Bricking: a new slicing method to reduce warping

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ABSTRACT

In this paper we describe a method for reduce warping in Fused Deposition Modeling (FDM) 3D printing technology, automatically splitting pieces in hexagonal or squared bricks spatially locked. We have developed a software application that calculates the necessary GCODE to build the bricking piece directly.

Keywords: 3D printing; warping; slicing method.

1. Introduction

Fused Deposition Modeling (FDM)™ is the most used 3D printing technology. In this technology, 3D pieces are built warming and extruding thermoplastic through a nozzle. When the thermoplastic gets cold, internal stresses may generate deformations, mainly in corners.

Mathematical model of the prototype warp deformation has been developed, showing that influencing factors of warping deformation include stacking section length, shrinkage coefficient of material and chamber temperature.

We have developed a method for reduce warping through limiting stacking section length, splitting model in bricks spatially locked, with configurable gaps between them.

2. Rapid prototyping process

Rapid prototyping technologies are based in the principle of dispersion-accumulation[1]. Pieces are modeled in three dimensions via CAD programs, and then they are sliced into thin layers, which are subsequently stacked in order to form the original shapes (Figure 1).

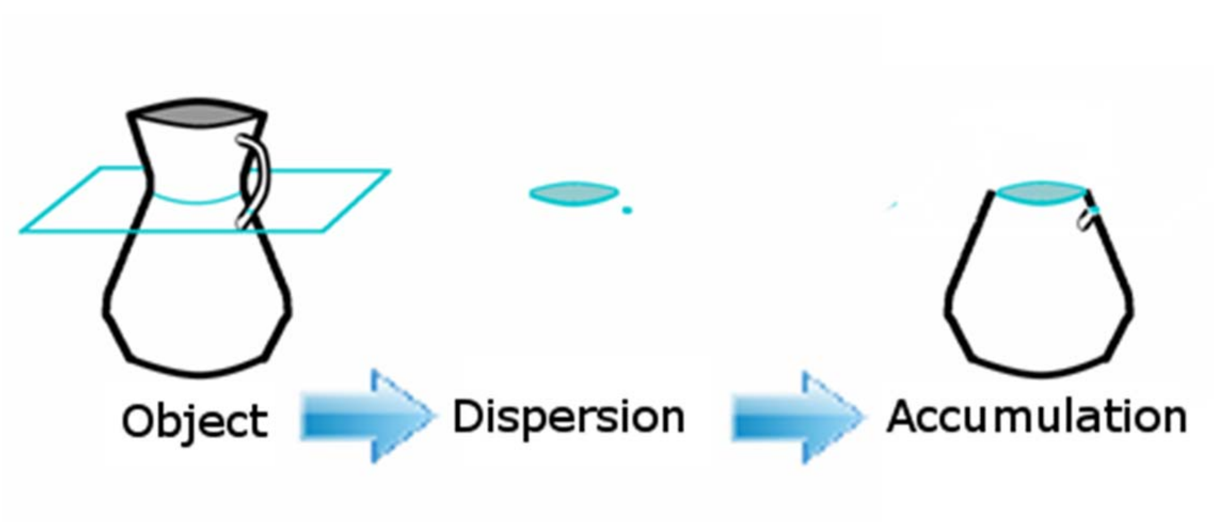

Figure 1. *Principle of Dispersion-Accumulation*

Prototypes are built following these phases:

1) 3D models are exported to a standardized format. The most used is STL, developed for a stereolithography machine in 1988[2]. In this format, pieces are transformed in polyhedrons with triangular faces. The STL file describes these triangles, indicating vertices and outside face of each one.

2) Object is discretized in thin layers, usually of a constant thickness. Each layer is made of polygons. Deposition paths are computed to build every polygon, including one or more strings in borders and filling paths for solid or interior surfaces. Those paths are transformed into GCODE commands, and sent one by one to prototyping machine. (GCODE is the common name for CNC machines programming languages). There are several open source applications that do this phase, like Slic3r[3]. A GCODE commands for temperature control is also generated.

3) Machine resident software (firmware) interprets GCODE commands, generating motor moves, heating hot-end, etc.

3. Warping deformations in Fused Deposition Modeling™

Currently, the most used 3D printing technology is Fused Deposition Modelling (FDM)™. In this technology, 3D pieces are built using thermoplastic polymers, like acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA). The thermoplastic polymer is warmed up to glass transition temperature, becoming fluid. Then, it is extruded through a nozzle, following a deposition path to build 3D pieces. But when the thermoplastic gets cold, internal stresses may generate deformations, mainly in corners (Figure 2).

Tian-Ming Wang et al[4] have developed a mathematical model for warp deformation in the FDM process. According to this model, one of the factors which heavily influences on warping deformation is stacking section length.

Our target was to limit the stacking section length, and thus reduce warp deformation. Splitting pieces in bricks limits the maximum stacking section length to brick size. Therefore, maximum warp deformation is also limited. Figure 3, based on figure 1 of Tiang-Ming Wang et al[4], shows the effect of bricking in warp deformations.

When warping occurs total height is reduced, because down layers are deformed while top layers are being built. Thus, we can measure warping like a ratio, subtracting the quotient between real height and design height from one.

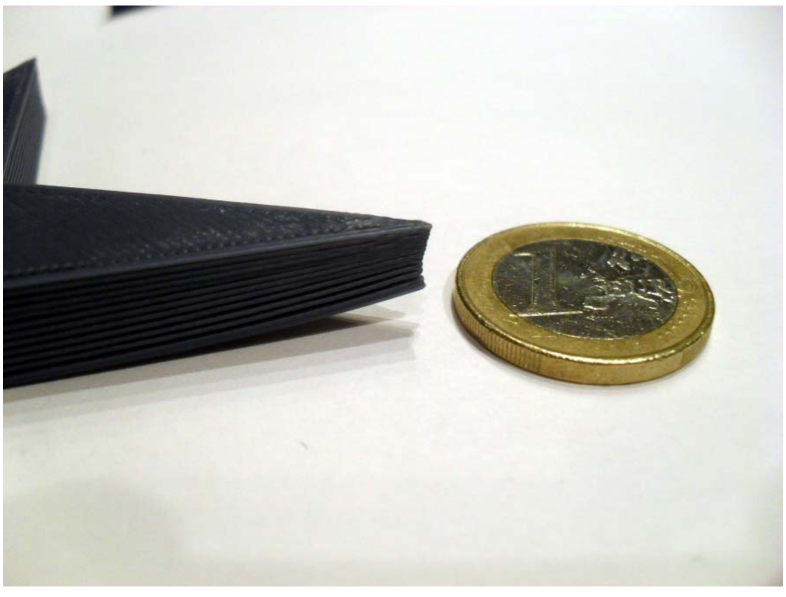

Figure 2. *Warping*

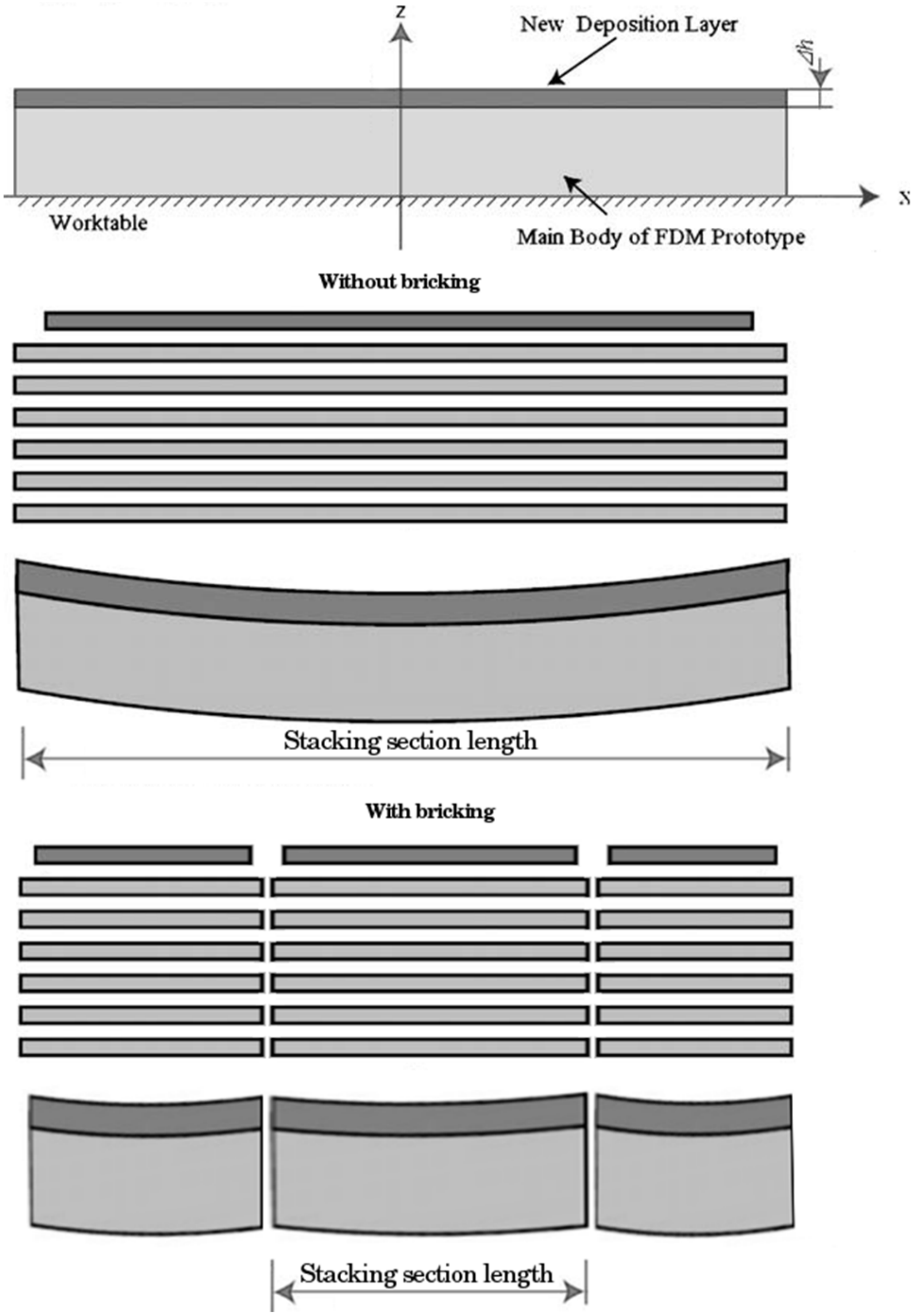

Figure 3. *Warping reduction schema*

4. Bricked slicing algorithm

Our target was to develop a software application to do phase 2 above, adding capacity for splitting models in hexagonal or squared bricks.

The specifications for the new software were as follows:

- Command line application, so can be used by embedded software.

- Variable layer thickness.

- Variable number of solid layers in horizontal outside shapes.

- Variable density in interior shapes.

- Variable number of strings in polygon borders.

- Different speeds for perimeter, infill, and travel.

- Variable size and height of bricks.

- Bricks could be limited to specific height range.

- Variable gap between bricks.

We have developed a C++ application, only using one external library: Clipper library[5]. Our application read a STL file, and generates GCODE as output, following these steps:

4.1 Initial phase

Application starts reading model and computing auxiliary patterns and models

a) Load STL file

Our application supports both binary and ASCII STL formats. The STL file is completely read and transformed into our custom 3D model, which uses integer coordinates (multiplying original number by a variable scale), and consists of:

- 3D vertices (x, y, z)

- Faces, composed of three vertices, with outside normal vector computed by right-hand rule. We use pointers to vertices.

- Maximum and minimum value for each coordinates, for computing purposes.

b) Adjust model.

Z coordinate of each vertex is adjusted to the nearest layer height, to avoid computation problems.

c) Generate model for horizontal faces.

Our application generates a 3D model (with the same format of general model) including horizontal shapes and their solid thickness.

d) Generate filling patterns

Our application generates patterns for solid and infill zones, for odd and even layers. Filling patterns are formed by parallels lines, and their gaps depend on fill density. Pattern limits are dimensioned using maximum and minimum X and Y values of general model.

e) Generate brick patterns

Our application generates patterns for hexagonal and squared bricks, for odd and even layers, including gaps. Brick patterns are formed by 2D polygons. Centre of an odd brick is situated in three bricks union (if hexagonal) or four bricks union (if squared) on even layer, thus getting spatial locked bricks (Figure 4).

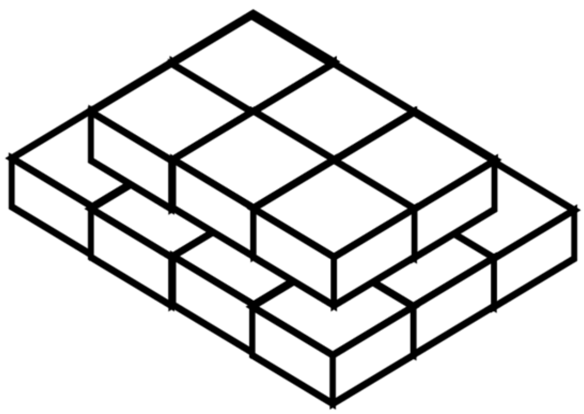

Figure 4. *Bricking 3D schema*

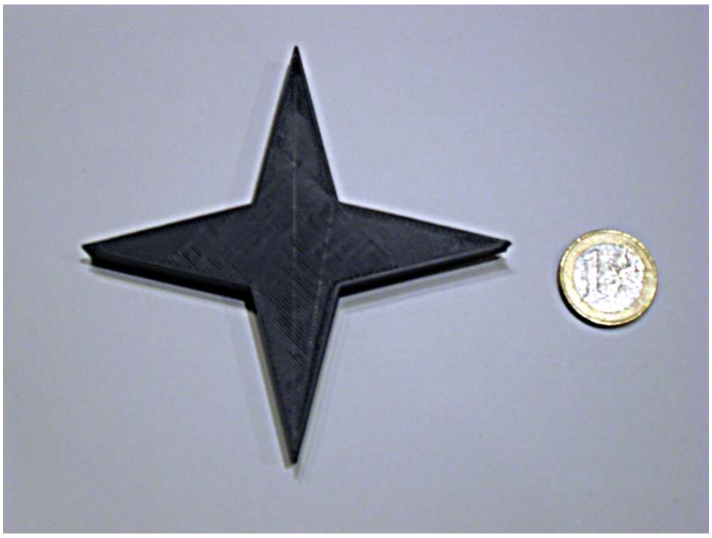

Figure 5. *Test part*

4.1 Slicing and computing deposition paths

For each layer, application slices model and computes deposition paths. Steps f to j are computed for each layer.

f) Compute slice at mid height of layer.

The application computes intersections between horizontal plane of layer and every 3D triangular face of general model. Each triangle-plane intersection is a two points segment. The order of points in segments derives from face's orientation. Then segments are concatenated joining match points, forming closed polygons.

g) Bricking slice.

The application bricks the slice, computing the intersection of slice and brick pattern. Thus, model is bricked (Figure 4). At this moment, we have a bricked slice, and we can begin computing deposition paths.

h) Shell and infill area

The application computes borders paths (also named shell), offsetting bricked slice paths towards interior of polygons. Then infill surfaces are calculated, offsetting the last border paths.

i) Solid filled surfaces and normal filled surfaces.

Solid fills paths are build, computing intersection between layer horizontal plane and solid model calculated in step C. Then these paths are intersected with infill section (see h) to obtain solid filled surfaces. Normal filled surfaces are obtained subtracting solid filled surfaces from infill surfaces. Paths for filled surfaces are computed intersecting patterns with surfaces.

j) Generating GCODE commands.

The application generates GCODE commands for shell, solid filled and normal filled, according with their respective speeds.

5. Testing the bricking algorithm

For tests, we have used our own variant of RepRap[6]. We have designed a test-part with the shape of a four-pointed star, with pronounced angular corners to increase warping risk. The star is 100mm wide and 10mm high (Figure 5).

All pieces were built with a layer height of 0,4mm, using the same printer with the same material (ABS) and deposition speeds, and with the same conditions of hot-end temperature, and bed temperature. We built pieces as follows:

a) Type A: parts without bricking.

b) Type B: parts with squared bricks of 40mm side length.

c) Type C: parts with squared bricks of 15mm side length.

d) Type D: parts with hexagonal bricks of 20mm side length.

e) Type E: parts with squared bricks of 15mm side length.

In all bricked parts, the first two layers (0,8mm) were not bricked, to avoid reduction of adherence to bed.

At start, printing, parts have no deformation. Stresses start to accumulate, until the adherence to base is not enough. Then parts begin to deform up to end of printing. So, deformations are proportional to accumulate stresses and inversely proportional to the time elapsed between start of printing and the beginning of warping. Since sharpen angles accumulate stresses, hexagonal bricks resist longer than squared, and deformations are lower. (Figure 6)

We have tested parts with several bricks height, with no differences in deformations. Also we have tested parts with no bricks in the top two layers, for aesthetic reasons, and deformations are similar.

Mean warp ratios for built pieces are indicated in Table 1.

Table 1. Warp Ratios

Sample	Type	Brick Length (mm)	Mean Warping Ratio (%)
No bricking	A		35%
Squared	B	40	28%
	C	15	17%
Hexagonal	D	20	13%
	E	15	9%

6. Conclusions

Warp deformations in Fused Deposition Modeling (FDM) depends of stacking section length, among other factors. Splitting pieces in bricks limits the maximum value of stacking section length. Therefore, warp deformation is reduced (Figure 6).

We have developed an algorithm and a C++ application to make bricks automatically in STL pieces, and we have measured a significant reduction in warp deformations, obtaining better results with hexagonal bricks than with squared bricks.

In parts tested, warp deformations are inversely proportional to the length of the bricks. Lower lengths reduce accumulate stresses, and deformations starts after and are lower.

Figure 6. *Warping without bricks (left)*
and with hexagonal bricks (right)

7. References

[1] A. Guerrero-de-Mier, M. M. Espinosa Escudero. "PROGRESS IN REPRAP: OPEN SOURCE 3D PRINTING". DYNA 89, no. 1 (2014). DOI: http://dx.doi.org/10.6036/5659

[2] 3D Systems, Inc. Stereolithography interface specification, P/N. 50065-S01-00, 1989.

[3] A. Ranellucci et al, Slic3, G-code generator for 3D printers. 2011-2015. http://slic3r.org.

[4] T. Wang et al, "A model research for prototype warp deformation in the FDM process," The International Journal of Advanced Manufacturing Technology, vol. 33, pp. 1087-1096, 2007

[5] A. Johnsson. Clipper – an open source freeware library for clipping and offsetting lines and polygons. 2010-2014. http://http://www.angusj.com/delphi/clipper.php

[6] L. Romero et al, Additive manufacturing with RepRap methodology: current situation and future prospects. 25th Annual International Solid Freeform Fabrication (SFF) Symposium, 2014, University of Texas. Austin

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BOOK OF ABSTRACTS

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1. Introduction

Fused Deposition Modeling (FDM) is the most used 3D printing technology. In this technology 3D pieces are built warming and extruding thermoplastic through a nozzle. When the thermoplastic gets cold, internal stresses may generate deformations, mainly in corners (Figure 1). These stresses are proportional to shrinkage coefficient of material and to the change of temperature during the cooling process[1], and deformation are produced by the accumulation of stresses along plastic fibres.

2. Methodology

Our method consist of automatically split 3D pieces in detached squared or hexagonal bricks spatially locked. In this way, accumulation of stresses is reduced, as well as warping (Figure 2).

We have developed an application to process 3D models, slicing into thin layers and tracing routes to build them, including bricking. In our application, type and size of bricks and size of hollows can be set freely. We have designed a test part with the shape of a four-pointed star, with sharp angles to increase warping risk. The star is 100mm wide and 10mm high. We used a RepRap Prusa 3 to build test parts, with the same material (ABS), with and without bricking. When warping occurs total height is reduced, because down layers are deformed while top layers are being built. Thus, we can measure warping like a ratio, subtracting the quotient between real height and design height from one.

3. Results

We have significantly reduced warping in printed pieces, obtaining better results with hexagonal bricks than with squared bricks. It's also important to highlight that first one or two layers must not be bricked, because it can increase warping.

Table I. *Warping ratio*

Feature	Side length (mm)	Warping
No bricking	-	35%
Squared	40/15	28%/17%
Hexagonal	20/15	13%/9%

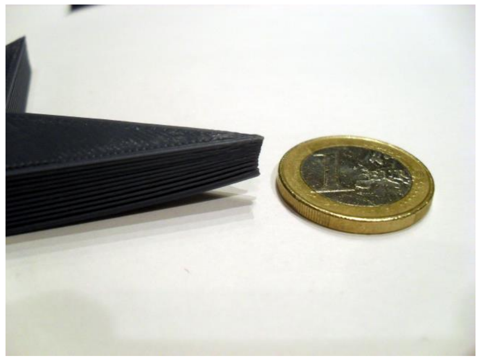

Figure 1. *Warping.*

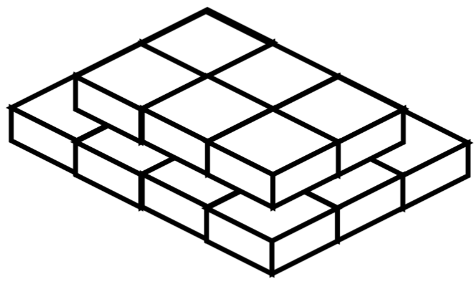

Figure 2. *Bricking schema.*

4. Conclusions

Warping in Fused Filament Fabrication (FFF) can be reduced splitting pieces in bricks, because this method avoids the accumulation of stresses. We have developed an algorithm and a C++ application to make bricks automatically in STL pieces, and we have measured a significant reduction in warp deformations, obtaining better results with hexagonal bricks than with squared bricks.

5. References

[1] T. Wang et al, "A model research for prototype warp deformation in the FDM process," The International Journal of Advanced Manufacturing Technology, vol. 33, pp. 1087-1096, 2007