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Continuous Extrusion Printing: Influence of the FDM Printing Trajectory on Thin-Walled 3d Printed Part Performance

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Abstract

This paper deals with a new approach of printing thin-walled parts with FDM technology by the use of continuous extrusion printing. Continuous extrusion printing is possible only if the part respects some specific constraints allowing a one-step printing path (no extrusion stop and no head travel). However, not all printing trajectories guarantee the same geometrical quality and mechanical strength due to the junctions of the path in the printing slices. This paper presents trajectory constraints in the case of continuous extrusion printing for thin-walled parts. A case study illustrates the principle, and some feasible trajectories are compared. The key problem of junction is presented, and the effect of path on geometrical quality and mechanical strength are evaluated.

Keywords: Thin-walled part • 3D printing • Eulerian path • FDM • Continuous extrusion printing

Introduction

This paper deals with a new approach of printing thin-walled parts by the use of a continuous extrusion printing. Continuous extrusion printing consists in printing the part in a continuous way (material extrusion never stop until the end of the part production) allowing a faster printing by suppressing the nonproductive travel of the printing head. The part wireframe geometry has to respect some constraints in order to generate a continuous printing path. However, for the same wireframe geometry, not all printing trajectories guarantee the same geometrical quality and mechanical strength only due to the junction of the frame branches. The aim of this paper is to present trajectory constraints in the case of continuous printing of thin-walled parts. A case study of a simple link is presented, and four feasible trajectories are presented. Tensile tests illustrate the large variation of mechanical strength of the different printing path. Microscope geometric observation of the filament deposition allows an explanation of the failure junction definition. Finally a conclusion ends the paper.

The aim of continuous extrusion printing is to minimize the FDM printing time by suppressing the travel of the printing head that are non-producing time. As an example of production loss due to head travel, the GCode file of the case study (Figure 1) generated by the Idea Maker slicing software contains around 25% of travel distance (non-printing movement) over the entire movement of the head.

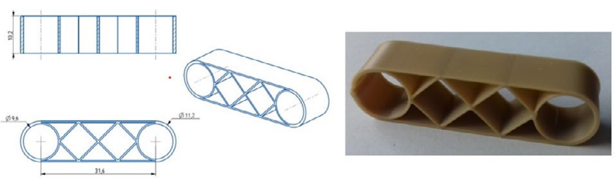

Figure 1. The link case study: (a) designed 3D model of the thin-walled study part and (b) One 3D printed part with the FDM 3D printer

Several authors deal with the tool path optimization to reduce airtime during machining [1,2]. A similar approach is applied on FDM 3D printing by allowing local production of several slices of a part before head travel [3]. Other works can be cited on toll path optimization for extrusion 3D printing dealing with the in-slice contour filling travels [4,5] for FDM 3D printer and for wire and arc additive manufacturing [6]. Few works are available on thin part filament printing, Ding, D deals with thin-walled structure produced by wire and arc, however production can be stopped, and airtime travel of the head is possible/necessary [7].

The impact of the printing path on the mechanical quality (strength) of the part is mainly due to the junction of the thin wall one to the others. Several works investigated the strength of full filled part depending on the filling orientation and process parameters [8,9]. Printing directions are favorable depending on the part mechanical solicitations. The weakest mechanical direction is the slice-to-slice direction due to bonding between slices. The bonding quality is observed by showing that time and temperature increases the filament-to-filament cohesion and the part strength [10]. However, in the case of a wireframe type junction, which is better or worse between a continuous filament deposition and a corner-to-corner junction?

In our chosen case study, the wireframe geometry is given and has to respect several continuity constraints in order to generate a continuous printing toolpath. Continuous extrusion printing is possible if a printing path can be identified to print each slice in once. Such problem corresponds to the Eulerian problem that consists in identifying a path that goes exactly once through each branch of a graph. In our case, the branches of the graph are the single toolpath that describes the geometrical beams of the part (line, arc …) and the nodes of the graph are the junctions/connections of the branches with the others. Identifying a continuous path on a graph is possible if and only if the graph is classified as Eulerian or semi-Eulerian. A graph is considered as Eulerian if each nodes have an even number of branches, every node can be the starting point of the path and will also be the ending point of the path. A graph is considered as semi-Eulerian if two

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and only two of its nodes have an odd number of branches, only one of the odd points (point with an odd number of branches) can be the starting point and the other one will be the ending point. Several algorithms exist to identify continuous paths through an Eulerian graph [11], however the path is not unique [12]. In the case where the graph contains more than two odd nodes, it is then impossible to identify an Eulerian path but it is possible to complete the graph by adding branches [13], the difficulty then is to translate these new branches to geometrical beams. To illustrate this point, the reader can experiment the continuous path finding on the following Figure 2. Figure 2a is the case study where every node can be a starting/ending point of an Eulerian graph. However, Figure 2b is the envelope example that corresponds to a semi-Eulerian graph where a continuous path is possible only by starting from either the left or right bottom corner of the letter. This implies that in the case of an Eulerian graph, the path printing of slices starts and ends at a constant point, whereas for a semi-Eulerian graph, the path printing has a constant change of the starting and ending points from slice to slice.

The question treated in this paper concerns the strength of the possible paths: do they have the same mechanical strength? To illustrate our purpose, the case study is presented in the next section the case study.

Continuous extrusion printing

The case study is a simple connection link that is tested with tensile test. Section the case study also presents the several printing paths studied in this paper. Results of the tensile test are presented in section results of tensile tests and section microscopic observation of the failure junction shows the microscopic observation of the failure junction.

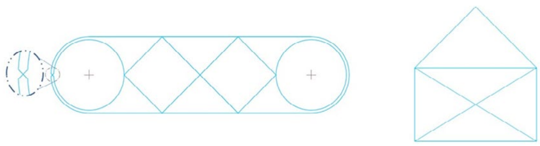

Figure 2. Paths: (a) the case study of the connection link with all even nodes and (b) the envelope example with two odd nodes

The case study

The study case presented in Figure 1a corresponds to a simple connection link: 31.6 mm length between the two 9.6 mm diameter holes and 10.2 mm of height. This link is an oblong outer contour, two interface holes, and a trellis in its inner part. The printed part showed in Figure 1b is the physical case study obtained by a continuous printing GCode generated on the part wireframe of Figure 2a. The potential failures of the part are the junctions corresponding to the connection of the inner trellis to the outer contour. These "K" type junctions are all identical with four branches.

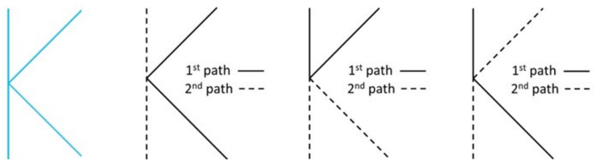

Figure 3. Junction: (a) the K type junction between the outer contour and the inner trellis, and the three possible paths through the branches such as (b) straight line + corner, (c) corner-to-corner, and (d) crossing

Several paths are possible through these branches as showed in Figure 3.

In the case of polymer FDM 3D printing, intuitively one can get the feeling that crossed paths (Figure 3d) will not have a good tensile strength because of the discontinued deposition of the fused filament due to the crossing of the already printed geometry. Hence, the case of the straight line+corner path (Figure 3b) and corner-to-corner path (Figure 3c) is the two-studied junction. Among the several possible paths that do not cross, two paths are manually identified using the straight line+corner path (V path) and the corner-to-corner path (H path). The V path consists in printing the contour in a continuous way and the inner geometries among the direction of the part main axis. The H path consists in printing the inner trellis geometry in a continuous way. For both V and H paths, printing can be made in the forward or backward direction, hence V and H paths are denoted as +V and +H for the forward paths and –V and –H for the backward paths respectively. Figure 4 shows some steps of the different V and H paths. Start/stop point is arbitrary chosen at the connection between the outer contour and the rest of the wireframe at the left side of the part (Figure 2a).

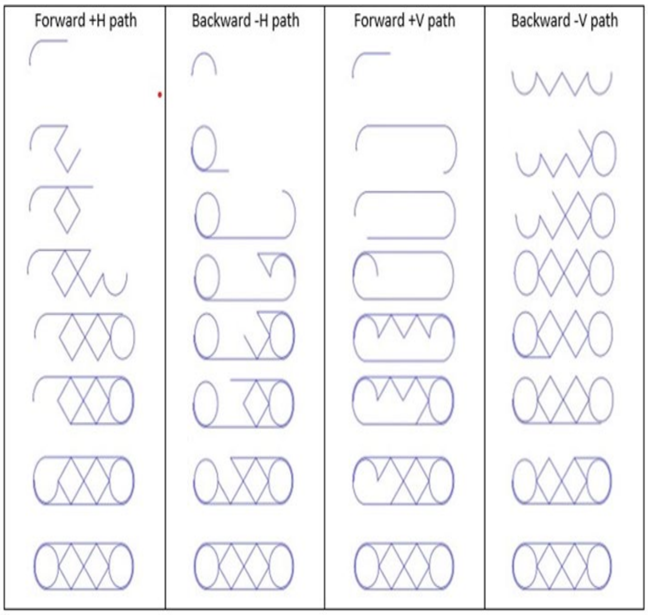

Figure 4. Forward and backward paths of the H and V paths: (a) +H path, (b) -H path, (c) +V path and (d) –V path

On top of these two directions of each V and H path, alternative paths are considered noted +/-V and +/-H respectively. These paths consist in alternatively printing the wireframe geometry with the +V or +H path on one slice and the following slice with the –V or –H path and so on. Hence, the V paths can either be +V, -V or +/-V. Similarly, the H paths can either be +H, -H or +/-H. Finally, a last combination of paths called the V/H path consists in combining the V and H paths, this V/H paths can either be +V/+H, +V/-H, -V/+H or -V/-H. Hence, ten paths are studied: three V paths, three H paths, and four V/H paths.

Results of tensile tests

The experimental study is made on FDM printed part. The printing material is a 1.75 mm ABS filament from Machine-3D. The printer is a semi-professional RAISE2 from RAISE3D. Printing parameters are as follows, nozzle diameter is 0.4 mm, slices are 0.3 mm thick, printing head temperature is 230°C, bed temperature is 110°C, printing speed is 40 mm/s except for the first layer that is printed at 15 mm/s. GCode files are generated using Mat lab based on the wireframe geometry and the chosen path. For each ten-case studies path, four specimens are printed and tested with a tensile solicitation on an INSTROM 4411 tensile machine.

The two Figures 5 and 6 present the force-displacement results of the tensile tests for the V and H paths (Figure 5) and the combined V/H paths (Figure 6). Most of the curves show brittle fracture modes. However, three of them (+V, -H and +V/-H) have a long ductile deformation and an incomplete fracture for some of them (mostly the +V/-H path) allowing the tensile test to continue. Hence, in order to compare the displacement results, instead of using the maximum displacement, it is chosen to consider the displacement value corresponding to 95% of the maximal tensile force.

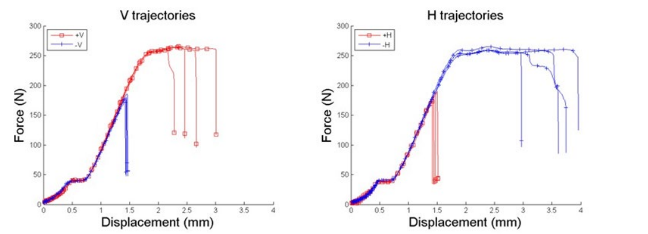

Figure 5. Result of the tensile tests for the (a) V trajectories in the left side and (b) H trajectories in the right side. The combined +/-V and +/-H trajectories are not showed for a clearer viewing

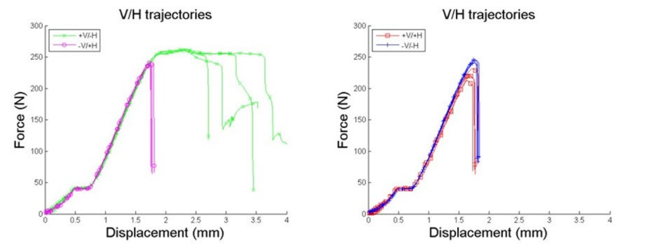

Figure 6. Result of the tensile tests for the combination of V/H trajectories

Table 1 summarizes the data of ten paths results and Figure 7 illustrates these results in term of average maximal force (Figure 7a) and average displacement (Figure 7b). Results are discussed in section 4.

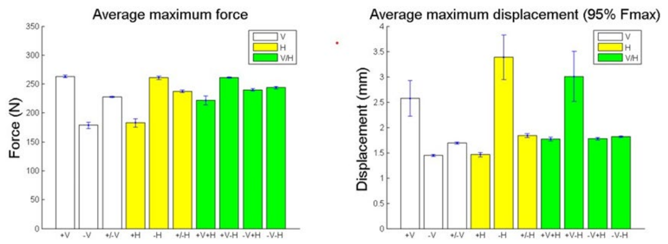

Figure 7. Summary of the tensile tests results: (a) average maximum displacement depending on the printing trajectory and (b) average maximum force depending on the printing trajectory

Trajectory	Average F_{max} (N)	Standard deviation of F_{max} (N)	Average $L_{95\%Fmax}$ (mm)	Standard deviation of $L_{95\%Fmax}$ (mm)
+V	263	2.46	2,57	0.35
-V	179	5.41	1,45	0.017
+/-V	228	1.06	1,69	0.022
+H	183	7.17	1,46	0.040
-H	261	2.84	3,39	0.44
+/-H	237	1.87	1,84	0.036
+V/+H	222	7.96	1,77	0.040
+V/-H	261	1.11	3,01	0.49
-V/+H	240	2.33	1,78	0.024
-V/-H	244	2.15	1,82	0.015

Table 1. Results of the tensile tests for all the tested path combinations

Microscopic observation of the failure junction

As expected, the brittle fracture appears at the 'K' junction. Geometry is observed from the bottom face (face in contact with the printing bed) with a Keyence VHX-6000 numerical microscope.

Figure 8 shows the influence of the printing direction for the same path, Figures 8a and 8b correspond to the 'K' junction with straight line+corner presented in Figure 3b and part of the V paths, the forward (+V) and the backward (-V) path respectively. Figures 8c and 8d correspond to the corner-to-corner path presented in Figure 3c and part of the H path.

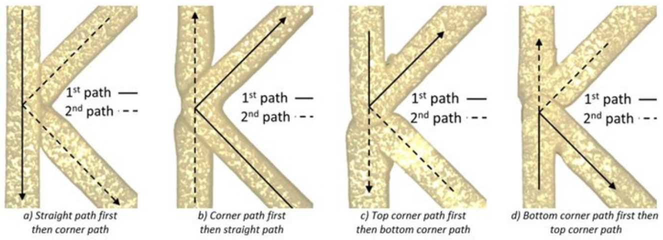

Figure 8. Different trajectories of the 'K' junction and effect on the fused filament deposition

Discussion

The analysis of the experimental study results is made over several criterion, the tensile tests results (fracture mode and the corresponding displacement, and the maximal breaking force), the paths combination (the +/- alternated path and V/H combined paths), and finally the failure junction.

Tensile tests results

Raw results of the tensile test are discussed here for the three best results that have the highest strength and ductile breaking mode.

Fracture mode and maximum displacement

Whereas most of the tested trajectories have a brittle fracture mode with a brutal break of a junction, the three best trajectories (+V, -H and +H/-V) have a ductile fracture mode with a plastic deformation plate that allows a large increase of the maximum displacement of +77%, +132% and +70% for V, H and V/H group respectively.

Breaking force

The three best trajectories (+V, -H and +H/-V) have the same highest breaking force (between 261 and 263N) that correspond to an increase of +47%, +43 and +18% for V, H and V/H group respectively compared to the worst trajectory. The force increase of the best V/H trajectory seems lower than the V and H groups, this is due to a higher performance of the V/H trajectories compared to the worst V and H group trajectories.

Combination of the path

As showed by the results, it appears that combining path give better results than pure simple path, for either +/- alternating printing or V/H combining printing.

Alternating the trajectories

Concerning the V and H groups, alternating the trajectories (+/-V and +/-H) implies a brittle fracture mode but significantly increases the maximum displacement of +17% and +26% respectively. Similarly, the trajectory alternation increases the maximum force of +27% and +30% for the V and H group respectively compared to the worst results in each group.

Combining the trajectories

A logical result is the combination of the best V and H trajectories that results in the best V/H trajectory: a ductile fracture mode with a long maximal displacement and a high force. However, the combination of the two worst V and H trajectories results in a good trajectory: brittle fracture mode but the maximal displacement and maximal force are similar to the alternated +/-V and +/-H trajectories, next chapter attempts an explanation just below. Finally, the two lasts V/H trajectories have similar results to +/-H alternated trajectories (maximal breaking force around 240N), however the +V/+H trajectory seems a bit lower and closer to the +/-V path in term of maximal force (maximal breaking force around 225N), a reason is also suggested just below.

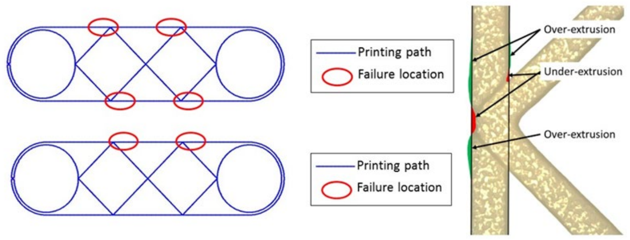

Figure 9. Location of the failure point for (a) The –V path (top left) and (b) The +H path (bottom left). (c) Deviation of the filament deposition of the corner path first then straight path failure junction with some over-extrusion and some under-extrusion

Failure junction and paths combination

The junction corner-to-corner (Figure 3c) do not seem to be a critical junction. Depending on the direction of the printing path, the fused filament deposition seems similar for the forward (Figure 8c) or backward direction (Figure 8d) and seems as strong as the straight line+corner path (Figure 3b) but only the straight path first then corner path direction (Figure 8a). It appears that the most critical junction corresponds to the corner path first then straight line (Figure 8b): the microscopic observation of the material deposition shows some lack of material designated by under-extrusion in Figure 9c. The fracture is caused by the inner under-extrusion and is located on the upper or the lower side of the 'K' junction, causing the same brittle fracture of the -V and +H paths but on the left side (Figure 9a) or on the right side (Figure 9b) of the junction respectively.

As the location of the failure point is different on both -V (Figure 9a) and +H (Figure 9b) paths, the mechanical behavior of the –V/+H path is correct and closer to the mixed path +/-V and +/-H than the worst –V or +H. Moreover, the over-extrusion at the outer side of the "K" junction seems to increase this compensation, what could be considered as a reinforcement. On contrary, the +V/+H and the +/-V paths combine the straight path first then corner path (no over-extrusion, Figure 8a) to the corner path first the straight path (failure junction, Figure 8b) implying a compensation but no reinforcement due to absence of over-extrusion of the above or below slices.

Conclusion

This paper presented the continuous extrusion printing and its application on a simple link case study. The continuous extrusion printing aims to minimize the printing time of thin-walled part viewed as wireframe part. Under some continuity constraints given by the Eulerian path problem, several continuous paths can be identified. This paper showed that not all printing paths give the same strength of the part with a large variation of maximal allowable tensile force, tensile displacement and even brittle or ductile fracture mode. Out of the presented paths, the simple tool head path can generate a failure junction under specific condition implying brittle fracture mode. However, the alternation of different paths along the printing slices can compensate this weakness in term of maximal allowable tensile force but the fracture mode keeps being a brittle fracture mode. Finally, the path planning of a thin-walled part has to take into account the observed results depending on the tolerated geometrical quality of the desired part or its strength and fracture mode.

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