The study on the influence of the 3D printing parameters on the mechanical properties of products

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Abstract:

Additive manufacturing, as known as 3D printing, nowadays, is utilized as the most potential manufacturing method which has revolutionized the manufacturing industry by its rapid and efficient. This thesis's purpose is to examine the influence of printing parameters on the mechanical of products manufactured by FDM technique (Fused Deposition Method) which is the most widely used method. There are many factors could affect the results of manufacture process, however, in the scope of this paper, 3 main configurations would be examined including layer thickness, infill percentage and building orientation. In general, the project was carried out in 4 steps including designing prototype, printing samples, mechanical test and evaluation. Firstly, 18 types of PLA dog-bones which were designed and printed by 3D printer, were prepare with 3 specimens for each one. After that, these specimens went through tensile test with Testometric testing machine to obtain Young's modulus, tensile strength and strain. The results were then recorded and represented in results chapter. The final results show the linear relation between infill percentage and mechanical properties, meanwhile not with layer thickness. The building orientaion also significantly changes the performance of 3D printing products.

Keywords:	Additive manufacturing, 3D printing, PLA, FDM, Tensile testing, mechanical properties.
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1 INTRODUCTION

Nowadays, additive manufacturing plays a strategic key in manufacturing industry both in consumer market and mass production. Due to its capability in producing components by building layer by layer, this technology could generate desired parts with very high accurate geometry and limited wasted materials. Therefore, the stability and durability of products are highly concerned. This paper intends to research how one could obtain these product characteristics by adjusting 3D printing settings.

1.1 Aims

The aim of this paper is to examine the influences of 3D printing settings on the mechanical properties of products. The printing process was set up with different configurations related to infill, layer thickness and building orientation.

The level of infill would be tested:

- Level of infill: 20 %
- Level of infill: 40 %
- Level of infill: 60 %

The level is chosen increasingly to examine whether increasing the material filled inside products leads to positive results or not.

The printed orientation would be performed:

- Horizontal
- Vertical

The level of layer thickness:

- Resolution: low
- Resolution: intermediate
- Resolution: high

1.2 Research question

FDM technology builds components by extruding the molten materials in certain paths in x-y plane. The nozzle draws the cross-section pattern of components layer by layer. Each layer would be cooled down and hardened prior the application of next layer. The process repeats until the model is completely built.

Due to the 3D printed products are created by extruding the layer over the layer, then the adhesion among layers is critically important. The working temperature should not be hot enough to soften the material, but not too high to avoid warping.

The infill setting also affects the strength of products highly. It is expected that more material inside, more durable and stronger the products are. The goal here is to determine level of infill in which there is no significant changes when one increases the infill further.

Orientation to print is also another factor which could influence to product qualities. The different inner structures of products are expected to result in different characteristics.

Lastly, layer thickness would be examined along with above factors. The layer thickness would affect the adhesion between two layers. As mentioned above, it directly influences the strength of products. However, the low layer thickness setting could result in low flexible products and waste of materials.

Research questions:

- The influence of infill percentage on mechanical properties on different levels
- How layer thickness affects final product’s properties
- The role of printing direction

2 THEORY

2.1 Additive manufacturing

The “additive manufacturing” term is officially defined in ASTM F2792-Standard Terminology for Additive Manufacturing Technologies as:

“The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms are additive fabrication, additive processes, additive technologies, additive layer manufacturing and freeform fabrication” [1]

Additive manufacturing, also known as 3D printing, has revolutionized the manufacturing industry due to its rapid and economic benefits. There are many industries has adopted this technology into their business including automotive, aerospace, biomedical or even food industry in recent. Moreover, this new trend technology has exceeded its own limitation and constantly evolved to new level. Nowadays, instead of printing single material, the most modern 3D printers have the ability to create multi-material components which have never been generated by traditional AM process. The used material range also has broadened from polymers to metals, ceramics or even complex materials such as composites. This means the opportunities for manufacturing industry which additive manufacturing brings out is countless and this trendy technology would be dominant in the future [2].

2.2 FDM technology

2.2.1 Definition

Fused Deposition Modelling (FDM), is an additive manufacturing technology among other 3D printing techniques such as Stereo lithography (SL), Selective Laser Sintering (SLS) etc. The technique was firstly developed by S. Scott Crump in the late 1980s and was commercialized in 1990 Stratasys [3].

Fused Deposition Modelling process builds components by depositing fused materials in layers. The filaments are molten and extruded through the nozzle and in a pre-determined path layer by layer [3].

2.2.2 Manufacturing Process

To prepare for FDM process, the spool of thermoplastic filament is firstly load into the 3D printer. Then it is heated up to working temperature, the filament is fed to the extrusion head and come from the nozzle.

In the FDM process, the nozzle moves through the X-Y plane to build the cross-section of the part. The working table where the filament is supposed to be deposited moves in Z-axis. Sometimes, the additional equipment such as cooling fans are attached on extrusion head to support the filament to solidify easily [3].

When a layer is deposited completely on the table, it moves down according to the layer thickness, then the subsequent layer is prepared to feed. The subsequent layer is extruded and fill over the previous layer to build the cross-section of part. This process repeats until the body component is built completely.

Sometimes, when the component geometry is too complex, FDM uses support materials apart from the build parts to hold the overhanging structures during the process as well help keep the component shape and its structure. This support parts usually are created simply in order to easily remove when process is complete and save the used materials [3]. The process of 3D printing is generally described as the Figure 1.

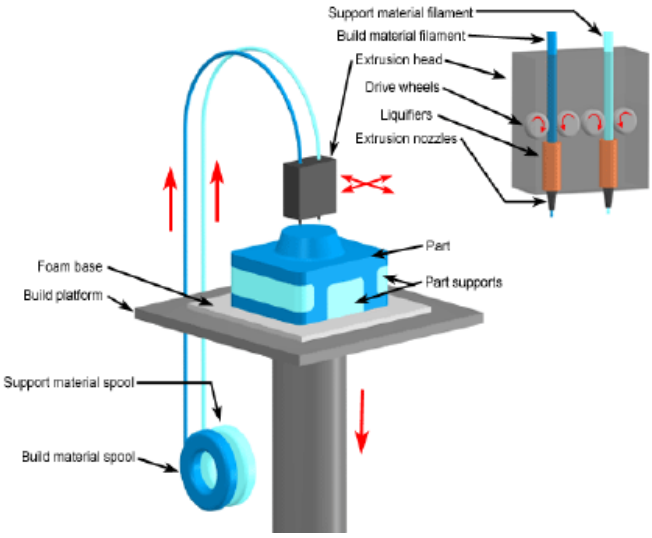


Figure 1. Schematic Representation of FDM [4].

2.2.3 Materials used in FDM

Most of existing FDM printers are using thermoplastic materials which are in filament form for the extrusion and deposition purpose. The advantages of FDM compared to other techniques is the wide range of used materials from commodity thermoplastics (PLA, ABS) to engineering materials (PA, TPU and PETG) and high-performance materials (PEEK and PEI) [5].

The available materials for FDM are classified into 3 categories with specific characteristics, high, intermediate and low performance respective to high, medium and low cost. Figure 2 represents the level of available materials using in FDM:

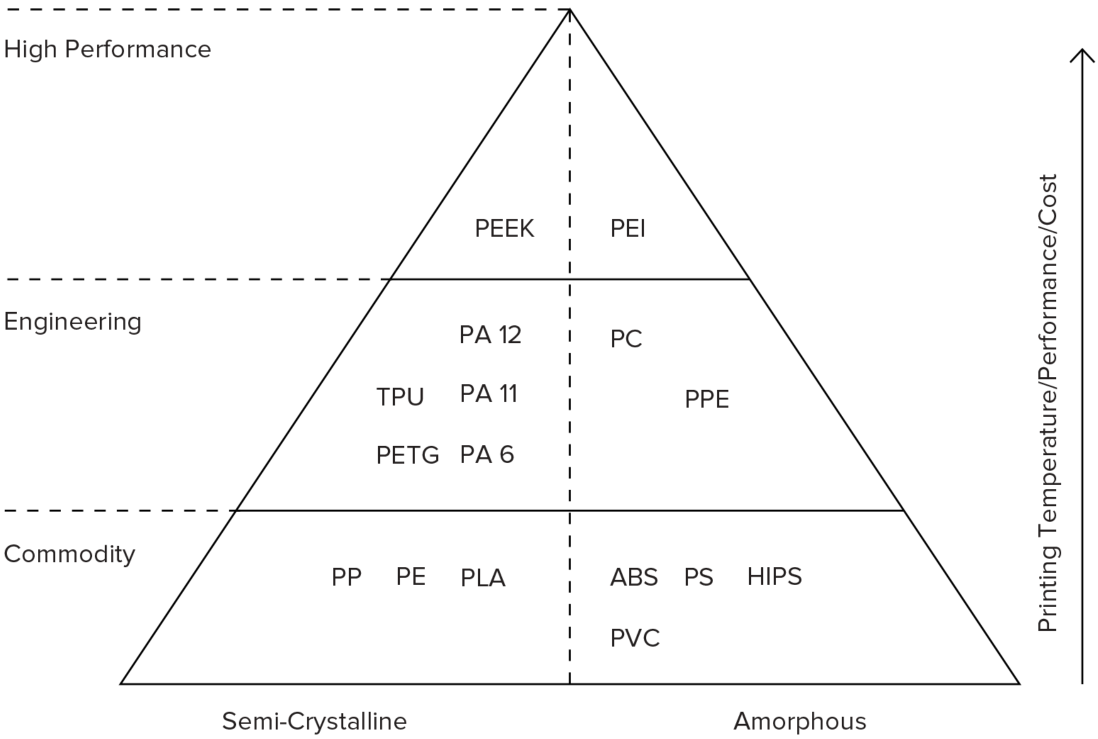


Figure 2. Available materials used in FDM [6].

Nowadays, Acrylonitrile Butadiene styrene (ABS) and Polylactide (PLA) are used most widely due to their characteristics.

Although, ABS and PLA have historically been used mostly as two major polymers, however, their dominance is gradually overwhelmed by other materials. During 3D printing process, the used materials would be examined through 3 aspects: mechanical performance, visual and printing process. Hence, the materials are usually grouped respectively into 3 main categories. This help printing user easily decide the appropriate materials for their own applications. Figure 3 demonstrates the relationship among criteria examined through additive manufacturing process. These are explained in detailed as [6]:

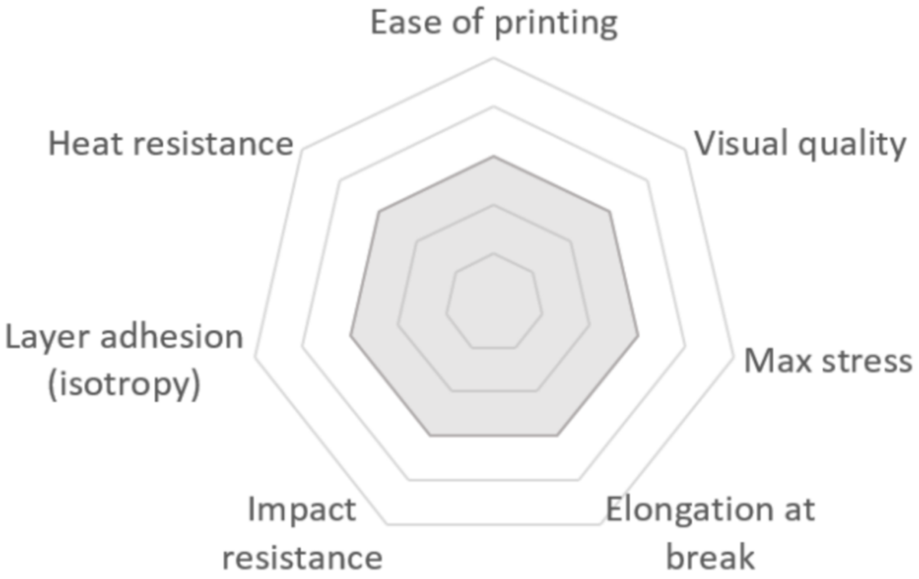


Figure 3. A graphic compares the 3D printing criteria [7].

- Ease of printing: indicates how easily the material is printed. Bad adhesion, failed ratings, maximum printing speed, how easily the material is to be fed;
- Visual quality: visual performance of final products, surface roughness;
- Max stress: the maximum stress could be applied into the products without causing any failures;
- Elongation at break: maximum length that objects could be stretched before breaking;
- Impact resistance: needed energy to break products by impact;
- Layer adhesion: how good the adhesion between two layers is;
- Heat resistance: the maximum heat object could absorb before softening and deforming.

Error! Reference source not found. indicates the criteria of each individual material. Each characteristic is graded on a 1 to 5 scale. In which, 1 is lowest, meanwhile 5 is highest.

Table 1. Table records the rank of criteria [6]

	Ease of printing	Visual quality	Max stress	Elongation at break	Impact resistance	Layer adhesion	Heat resistance
PLA	5	4	4	1	1	4	1
ABS	2	3	3	1	3	2	5
PET	4	3	2	1	3	3	2
Nylon	3	3	2	3	4	1	1
TPU	1	2	2	5	5	3	2
PC	2	3	5	1	3	3	5

2.2.3.1 PLA

In order to make a comparison, these below web graphs were generated by Excel. As a glance at this graph, it is concluded that the advantages of PLA are the most ease to print and providing the very good visual quality. PLA is very rigid and strong due to its high layer adhesion but is very brittle.

Besides, there are several advantages and drawbacks of PLA which printer should consider carefully prior to utilizing it during additive manufacturing process.

Table 2. Table records the rank of criteria [6]

Pros	Cons
Bio-sourced, biodegradable	Low humidity resistance
Odorless	Hard to be glued
Good UV resistance	
Be able to be applied surfacing technique such as painting and using sanding paper	

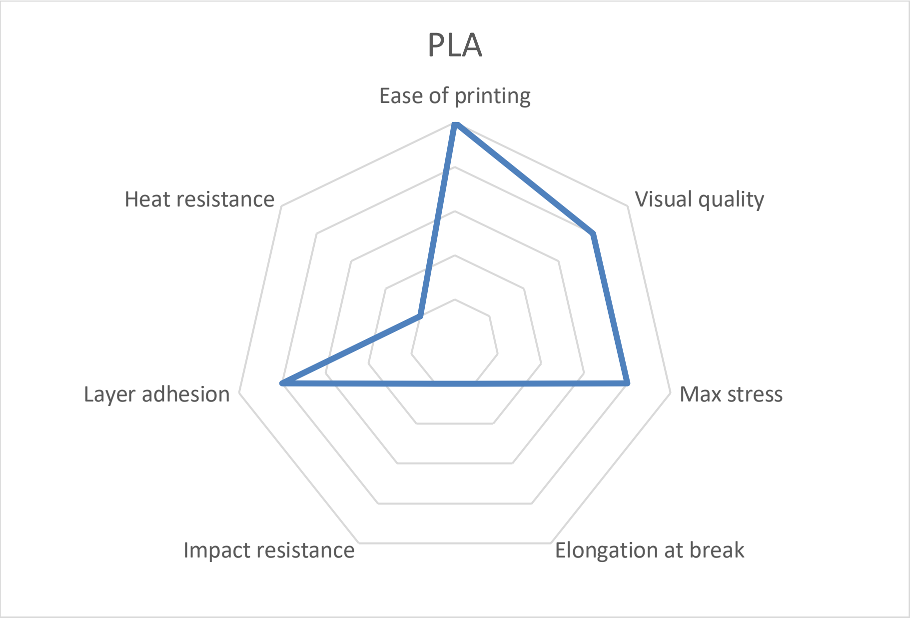


Figure 4. PLA material profile.

2.2.3.2 ABS

Meanwhile PLA is usually good option in normal case, ABS is picked over PLA when high temperature resistance and high toughness is required. Clearly, ABS is much more difficult to print than PLA and provide lower visual quality, however heat and impact resistance is significantly higher than. Figure 5 and **Error! Reference source not found.** compares the properties of ABS and PLA.

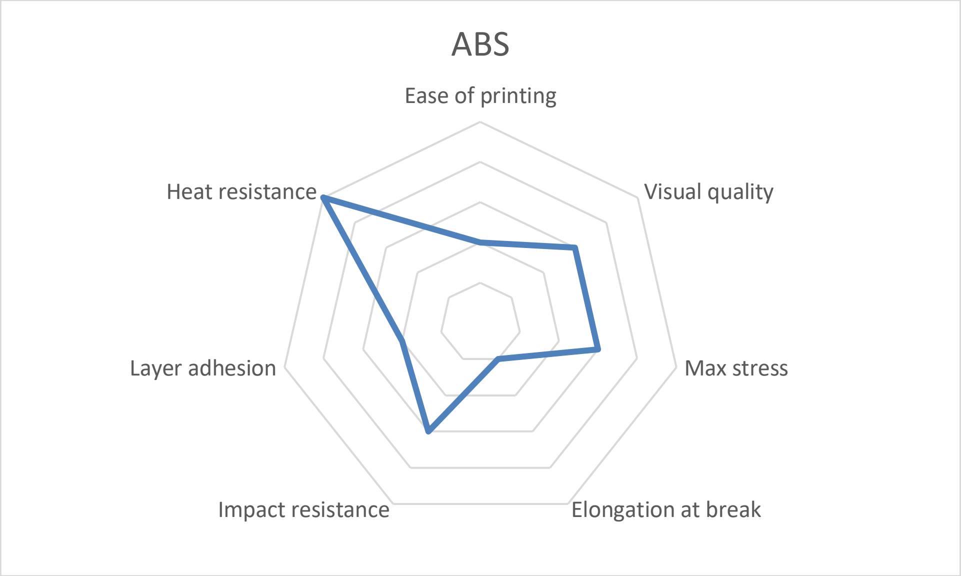


Figure 5. ABS material profile.

Table 3. Pros and Cons of ABS [6]

Pros	Cons
Can be post-processed with acetone vapors for a glossy finish	Low UV resistance
Be able to be painted with acrylics	Oder when printing
Acetone can be applied as strong glue	Potentially high fume emissions
Good abrasion resistance	

2.3 PLA Polymers

2.3.1 PLA introduction

Most thermoplastic polymers are produced by distillation and polymerization of nonrenewable petroleum reserves. Meanwhile, PLA, also known as polylactic acid or polylactide, is different than them obtaining from lactic acid which could be derived from renewable resources such as corn starch or sugar cane. Hence, PLA is biodegradable polymer which belongs to bioplastic family in which polymers are derived from biomass [8].

In general, PLA is principally synthesized by two different methods: condensation and polymerization. The most common polymerization method as known is ring-opening polymerization. This process uses metal catalysts in combine with lactide to generate PLA [9].

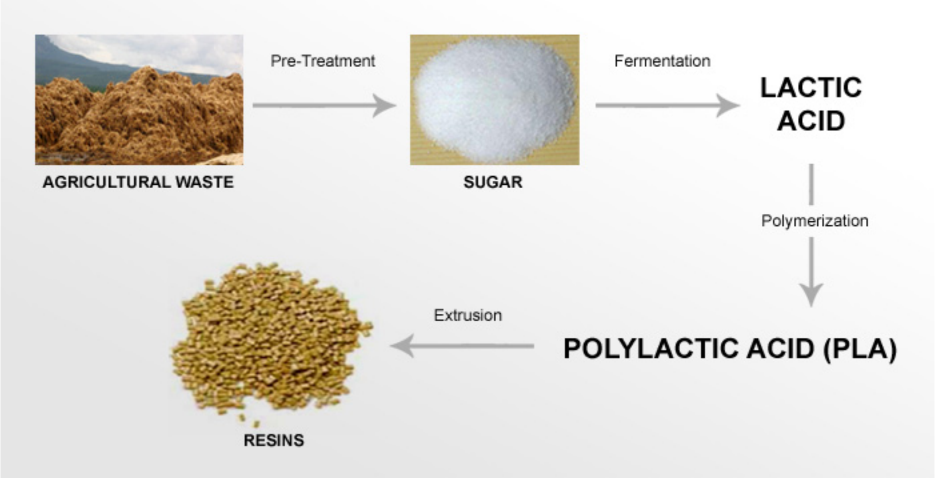


Figure 6. Production process of PLA [10].

Polylactic has characteristics similar to polypropylene (PP), polyethylene (PE), or polystyrene (PS). It could be able to be reproduced from existing manufacturing equipment which are used and produced initially for petrochemical industry. Obviously, PLA products are convincedly economical and ecological. Otherwise, the extreme benefit of Polylactic as degradable polymer is that it could degrade naturally when exposes to the environment. This ability brings out huge impact and revolutionizes the manufacturing industry with cost-efficient and non-petroleum products. It would be utilized widely specially in such short lifespan product industry where biodegradability is crucial required. For example, there are many PLA products gain that benefit such as plastic water bottles or containers for foods or fruits. These demands high volume products per year, hence, wasted substance is a challenging problem. But now, it would be hopefully addressed with PLA. Accordingly, the bottle water made from PLA would degrade typically in six to twenty months when left in ocean as opposed to traditional products which needs till hundred or even thousand years to degrade in same environment [8].

2.3.2 PLA characteristics

Polylactic is classified as thermoplastic polymers, hence it has fully specific characteristics of its family. As defined, thermoplastic polymers transform into liquid phase at their melting point. In case of PLA, that temperature is 150-160 degrees Celsius. The key difference among thermoplastics and others is that they could be heated up, cooled down and reheated over without any significant degradation. As opposed to thermosets, they could only be heated once. Once thermoset plastics are heated and melted ever, they are not able to keep their properties remained. The chemical properties are not reversed even when they solidify. Moreover, it will burn when one tries to heat it up to high temperature second time. Clearly, this makes thermoplastic polymers become ideal materials for recycling purpose as well additive manufacturing process, specially FDM technique. The PLA filament goes through heated up process prior to extruded via nozzle, then solidify to final product without much property changes [8].

2.3.3 Why choose PLA for additive manufacturing?

Table 4 and **Error! Reference source not found.** reveals some important properties of PLA which considered for additive manufacturing:

Table 4. Mechanical properties of PLA [11] [12] [13] [14] [15]

Tensile modulus	310-5600 MPa
Tensile strength	61-66 MPa
Tensile elongation	1-8.5 %
Flexural modulus	300-9500 MPa
Flexural strength	48-110 MPa

Table 5. Thermal properties of PLA [12] [13] [14] [15]

Melt Temperature	157-170 °C
Heat Deflection Temperature	49-52 °C
Glass transition Temperature	60-65 °C
Shrinkage Rate	0.37-0.41 %
Printing Temperature	190-220 °C

PLA and ABS as mentioned are 2 most common materials used in additive manufacturing applications due to their specific characteristics. With a higher flexural strength and better elongation prior to breaking, ABS is more utilized for end used applications. Meanwhile, PLA, with higher visual quality performance, is more popular for such applications when form and shape are considered. Additional, PLA has lots of remarkable things that overwhelm ABS which determines PLA as the first choice in its field [16].

Firstly, as opposed to ABS, PLA is favored for its absence of unpleasant odors when heated, and for its overall environmental compatibility in its life cycle. For example, the amount of potentially dangerous ultra-fine particles emitted from PLA is less than ten times compared to ABS [17]. In additional, the biodegradability of PLA also makes it more recommended materials compared to ABS in some cases. Polylactic is stable in general atmospheric conditions and will biodegrade within around 50-60 days in industrial composters and 48 months in water. In contrast, ABS is not biodegradable, although it could be recycled. PLA is also confirmed as safe products by filament manufacture, then it is even used in food industry [16].

Secondly, the low level of shrinkage and relatively low melting point are considered as main advantages compared to other alternatives used in additive manufacturing process. The former results in the PLA final parts with minimum level of residual stresses, avoiding the occurrence of deformation and delamination. Otherwise, the latter leads to highly efficient printing process. The less melting point material has, the less energy needed to provide for pre-process. The residual stresses inside the ABS parts caused by hindered shrinkage during the cooling process makes them fail by delamination at minimal or even no external loads. ABS parts even proceed to delaminate prior to the printing process is finished. Hence, 3D printed parts made from PLA (which is less prone to shrinking) is regularly considered as better performance products in mechanical properties, especially tensile strength. [17]. Although, PLA products is usually criticized with its relatively low durability compared to ABS's at high temperature, however this difference is not significant at low and medium temperature conditions [16].

The low level of shrinkage not only makes PLA final parts more durable, it also gives PLA components high accurate form. Due to its lower printing temperature in comparison to ABS's (180 of PLA and 230 of ABS) [18], PLA products is less likely to warp and can print sharper corners and features. It makes PLA ease to print than ABS [16]. Figure 7 compares the performance of PLA and ABS in additive manufacturing process.

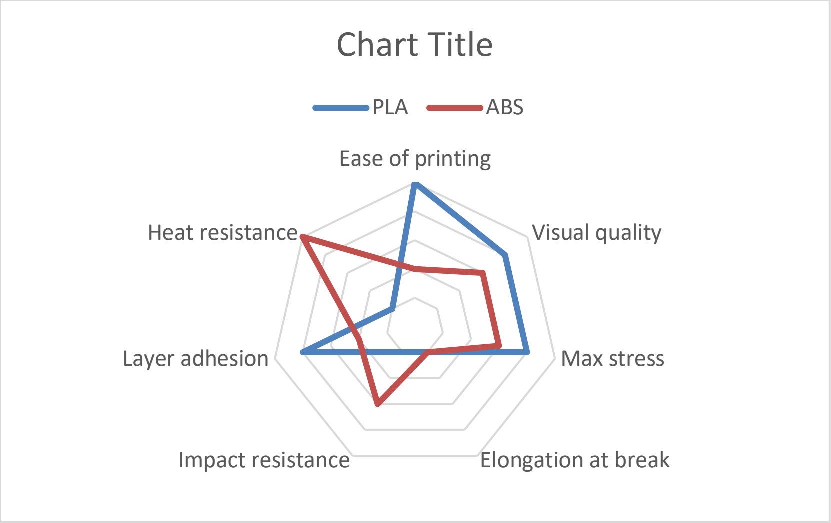


Figure 7. Web graph compares ABS and PLA.

In general, both PLA and ABS are thermoplastic polymers that makes them become adequate to additive manufacturing process. Due to higher flexural strength and durability, ABS are regularly preferred for such applications where using purpose is priority. With high level of heat resistance, ABS also is first choice for high temperature applications. Meanwhile, PLA is ideal for 3D prints where aesthetics is considered. In additional, the ease of printing also makes PLA graded higher in comparison to ABS for efficient process.

2.4 FDM Parameters.

The quality of 3D printing products is not only depended on the properties of used filaments, but also significantly influenced by the additive manufacturing parameters. Optimum process variables greatly enhance the performance of final products. Hence, it is necessary to examine the insights of each parameters to understand how they drive the final results [19].

There are several factors which need to be considered in FDM technique to obtain desired results:

- Orientation: defined as part build orientation or orientation refers to the inclination of the part in the working platform with respect to X, Y and Z axis in which X and Y-axis are horizontal plane as default and Z is the direction of building;
- Layer thickness: the thickness of layer deposited by nozzle;
- Raster angle: the direction of raster relative to the X-axis of the build table;
- Part raster width: the width of raster pattern utilized to fill inner regions of building parts;
- Raster to raster gap: the gap between two adjacent rasters in same layer;
- Necking: a shape formed due to molecular bonding between two rasters;
- Cusp height: Calculated as the maximum distance between facet and deposited part considering the edges of slices. Figure 8 demonstrates the cusp height.

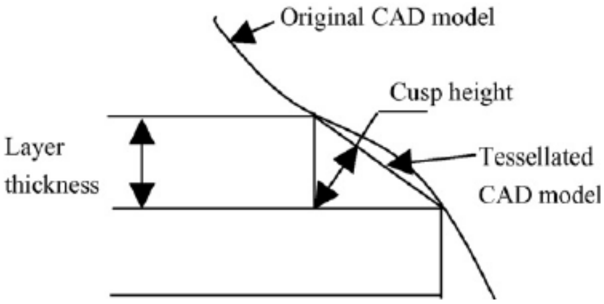


Figure 8. Figure demonstrates the cusp height [20].

- Printing speed: how fast the nozzle deposits the raster [21];
- Working Temperature: the defined working temperature which is regularly same as melting point of used materials;
- Infill: the percentage of material filled in building parts.

The performance of 3D printing products is assessed based on 3 criteria following dimensional accuracy, surface roughness and mechanical strength characteristics. Each of parameters mentioned above have direct or indirect influence on the product qualities.

2.4.1 Dimensional Accuracy

Dimensional accuracy is defined as the compatibility of basic dimensions of final products with dimensions of the ideal products, called nominal dimensions [22]. This level of accuracy could be affected by some 3D printing settings and the building orientation is the most important factor among other parameters.

The building orientation as mentioned above, is defined as the angle between plane determining the object division into layers and horizontal plane (Figure 9). Orientation could be defined by three angular values in which rotation in Z-axis has no influence on the dimensional accuracy of parts [22].

It has been proved by experiments that the level of accuracy increases with the decrease in the orientations. Hence, as usual, the parts are built in horizontal plane with 0 orientation. In other cases, the level of orientation should be adjusted as minimum as possible to obtain highest dimensional accuracy as well as better components [22].

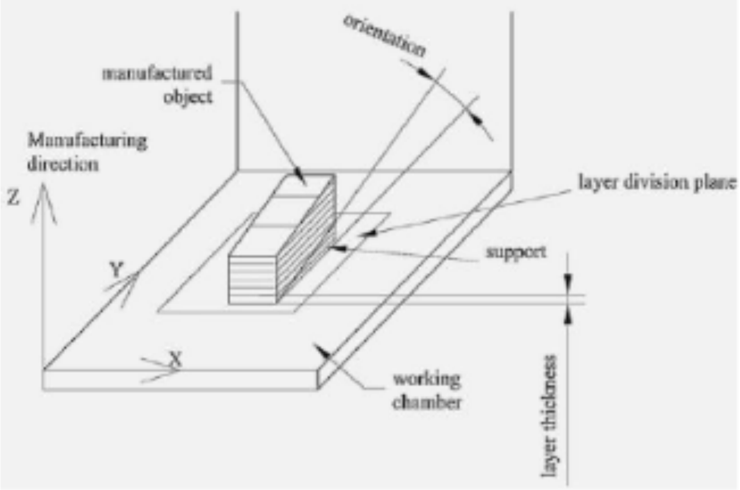


Figure 9. The picture represents the building orientation [22].

Moreover, the building orientation sometimes affect directly the shape of final products. By orientating the part in different directions, the way that nozzle creates the cross-section area of components changes as well. Let’s consider a cylinder manufactured using FDM technique with its center axis orientated vertical. The nozzle would construct the object by printing a bunch of concentric circle layers on top of another. As a result, the complete cylinder would have homogeneous cross section leading to smooth outer surface. In contrast, the cylinder manufactured with its axis orientated horizontal would have undesired shape. Instead of circular shape, the cross section of part would be constructed as a series of rectangles layered on top of each other. Obviously, the size of these rectangles is not the same, hence, this leads to low smooth part. The worst thing is that the outer surface of cylinder could not be exact as expected. If the support materials are missing in this case, the surface of the cylinder which touches the working platform will be flat as Figure 10.

Figure 10. A picture shows the difference in 2 cylinders manufactured by 2 different ways [23].

2.4.2 Surface roughness.

Surface roughness is one of important thing needed to be considered carefully to access the performance of products manufactured by not only conventional, also unconventional process. Hence, it plays the key role in FDM process too. Nowadays, surface roughness is arising as the most challenging problem for researchers, and there are few approaches have been figured out to improve surface quality.

The increase in the level of roughness mainly comes from the inherent disadvantages in the layered manufacturing processes. They are classified as two major groups [24]:

- Layer thickness
- Stair case effect

The level of roughness is supposed to increase as the layer thickness increases. Figure 11 illustrates the influence of layer thickness on the roughness:

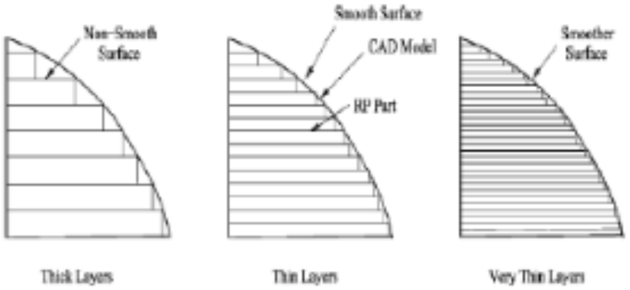
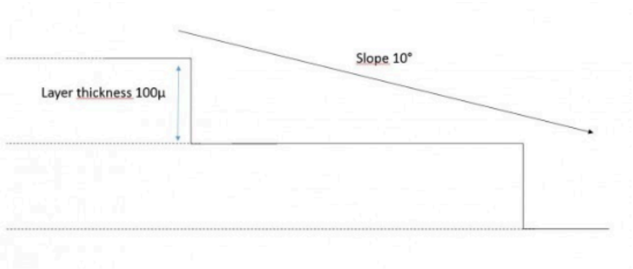
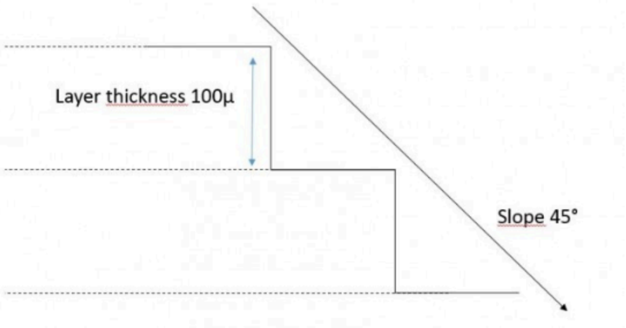


Figure 11. The influence of thickness on roughness [24].

Meanwhile, the staircase effect is caused by the offset between an object layers when its curves vary. This phenomenon becomes more noticeable on oblique and curved surfaces. Figure 12 helps visualize it:



Representation of 3D printed layers on a 10° slope.



Representation of 3D printed layers on a 45° slope.

Figure 12. The staircase effect on different part's slopes [25].

As mentioned above, the building orientation plays a key role in the quality of dimensional accuracy. Moreover, it has also significant influence on the quality of part surfaces. Indeed, the effect of staircase is impossible to remove completely. However, by adjusting and controlling the settings, it could be reduced to reach the acceptable level. Among few approaches, low layer thickness and proper building orientation are first choices preferred. As illustrated in the picture above, it is revealed that there is greater spacing between adjacent layers in case of 10° slope in comparison to 45° (with same layer thickness). As a result, the layers are much more visible leading to the low visual quality on a very gradual slope. Consequently, the objective is to minimize the existence of curved parts during printing process. This could be controlled during pre-process when building orientation determines. The component should be constructed in way such that the effect of staircase overall is greatly reduced [3].

Besides, the surface quality of products could be greatly enhanced due to additional techniques applied during process or post-process. These significantly changes the resulted objects.

- Adaptive slicing: this technique is utilized to decrease the surface roughness of products. As usual, the layer thickness is set constant as default. However, as mentioned above, layer thickness affects directly to the visual quality. Thus, the slicing software integrated will slices the CAD model into adaptive slices. This helps reduce the staircase error [26]. The software is equipped with special algorithms that can identify the complex structure and change the slicing pattern in order to achieve best results. Figure 13 helps visualize this:

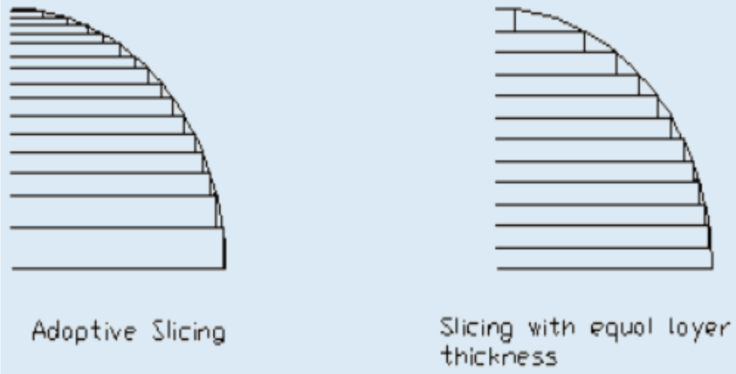


Figure 13. The comparison between adaptive slicing and traditional slicing [27].

- Chemical Processing

It has been proved by experiments that the surface roughness could be greatly enhanced by adding some chemical process during pre-process and post-process. Although, the implementation of the chemical treatment on the FDM part causes the negative effects on the tensile strength, however, it betters the performance overall. The FDM parts would be dipped in the appropriate solvent. Acetone, also known as Dimethyl ketone is usually preferred due to its low cost, very low toxicity and very high diffusion. Besides, ester and chloride solvent are other choices [28]. There are some difficulties while using acetone, too strong for solvent, therefore water is added to mix with pure acetone with ratio 9:1 in which 90 % volume is acetone, water keeps 10 %. The immersion process lasts about 5 mins then, the parts is taken out. Any part's sizes are recorded before and after process to examine the variations. The roughness of specimens is then measured by using the conoscopic sensor to access the improvements in visual quality [3].

2.4.3 Mechanical properties

Due to the scope of this thesis is to examine the influence of FDM parameters on the mechanical properties, hence some most important factors listed above would be reminded. These factors also be tested by performing experiment and the obtained results would be compared to the theory to examine.

Building orientation: defined as part build orientation or orientation refers to the inclination of the part in the working platform with respect to X, Y and Z axis in which X and Y-axis are horizontal plane as default and Z is the direction of building. The FDM technology builds the part by extruding the layer on top of other, thus the bonding between them plays a key role on the strength of products. Not only how rigid the individual raster's bonds are, but also the way they are connected would affects the mechanical properties. The tensile strength and elongation of specimens which are built by 2 different building orientations would perform differently when undergo experiments. In our case, the dog bone would be manufactured as the Figure 14:

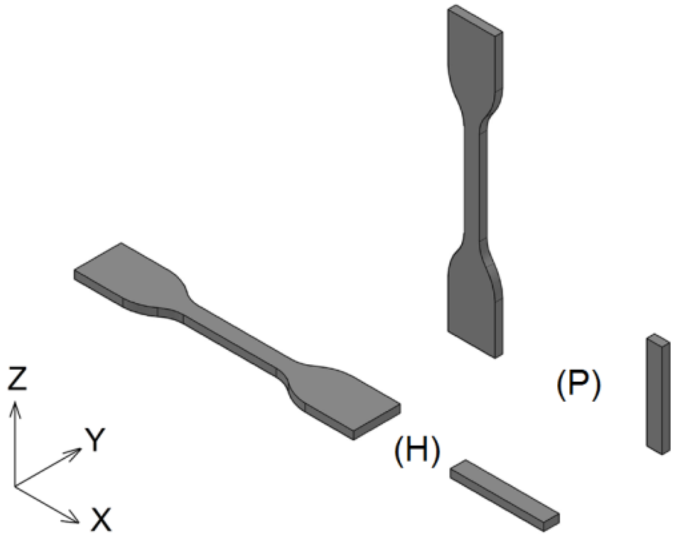


Figure 14. Building orientation [29].

Secondly, layer thickness is defined as the thickness of layer deposited by nozzle. The tensile strength of samples is expected to increase as the layer thickness decreases. That means the samples with lowest layer thickness have highest ultimate tensile strength, meanwhile, ones with highest layer thickness perform poor ultimate tensile strength. This could be explained by studying the inter-layer bond between adjacent layers. Obviously, the samples with low layer thickness are closely stacked together, thus it is expected that the inter-layer bonds are more rigid and stable leading to higher tensile strength. This explains better elongation as well [30].

Infill presents the percentage of material filled in building parts. Clearly, more materials filled into the products, better mechanical properties they perform. Hence, the tensile strength is expected to increase proportional with the infill. However, the samples with high infill take more time to print leading to less time-efficient products. Hence, the aim is to examine how much tensile strength increases when increase the infill at low level and high level. This difference would tell if it is important to set the infill at high level compare to time consuming factor.

2.5 Mechanical Properties

2.5.1 Young's Modulus

Young's modulus indicates the elastic properties of materials undergoing the tension or compression in one direction. It measures the ability of material to withstand changes in length when being stretched or compressed. More Young's modulus the material has, stiffer the material is. Young's modulus is calculated as the following formula [31]:

$$E = \frac{\gamma}{\sigma} (N/m^2) \text{ [32]}$$

In which:

- E: Young's modulus has N/m^2 unit
- γ: Stress, N/mm^2
- σ: Strain, no unit

Young's Modulus is only meaningful in the range in which the stress is proportional to the strain, and the material are capable to return to its original shape when applied load is removed. It means prior to reach the yield point, the Young's modulus could be found by the formula above. Young's Modulus also is figured out by the slope of linear portion of the stress-strain graph. This linear part is also known as the elastic region of material.

2.5.2 Tensile Strength

Tensile strength displays the ability of material to resist the tension load. It is defined as the maximum load material could support with fracture during being stretched, divided by the original cross-sectional area of the material [33]. Tensile strength has dimensions of force per unit area. In general, when the stresses which are less than tensile strength are removed, the material returns to its original shape without any deformation. However, as the stress reaches the value of tensile strength, the ductile material starts undergoing through plastic region, experiences great elongation before fracture occurs.

2.5.3 Strain

Elongation at break, also known as fracture strain or tensile elongation at break, is the ratio between increased length and initial length after breakage of test specimen. This value indicates the ductility of a polymer [34]. It is defined as:

$$\sigma = \frac{\Delta l}{l_0} [35]$$

In which:

- σ is the strain, no unit
- Δl is the change in length
- l_0 is the original length

3 RESEARCH METHOD

3.1 Material & Equipments

The experiment was implemented by using 3D printer at Arcada B255 laboratory. The utilized filament is provided by MakerBot.

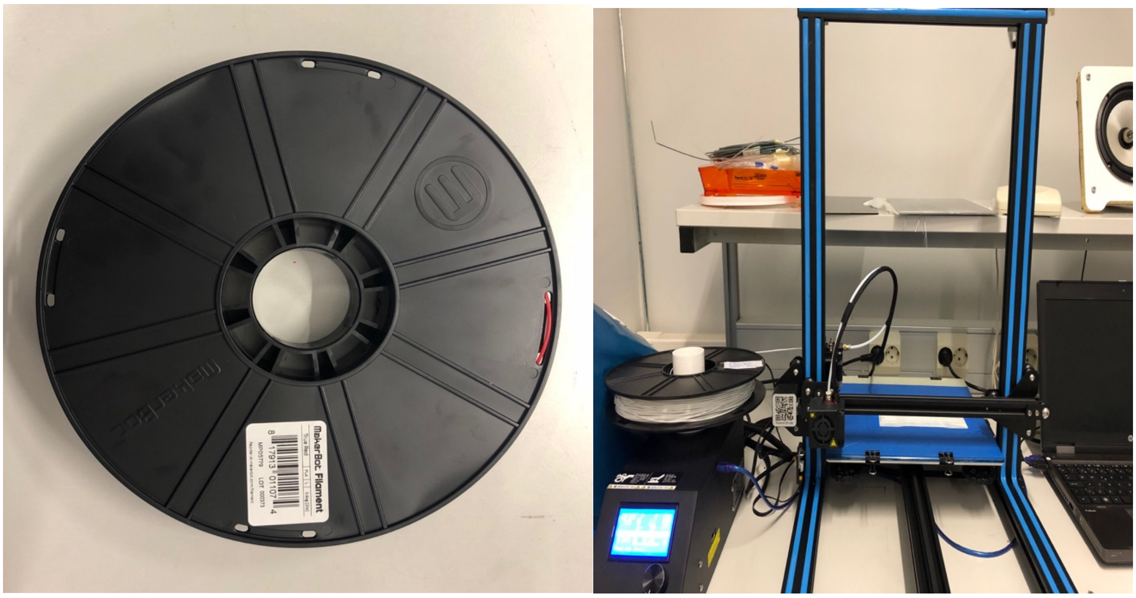


Figure 15. PLA filament and 3D printer.

In general, there are 3 main works including CAD phase, 3D printing and tensile testing. Figure 16 helps visualize the process.

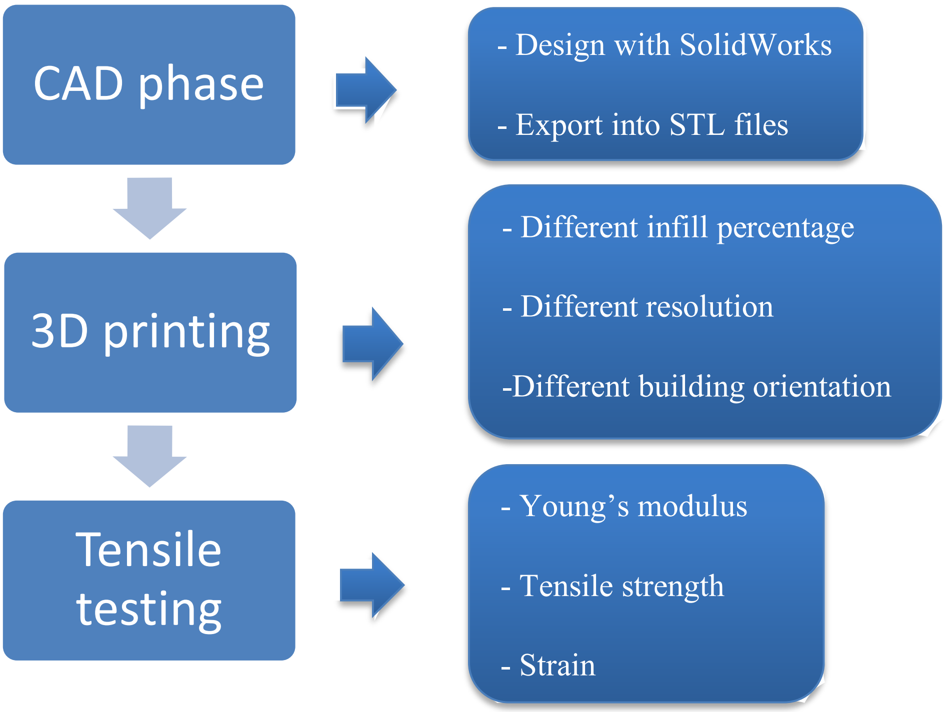


Figure 16. Flow process chart.

3.2 Specimen preparation

In total, there are 3 specimens would be tested for each type.

The test specimens were designed by SolidWorks with the specific dimensions as the ISO 527 standard. Strict control of all conditions of the specimen preparation is important to ensure all specimens are in same state [36].

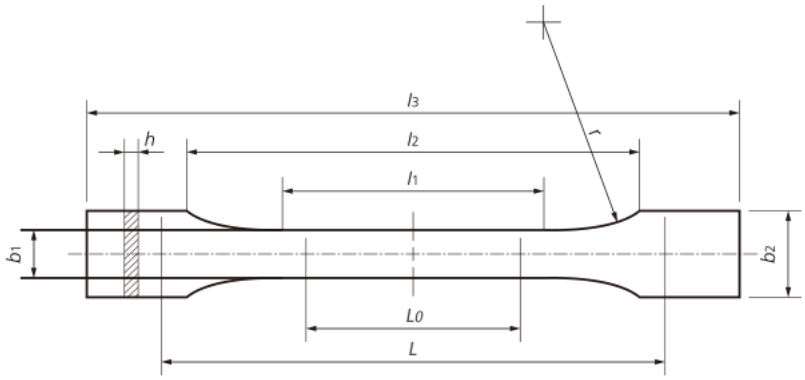


Figure 17. Specimen Dimensions [37].

Table 6. Dimensions of specimens in millimeters [36]

	Specimen type	1A
l3	Overall length	170
l1	Length of narrow parallel-sided portion	80 ± 2
r	Radius	24 ± 1
l2	Distance between broad parallel-sided portions	109,3 ± 3,2
b2	Width at ends	20,0 ± 0,2
b1	Width at narrow portion	10,0 ± 0,2
h	Preferred thickness	4,0 ± 0,2
L0	Gauge length(preferred) Gauge length (acceptable if required for quality control or when specified)	75,0 ± 0,5 50,0 ± 0,5
L	Initial distance between grips	115 ± 1

During manufacturing process, ones have to make sure all surfaces of specimen are free from visible flaws, scratches or other imperfections [36].

The specimens would be printed with different layer thicknesses, building orientations and infills:

- Layer thickness: 0.2, 0.3 and 0.4
- Infills: 20 %, 40 % and 60 %
- Orientation: 0° and 45°

There are 18 types of samples in total marked from 1 to 18. Three specimens are printed for each type, so we have 54 samples in total. The number of types is listed in the table below with respective to resolution, layer thickness and building orientation.

Table 7. Specimens with 0° building orientation

Infill level Layer thickness	20 %	40 %	60 %
0.2	1	2	3
0.3	4	5	6
0.4	7	8	9

Table 8. Specimens with 45° building orientation

Infill level Layer thickness	20 %	40 %	60 %
0.2	10	11	12
0.3	13	14	15
0.4	16	17	18

3.3 Printing process

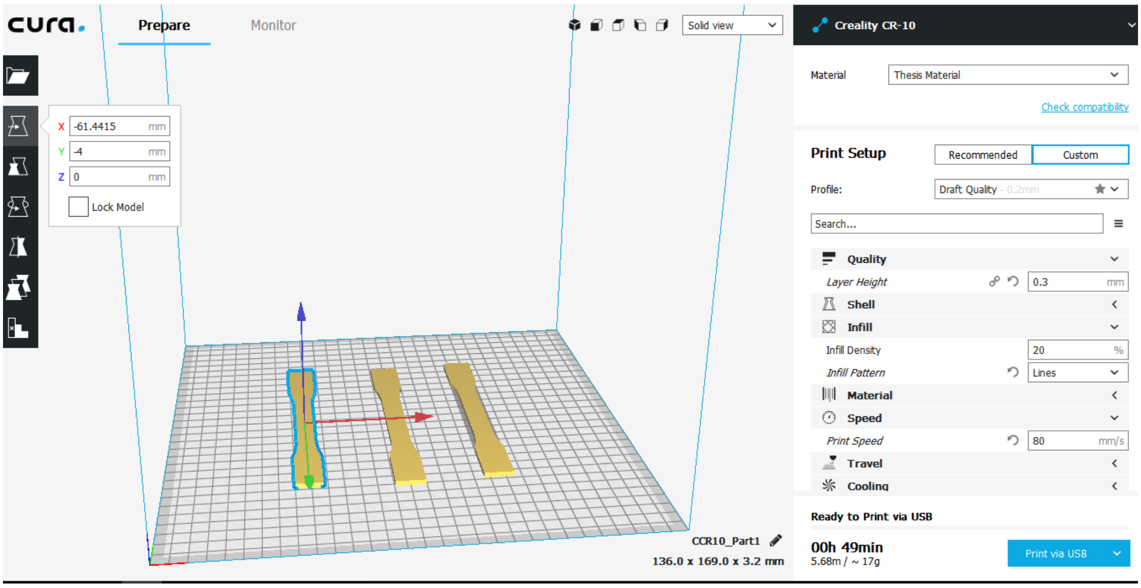
There are basically 3 main steps to create 3D print including, firstly, creating a CAD design, exporting to STL and send to printer, then setting up the printing process.

1. The model of specimens firstly was created by using SolidWorks software with the dimensions as mentioned above. The object was saved in SLDRT file format as default.

2. Because the Cura software and other 3D printing software only works with STL file then the model file must to be converted into STL file to be compatible with Cura. It could be done easily by using export function in SolidWorks.

3. Once STL file is created completely, importing it into MakerBot software as a new project.

4. Cura offers many options which allow users to adjust the position, orientation and real size of objects as Figure 18.



X -61.4415 mm
Y -4 mm
Z 0 mm
☐ Lock Model

CCR10_Part1
136.0 x 169.0 x 3.2 mm

Material: Thesis Material
Profile: Draft Quality - 0.2mm
Layer Height: 0.3 mm
Infill Density: 20 %
Infill Pattern: Lines
Print Speed: 80 mm/s

00h 49min
5.68m / ~ 17g

Figure 18. Cura configuration.

Whenever users would like to modify the model, they could do adjustments with the tools on the left side as in the picture above. The model must to be picked first, then click on the preferred tool. The arrows would be appeared around the model. You could decide to modify manually by dragging the arrows or inserting the values into the boxes on the left side to get the desired position.

On the right side, the printer setting box appears with multiple options such that users could modify to obtain preferred setting. Firstly, the material would be picked up. Users could choose the materials in the library of Cura which are registered with required technical values already or customize the new one in material manage option.

With print setup, users could choose recommended choice or custom choice. Cura will automatically offers such options with respective to the chosen material if recommended mode is picked. Otherwise, users could adjust manually others printing parameters with custom.

- Quality: the layer height is picked in this option;
- Shell: users could choose to pick some shell adjustments such as wall thickness, top thickness, bottom thickness, etc;
- Infill: in which infill density and infill pattern are chosen. Cura offers variety of pattern to choose as linear, zigzag, triangle, concentric...;
- Material: this field shows the material printing temperature and build plate temperature which are matched with chosen material;

Table 9. Printing setup

Printing setup	Value
Density	1.24 (g/cm^3)
Diameter	1.75 mm
Printing temperature	230 °C
Plate temperature	80 °C

- Speed: allows users to adjust print speed. The default speed is 60 mm/s;
- Support: creates the support part if necessary, to hold hanging part. This part is easily removed from the model after printing.

5. Once the object is fix in proper location and users then set the printing parameters which are very important. In general, there are 3 main settings people should consider listed as infill, resolution (layer thickness) and pattern. In addition, raft and support sometimes are necessary to add in. Other technical settings such as extrusion temperature, nozzle speed, etc., are highly recommended to keep unchanged.

6. Then before getting started, one should recheck the printer to ensure the high printing performance. Firstly, the printer is turn on to warm up the heater and get desired extrusion temperature. The filament also needs to be revised. The unloading and loading process needs to be performed under the supervision of technicians. The working plate is taken care after that. After many prints, the tape is supposed to be damaged or in bad conditions, so it is required to change it. It is easy to find tape to replace and make sure there are no overlaps, creases or bubbles when changing new tape.

7. Once preparation is done, printing process could be started. There are 2 ways to print with MakerBot by connecting directly from laptop to printer or connecting through USB. The printing file after being prepared is saved and stored in USB, then we could connect it through USB port in printer.

8. When it finished printing, taking off the object from plate carefully to avoid any damages to products and plate as well. Eliminating the rafts and supports if necessary.

9. Cleaning the printing plate, and removing all materials left. Disconnecting the printer and laptop, then turning off. Obtained samples after printing process showed as Figure 19.

Figure 19. Samples after printing.

3.4 Testing method

"The tensile test is used to investigate the tensile behavior of the test specimens and for determining the tensile strength, tensile modulus and other aspect of tensile stress/strain relationship under the conditions defined." [36].

The test specimens under the load are extended along its major longitudinal axis at a constant speed until break occurs or the stress or the strain reaches expected value. The applied load and elongation of specimen are also measured and recorded automatically meanwhile.

In order to obtain the exact results in standard conditions, the tensile-testing machine shall comply with ISO 7500-1 and ISO 9513 and meet the specifications given below [36].

3.4.1 Test speed

The test speed is recommended to set as Table 10. The values could be changed depended on the experiment conditions with tolerance around 10-20 %.

Table 10. Recommended test speeds *[36]*

Test speed v mm/min	**Tolerance** %
0,125	±20
0,25	
0,5	
1	
2	
5	
10	
20	±10
50	
100	
200	
300	
500	

Before performing experiment, the tensile test machine should be checked carefully to ensure good conditions. Grips which hold the specimens should be attached to the machine tightly and the major axis of the test specimen coincides with the directions of extension through the center line of grip assembly. The grip also should be tight enough to prevent the test specimens from slipping relative to gripping jaws. In other hand, the gripping system shall not cause any damage or premature fracture at the jaws or break the specimens.

4 RESULTS

4.1 Tensile testing results

The tests were performed by using Testometric-tensile testing machine. There are 3 specimens of each type tested and results obtained by getting the mean values. In the scope of this paper, 7 information needed to take insights the material's properties included Young's modulus, Stress Yield, Stress Peak, Elongation Break, Elongation Yield, Force at Yield and Force at Peak.

In order to make it easy to follow, the type of specimen is named as the following rule:

Name = building orientation – infill percentage – resolution.

For example, the specimens which were built in 0° orientation with 20 % infill and 0.4 resolution will be called as: 0-20-0.4.

The results were automatically recorded when tests finished along with the graphs. The graphs show the relationship between stress and strain.

4.1.1 Type 1: 0-20-0.2

The results of specimens which were built in 0° building orientation with 20 % infill and 0.2 resolution were showed in Table 11 and Figure 20:

Table 11. Type 0-20-0.2 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	792.903	20.202	20.202	3.332	3.013	856.1	856.1
Max	807.027	20.214	20.214	3.546	3.227	856.500	856.500
Mean	799.275	20.208	20.208	3.439	3.119	856.267	856.267

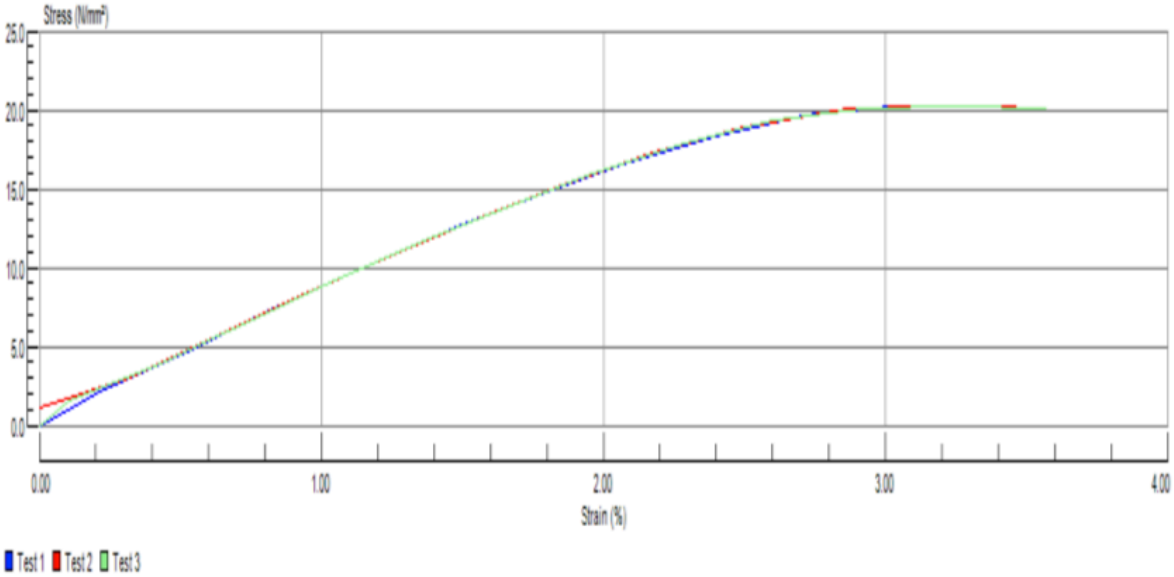


Figure 20. Type 0-20-0.2 Stress-strain graph.

4.1.2 Type 2: 0-40-0.2

The results of specimens which were built in 0° building orientation with 40 % infill and 0.2 resolution were showed in Table 12 and Figure 21:

Table 12. Type 0-40-0.2 results.

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	916.116	23.648	23.648	2.532	2.532	1002	1002
Max	922.728	23.801	23.801	2.587	2.587	1008.5	1008.5
Mean	919.422	23.724	23.724	2.56	2.56	1005.25	1005.25

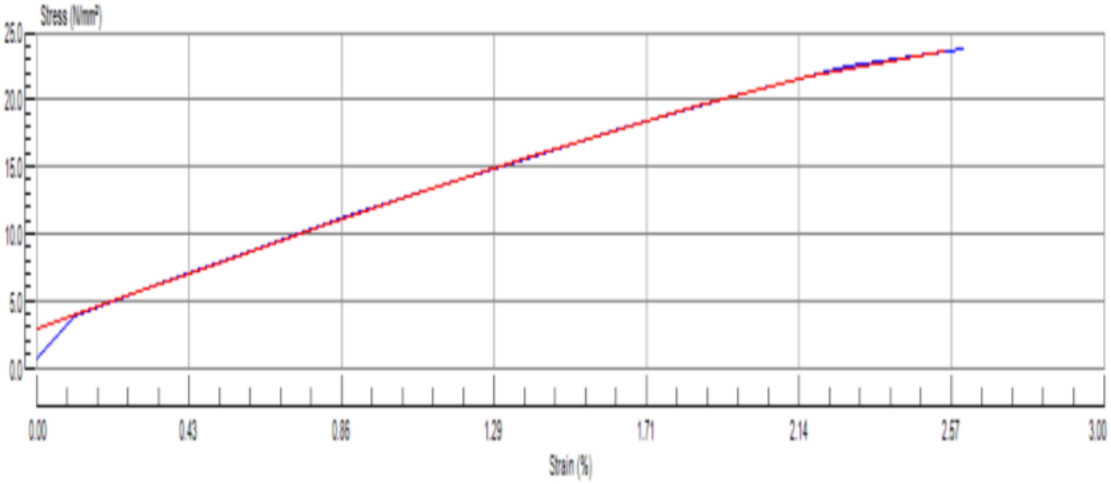


Figure 21. Type 0-40-0.2 Stress-strain graph.

4.1.3 Type 3: 0-60-0.2

The results of specimens which were built in 0° building orientation with 60 % infill and 0.2 resolution were showed in Table 13 and Figure 22:

Table 13. Type 0-60-0.2 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	988.587	25.821	25.821	2.577	2.577	1094.1	1094.1
Max	1080.522	28.908	28.908	2.949	2.949	1224.9	1224.9
Mean	1019.82	27.071	27.071	2.724	2.724	1147.067	1147.067

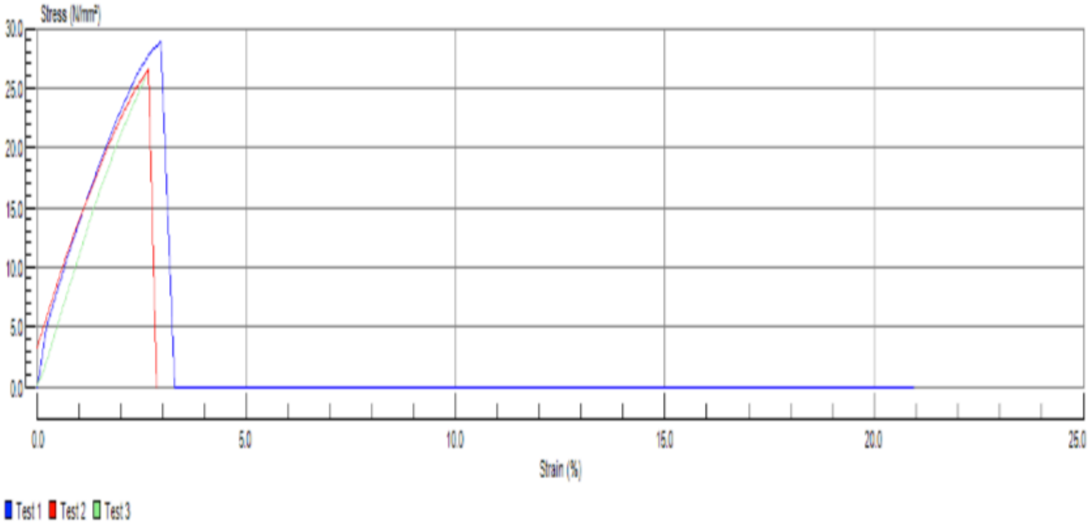


Figure 22. Type 0-60-0.2 Stress-strain graph.

4.1.4 Type 4: 0-20-0.3

The results of specimens which were built in 0° building orientation with 20 % infill and 0.3 resolution were showed in Table 14:

Table 14. Type 0-20-0.3 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	870.835	22.527	22.527	2.211	2.211	954.500	954.500
Max	883.870	23.105	23.105	2.426	2.426	979.000	979.000
Mean	876.412	22.856	22.856	2.319	2.319	968.367	968.367

4.1.5 Type 5: 0-40-0.3

The results of specimens which were built in 0° building orientation with 40 % infill and 0.3 resolution were showed in Table 15 and Figure 23:

Table 15. Type 0-40-0.3 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1018.020	23.749	23.749	2.824	2.824	1006.3	1006.3
Max	1078.889	27.445	27.445	3.832	3.502	1162.900	1162.900
Mean	1046.846	25.969	25.969	3.422	3.189	1100.367	1100.367

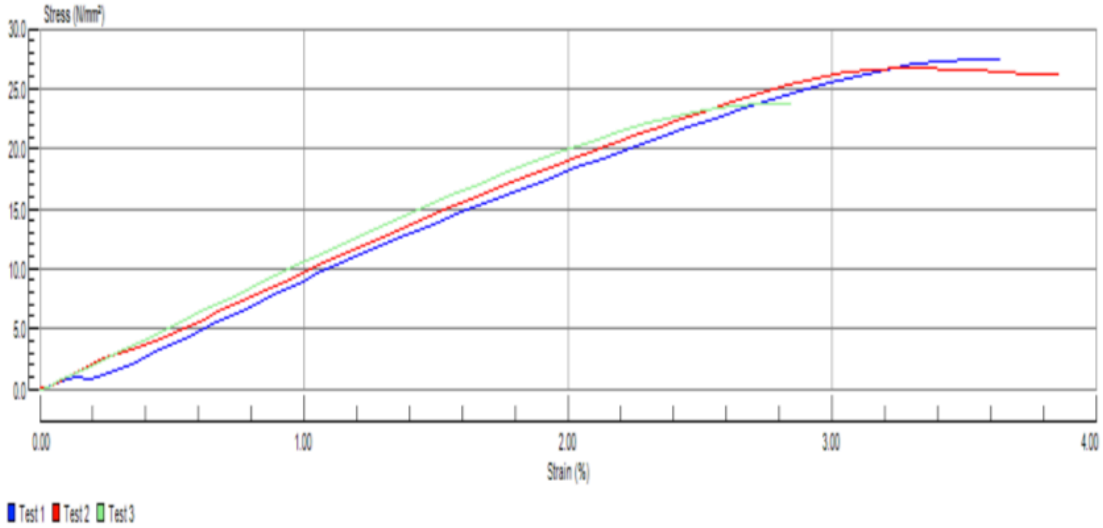


Figure 23. Type 0-40-0.3 Stress-strain graph.

4.1.6 Type 6: 0-60-0.3

The results of specimens which were built in 0° building orientation with 60 % infill and 0.3 resolution were showed in Table 16 and Figure 24:

Table 16. Type 0-60-0.3 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1051.756	29.210	29.210	3.231	3.231	1237.700	1237.700
Max	1176.617	29.725	29.725	4.250	3.612	1259.500	1295.500
Mean	1100.815	29.386	29.386	3.694	3.374	1245.133	1245.133

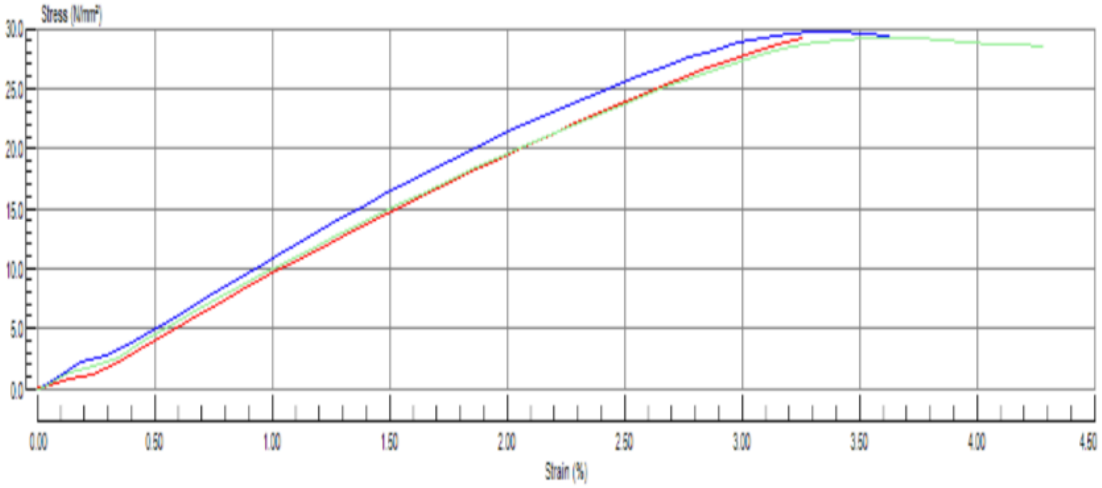


Figure 24. Type 0-60-0.3 Stress-strain graph.

4.1.7 Type 7: 0-20-0.4

The results of specimens which were built in 0° building orientation with 20 % infill and 0.4 resolution were showed in Table 17 and Figure 25:

Table 17. Type 0-20-0.4 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1081.738	28.174	28.174	3.083	2.763	1193.800	1193.800
Max	1259.866	29.746	29.746	3.083	3.083	1260.400	1260.400
Mean	1182.010	28.966	28.966	2.974	2.974	1245.133	1245.133

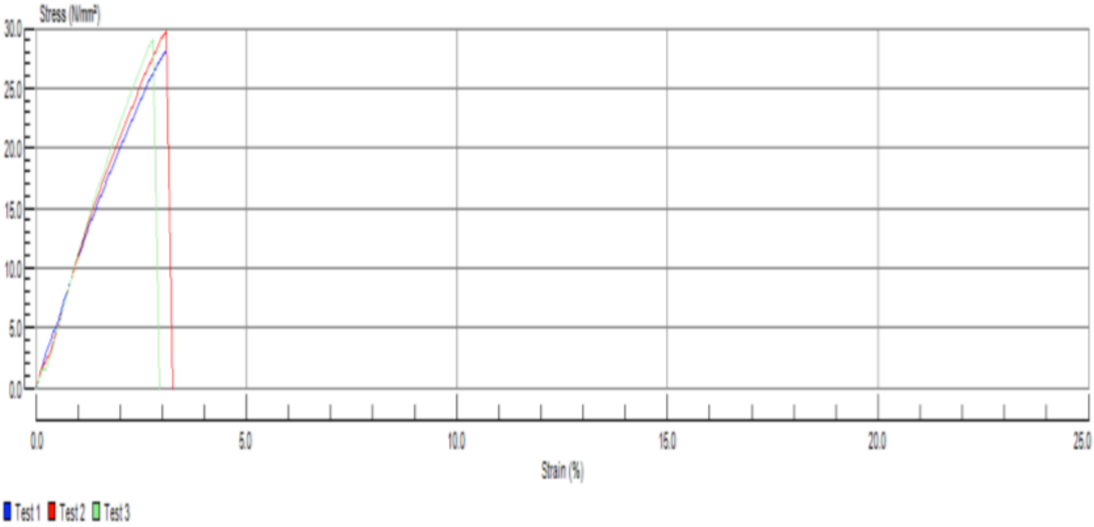


Figure 25. Type 0-20-0.4 Stress-strain graph.

4.1.8 Type 8: 0-40-0.4

The results of specimens which were built in 0° building orientation with 40 % infill and 0.4 resolution were showed in Table 18 and Figure 26:

Table 18. Type 0-40-0.4 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1033.901	27.344	27.344	2.699	2.699	1158.600	1158.600
Max	1282.792	32.566	32.566	5.662	4.147	1379.900	1379.900
Mean	1194.298	30.722	30.722	4.180	3.398	1301.733	1301.733

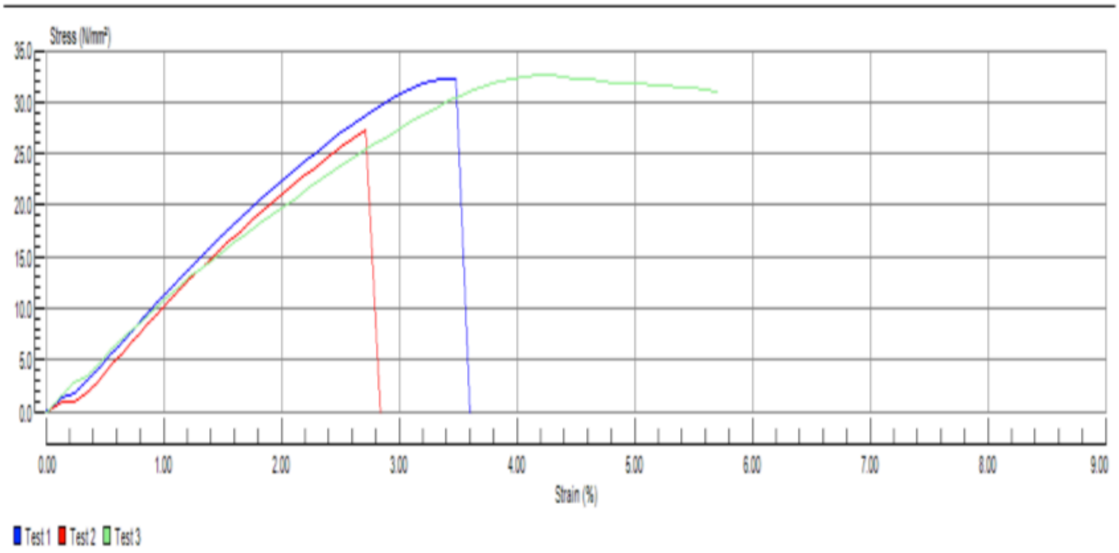


Figure 26. Type 0-40-0.4 Stress-strain relationship.

4.1.9 Type 9: 0-60-0.4

The results of specimens which were built in 0° building orientation with 60 % infill and 0.4 resolution were showed in Table 19:

Table 19. Type 0-60-0.4 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1233.387	32.918	32.918	3.211	3.211	1394.800	1394.800
Max	1307.624	34.756	34.756	5.260	5.260	1472.700	1472.700
Mean	1259.591	34.053	34.053	4.235	4.235	1442.900	1442.900

4.1.10 Type 10: 45-20-0.2

The results of specimens which were built in 45° building orientation with 20 % infill and 0.2 resolution were showed in Table 20 and Figure 27:

Table 20. Type 45-20-0.2 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	967.017	20.407	20.407	2.123	2.123	864.700	864.700
Max	1078.773	25.533	25.533	2.975	2.975	1081.900	1081.900
Mean	1025.561	22.985	22.985	2.568	2.568	973.900	973.900

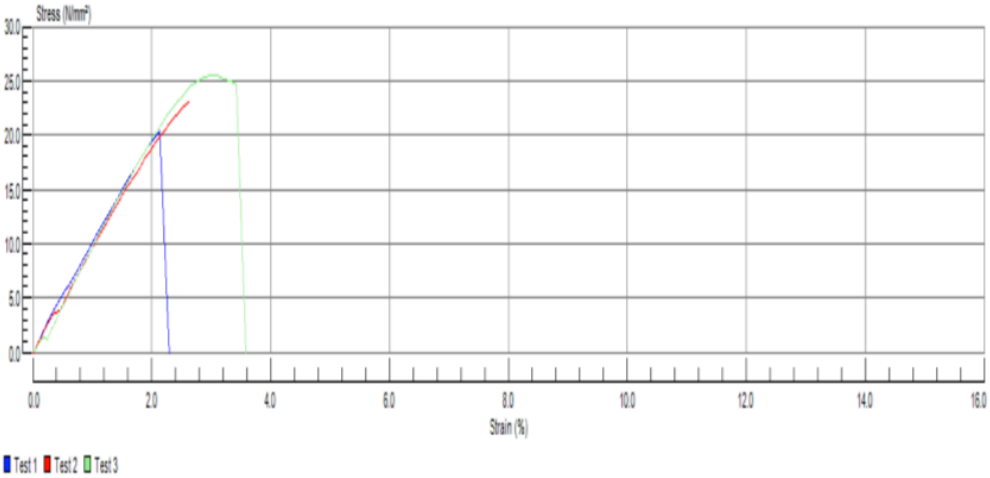


Figure 27. Type 45-20-0.2 Stress-strain graph.

4.1.11 Type 11: 45-40-0.2

The results of specimens which were built in 45° building orientation with 40 % infill and 0.2 resolution were showed in Table 21:

Table 21. Type 45-40-0.2 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1117.610	28.361	28.361	2.920	2.920	1201.700	1201.700
Max	1167.678	29.649	29.649	3.290	3.290	1256.300	1256.300
Mean	1146.531	29.039	29.039	3.233	3.133	973.900	973.900

4.1.12 Type 12: 45-60-0.2

The results of specimens which were built in 45° building orientation with 60 % infill and 0.2 resolution were showed in Table 22 and Figure 28:

Table 22. Type 45-60-0.2 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1251.763	31.148	31.148	2.917	2.917	1319.800	1319.800
Max	1313.068	32.925	32.925	4.208	3.232	1395.100	1395.100
Mean	1284.579	32.043	32.043	3.56	3.056	1357.733	1357.733

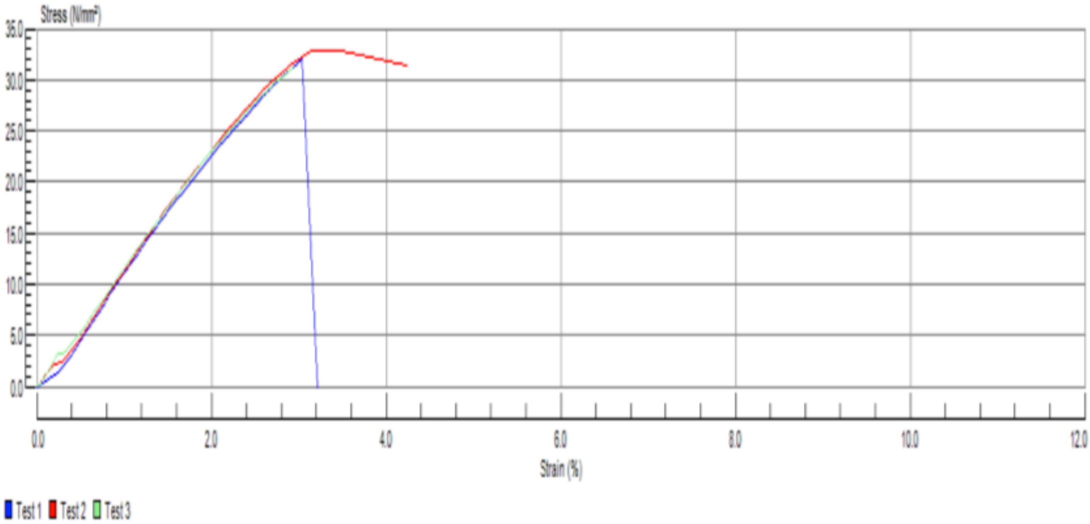


Figure 28. Type 45-60-0.2 Stress-strain graph.

4.1.13 Type 13: 45-20-0.3

The results of specimens which were built in 45° building orientation with 20 % infill and 0.3 resolution were showed in Table 23 and Figure 29:

Table 23. Type 45-20-0.3 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	980.451	19.666	19.666	2.231	2.231	833.300	833.300
Max	1035.121	23.612	23.612	3.182	2.862	1000.500	1000.500
Mean	1016.544	21.969	21.969	2.70	2.582	930.867	930.867

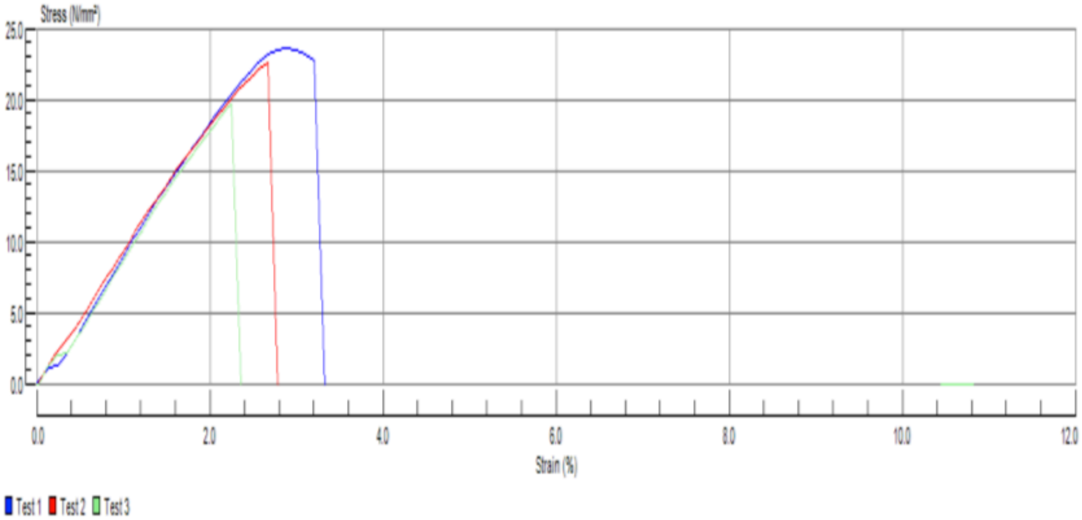


Figure 29. Type 45-20-0.3 Stress-strain graph.

4.1.14 Type 14: 45-40-0.3

The results of specimens which were built in 45° building orientation with 40 % infill and 0.3 resolution were showed in Table and Figure 30:

Table 25. Type 45-40-0.3 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	959.814	20.329	20.329	2.493	2.493	861.400	861.400
Max	1041.241	24.979	24.979	3.234	3.234	1058.400	1058.400
Mean	1030.274	23.254	23.254	2.954	2.582	985.300	985.300

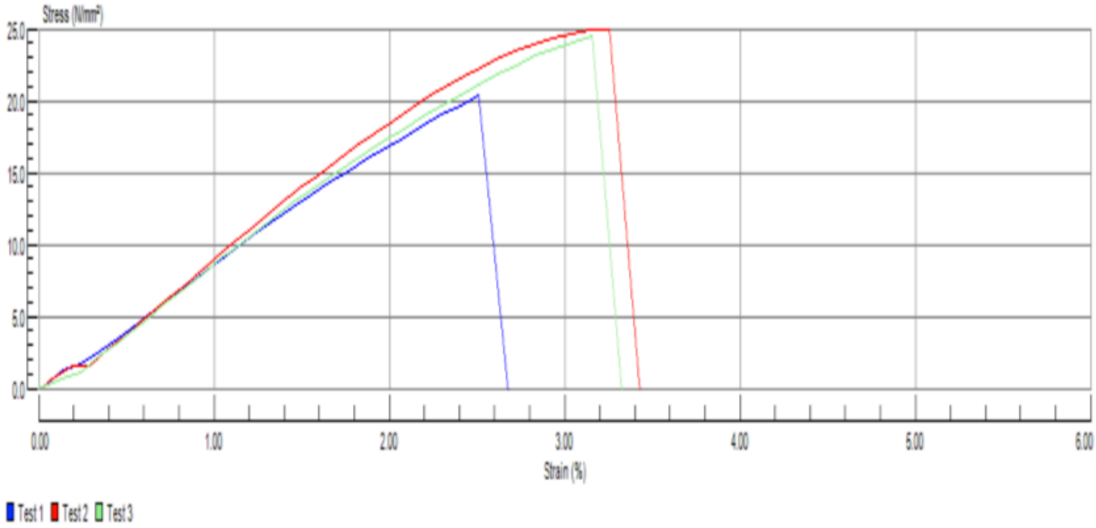


Figure 30. Type 45-40-0.3 Stress-strain graph.

4.1.15 Type 15: 45-60-0.3

The results of specimens which were built in 45° building orientation with 60 % infill and 0.3 resolution were showed in Table 24 and Figure 31:

Table 24. Type 45-60-0.3 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1151.504	26.730	26.730	2.978	2.978	1132.600	1132.600
Max	1205.561	28.696	28.696	4.7	3.298	1215.900	1215.900
Mean	1178.668	28.007	28.007	3.839	3.099	1186.700	1186.700

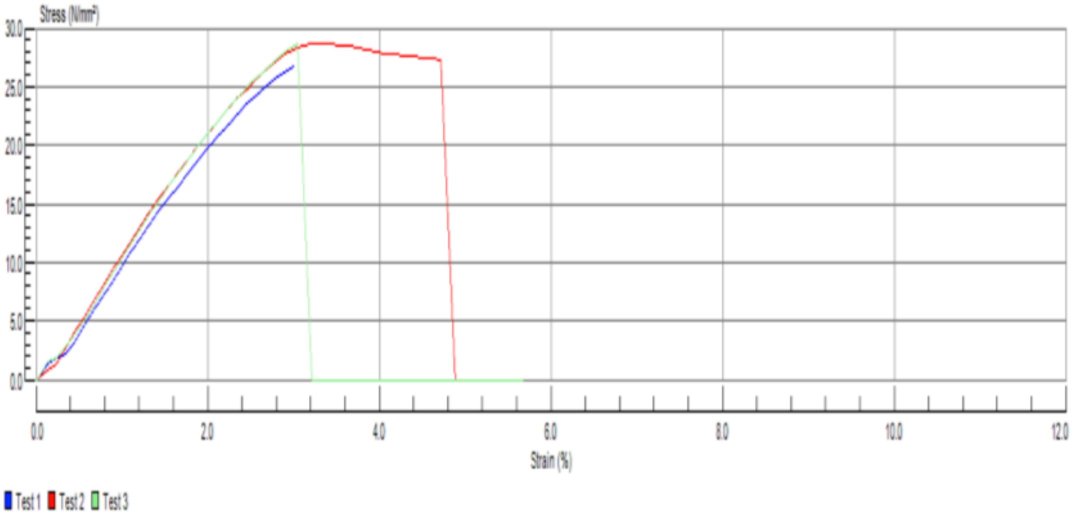


Figure 31. Type 45-60-0.3 Stress-strain graph.

4.1.16 Type 16 45-20-0.4

The results of specimens which were built in 45° building orientation with 20 % infill and 0.4 resolution were showed in Table 25 and Figure 32:

Table 25. Type 45-20-0.4 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1170.333	29.489	26.730	2.978	2.978	1132.600	1132.600
Max	1205.561	28.696	28.696	4.7	3.298	1215.900	1215.900
Mean	1178.668	28.007	28.007	3.839	3.099	1186.700	1186.700

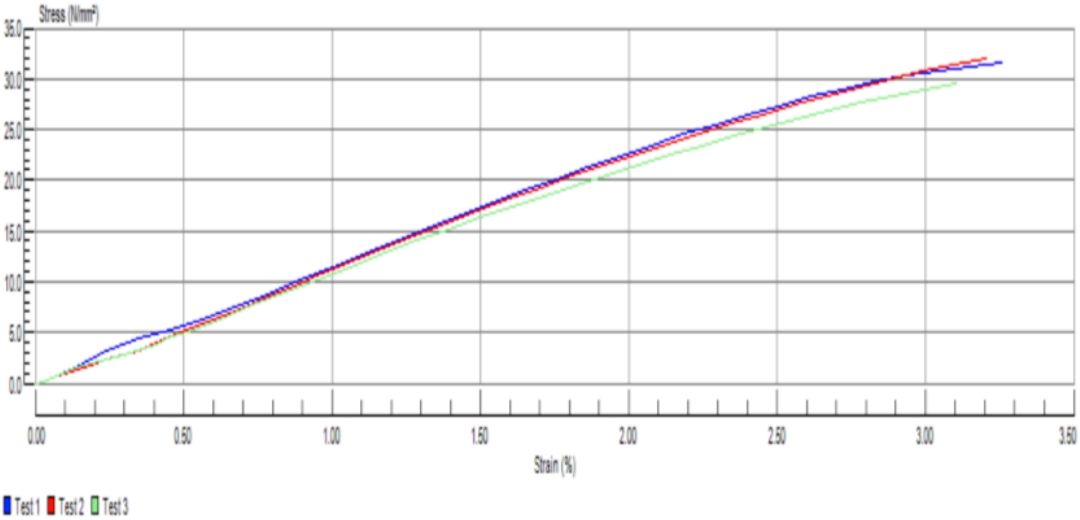


Figure 32. Type 45-20-0.4 Strain-stress graph.

4.1.17 Type 17: 45-40-0.4

The results of specimens which were built in 45° building orientation with 40 % infill and 0.4 resolution were showed in Table 26 and Figure 33:

Table 26. Type 45-40-0.4 results

	Young's Modulus(N/mm^2)	Stress Yield(N/mm^2)	Stress Peak(N/mm^2)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1101.892	22.942	22.942	2.115	2.115	972.100	972.100
Max	1261.231	31.245	31.245	3.395	3.395	1323.900	1323.900
Mean	1192.707	27.347	27.347	2.774	2.774	1158.767	1158.767

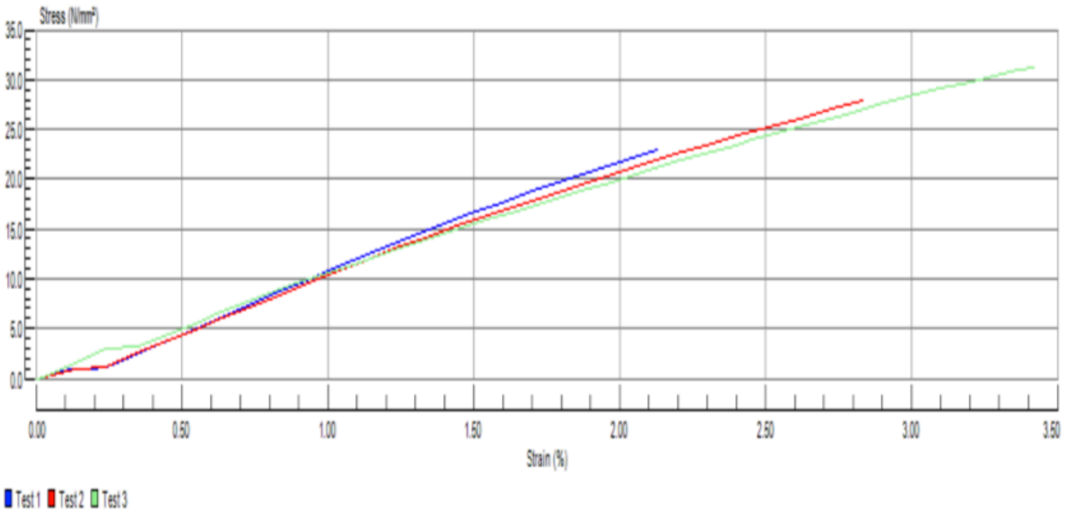


Figure 33. Type 45-40-0.4 Stress-strain graph.

4.1.18 Type 18: 45-60-0.4

The results of specimens which were built in 45° building orientation with 60 % infill and 0.4 resolution were showed in Table 27 and Figure 34:

Table 27. Type 45-60-0.4 results

	Young's Modulus(N/mm²)	Stress Yield(N/mm²)	Stress Peak(N/mm²)	Elongation Break(mm)	Elongation Yield(mm)	Force Yield(N)	Force Peak(N)
Min	1320.173	27.259	27.259	2.487	2.487	1155.000	1155.000
Max	1361.078	36.982	36.982	4.292	3.740	1567.000	1567.000
Mean	1337.383	31.588	31.588	3.176	2.992	1338.433	1338.433

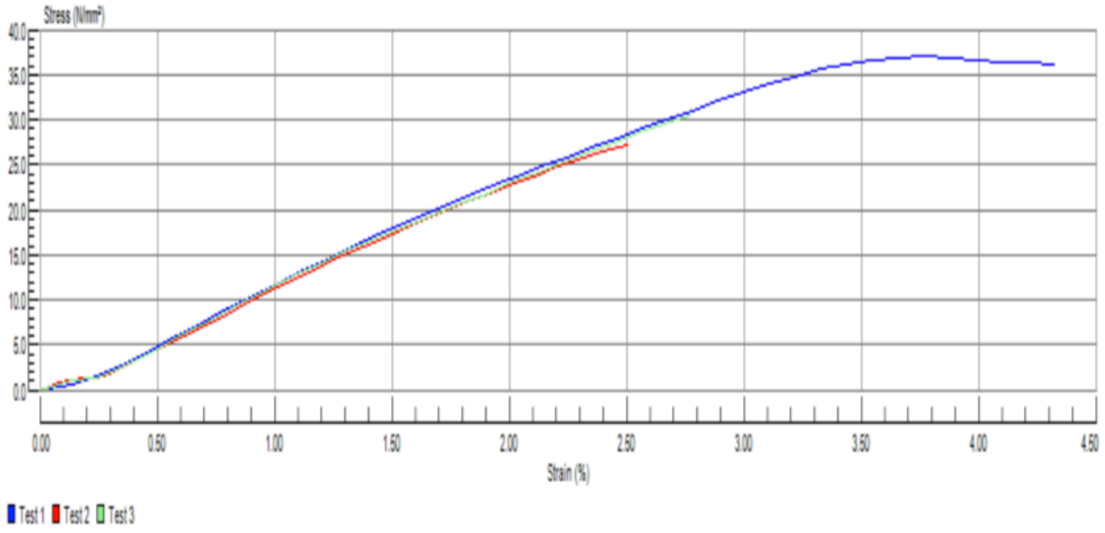


Figure 34. Type 45-60-0.4 Stress-strain graph.

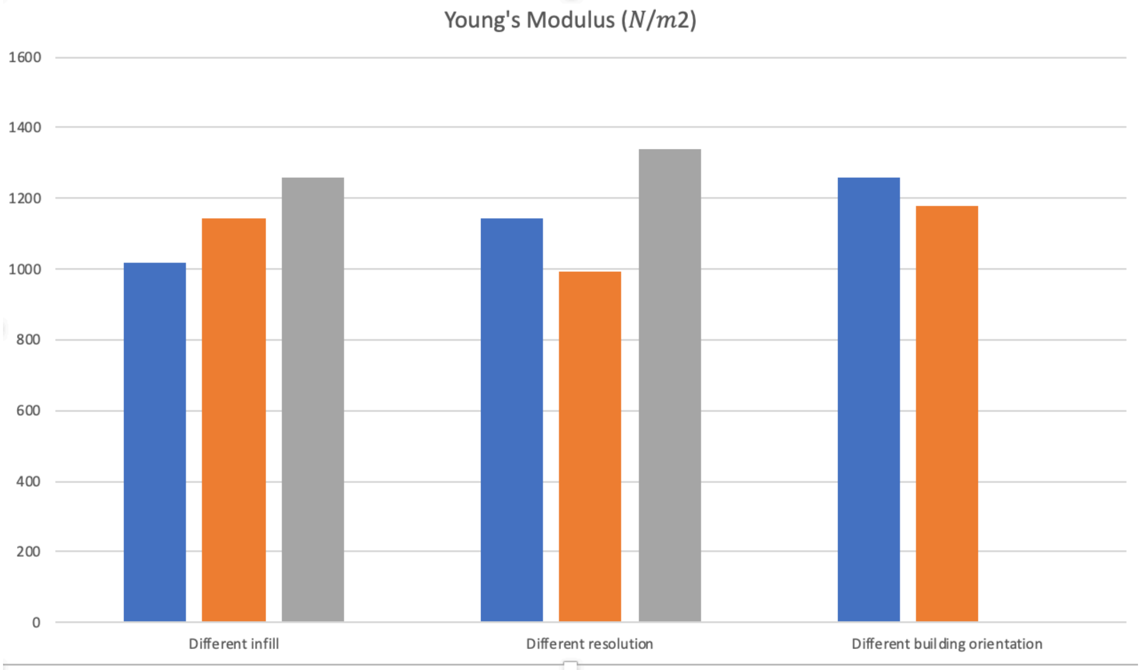


Figure 35. Young's Modulus column chart.

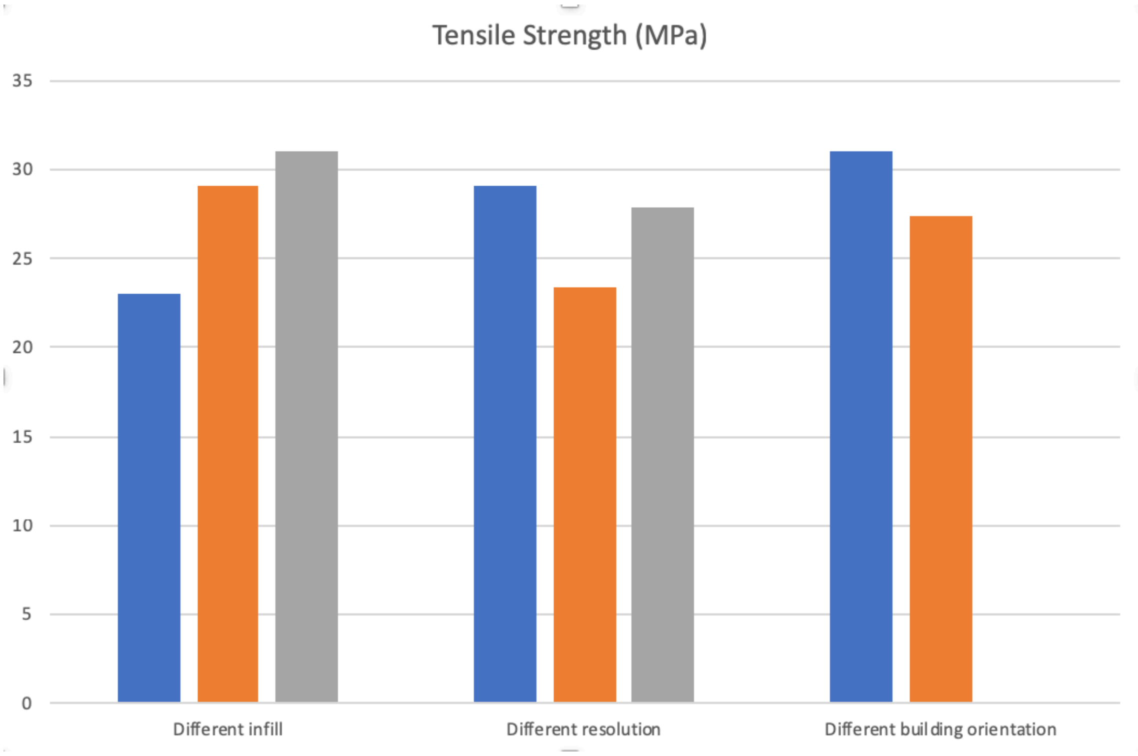


Figure 36. Tensile strength results.

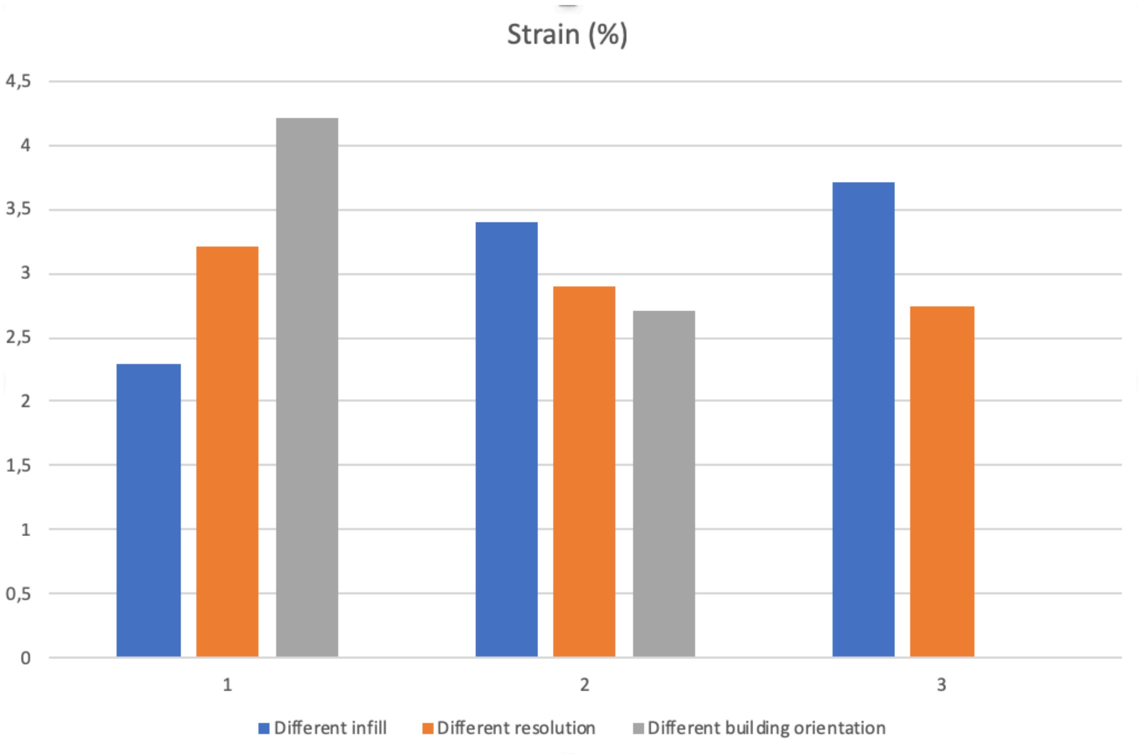


Figure 37. Strain results.

5 DISCUSSIONS

5.1 Young’s Modulus results

In order to figure out how Young’s modulus is influenced by printing settings, we will compare the results among the specimens in three cases: different infill percentage, different resolution and different building orientation. The Figure 35 compiles three situation to make a comparison.

As a glance at chart, the Young’s modulus increases when all three factors change. Clearly, the infill level influence directly the strength of materials. High level of infill indicates the stiffer material leading to higher Young’s modulus. Young’s modulus slightly increased to 1030.274 MPa from 1016.544 MPa then climbed around 50 units when infill level was set consecutively 20 %, 40 % and 60 %. However, as this trend indicates, it is expected that Young’s modulus will change significantly when infill percentage gets to higher level. Meanwhile, the layer thickness determines the stiffness of materials. As explained before, the specimens with lower layer thickness are formed by more condensed stacked layers. It means the inter-layer bonds are much stronger. Then it is hard to pull them far from each other. It’s expected that more energy and tension force are required to extend the specimen. However, the Young’s modulus has descreased from 1146.531MPa to 992.274 MPa, about 8 %, when layer thickness went from 0.4 down to 0.3. Meanwhile, it has even skyrocketed when decreased the resolution from 0.3 to 0.2. It changed 200 units. It reveals that there is no linear relation between layer thickness and Young ’s Modulus. In other hand, rotating the building orientation brings a slightly change in material properties. Young’s Modulus value of specimen is 1259.591 at 0° building degree compared to 1337.383 at 45°. However, this change could be considered when the products need more stiffness. In conclusion, when one needs increase the Young’s modulus of products, he could consider among increasing the infill percentage, decreasing the layer thickness or change the building orientation. As discussed above, increasing infill percentage might influence significantly at low level, meanwhile, at high infill level, the increase is not meaningful compared to the printing time wasted.

5.2 Tensile strength results

In this paper, we aim to figure out how the printing setting affects the tensile strength of material. Obtained results are compared among different groups of materials: different infill, different resolution and different building orientation. The Figure 36 shows the difference in the tensile strength among groups:

The tensile strength intends to increase when the infill level goes up. This is explained that much material have been filled inside specimens, much strong and rigid the specimens are. More tension stress is needed to break the sample while stretching it. The ultimate strength increases from 22.985 MPa to 29.039 MPa, about 26 % when infill level comes from 20 % to 40 %. It continued going up, but less, to 32.043 MPa when infill level reached 60 %, only 10 %. It is expected that the tensile strength will increase even slightly when the infill percentage is brought up. In contrast, the ultimate strength continued fluctuating when resolution gradually increased. It significantly felt down from 29.039 MPa to 23.354 MPa while resolution was adjusted from 0.2 to 0.3. It was expected to drop down more when resolution got high, however, it suddenly climbed to 27.347 MPa, about 25 % at 0.4 mm of layer thickness. It is clear that this change is completely remarkable and could not be error during testing. Therefore, it is proven again that there is no linear relation between layer thickness and tensile strength. Otherwise, the tensile strength has been decreased when building direction was changed from 0° to 45°. This could be explained that the inner layer which is arranged in 45° degree makes the ability of material to resist the axial load weaker. Even the Young’s modulus is getting higher, however, the tensile strength is decreasing significantly.

5.3 Strain results

Figure 37 represents the results of elongation break values obtained from three different groups of specimens: different infill, different resolution and different building orientation.

The elongation break increased proportionally when infill level went up. The specimen extended about 2.3 % of its length at 20 % infill percentage, meanwhile at 40 %, the elongation break value was 3.42 %, a significant change. It was not like this when the infill level was brought up once more time to 60 %, just only 0.2 % more. Otherwise, increasing layer thickness brought a negative effect on fracture strain. It was recorded that the ductility of material was gradually decreased when resolution increases from 0.2 to 0.4 and 0.6. The change seemed like stable and not be too much different when layer thickness fell down. At next group, it experienced a great change at fracture strain. It was nearly cut a half down when building orientation was switched from 0° to 45° creating a biggest change among 3 groups. Clearly, the arrangement of filament inside the specimen influences the ductility of material. Hence, if high ductility material is needed, it should be printed in 0° building orientation. It is highly recommended compared to increase infill percentage or decrease layer thickness which results in much more printing time.

6 CONCLUSIONS

This thesis has researched the influence of printing parameters on the mechanical properties of materials by using FDM technology. The background and relevant definitions of FDM were reviewed and discussed in detailed in literature chapter. The number of popular materials used in FDM technology were listed also along with their benefits, drawbacks and application. Therefore, people could have a general view of how to choose proper material for specific purposes. Besides, the paper went deeply on the historical information, manufacturing processes of PLA which is used in experiment. It was also compared to ABS, another popular material in FDM, to explain why PLA is chosen for this research.

The thesis included the insight of FDM technology with processes and its significant settings. Each setting will influence the performance of products in separately ways, hence they were researched carefully and led to the roles of them.

The preparation of samples then was represented on the method chapter. There was 18 type of specimens with different characteristics was tested. 3 specimens per type sums up 54 samples in total. All specimens were designed by SolidWorks then imported to printing software to manufacture. During manufacturing process, firstly, all finished samples were created perfectly but without the center line. This deficiency was due to the original STL file. When convert SLDRT file to STL file in SolidWorks, the quality of exported file should be adjusted high enough to avoid the lack of centerline.

At the beginning, the paper aimed to test the specimens printed in 90° instead of 45°. However, the setup was failed, because printer kept printing in 0° degree even changed the direction of specimens and the printing pattern. Therefore, the direction was chosen as 45° and it was succeeded.

During printing specimens, there were some points affecting the working efficiency and results. Firstly, the connection between the printer and computer is really unstable. It usually took 15 minutes to connect successfully whenever the printer is restarted. Fortunately, this only happened at the beginning, then the printer run smoothly. Besides, the heating temperature is going up slowly to get desired temperature, meanwhile, cooling up too fast. This is due to the metal part sticking under the working plate. It allows heat emitting easily but absorbs heat gradually.

The results were then recorded and represented in results chapter. Tensile strength, Young's modulus and strain were compared among three different categories: different infill level, different resolution and different building orientation. It concluded that the infill percentage increasing results in the positive effect both in tensile strength, Young's modulus and strain. At low level of infill percentage, any changes do not make much different in Young's modulus, however at high level, 60 %, Young's modulus is remarkably high compared to 20 % or 40 %. Therefore, it is worth to increase infill setting if material needs more toughness. In contrast, infill percentage influences significantly on the tensile strength and elongation break even at low level. The obtained results figured out the 20-30 % increasing in these when infill goes up from 20 % to 40 %. Meanwhile, not much different if infill goes to 60 %. Hence, it should be considered if one would like to increase the strength and ductility of products by giving them more infill. That is paid off due to the high level of infill leads to increasing in printing time.

The layer thickness, however, is much more unpredictable. The graphs showed that there is no linear relation between resolution and Young's modulus, tensile strength but fraction fracture. The best tensile strength and Young's modulus often obtained by the middle values of resolution or in the flanges. Hence, in order to improve the accurate of research, more samples printed in broader resolution range needed to be done. After that, one could see at which resolution that material would produce best performance. In the scope of this paper, it only could be concluded that no linear relation between layer thickness and Young's modulus.

Lastly, samples built with different orientation were tested and compiled the results. It figured out that the influences of orientation on the mechanical properties is real and predictable. The 45° samples are stronger and tougher than 0° ones in general, however, other sides indicated that 0° ones overwhelm and win at tensile strength and elongation break. The changes in building orientation also lead to changes in printing time, however it's not comparable. Hence, it should be considered first then other settings when one would like to change product's characteristics.

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