Topology Driven Improvement of FDC Build Parameters

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Abstract

The likeliest failure origin for advanced ceramics parts, prepared by fused deposition, is a void from improper fill. Adequate filling of each cross-section is dependent upon the deposition toolpath. Cross-sectional spaces are conventionally filled with pre-defined parameters. We propose that adaptive build parameters will control variations in geometry and property of a part. Voids, overfilling, incomplete bonding and excess traversing can be suppressed by adjusting the fill parameters for cross-sectional areas. Improved build parameters and toolpath allows for faster build time and components of full density. Some implementations are discussed and presented.

Introduction

Fused Deposition of Ceramics (FDC) as a process has been shown to be a feasible and competitive technique for ceramic component manufacture. Descriptions of the FDC process, its advantages, limitations and achievements are documented in numerous articles [1, 2 & 3]. To briefly describe the process, the relevant zone (Figure 1) involves the deposition of a thermoplastic material, loaded with ceramic powder, in the form of a bead or "road". Roads are deposited exclusively in the areas that the part "exists", effectively building up the part. The part thus deposited is called a "green" part and this completes the FDC stage of the process.

The thermoplastic is then removed from the green artifact by a binder burnout (BBO) process. The residual powder is packed closely enough to retain the shape of the initial part but has no strength and has a volume density of ~55%. The part, in the "brown" stage, is then consolidated by sintering to full density (~99.9%). The last stage of sintering results in shrinkage of about 17% in X and Y and about 19% in Z [4].

The entire process is driven automatically by computer-generated code and firmware. From the initial CAD part, its conversion to an augmented shape (to take into account the post-processing shrinkage) and the generation of the toolpath control code, FDC is, as is all of SFF, enabled by computational algorithms. In this article, we will discuss some work done at AlliedSignal over the past few months relating to software for toolpath generation.

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Commercial software for toolpath generation reflects the absence of a large family of SFF users interested in fully dense parts. We are currently using QuickSlice™, the software provided by Stratasys Inc., for the generation of toolpath codes to drive the FDM1650™ at our location. While this is an excellent package for most purposes it lacks the ability to generate toolpath codes to fully densify parts. Painstaking development of toolpaths comes to naught when a minor parameter is changed. We are in the process of developing technology that will remove the intensive and iterative nature of toolpath design that is currently required of FDC. Work at the University of Illinois [5] and to some extent Case Western Reserve [6] is beginning to look at aspects of toolpath layout that is relevant to SFF.

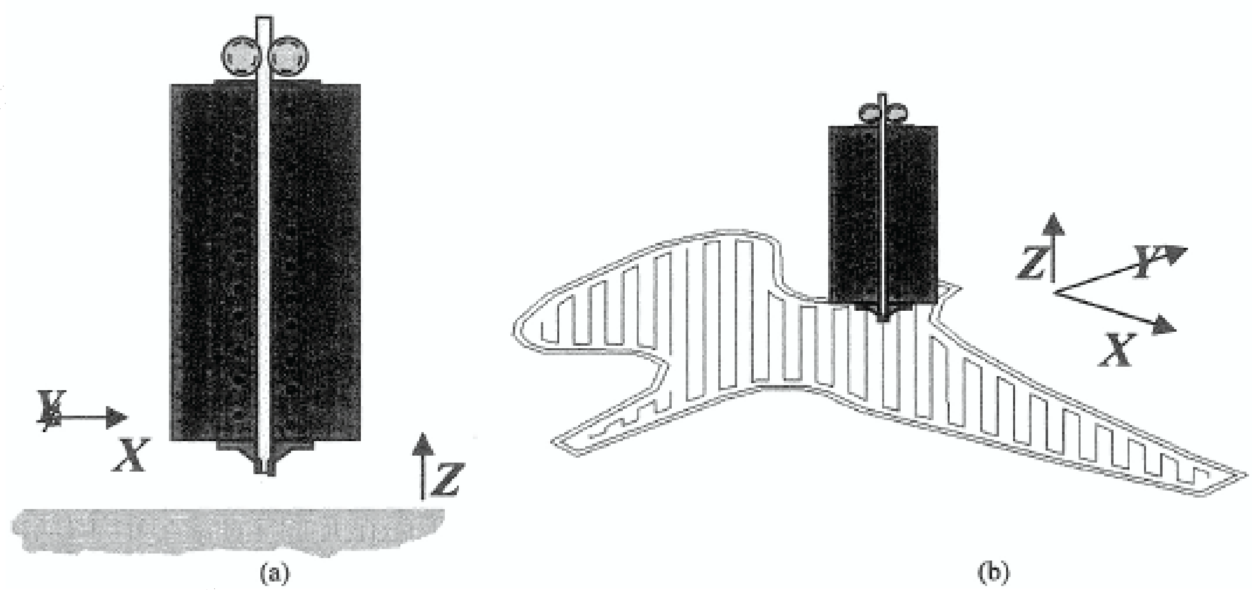


Figure 1: Schematic of the Fused Deposition (FD) process. To the left (a) is a close up of a straightened liquefier, showing the material being deposited on a flat platen to form the part. At right (b), the tool is shown traversing a path that describes the cross section of the part.

True three-dimensional parts are reduced to a single-dimensional road representation that cumulatively draws, or describes, the original part. The 3-d object (contemporarily in "StL" form) is partitioned into two-dimensional "slice" representations. Each slice is then used to generate the single dimensional road that will describe the slice. The conversion from 3-d to 1-d results in a loss of information at each step of the process. For instance, the fin of a blade in 3-d is not a "fin" feature in 1-d, but a series of locations for the tool to visit. While there may be no way to retain the required information at the road build level, determining the toolpath in accordance with the features that are to be built would lead to a better build process. These *procedural losses* are compounded with *systemic losses* that occur during the build itself. Systemic losses include voids and improper filling, incomplete bonding, etc [7] that need to be accounted for prior to generating the toolpath.

In the current work, we attempt to treat these problems at the slice level. Since most current SFF techniques, not just FDC, rely on 2-d slices (albeit of varying thickness or shape), this is a fair assumption. Considering each slice to be the elemental structure, four issues are crucial to the effort:

- Adequate filling of the particular slice with no unintended voids (systemic).
- Adequate bonding of all the deposited roads (systemic)

- Retention of 2–d features to the best ability of machine control (procedural).
- Incorporation of multi-material deposition to leverage 2-head machine (procedural).

Given a particular material and shape to be built, the only parameters at our disposal are the road deposition path and the flow-control of the material. While the two parameters are linked, there is an inherent independence in the deposition path from the process (it is applicable to any SFF technique using 1-d fabrication procedures). The flow control aspect is tied in with the material being deposited or the SFF process that is being used. In this paper we will concentrate on our efforts of the road path.

FEATURE DEFINITION AND VOID REMOVAL

One of the limiting features of Fused Deposition of Ceramics is the formation of voids during slice filling. These voids can be caused by both procedural and systemic causes. Systemic loss of fill information was dealt with to a larger degree in earlier work [7]. In the current work, procedural causes are addressed. The solutions to these problems include systemic errors as well. It should be noted that surface finish of parts (primarily the stair-casing effect) is not considered here. We believe that the limits of surface improvement have almost been reached in our process and physical machining is the only alternative for further improvement.

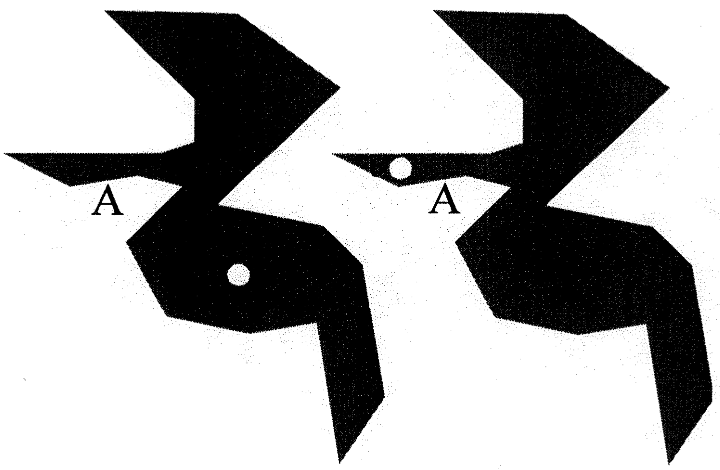


Figure 2: Two features, the fin "A" and the hole "b", can be built independently but not necessarily together.

To keep the surface finish of the generated path as smooth as possible, the build procedure utilizes a perimeter deposition followed by an optional contour deposition and subsequent rastering of the internal areas of the slice. Features that are smaller than the road width cannot be defined. The focus here is to define these features better with improved deposition procedures.

We can look at features on two scales – the macro- and, for the lack of a better term, the meso- levels. Artifacts such as "thin fins" and "small holes" are defined as macro level features. We will address problems associated with interactions of macro-level features. Meso level features would include sharp edges and fillets. While this definition is rather arbitrary, it can be considered to be a separation between preservation of topology and the exact recreation of features.

<u>"Macro" Features:</u> Consider the construction of two features in a particular cross-section (Figure 2). The features that the designer wants to create are the fin "A" and the hole "b". While these features can be built in the first configuration, the process may not be able to build the second configuration due to the road width being too wide. Moreover, even if the feature were possible with a fine road deposition, the time to build the entire part with those settings would increase significantly.

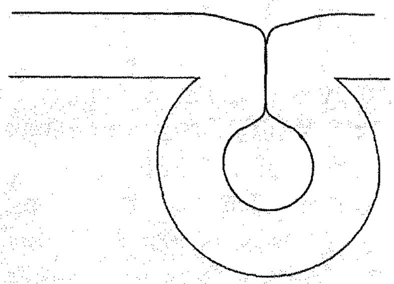


Figure 3: Toolpath generated by QuickSlice™ for the interacting features of Figure 2 and the resulting part.

Figure 3 describes the phenomenon in a toolpath generated by QuickSlice™. An expected hole is not completed in the fin structure. Unless thickness of the road is larger than designed, the gap may not fill. Moreover, a seam will be present at the juncture of the two sharply turning roads.

Figure 4 shows an alternate approach that allows the designer to choose the level of feature definition. Feature loss occurred here when two offset contours intersected, as shown in Figure 3. During toolpath generation, the designer is queried at such locations and given the option of continuing with the conservative procedure of Figure 3 or the overfills of Figure 4.

The advantage of this procedure is that design intent can be maintained while the part is being manufactured. Assuming that the hole is a locating pin with the outer surface unimportant, the toolpath of Figure 4(a) would be appropriate. For the case where the smoothness of the outer surface is more important, the hole can be deformed as long as it is retained (in this case the feature is a hole of some shape).

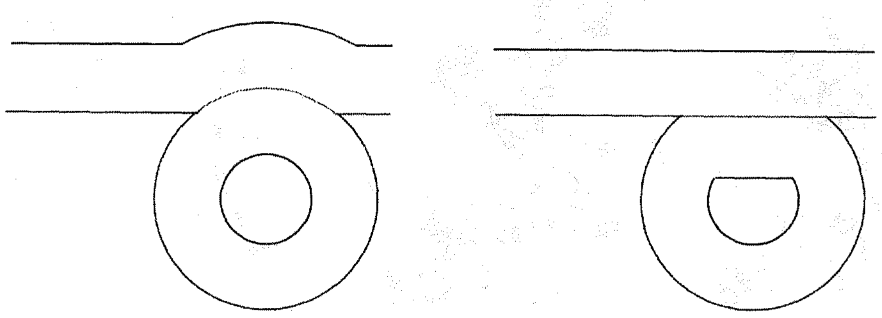
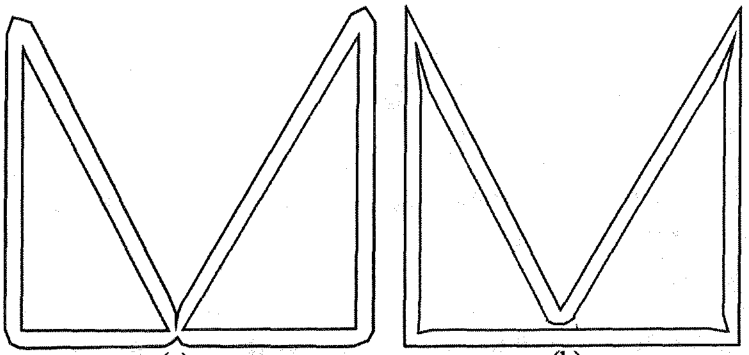


Figure 4: Two options of the new toolpath giving the designer control over feature retention. On the left the circularity of the hole is preserved, while on the right the fin surface is preserved.

Meso-level Features: Another drawback of the FD procedure for making parts is the rounding of corners that occurs during material deposition. This may not be such a bad thing for engineering applications, especially ceramics, as sharp corners are sites for stress concentration. However, the rounding of the internal roads leads to sub-perimeter voids* and other incomplete filling. "Dog-earing" and offsetting of the rasters has been used successfully in suppressing these problems [7]. Apart from offsetting, a preliminary form of the dog-earing is available in QuickSlice™ to users through an escape sequence. However, the effects of both dog-earing and offsetting depend upon the angle of incidence of the raster & perimeter and the width of the road. The algorithms being currently developed and implemented take these empirically observed parameters into account.

* Sub-perimeter voids are persistent errors occurring below the perimetric road due to incomplete filling – the cause of these voids is uncertain, but some of the parameters that treat them have been identified and implemented [7].



(a) (b)

Figure 5: Improvement in perimeter feature definition.

We use dog-earing based on earlier work[*Ibid*], offsetting and rounding similar to [8 & 9] and some proprietary techniques to develop the perimeter and internal roads. The intent of dog-earing here is slightly different from when it was introduced in [7]. In the present case we use dog-earing to make sure that all points on the perimeter are *at most* the specified distance from the original shape. Definition of features such as sharp corners or rounded fillets is thereby achieved. We assume that material and deposition properties are constraints, established for proper build†. These properties are used to establish flow criteria required in the FD machine. Specifically, we will look at sharp corners (outer and inner perimeter).

Using standard procedures, the perimeter for a double wedge shape generated by QuickSlice™ is shown in Figure 5(a). The part obtained is made constructed as two separate pieces welded together at the bottom. The top corners are defined as rounds. Apart from the inaccurate part, the weld area has notches on both surfaces. Utilizing the dog-earing procedure and rounding, the perimeter defined by the altered algorithm is shown in Figure 5(b). The part is now built as a single piece, which ensures that knit-lines or notches will not be created.

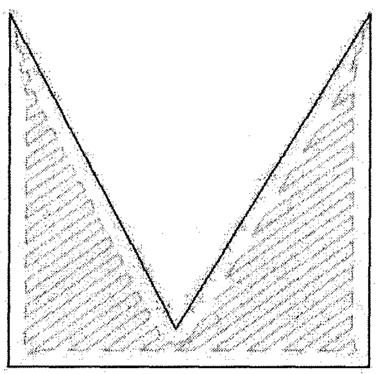


Figure 6: Raster toolpath for a double-wedge with no external perimeter.

The effect of these alterations has ramifications that extend to internal road patterns. Assuming that the same part is created strictly by rastering, Figure 6 describes the toolpath as generated by our algorithms. The rastering road deposits material in the areas that regular rastering (as done by QuickSlice™) would not. Overfilling does occur, especially in the areas such as the lower right corner and in the notch area (as with the contouring build pattern of Figure 5(b)). However, overfilling can be contained while under-filling is intolerable.

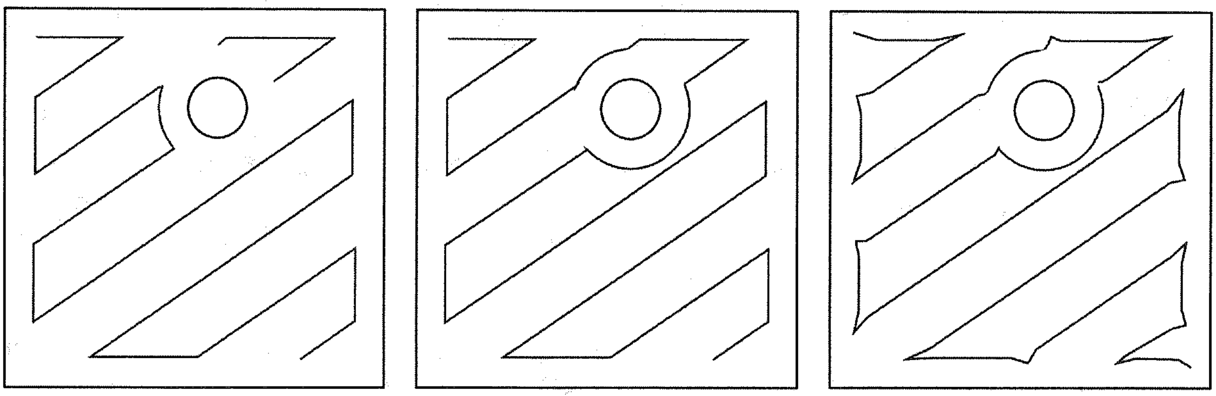
INTERNAL PATH DETERMINATION – OPTIMIZATION OF TOOLPATHS

Deposition of the material in the internal sections of the slice requires adjustments that extend beyond the geometry of the cross-section. For the shape defined in Figure 7, the fill defined by QuickSlice™ is optimized for ensuring minimal fill. With the techniques used in

† These properties include the material composition, temperature of deposition, environmental temperature, etc.

the last section, the fill for the slice improves to the extent that voids from incomplete paths, inter-lamellar and sub-perimeter voids‡ are filled in.

We are currently implementing a procedure by which the contour of the slice perimeter will direct the internal raster pattern. As the raster intersects an offset of the contour, a decision of breaking the raster or including the contour path is made. Comparing Figure 7(a) with 7(b), the effects of this method can be seen. Around the hole, the standard rastering technique terminates. This causes voids in the part, especially in the region just above the hole (Figure 7(a)). In Figure 7(b), the area above the hole is filled in with the contour following raster. Moreover, the hole is also adequately defined. A negative aspect of this method is the overfilling that occurs at the lower end of the curve where the offset road will interfere with the straight raster. Figure 7(c) shows the internal raster laid down taking into account the geometric features of the slice. Note the dog-earing of individual corners of the internal rastering. This ensures that the part is completely filled in.



(a) (b) (c)

Figure 7: Internal raster filling with progressively increasing quality of fill.

Another advantage of the procedure is the reduction in the number of separate roads. From the analogy of a welding procedure, it is important to keep the material flowing continuously. Stopping and starting leads to higher chances of errors and under-fills. In Figures 7(b) and (c), there is a single toolpath that rasters the entire area. Tests have shown that this comparison is valid for more complex shapes.

CONCLUSIONS

We have shown that utilizing the artifacts of geometry from the original shape of the slice help in ensuring that certain levels of feature are maintained in parts built by Fused Deposition. Dog-earing and rounding perimeter curves enables adequate filling of slice-sections. We have also demonstrated that using curves conformal to the perimeter as part of the internal raster improves the surface definition and the internal fill. A reduction in the number of stops and starts in the interior is also observed, thereby reducing the problems associated with startup.

‡ Sub-perimeter voids are removed in response to the angle of incidence and road width.

Further work is being conducted in determining the flow parameters of the roads based upon the geometric aspects of the slice. The order of road deposition and multiple materials are areas that are to be developed.

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REFERENCES

[1] Comb, J. W., Priedeman, W. R. and Turley, P. W., "FDM technology process improvements", *Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX, August 1994, pp. 42–9.

[2] Agarwala, M. K., *et al.*, "Structural quality of parts processed by Fused Deposition", *Rapid Prototyping Journal*, Vol. 2, No. 4, 1996, pp. 4–19.

[3] Agarwala, M. K., *et al.*, "FDC, Rapid fabrication of structural components", *The American Ceramic Society Bulletin*, Vol. 75, No. 11, November 1996, pp. 60–5.

[4] Clancy, R. B., *et al.*, "Fused Deposition of Ceramics: Progress towards a robust and controlled process for commercialization", *Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX, August 1997, pp. 185–94.

[5] Yardimci, M. A., Personal communication, Morristown, NJ, July 1997.

[6] Choi S. *et al.*, "CAD and control technologies for computer-aided manufacturing of laminated engineering materials", *Proceedings of the Solid Freeform Symposium*, Austin, TX, August 1997, pp. 643–52.

[7] Jamalabad, V. R. *et al.*, "Process improvements in Fused Deposition of Ceramics (FDC): Progress towards structurally sound components", *Proceedings of the 1996 ASME Design for Manufacture Conference*, Irvine, CA, August 1996, pp. 18–22.

[8] Tiller, W. and Hanson, E. G., "Offsets of two-dimensional profiles", *IEEE Computer Graphics and Applications*, Vol. 4, No. 9, September 1984, pp. 36–47.

[9] Held, M., "A geometry-based investigation of the tool path generation for zigzag pocket machining", *The Visual Computer*, Vol. 17, No. 5/6, 1991, pp. 296–308.