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EFFECTS OF PROCESS PARAMETERS ON THE QUALITY OFF NON-PLANAR 5-AXIS PRINTING OF FREE FORM SURFACES

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Abstract: *Additive manufacturing of composite structures has been an important research and application area for light weighting. As opposed to layer-by-layer approach, non-planar directional printing offers better use of the material strength according to the loading conditions. As for all of the manufacturing processes, parameters have significant effects on the product quality and hence mechanical performance. In this study, the effects of printing parameters such as layer thickness and side step distance, i.e. bead distance, on 3D directional printing are discussed in the sense of visual part quality. Design of experiments approach is used to identify the level of process parameters; the tool path is generated and planned using the built-in surface machining operations in Siemens NX.*

Key words: *Non-planar printing, FDM, PLA*

1. INTRODUCTION

Fiber-reinforced plastic (FRP) filaments have the potential in additive manufacturing (3D printing) of load-bearing components in the aerospace and automotive industries [1]. Along this potential, earlier research findings highlighted significant anisotropy in the tensile strength of 3D-printed FRP components, primarily due to the pronounced disparity in strength along and across the filament [2].

Conventionally, 3D printing is performed layer-by-layer according to the sliced STL models, where in-fill and support materials need to be deposited. Such kind of additive manufacturing is acceptable for prototyping purposes, potentially the part is non-functional and will not be subjected to loading. However, as far as functional parts are concerned, the loading conditions are critical in determination of the deposit direction, otherwise strength-to-weight ratio may be significantly low.

In one of the recent CIRP keynote papers [3], it was inspired that the mechanical strength of printed components can be maximized by aligning the printing paths with the principal stress directions arising from external loads. This principal direction can be pre-determined to guide the actual printing process. Experimental data suggests that aligning the printing paths with principal directions results in a remarkable 176% increase in tensile strength and a 21% increase in compressive strength compared to using perpendicular paths [4]. This underscores the critical importance of optimizing filament layout to enhance the functional performance of components under external loading conditions. In another recent study [5], it was shown that that stress-oriented toolpath planning in 3D printing leads to significant improvements in mechanical properties.

Compared to several other techniques, especially in fused deposition modeling (FDM), filament placement and alignment can be easily controlled by the generated tool path. For such a purpose, the filament layout, i.e., printing path, should be meticulously planned and assessed to align with principal directions [6],[7].

Apart from the commercial 3D printing software, path planning algorithms for enhanced strength-to-weight ratio, has been a rising research area. Steuben et al. [8] studied generation of the level-set infill paths based on the von Mises stress field, which led to uneven spacing due to the irregular stress field. Tam and Mueller [9] introduced stress-aligning additive manufacturing for two-manifold structures. A greedy tracing algorithm was put forth [10] to enhance mechanical properties by following the load transmission path during FRP printing. Furthermore, Fang et al. [11] suggested reinforced fused deposition modeling for multi-axis printing of freeform components, leading to improved load-bearing performance. Although these methods have shown promising progress in fortifying 3D-printed parts, they all had certain limitations. Specifically, aligning the filament with the principal direction was found to be effective in enhancing the mechanical strength of specific local areas. However, it could lead to irregular material deposition with voids and overlaps between neighboring filaments, potentially undermining the overall mechanical behavior.

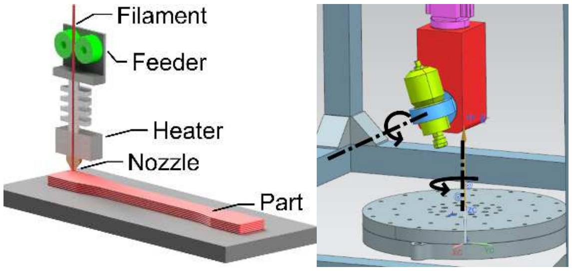
Essentially, there exists a trade-off between aligning paths with principal directions and maintaining consistent path intervals, as most principal directions induced by external loading are irregularly distributed, with non-zero divergence and rotation. Prior path planning methods, whether employing local or global optimization, were theoretically unable to simultaneously meet both requirements due to this inherent contradiction.

In this study, the effects of process parameters, namely the layer thickness and step over distance, on the quality of non-planar printing of PLA, are discussed.

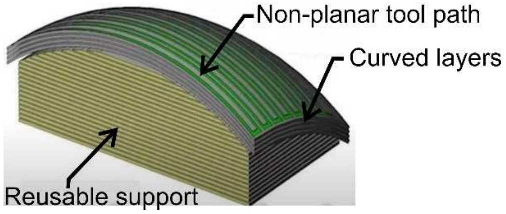
Henceforth, the manuscript is organized as follows; the fused deposition modelling (FDM) process is explained together with process parameters and tool path planning approach, in Section 2. Later, the experimental setup and design of experiments are explained in Section 3. The manuscript is finalized with the discussion of experimental results and conclusions in Section 4 and Section 5, respectively.

2. FDM BASED NON-PLANAR PRINTING

Contrary to the conventional layer-by-layer 3D printing, multi-axis non-planar printing (see Fig. 1) offers several advantages. In this section, this concept is explained together with the FDM process and the machine layout.



(a) FDM process. (b) Multi-axis printing.



(c) Non-planar printing concept.

Fig. 1. Illustration of multi-axis FDM process.

FDM process involves the material to be extruded through a nozzle after heated up to the melting temperature. Then, the nozzle, presses the extruded material towards the bed along the tool path as illustrated in Fig. 1a. In multi-axis printing, the machine layout has additional rotary axes as shown in Fig. 1b. Thus, the extrusion can be performed along any vector direction, enabling curved layer control once there is a reusable support, i.e., mold, underneath as illustrated in Fig. 1c.

2.1. Process geometry and parameters

Deposition of a single layer requires the extruded filament to be placed along a non-planar tool path (see Fig. 1c), where step over and layer thickness are the two major parameters to generate the tool path. As the extruded material is in melt phase, the gaps and overlaps between the consecutive beads and the amount of compression between the layers, affect the sticking of the deposited beads during the solidification phase.

As illustrated in Fig. 2a, the gap and overlap between consecutive beads depend on the side step, s, whereas the compression depends on the layer thickness, t, left to the upper layer. Hence, layer thickness and sidestep are critical parameters for the visual and mechanical quality of the part.

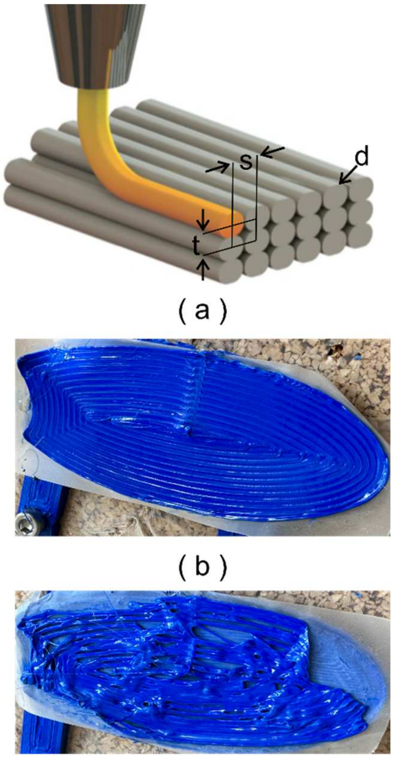


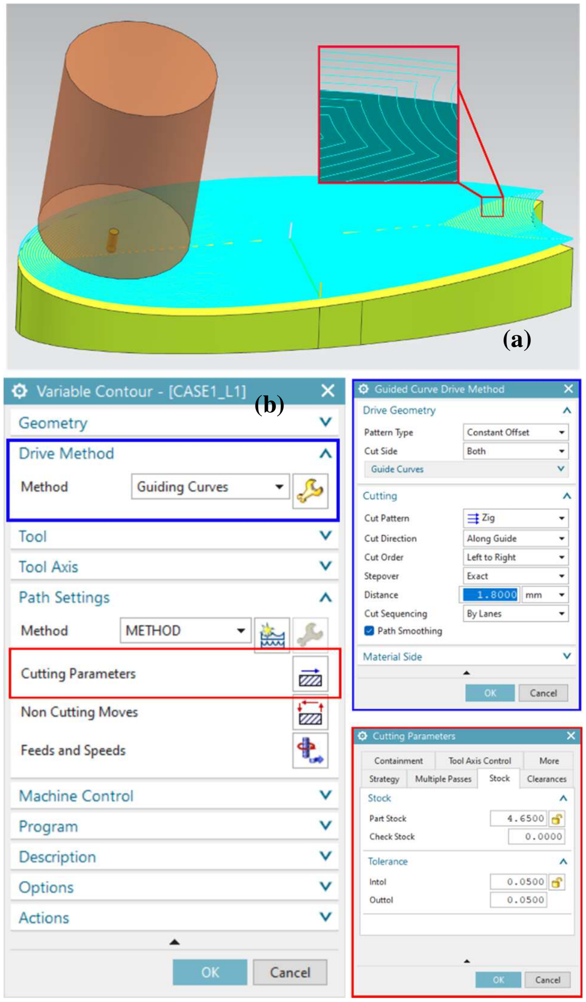
Fig. 2. Fundamental process parameters in FDM. (a) layer thickness, sidestep and filament diameter, (b) appropriate deposition with 75% sidestep (c) inappropriate deposition with 25% sidestep.

A representative example to show the effect of sidestep on the printing quality is given in **Fig. 2**b, where two identical layers are deposited with appropriate and extremely inappropriate sidestep values. It is clearly seen that sidestep is a crucial parameter in FDM.

2.2. Tool path planning and generation

Most of the commercially available 3D printing software platforms do not support non-planar printing. In this regard, tool path planning and generation is required to achieve desired material deposition in non-planar printing. In this study, Siemens NX © multi-axis surface milling operations was used to define the tool path accordingly. A representative tool path and corresponding operation is given in Fig. **3**.

As illustrated in Fig. 3a, tool path planning for non-planar printing is treated as multi-layer surface machining. However, there are two major considerations as listed below.



Method Guiding Curves
Method METHOD
Pattern Type Constant Offset
Cut Side Both
Cut Pattern Zig
Cut Direction Along Guide
Cut Order Left to Right
Stepover Exact
Distance 1.8000 mm
Cut Sequencing By Lanes
☑ Path Smoothing
Part Stock 4.6500
Check Stock 0.0000
Intol 0.0500
Outtol 0.0500

Fig. 3. Tool path planning in Siemens NX ©.

- The tool path layers are sorted in reverse order. In other words, the tool path layer closest to the mold surface is complete first.
- At each layer, a different tool path pattern is used to create a mesh filament beads in order to cover several loading directions.

3. EXPERIMENTS

As part of this study, FDM deposition experiments were performed on a 5-axis printer manufactured by 5axismaker©, where experimental parameters were decided according to orthogonal design of experiments as discussed in this section.

3.1. Experimental setup

In the 5-axis 3D printing system, the FDM nozzle is attached on a spindle with a rotary axis, i.e. A-axis, where the other rotary axis is on the table, i.e., C-axis. The spindle carrying the FDM nozzle can linearly move along X, Y, and Z axis. (Figure 4). The support structure, required to perform non-planar lay up of the extruded filament, is 3D printed on the same machine.

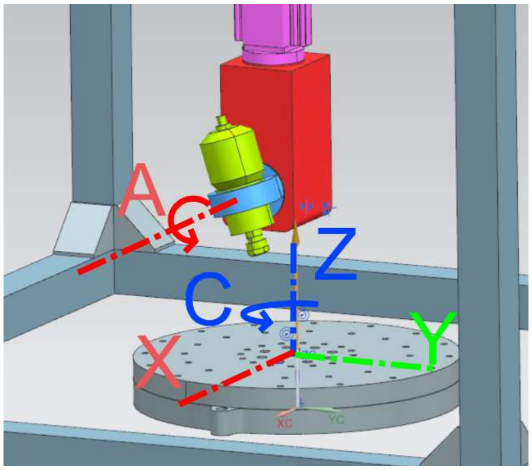


Fig. 4. 5-axis printing machine configuration.

3.2. Design of experiments

In the experiments, the layer thickness (t) and step over (d) varied non-dimensionally as the percentage of the extruded filament diameter which is 1.8 mm.

The levels of the two process parameters are given in *Table 1*, where it is shown that layer thickness varies from 25% to 75% of the filament diameter, whereas step over varies from 25% to 100%.

Table 1

Levels of process parameters for design of experiments

Layer, t	**mm**	**Side, s**	**mm**
25%	0.45	25%	0.45
50%	0.90	50%	0.90
60%	1.08	80%	1.44
35%	0.63	90%	1.62
75%	1.35	100%	1.80

Based on the identified levels of the process parameters, the orthogonal design of experiments is performed, where one parameter is varied at once.

The created cases together with the comments are shown in Table *2*.

Table 2

Experimental cases and relevant comments

Case #	**Layer, t (mm)**	**Side, s (mm)**	**Comment**
Case 1	0.45	1.80	
Case 2	0.90	1.80	
Case 3	1.35	1.80	No Sticking
Case 4	1.08	1.80	
Case 5	0.63	1.80	
Case 6	0.90	1.44	
Case 7	0.90	0.90	Material accumulation due to sidestep push.
Case 8	1.08	0.90	
Case 9	0.90	1.62	

The cases are grouped into two as G1:[Case 1 to Case 5] and G2: [Case 7, Case 6, Case 9 and Case 2] in order to observe the effect of layer thickness and sidestep, respectively.

3.3. Experimental results

As a result of experimental trials, in three of the cases, namely Case 3, Case 7 and Case 8, non-planar printing was inappropriate. In Case 3, the layer thickness value was too high that sticking between filament layers was not possible.

In Case 7 and Case 8, the sidestep value was too small that material accumulation was observed due to pushing of the nozzle on the extruded filament. In this regard, it can be said that sidestep values less than 50% of the extruded filament diameter are not physically feasible. As sticking of layers is of great importance, it can be said that layer thickness values high than the 75% of the extrusion diameter are now physically feasible.

The printing quality of all the cases are compared in Fig. **5**. Case 3 given in Fig. **5**d clearly shows that increasing the layer thickness more than the half of the extrusion diameter prevents the printed layer bonding to the previous layer, beneath. Whereas the photos of Case 7 and Case 8 in Fig. **5**g and Fig. **5**h, show that although the layer bonds to the previous layer, there is too much of material pushed due to sidestep equal to 50% of the extrusion diameter.

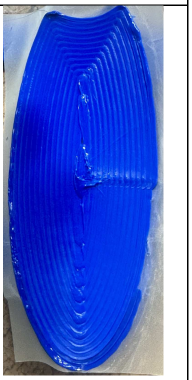
 (a) Case 1 s=1.80mm t=0.45mm	 (b) Case 5 s=1.80mm t=0.63mm	 (c) Case 2 s=1.80mm t=0.90mm
 (e) Case 4 s=1.80mm t=1.08mm	 (d) Case 3 s=1.80mm t=1.35mm	 (f) Case 6 s=0.90mm t=1.44mm
 (g) Case 7 s=0.90mm t=0.90mm	 (h) Case 8 s=1.08mm t=0.90mm	 (i) Case 9 s=0.90mm t=1.62mm

Fig. 5. Comparison of printing quality.

As Case 1, Case 5, Case 2 and Case 4 are progressively observed, acceptable printing quality is seen. However, in Case 4, the layer sticking seems to be deteriorated if the gaps between extrusion beads are noticed.

Comparison of Case 7, Case 6, Case 9 and Case 2 shows that sidestep values larger than 50% of the extrusion diameter results in acceptable quality in printing. However, as the sidestep is decreased to 50%, i.e. 0.90 mm, the printing quality is not acceptable.

4. CONCLUSIONS

In this study, the effects of the two critical parameters, i.e. layer thickness and side step, on the quality of non-planar 3D printing are discussed. The comparisons are performed virtually. It can be concluded that especially sidestep, i.e. the distance between filament beads, should be higher than 50% of the extrusion diameter.

Whereas the layer thickness should be preferably between 50% and 75% of the extrusion diameter. In this regard, in order to achieve acceptable printing quality, the sidestep value is suggested to be larger than 50% of the bead diameter, and the layer thickness is suggested to be less than 75% of the bead diameter. The analysis of variation of the mechanical performance with printing parameters stands as the future and important work to complete.

5. ACKNOWLEDGEMENTS

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EFECTELE PARAMETRILOR DE PROCES ASUPRA CALITĂȚII ÎN IMPRIMAREA 5-AXE NON-PLANARĂ A SUPRAFEȚELOR DE FORMĂ LIBERĂ

Rezumat: Fabricația aditivă a structurilor compozite a fost o zonă importantă de cercetare și aplicație pentru reducerea greutății. În opoziție față de abordarea strat cu strat, imprimarea direcțională non-planară oferă o utilizare mai bună a rezistenței materialului în funcție de condițiile de încărcare. Ca în cazul tuturor proceselor de fabricație, parametrii au efecte semnificative asupra calității produsului și, prin urmare, asupra performanței mecanice. În acest studiu, se discută efectele parametrilor de imprimare, cum ar fi grosimea stratului și distanța laterală, adică distanța dintre straturi, în ceea ce privește calitatea vizuală a pieselor tridimensionale. Se folosește abordarea de proiectare a experimentelor pentru a identifica nivelul parametrilor de proces; traseul sculei este generat și planificat folosind operațiunile de prelucrare a suprafeței încorporate în Siemens NX.

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