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Influence of Fill Gap on Flexural Strength of Parts Fabricated by Curved Layer Fused Deposition Modeling

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Abstract

Rapid Prototyping Techniques (RPT) have evolved over the last decade. Novel RP techniques are being developed to improve the overall properties of parts manufactured using RPT. One such technique is the Curved layer fused deposition modeling (CLFDM) which has been developed based on the conventional Fused Deposition Modeling (FDM) technique. The CLFDM technique has gained significant amount of attention as a result of its advantages such as increased flexural strength, reduction of the stair-stepping effect and the reduction in the number of layers, especially for thin shell-like structures. This paper studies the effects of fill gap (FG) on flexural strength and bead dimension, middle-plane cross section profiles and the fracture surface and compares the results to parts made using the traditional planar layer-by-layer approach. Also, in the end some meaningful and interesting future study areas both in hardware design and software development for the CLFDM are proposed.

Keywords: Fill gap, Flexural strength, microscopic structure, CLFDM

1. Introduction

Parameter optimization for rapid prototyping has been reported by many for traditional planar layer FDM, such as layer thickness, fill gap, road width and nozzle temperature [1, 2]. In order to improve the mechanical property and

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surface finish of the printed parts, parameter optimization has its significance. However, there is a limited amount of research on Curved layer fused deposition modeling (CLFDM). Klosterman [3] has successfully applied a similar technique using laminated object manufacturing (LOM) and demonstrated that this fabrication process could eliminate the staircase effect, reduce waste, maintain a continuous fiber composite and reduce building time. Chakraborty [4], in theory, developed extruder path generation algorithm for CLFDM and compared some examples with those being sliced by traditional layer FDM. Singamneni [5] reported a new CLFDM path generating algorithm and then illustrated that parts made with CLFDM could withstand much greater overall forces than parts fabricated by traditional layered FDM because of the structural integrity of fibers incorporated into CLFDM. Huang [6] developed a mixed-layer approach combining CLFDM and traditional layered FDM to slice the object with STL format files to generate tool paths. Results showed a better surface and internal meso-structure. However, printing parameters during fabrication are also important for CLFDM since they could affect the mechanical properties, especially the fill gap which is directly related with the bond area between each filament within intra-layer. In this article, the mechanical property of parts printed with different fill gap ranging from 0.5mm to 1.1mm with increase of 0.2mm are compared. The parts were fabricated using two kinds of approaches, traditional planar layer FDM and CLFDM. Also in the later section, the middle plane microstructure of each samples are presented.

2. Experiment design

2.1. Sample dimension

The sample dimension chosen could also be referred in previous works by Huang, B. [7], however as a result of the jig and fixture requirement an additional 10mm for the length of the samples was included, hence the length changed from 50mm to 60mm.

![Fig. 1. Sample dimension (mm)](image)

2.2. Printing parameter setting

The printing temperature chosen was 230°C. Five specimens for each sample are fabricated. Parameters for both the planar layered FDM and curved layer FDM are the same as listed below in Table 1:

| Approaches       | Fill Gap (mm) | Filament Dia. (mm) | Nozzle Dia.(mm) | Layer Thickness (mm) |
|------------------|---------------|--------------------|-----------------|----------------------|
| Planar layer FDM | 0.5, 0.7, 0.9, 1.1 mm | 1.75               | 1               | 1                    |
| CLFDM            | 0.5, 0.7, 0.9, 1.1 mm | 1.75               | 1               | 1                    |
2.3. Three point bending test

An INSTRON 5566 material testing equipment was used to do a three point bending test. Five samples were tested for each parameter and the loading speed was set at 5mm/sec based preliminary trials and the ISO 1209.

2.4. Microscopic structure measurement equipment

A Leica stereomicroscope system was used to view the microscopic structure (center of the part), which showed the filaments laid down by the process and the bonding between these filaments. Figs 4&5 illustrate the measurements taken of the length and width of the beads to get some comparative values.

3. Results and discussion

3.1. Part Dimensions and bead width and length studies

Fig.2 illustrates that the sample width of the parts built by CLFDM are between 0.23 - 0.67 mm narrower in width than that built using traditional layer-by-layer FDM. This could be explained by the fact that the bead width of each of the filaments is approximately 12.6% thinner in width if processed using the CLFDM (as shown in Fig.3). The bead width of these filaments are less than those processed by conventional layer-by-layer FDM possibly because during the deposition process the filament is experiencing gravitational forces, both in the tangential (Ft) and normal (Fn) direction as suppose to a single force (Fn) experienced by the conventional layer-by-layer FDM process (as shown in Fig. 4 and Fig. 5). As a result each element of the filament is experiencing an additional force (Ft) generated by the previous element.
On the other hand, Fig. 6 illustrates that the sample length is relatively uniform for parts built by both the techniques and Fig. 7 shows the relationship of bead length and different fill gaps. In the curved layer samples an increase in the fill gap allows the beads to spread into their natural oval shape since they are not constrained by the beads adjacent to it, as a result an increase in the fill gap causes an increase in the bead length. However, in the flat layer samples at a small fill gap the beads interfere with the beads adjacent to it as a result the beads deform as shown in Fig. 9. As the fill gap continues to increase the bead length become more regular and begins to stabilise at a fill gap of 0.9 mm (illustrated in Fig.9).

3.2. Three point bending test and microstructure studies

The three point bending test results shown in Fig. 8 illustrates that for the same fill gap, parts fabricated by CLFDM could withstand a force approximately 55% higher than that of parts made by conventional planar layer FDM. This is because CLFDM is capable of printing curved structures with continuous fibers while the principle of conventional FDM causes severe stress concentration at the transaction areas between curved features and planar features. This has been supported by previous works illustrated by Huang et al. [7]. In addition, Fig. 4 also illustrates that an increase in the fill gap results in the decrease of the flexural strength in both the CLFDM and planar layer FDM. This has been attributed to the decrease in the bond area between the filaments as the fill gap increases which can be supported by microstructural evidence shown in Fig. 9 and is particularly highlighted with fill gap of 1.1 mm for both CLFDM and conventional FDM.
Fig. 9 Microscopic structure of the centre of the parts: The left side column is of parts made by CLFDM and right side column is these made by conventional FDM, both column show parts of fill gap increasing from 0.5 mm to 1.1 mm with increase of 0.2 mm.
4. Conclusion and future study

In conclusion, the fill gap effect to the flexural strength of samples fabricated in two ways have been reported, one is traditional planar layer FDM and another is CLFDM. Results showed that CLFDM has its advantages over traditional planar layer FDM because of continuousness of fibers made by CLFDM. Also, with the increase of fill gap, the flexural strength of parts decreased since the bond area of each filament decreased shown by the microscopic structure. Another phenomenon is that for bead length, it is longer for CLFDM than conventional FDM since the principle shown in Fig. 4 & Fig. 5. Thus, it would be ideal to design 5-axis printer so that axis of the nozzle will be perpendicular to the normal vector of the printed surface, which will reduce the gravitational effect in Fig. 4. and lead to much more accurate sample dimension. Also some new kinds of curved slicing algorithm will be developed later. For example, when offsetting the boundary after importing the STL file, it could be offset along with the normal direction of the patch.

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Appendix A. Equipment for three point bending and measurement of microstructure

A.1. Three point bending test process
A.2. Leica stereomicroscope system

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