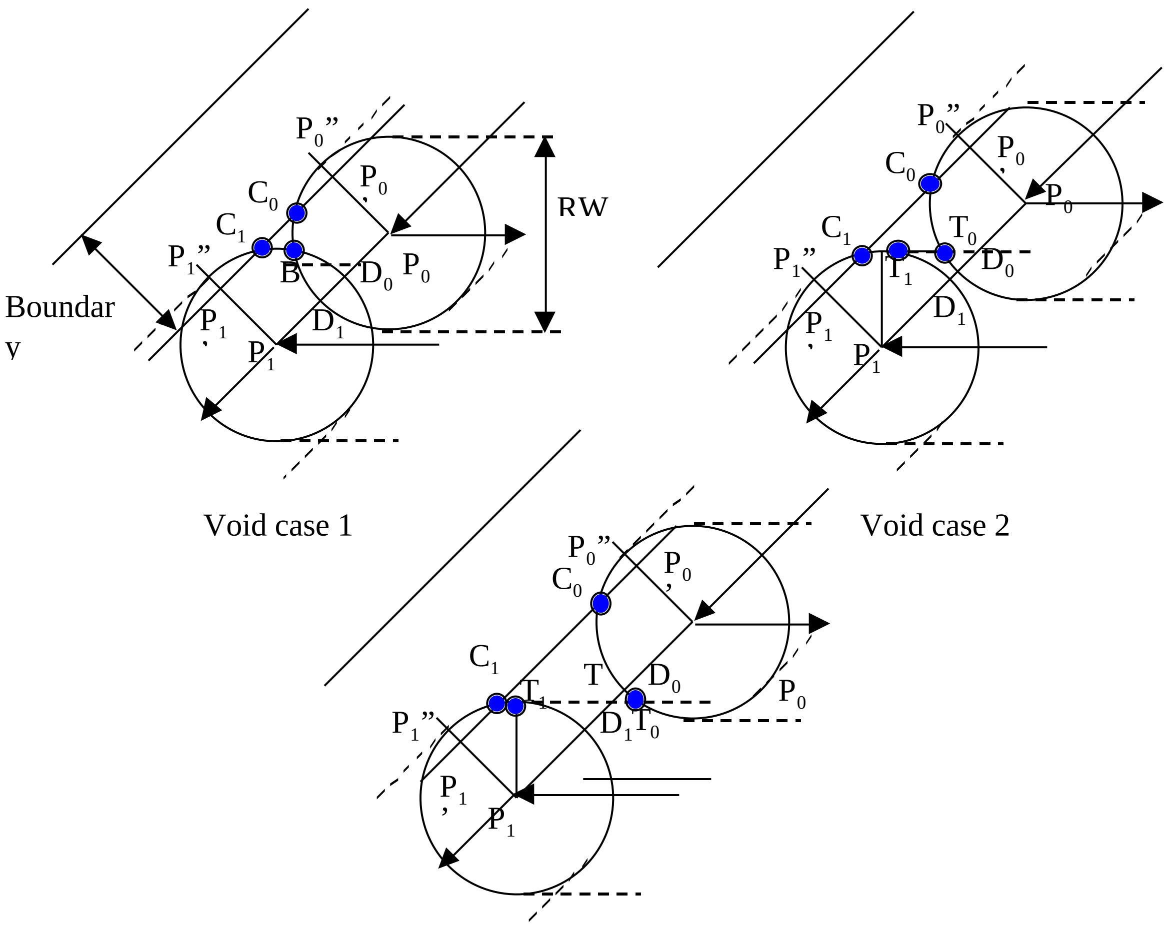
SRV Void Size Calculation

For case 1, void area is $C_0\ C_1B$. For case 2, void area is $C_0\ C_1\ T_1\ T_0$. For case 3, void area is $C_0\ C_1\ T_1\ T_1D_0$. For all the cases, the void size can be calculated as below:

$$\text{Void Size} = P_0\ P_0'\ P_1'\ P_1 - P_0\ P_0'C_0\ D_0 - P_1\ P_1'C_1\ D_1 - (\text{Make-up Area})_i\ ;$$
$$(\text{Make-up Area})_1 = -\ BD_0D_1; \quad (\text{Make-up Area})_2 = T_1TDD_1.$$
$$(\text{Make-up Area})_3 = T_1TD_1 - T_0TD_0\ .\ (\text{Fig 3})$$

Void Contour Identification

If the void size is acceptable, the two turning points (P_0 P_1) will be identified into a VC. As marked by dotted lines in Fig 2c, a VC is a convex domain whose boundary is made of all neighbor locations where SRV is unacceptable. In another word, all continuous SRV locations form a VC. SRV is calculated along the original vector path. An algorithm is developed to form VC boundary out of SRV location points along the vector path. If the void size is acceptable, the two turning points will be identified into the original roadwidth contour. The original roadwidth path will be unaltered.



Void case 1

Void case 2

Void case 3

Figure 3: SRV Void cases

New Roadwidth Calculation

To eliminate voids in VC, a new and finer roadwidth is calculated. Among all void locations in a VC, the largest void size & location is identified. At this location, the intersection angle between vector road & perimeter road must be minimum in this VC. The roadwidth is decreased so that the new path generates acceptable void size for the largest void location. Then in all locations within VC, new void sizes are acceptable. This roadwidth reduction at largest void location is performed in an iterative fashion. The user can select the reduction step size in roadwidth.

Regeneration of Toolpath in VC

The VC is a single boundary surface, and the new toolpath is generated in the identical fashion as before. The issues here are the path generated here must be continuous to the previous and the post path. The 1st issue is achieved by using the end point of the previous original roadwidth path as the starting point of the adaptive roadwidth path in VC. The 2nd issue on the post connection path is achieved by adding even number of vector paths.

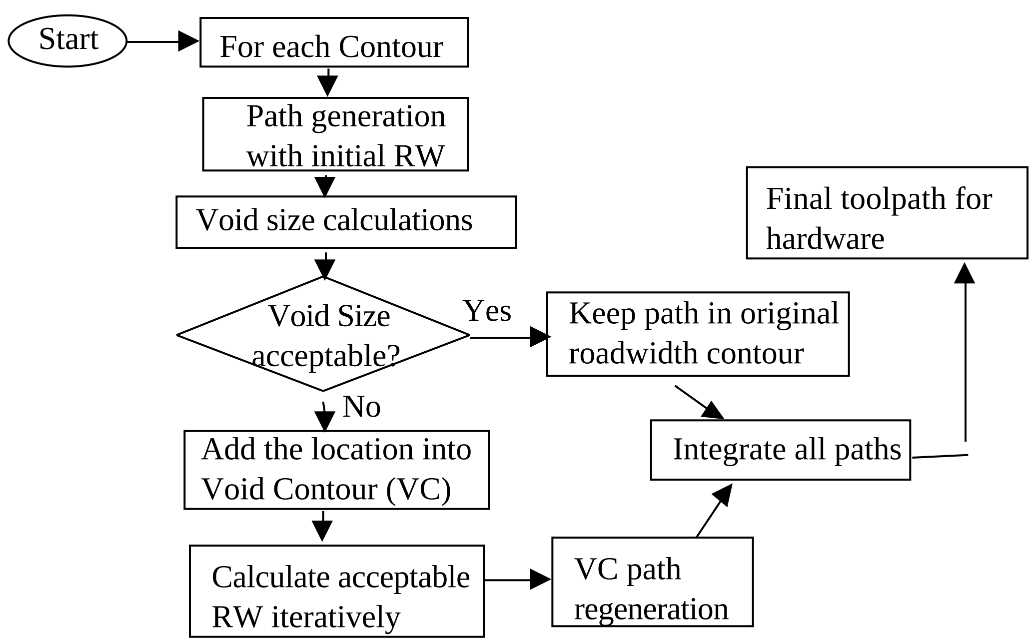


Figure 4: Adaptive Roadwidth Toolpath Generation

The flowchart Fig 4 shows the integration of above mentioned steps in a systematic manner. Initially, the constant roadwidth path will be generated. The path contours are sub-divided into original roadwidth contours and VCs. Adaptive roadwidth for each VC is calculated. New path using adaptive roadwidth is generated for each VC. After all this, the paths in original roadwidth contours and VCs are integrated. The fully integrated toolpath file is created to send to FDMC hardware.

5. Results

A Concave Polygon

A concave polygon part was designed. The acceptable void size for it is selected as 10 mil^2. The toolpath with constant 20 mil roadwidth was generated at first (Fig 5, bottom left). There are a lot of SRV existing with this toolpath. When adaptive roadwidth algorithm is applied to the toolpath, this layer is divided into four void contours and one original contour (Fig 5, upper left). In void contours, the SRV sizes are unacceptable. The largest void sizes in each void contour are listed in Table 1. The new adaptive roadwidths for each void contour are computed and they make SRV sizes in each contour acceptable, Table 1. Toolpath using new roadwidth is formed for each void contour (Fig 5, upper right, in different colors). The toolpath in void contour is continuous to the previous and post toolpath in original contour. So the number of continuous paths on the layer keeps the minimum which is good for hardware control. To make the toolpath in void contour obvious, we used red color for their simulation. The bottom right image of Fig 5 is identical to upper right image but shown in one color, as the real image for the part. From this analysis, a void free part is achieved.

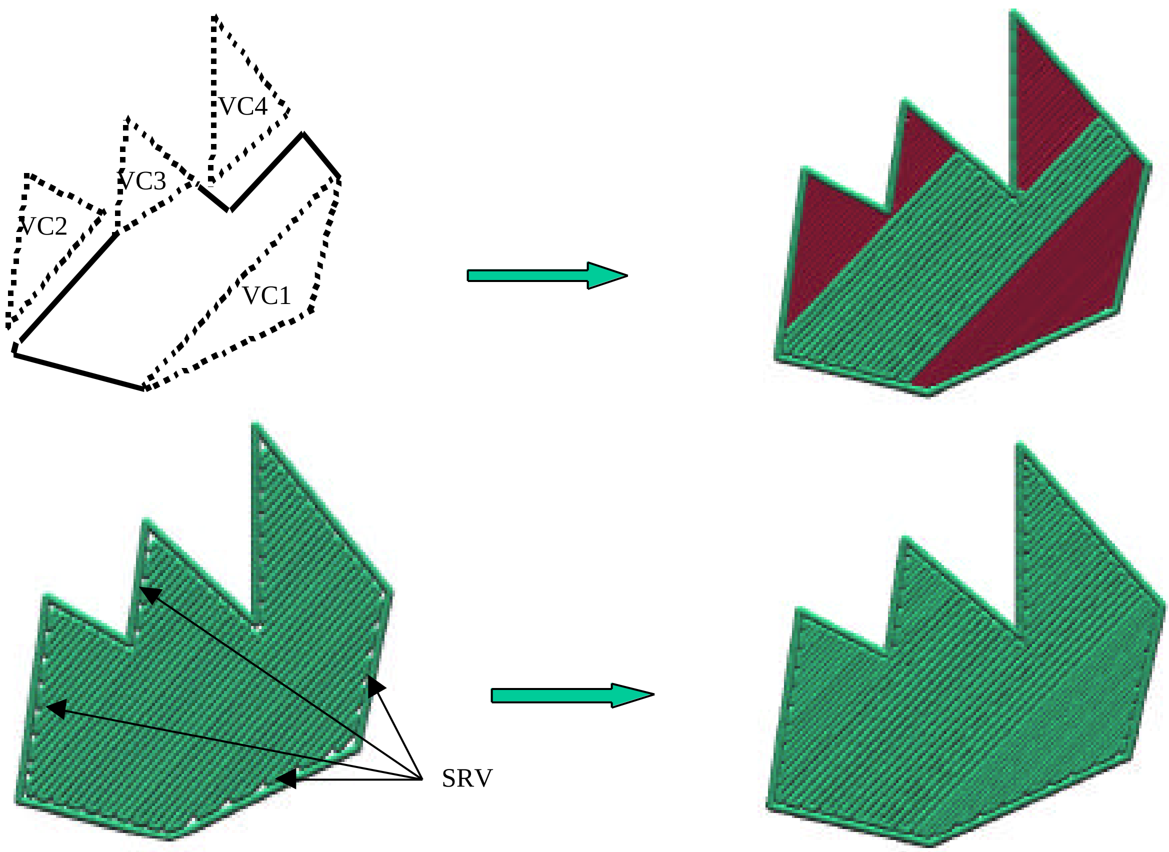


Figure 5: Adaptive Roadwidth for Concave Polygon

VC #	Original RW (mil)	SRV size (mil^2)	Adaptive RW (mil)	New SRV size (mil^2)
VC1	20	73.91	14	7.91
VC2	20	13.83	18	7.04
VC3	20	28.61	16	6.86
VC4	20	28.61	16	6.86

Table 1: Void Contour Information for Concave Polygon

A Circular Object with Holes

A circular object (1” Φ) with one circular and two elliptical holes is designed. The toolpath with constant roadwidth 20 mil is generated. There are a lot of SRV on the layer (Fig 6, bottom left). The adaptive roadwidth algorithm was applied to the part as before. Void contours are formed and new roadwidth for each void contour is computed (Fig 6, upper left). Toolpath using new roadwidth for each void contour is formed (Fig 6, upper right). The void free part is achieved (Fig 6, bottom right). The number of continuous path is still the minimum.

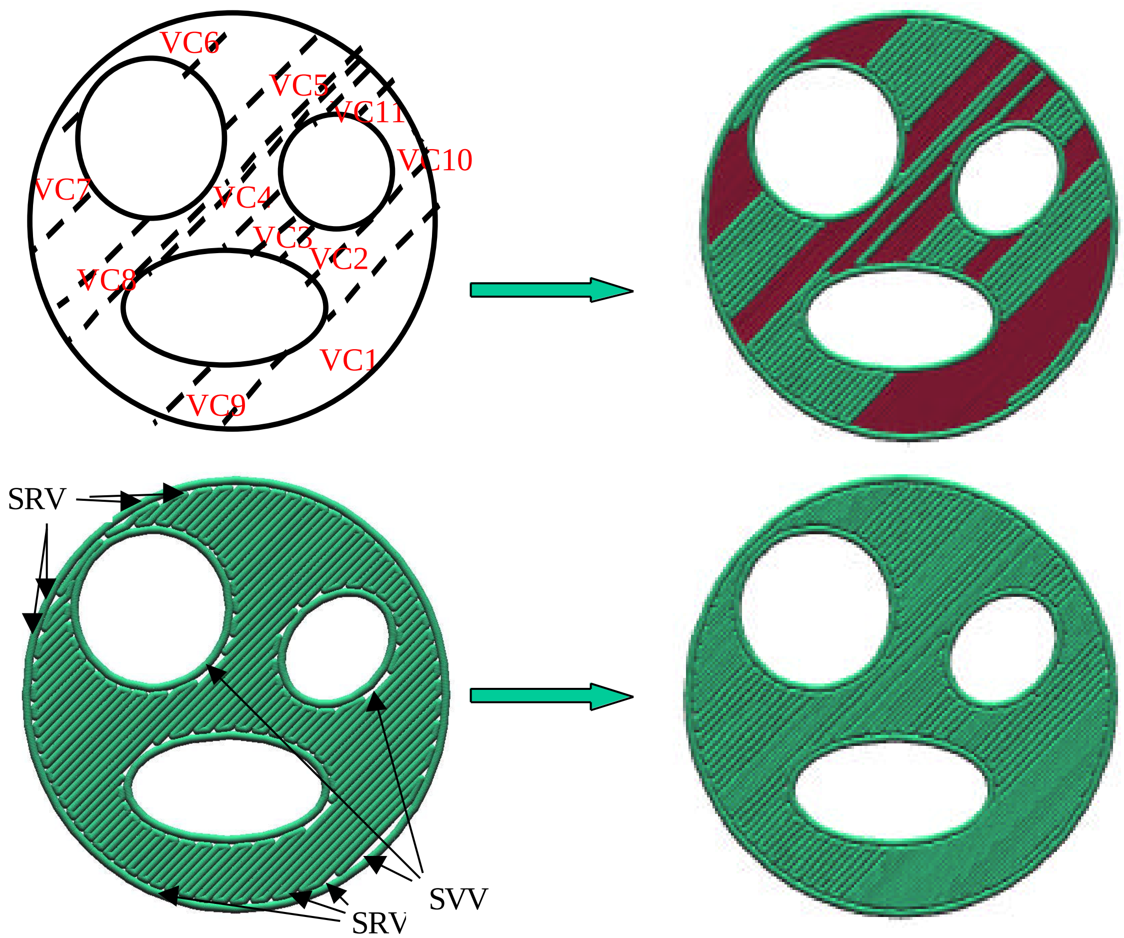


Figure 6: Adaptive Roadwidth for a Circular Object with Holes

8. Conclusion

A multi-material toolpath generation system with new intelligent features - adaptive roadwidth - has been successfully accomplished. A variety of parts with complex boundary shapes and multi-material parts with interconnectivity have been visualized and quantified. Now, the multi-material CAD system provides tools to computationally adjust the multi-material toolpath parameters, alter the toolpaths to create defect free green parts. This software is flexible and general purpose and should be applicable to a number of extrusion based SFF methods.

VC #	Original RW mil	SRV size mil^2	Adaptive RW mil	New SRV size mil^2
VC1	20	89.65	13	2.13
VC2	20	44.67	15	6.57
VC3	20	30.07	16	7.34
VC4	20	71.51	14	7.53
VC5	20	35.44	16	9.27
VC6	20	88.44	13	2.08
VC7	20	61.02	14	5.71
VC8	20	81.92	14	9.12
VC9	20	129.11	13	2.79
VC10	20	78.89	14	8.67
VC11	20	53.94	14	4.41

Table 2: Void Contour Information for a Circular Object with Holes

9. Acknowledgments

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