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Mechanical strength of chunk-based printed parts for cooperative 3D printing

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Abstract

Cooperative 3D printing is an emerging technology that envisions a large number of mobile 3D printing robots working cooperatively to finish a print job. To support the cooperative 3D printing, we have developed a chunk-based printing approach. In chunk-based printing, the workpiece is first divided into small chunks and then the chunks are allocated to an army of robots for printing. Although the chunk-based printing has demonstrated its capability in speeding up the printing process and scaling up the printing size, the bond strength at chunk joint is still unclear. The lack of this knowledge limits the potentials of the chunk-based printing. To this end, we assess the tensile strength of chunk-printed parts and compare their strength against those normally printed by traditional layer-based 3D printing. We first identify the parameters associated with chunk-based printing, such as the chunk slope angle and the chunk overlapping depth, which can directly influence the bond strength. Then, the design of experiment is performed based on different combinations of these parameters. Based on the experimental results, we conclude that the existence of chunk joint will not weaken the strength for the chunk-based printed parts under the proper selection of chunk-based printing parameters. The results therefore prove the validity of the chunk-based printing and provides the fundamental knowledge support for the chunk-based cooperative 3D printing of the future.

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Keywords: Cooperative 3D printing; chunk-based printing; tensile strength; swarm robotics

1. Introduction

Fused Deposition Modelling (FDM) has grown into one of the most popular 3D printing methods over the past decades due to its ease of use as it allows fabrication of complicated 3D structures without need for special manufacturing skills, tooling and/or resources. RepRap community provides great support

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by providing open design platform for both hardware and software development that has driven down the cost of 3D printing and impelled the development further. Gone are the days when the use of FDM was limited for Rapid Prototyping (RP). In the past few years, the focus has been shifting to push the technological development towards the manufacturing sector. Significant efforts are being made in order to improve the quality of the finished part to resemble manufacturing production-grade [1]. However, even with all the endeavours, two holdbacks remain: a) the low printing speed, and 2) the limited printing size. Cooperative 3D printing is an emerging technology that holds the potential to address both limitations by enabling many mobile 3D printers working together to print cooperatively on a factory floor.

In our previous study [2], we have successfully developed a 3D printing robot by integrating the FDM technique into the mobile robotics. To enable cooperative 3D printing, we developed a novel chunk-based 3D printing strategy, which allows multiple mobile 3D printers to work together by printing one "chunk" of the object at a time for accomplishing the entire object, as illustrated in Fig.1. In chunk-based 3D printing, a chunker software first divides the CAD model of the object into many small chunks. Then, the chunks are sent to a slicer software, which generates the G-code commands that define the tool path, the printing sequence, the material extrusion, and the transitions between chunks for every robot [2]. Each of the mobile robot is then capable of extruding the material as commanded by the generated G-code to finish the entire object chunk by chunk. With such a chunk-based printing strategy, a large part can be divided into smaller chunks and those chunks can be printed simultaneously by multiple mobile printing robots, therefore can significantly shorten the overall printing time.

Despite the great potential of the chunk-based printing, one of the major concerns is the bond strength between the chunks. It is crucial to understand how the bond strength of the chunk joints affect the overall strength of the chunk-based printed parts, and how it compares to the "standard single-piece FDM parts" which are realized by traditional layer-based 3D printing without chunks.

In the existing literature, many studies were reported on the strength of the FDM 3D printed parts and their anisotropic behaviour using the traditional layer-based 3D printing. For example, Ahn et al. performed a seminal study on the relationship between the strength and anisotropic behaviour of the FDM part and various build parameters, such as air gap, raster orientation, bead width and, model temperature [3]. Rezayat et al. investigated the contribution of the infill materials to bear the load of the part and concluded that the infill materials do not contribute as much to the strength of the part as the perimeter materials based on a multiscale study [4]. Similarly, J. Chacon et al. conducted a study to characterize the effect of feed rate and layer thickness along with build orientation on mechanical strength [5]. They concluded that ductility of a part decreases as layer thickness and feed rate increases whereas, the mechanical properties get better as layer thickness increases but decreases with increase in feed rate. H. Kim et al. studied the impact of the bond strength at the interface between two different materials (ABS and PLA in this case) on the overall strength of a part printed with dual materials [6]. In their study, it was

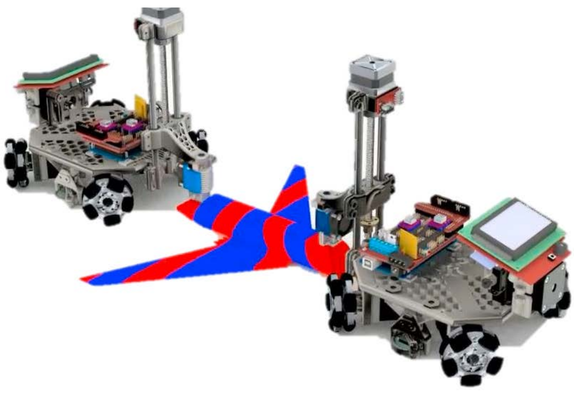

Fig. 1 Chunk-based cooperative 3D printing. Two mobile printers are working together to print an airplane model. The chunks are separated by the alternating blue and red colours.

observed that there were voids and overlaps between the two-materials printed in vertical layers. It was concluded that such defects may affect the adhesion between two materials and weaken the part. They also concluded that adding vertical layers to a part might not be effective because of the defect mentioned earlier whereas adding horizontal layers improved the mechanical properties of the FDM part. D. Espalin et al. conducted similar studies using multi-material extrusion using two different FDM printers [7]. In their study, raster beads were printed using one printer with one type of material and the contours were printed using second FDM printer with different material. Along with this, they also ran some experiments with different material per layer, similar to the studies done by Kim et al. In the study, they concluded that the multi-material FDM part exhibits similar tensile properties as standard FDM part. They did, however, find that there is improvement in surface roughness of finished part using coarser infill but finer contours. They also concluded in the study that using two FDM printers instead of one, reduces the total print time by more than half. Both the multi-material FDM studies discussed above may seem similar to the chunk-based printing at first glance but are fundamentally different. Multi-material FDM is accomplished using traditional layer-based printing unlike chunk-based printing. Additionally, the tensile loading is in perpendicular direction to the multi-material printing whereas in chunk-based printing, it is in the same direction as the adhesion between the chunks. While these studies are helpful in understanding how the build parameters in the traditional layer-based 3D printing influence the mechanical strength of the printed part, little is known on how the chunk-based build parameters would impact the bond strength between chunks and the mechanical strength of the chunk-based 3D printed parts.

In this paper, we fill this knowledge gap by comparing the strength of the chunk-based printed parts against the standard FDM parts. We first identify the chunk-based printing parameters that can directly influence the bond strength between chunks, such as the chunk slope angle, the chunk overlapping depth, and the number of perimeter shells. We then conducted design of experiment to understand how various combinations of those identified parameters would affect the tensile strength of the printed parts. It however needs to be clarified that it is out of the scope of this paper to analyse the change in underlying material properties such as local properties at different location due to the changes of the printing parameters.

This paper is organized as follows. In Section 2, the chunk-based build parameters are discussed and differentiated from layer-based parameters. The experimental setup and methodology are presented in Section 3. The experimental results are discussed in Section 4. In Section 5, the conclusions are drawn, and the closing thoughts and future work presented.

2. Chunk-based printing parameters

Compared to the traditional layer-based 3D printing, chunk-based printing first divides the digital model into many small chunks interfaced by a sloped chunking plane to allow bonding between chunks as shown in Fig. 2. Each chunk is then sliced into layers for printing. Therefore, the overall strength of chunk-based 3D printed part will be influenced by both the traditional layer-based printing parameters and the additional chunk-based printing parameters. Based on whether or not the parameters have direct impact on the bond strength between chunks, they can be categorized in two groups: a) *Direct parameters*, and b) *Indirect parameters*. In this section, we summarize

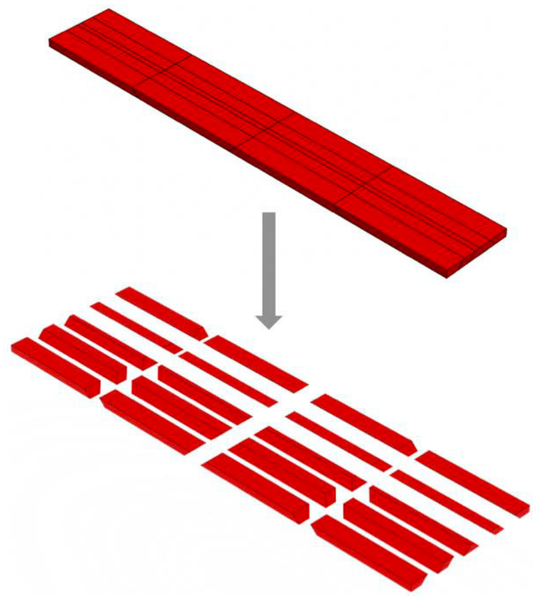

Fig. 2 Top: Part showing outline of chunks Bottom: Exploded view of the chunks that were outlined in top image.

both direct and indirect parameters that are considered and tested in this study.

2.1. Direct parameters

In this paper, three parameters are identified to be directly influential to the strength of the chunk-based printed parts.

1. **Chunk slope angle:** Considering the characteristics of the FDM process, the chunks are not divided by a vertical plane, but a sloped plane, as illustrated in Fig. 3, such that the printhead can deposit materials on the chunking plane to facilitate the bonding between chunks. Therefore, the slope angle of the chunking plane will have direct impact on the bonding strength between chunks.
2. **Chunk overlapping:** In the same way that FDM overlaps the filament to increase the infill density of the print, the chunks can also be slightly overlapped to improve bonding strength as illustrated in Fig. 4. If the chunks are printed exactly along the chunking plane, the overlapping is zero. A positive overlapping means more materials are squeezed into the chunking plane and will make the contact area between chunks denser. A negative overlapping indicates the chunks are not in contact with one another.
3. **Number of perimeter shells**: As indicated by Rezayat et al. in their study, the perimeter shells carry much more load and contributes much more to the strength of the printed part than the infill materials in the traditional layer-based FDM printing [4]. Therefore, the presence or absence of a perimeter shell at the chunking plane could significantly impact the bond strength between the chunks. As illustrated in Fig. 5, the presence of a perimeter (Fig. 5(b)) results in uniform contact between the chunks, whereas the absence of it (Fig. 5(a)) creates voids and overlaps in the interface, thus adding additional uncertainties to the strength of chunk-based printed parts.

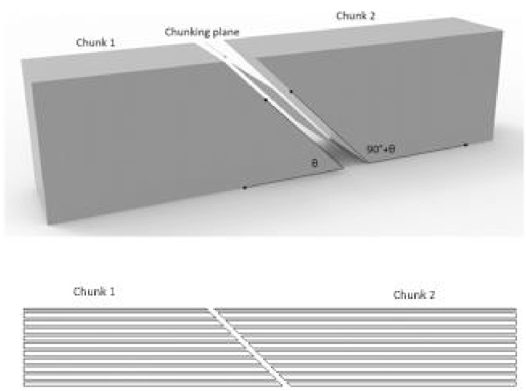

Fig. 4 Illustration of the chunking plane between two chunks (top) and representation of slicing done to the chunks above (bottom)

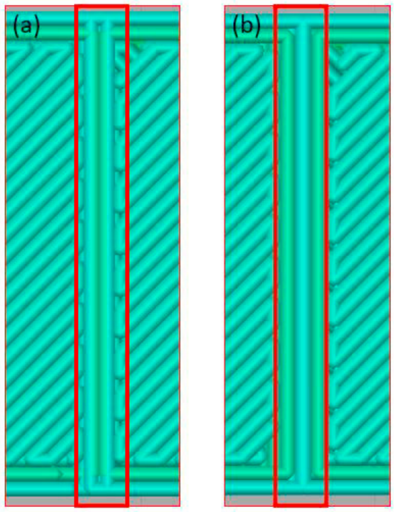

Fig. 3 Illustration of chunk overlapping; (a) overlapping of 0.3mm; (b) 0 mm overlapping

2.2. Indirect parameters

Other than the identified parameters that are directly related to the chunk bond, the traditional layer-based printing parameters, such as raster orientation, infill density, air gap, bead width, print temperature, etc., also influence the overall strength of the chunk-based 3D printed parts. The most important indirect parameters are listed below.

1. **Raster orientation:** Raster orientation is the angle orientation of road or bead compared to the tensile loading. The default setting of 45°/-45° was used for this experiment. Raster orientation of 90° has the lowest tensile strength and 0° has the highest one [3].
2. **Infill density:** Infill rate is the percentage of material inside the part. Higher the infill density is, more material inside the part. This makes a part stronger and sturdier. On the

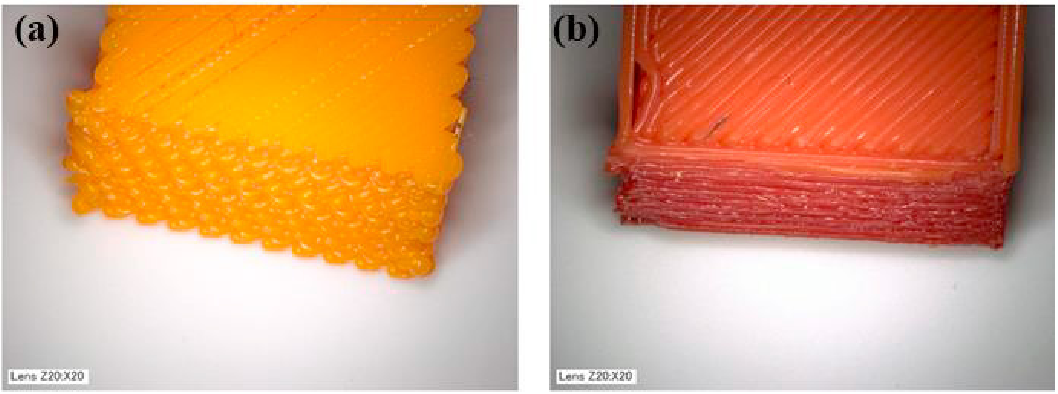

Fig. 5 Illustration of the perimeter shells; (a) with no shell; (b) two shells at chunk bond surface

other hand, lower infill density results in parts that are more fragile, but printing time is shorter. 100% infill rate is used as default for all the samples in this study.

3. **Air Gap:** Air gap is the distance between two beads in traditional layer-based printing. Increasing the air gap weakens the part because it creates spaces between the beads. On the other hand, using negative air gap, enhances the strength of the parts as it makes the structure denser**.** The default value used in this study is zero.

Indirect parameters and their impact on tensile strength of traditional layer-based part has been thoroughly studied in existing literatures and it is assumed that those parameters will have similar impact on the tensile strength of chunk-based 3D printed parts. Therefore, the main focus of this paper will be on the effects of the direct parameters on the overall strength of the chunk-based parts and the indirect parameters are kept constant.

Prior to the experiment, the following hypothesis were postulated about the relationship between each of the direct parameters and the tensile strength

1. *The lower the slope angle, higher is the tensile strength between the chunks.* Lower slope angle means larger contact area for the same thickness of chunks. This could result in higher tensile strength. Thus, it is predicted that the chunks with 30° slope will have stronger tensile strength than that with 50° slope.
2. *Absence of perimeter shells in bond area makes a chunk-based part stronger.* Presence of shells imitates behaviour similar to 90° raster orientations between the infill raster and the boundary. Existing study [3] has shown that 90° raster orientations lead to weaker tensile strength. So, it is predicted to have stronger bond between the chunks that are printed without perimeter shells.
3. *Higher the overlapping between the chunks, higher is the tensile strength.* More overlapping implies more materials from two chunks are fused together. Therefore, it is expected that lager overlapping will produce a stronger bond between chunks as compared to smaller overlapping.

3. Experimental setup and methodology

In order to assess the impact of the direct parameters on the bond strength, three steps are required. First, the specimen needs to be fabricated. Second, a systematic design of experiment is necessary. Third, the tensile tests need to be conducted on the fabricated specimens. In this section, we describe the three steps in sequence.

3.1 Specimen Fabrication by Chunk-based Printing

Although chunk-based 3D printing is originally developed for cooperative 3D printing with mobile 3D printers, it can be applied to existing FDM 3D printers because the depositing process for both techniques are the same. Since the mobile 3D printers are still under development and their reliability and consistency are not sufficient for the purpose of this study, we use a commercially available Ultimaker 3D printer to print the specimen chunk by chunk. To achieve this, the printing path needs to be altered so that the resulting paths mimic the printing process of two robots. In this study, the slicing software, Simplify3D, is used to generate the printing paths slicing the chunks and generate the corresponding G-code.

A test coupon (Fig. 6) is first designed according to ASTM D638 Type I Standard [8] using SolidWorks. The test coupon is then divided into two equal chunks with specified chunking parameters (e.g., slope angle, location of the chunking plane, etc.). The G-code are then manipulated such that Ultimaker prints the left chunk first with a sloped chunking plane at the end, and then print the right chunk as shown in Fig. 7. The printing parameters are listed in Table 1.

Table 1. Printing parameters for fabrication of the samples

Printing Parameters	Values
Filament material	PLA
Printhead temperature	215 ° C
Print bed temperature	80° C
Nozzle diameter	0.4 mm
First layer thickness	0.26 mm
Subsequent layer thickness	0.2 mm
Printing speed	28 mm/s
Infill printing speed	42 mm/s
Raster angle	45/-45°
Infill density	100%
Air gap	0 mm

3.2 Design of Experiment

To study the impact of the direct parameters on the strength of the chunk-based 3D printed parts, we need to properly define the range of the parameters for the samples to be fabricated and tested. Preliminary tests were conducted to investigate the correlation between the direct parameters and tensile strength. These tests were done by altering one variable at a time while keeping the rest of them constant.

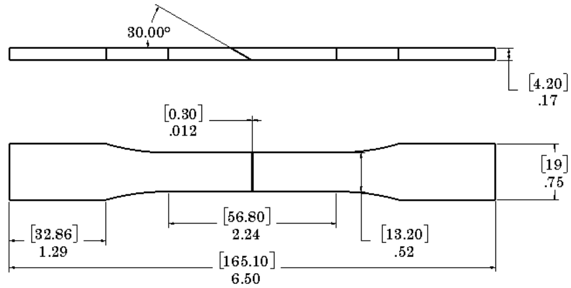

Fig. 6 Sample geometry with chunk overlapping of 0.3mm and 30° slope angle

The two values used for slope angles are 30° and 50°. We could not find nozzles on the market that can print on slope angle larger than 50°, thereby this angle is set as the upper bound. Any slope angle below 30° limits the height of the chunk, so they are ignored [2]. Chunk overlapping of 0.3mm and 0.5mm are selected. The reason for choosing 0.3mm is that this value is equal to the width of a single “raster”. To understand whether the presence of shells would affect the strength, 0 and 2 shells were chosen, 2 being default setting with perimeter shells and 0 being absence of shell altogether. Table 2 summarizes the all the design variables and the ones chosen for the experiment.

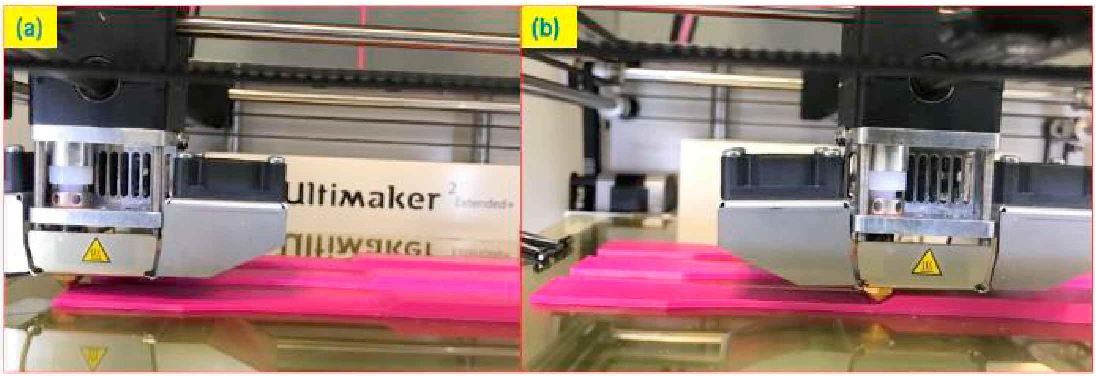

Fig. 7 Chunk-based printing using Ultimaker 3D. The printer completes the right chunk first and then starts printing the left chunk

Table 2. Range of Direct Parameters

Variable	Abbreviation	Low level	High level
Chunk Slope Angle (°)	SA	30	50
Chunk Overlapping (mm)	CO	0.3	0.5
Number of shells (#)	NS	0	2

In order to maximize the test coverage, orthogonal arrays are created. Three parameters with two level of values provide eight different specimens. The orthogonal arrays of 8 specimen variations are provided in Table 3. Columns 2 – 4 represent test levels of the factor. Each of the row represents the test runs. The table is used as the plan for multifactorial experiments to detect the effects of various direct parameters on the tensile strength. Five samples are printed for each combination and five tests are performed, respectively, as per ASTM testing standard.

Table 3. Design of experiments for the three direct parameters

Specimen index	Chunk Angle (SA)	Chunk Overlapping (CO)	No. of Shells (NS)
1	Low	Low	High
2	Low	High	Low
3	Low	High	High
4	Low	Low	Low
5	High	High	High
6	High	High	Low
7	High	Low	High
8	High	Low	Low

3.3 Testing Setup

The tensile test is conducted on MTS® with MTS microcontroller®. A 5 kN loadcell is used to load the samples in tension. The samples are loaded at the rate of 2mm/min, and each sample is loaded until the failure occurs. Ultimate tensile strength is chosen as the measure of mechanical properties. In the test, all the failures take place at the chunk joint, so we are assured that the test results measure the strength of the chunk joint. The macroscopic view of the failure along with samples is shown in Fig. 8.

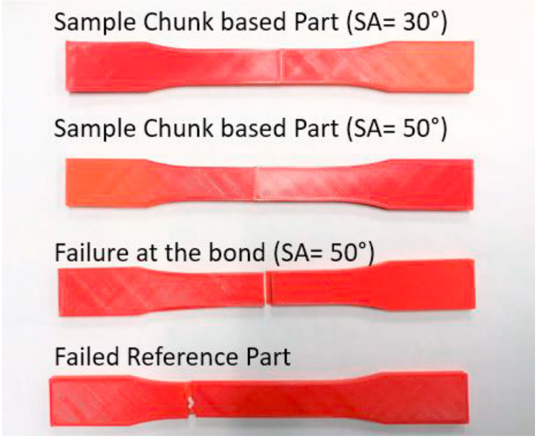

Fig. 8 Test specimens

4. Results and discussion

4.1 The Effect of Chunk Angle

The results of the tensile test for three different slope angles (30°, 45°, and 50°) is plotted in Fig. 9. Since two points (30° and 50°) are not sufficient to express the functional relationship between the angle and the tensile strength, we have added another data point (45°) to the graph. Five iterations of printing and testing were done for each slope angle. The other two parameters are controlled, and all the samples have two perimeter shells and 0.3mm chunk overlapping depth. For the indirect parameter settings, the samples have 100% infill, 45°/-45° raster angle with no air gap between the beads. The results indicate that the chunk bond with slope angle of 30° fails at the average tensile

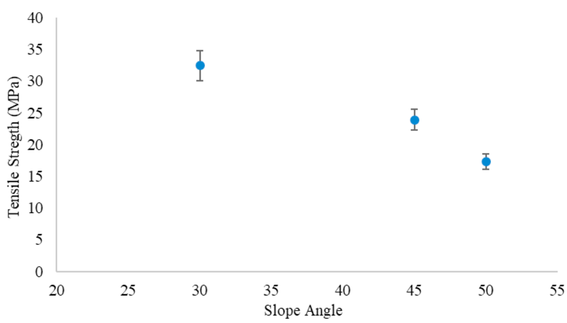

Fig. 9 Tensile strength of specimen with different chunk slope Angle

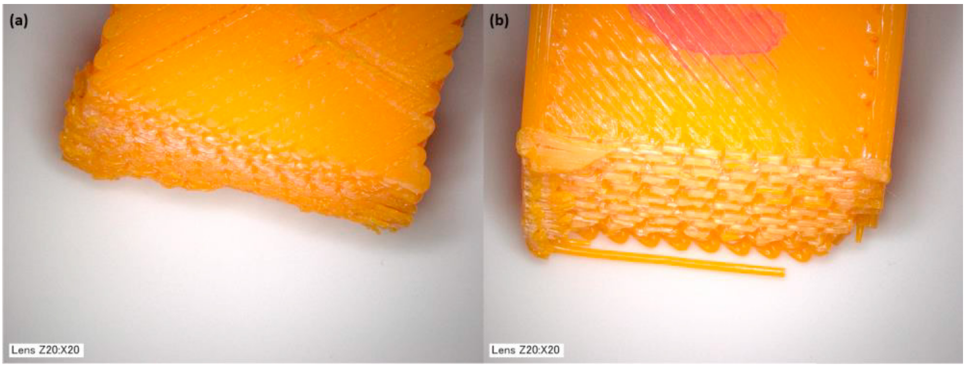

Fig. 10 The failure occurred at the chunk joint. (a) Chunk printed without shells around contact area (b) Chunk printed with two shells around contact area

strength of 32.42 MPa and the strength decreases as the slope angle increases. The strength of the samples with 30° chunk slope is about twice as much stronger as the one with 50°. This trend could be explained by the possible increase or decrease in bonding area due to change in slope angle. As a result of smaller chunk angle, the length of slope increases which in turn leads to larger overall bonding area. Larger bonding area results in increase in number of bond formed between two chunks making the part stronger. Similarly, increase in chunk angle results in a reduction of length of slope and thus the smaller bonding area. This leads to a decrease in number of bonds between the chunks, making the part weaker.

Table 4. t-Test result for chunks with different slope angles (30° vs. 50°)

t-test assuming unequal variances (Welch's t-test)	50° SA	30° SA
Mean	24.81	32.57
Variance	37.72	3.24
Observations	20	15
One-tail P-value	9.75e-06	
t Critical one-tail	1.71	

To validate the hypothesis proposed in Section 2, a Welch's two-sample t-test is performed on the chunks with 30° slope angle and the ones with 50°, as shown in Table 4. The one-tail P-value (<0.05) indicates the strength of the parts printed with 30° chunk slope angle is statistically significant higher than that with 50° chunk angle.

4.2 The Effect of the Number of Perimeter Shells

Upon closer inspection, the failure of parts with shells took place between the infill and the shells but not at the bond between two chunks (Fig. 10) essentially. This is because the shells are oriented at 90° with the loading direction, which decreases the strength in that region. One way to improve the strength is to increase the outline overlapping between the shell and infill so that a better contact between the infill and shell can be achieved. The default value used for all the experiment is zero.

The general data trend in Fig. 12 suggests that the chunk-based part without perimeter shells have tensile strength higher than the ones with two perimeter shells except for sample 4 (SA=30°, CO=0.3, NS=0). This anomaly is due to the fact that the bond between the chunks is not properly formed at the bottom of the specimen, as shown in Fig. 11. Even though the overlapping is set to 0.3mm, the chunks are not well bonded at the bottom as compared to the top surface. This reduction of effective contact area between chunks results in significantly lower tensile strength.

In order to better investigate the influence of shells

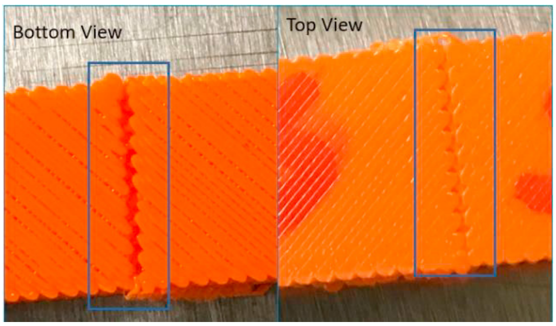

Fig. 11 The gap between two chunks on sample 4 at the bottom layer. The gap at the top layer is significantly smaller. This gap results in reduction of the effective contact between the chunks resulting in weaker chunk bond.

(absence or presence) on the tensile strength, a Welch's t-test is conducted as well. Due to anomalous behaviour of sample 4, it is treated as an outlier and is excluded for the hypothesis testing. The analysis of the t-test is provided in Table 5. The result shows that there is a statistically significant difference between the chunk-based part printed with shells and the ones printed without shells.

Table 5 t-Test result for absence/presence of perimeter shells in sample

t-test assuming unequal variances (Welch's t-test)	No Shells	2 Shells
Mean	31	25.99
Variance	11.88	47.23
Observations	15	20
One-tail P-value	0.004	
t Critical one-tail	1.70	

4.3 *The effect of chunk overlapping*

It is intuitive that the bond between chunks become stronger as chunk overlapping increases. Using the graph presented in Fig. 12 and Table 3, we can compare the strength of the chunk bonds based on the chunk overlapping keeping rest of the parameters constant. The general data trend in Fig. 12 shows that with the increase in overlapping, the strength of the chunk bond increases as well except in the case of sample 1 and sample 3. Both the samples 1 and 3 have other parameters constant (SA=30°, NS=2) the only change being the chunk overlapping. Sample 3 has 0.50 mm overlapping whereas, the sample 1 has 0.30 mm overlapping but the sample 1 shows higher tensile strength than that of sample 3. Even though the difference is smaller than 1 MPa (~0.6 MPa), it is contrary to the conclusion we derived. On the other hand, the rest of the samples (4 and 2, 7 and 5, 8 and 6) follow the conclusion obtained above. This leads us to believe that the samples 1 and 3 represent anomaly rather than the trend.

Table 6 t-Test result for chunk overlapping in sample

t-test assuming unequal variances (Welch's t-test)	.30mm	.50mm
Mean	22.75	31.22
Variance	41.22	8.41
Observations	20	20
One-tail P-value	6.23604E-06	
t Critical one-tail	1.71	

In order to confirm this, we ran a Welch's two sample t-test similar to the one we ran for other two parameters (i.e., the slope angle and the perimeter shells). The results are presented in the Table 6 and show that the strength of the parts with 0.30 mm overlapping is statistically significant different (p-value < 0.05) from the strength of the ones with 0.50 mm overlapping.

4.4 *Surface Failure*

From the tests, all samples without perimeter shells failed at the chunking surface (samples 2, 4, 6 and, 8). On the other hand, as mentioned earlier, the presence of shells resulted in failure at the transition between the shell and infill upon closer inspection. It can be observed that the failure in first case is due to the breaking of the filament. As shown in Fig. 10(a), a crack started at a weakest point at the bond but then propagated vertically upward breaking the filament rather than following the adhesion boundary between the chunks. On the other hand, the failure in latter case is due to the de-bonding between the rasters and shell, as shown in Fig. 10(b).

4.5 *Chunk-based Printing vs. Layer-based Printing*

Fig. 12 shows the results of the tensile test for the orthogonal arrays presented in Table 3. Each of the specimen have the same indirect parameters (100% infill, 45°/-45° orientation, no air gap). The reference or the control sample part is printed as a single piece without being divided into chunks. The tensile strength of the reference part is 28.23 MPa, as shown in Fig. 12. Specimen 1 (SA=30°, CO= 0.3mm, and NS=2), specimen 2 (SA= 30°, CO= 0.5mm, NS=0), specimen 3 (SA= 30°, CO= 0.5mm, NS=2), and specimen 6 (SA= 50°, CO= 0.5mm, NS=0) failed at

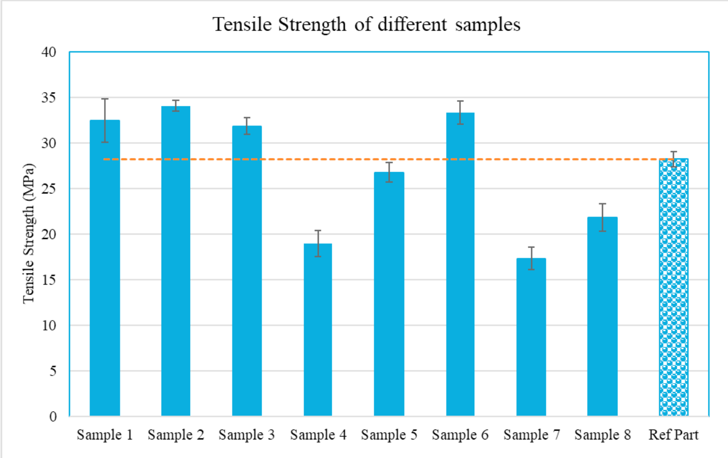

Fig. 12 Tensile strength (MPa) of the specimens printed with various combination of chunk-based parameters in Table 2 (solid fill) along with tensile strength of reference part (Pattern fill)

tensile strength higher than that of the reference part. Specimen 2 has the highest tensile strength on average among all the specimens (34.05 MPa). Therefore, with appropriate combinations of the chunk-based printing parameters, we can even obtain a part with strength higher than that of traditional 3D printed parts.

On the other hand, specimen 4 (SA= 30°, CO= 0.3mm, NS=0), specimen 5 (SA= 50°, CO= 0.5mm, NS=2), specimen 7 (SA= 50°, CO= 0.3mm, NS=2), and specimen 8 (SA= 50°, CO= 0.3mm, NS=0) failed at 18.95 MPa, 26.76 MPa, 17.34 MPa, and 21.84 MPa respectively. Those values correspond to 67, 95, 61, and 77 percent of the reference part's tensile strength respectively. Specimen 7 has the lowest of tensile strength of all the test specimens (17.34 MPa). Therefore, in chunk-based 3D printing, it is recommended to avoid setting high chunking angle, low overlapping depth and large number of shells at the same time.

5. Conclusion and future work

In this paper, tensile specimens using PLA are fabricated with varying chunk-based parameters to investigate how those parameters would affect the tensile strength of chunk-based 3D printed parts. A comparative study is performed in order to understand how the strength of those chunk-based printed parts collated with the standard FDM parts, i.e., the ones printed normally layer by layer. Design of experiment is conducted to understand how parameters such as the chunk slope angle, the overlapping depth, and the number of perimeter shells affect the tensile strength of chunk-based printed parts.

The tensile strength of chunk-based part ranges from 121 to 61 percent of the tensile strength of the standard FDM part. Based on our study, it is found that proper selection of the combinations of the chunk-based printing parameters make chunk-based parts stronger than traditional layer-based parts, while some combinations could make it weaker. Following recommendations regarding chunk-based parameters are provided:

- **Use smaller slope angle to strengthen a part.** Tensile strength decreases with increase in chunking slope angle. This is due to increased contact area between the chunks.
- **Avoid shells at the contact area between chunks to increase strength.** Printing chunks without any perimeter shells at the bonding surface strengthens the adhesion between chunks. This is due to the fact that presence of shells mimics the 90° raster orientation to the tensile load, which have lowest tensile strength. If the shells are to be printed at the bonding area, the outline overlap can be increased to somewhat improve the strength.
- **Increase chunk overlapping to strengthen a part.** Overlapping increases the strength of the part. It is important to bear in mind that increasing the overlapping will affect the overall dimension of the part in overlapping direction and there is only so much overlapping that can be done before printing becomes infeasible.

The future work will be built on the foundation laid by the results from this study. Further experiments need to be conducted to identify any additional parameters, if exists, that might have an impact on the tensile strength. We will also investigate the combinational effect of both the direct parameters and indirect parameters on the mechanical property of the chunk-based 3D printed part. In addition to this, other mechanical properties such as compressive strength, shear strength, flexural strength, fatigue etc. needs to be studied to fully comprehend the mechanical behaviour of chunk-based parts. Furthermore, mechanical properties at the joints need to be studied in further details to understand the underlying causes of change in strength due to the changes of parameters. Equally important is to search other avenues for chunking interface such as interlocks. This will enable us to compare different chunking interface and choose the best one for a printing strategy. Lastly, we would also like to investigate multi-material chunk-based printing to understand the mechanical properties when the combining chunks are made up of different materials.

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