Additive Manufacturing In Medical Application, A Comparative Study Between Conventionally Made Prosthesis (Pylon) And 3D Printed Prosthesis (Pylon)

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Abstract

Prosthesis is an important device in helping amputee to recover from traumatizes experience. Prosthesis is an expensive device and not all amputees afford to own one, especially in the third world country. The method of fabrication and specialize person contributed to the high price. The short life cycle of the prosthesis doesn't match with the high cost of ownership. The advancement of manufacturing technologies gives birth to additive manufacturing, a manufacturing process that did not use any tooling or molding. With additive manufacturing process, it is possible to produce low cost prosthesis due to the nature of the process. Additive manufacturing excels in producing low volume with high customizable product. The objective of this project is to compare between conventionally made prosthesis with additive manufactured prosthesis. The comparison was done using statistical analysis focusing on the pylon in term of impact energy with print time and weight as the secondary proof. The study found that by comparing the impact energy between HDPE and fabricated ABS sample, 4 of the sample impact energy exceed the HDPE. The print time and weight of the sample help to determine which FDM parameter of the print is the best. Comparing the weight of both specimen HDPE and FDM sample the FDM exceed the weight of the HDPE sample but it is not significant. The Hardness test also concluded that FDM have high HR numbers. The result of the master report shows that it is possible to produce prosthesis pylon using FDM process.

Key Words: FDM, 3d printing; advance manufacturing; prosthetic; ABS; HDPE

1.0 INTRODUCTION

The prosthesis is a necessity for any amputee in order to recover from any traumatic experience either due to accident or disease. Currently, there are many methods used in the fabrication of prosthetic limb and the process is different from the manufacturer or fabricator and material type used. The usual material used for fabricating the prosthetic limb either polymer or aluminium and for the high end user, the prostheses are made from carbon fiber. The fabrication of the prosthetic is a time consuming and expensive process. Every prosthetic is individually fabricated for each patient. With the advancement of manufacturing process came additive manufacturing. Additive manufacturing is a process where the parts or product is built layer by layer without conventional tooling. This method of manufacturing could revolutionize the process of manufacturing prosthesis where it will reduce the manufacturing time and increase the customization factor.

This report will cover the possibility and benefit of using additive manufacturing, focusing on fused deposition modelling in producing prosthetic limb. The most important characteristic to be investigated is the ability of Fused Deposition Modelling (FDM) printed prosthesis to outperform the conventional High Density Polyethylene (HDPE) made prosthesis. This project will use Charpy impact experiment to find the impact energy and compared it between the FDM and HDPE specimen.

Additive manufacturing (AM) is a highly versatile manufacturing process with huge possibilities in producing high quality end product without using conventional manufacturing method. AM, typically known as 3D printing, is currently being promoted as the spark of a new industrial revolution. The technology allows one to make customized products without incurring any cost penalties in manufacturing as neither tools nor models are required (Weller et al 2014). One of the areas that are not widely explored is in the manufacturing of prosthetic limb using additive manufacturing. The current method producing the prosthetic limb involves casting, molding and machining and this method is expensive and it is not a onetime cost because the prosthetic deteriorate when use. The price of a new prosthetic limb is anywhere from $5000 to $50000 depending on the quality and it will withstand 3 to 5 years of wear and tear(Gillian, 2013). Furthermore the prosthetic limb needed to be custom fit for each individual and this will add more to the cost. The prosthetic in comparison is made from HDPE pipe using conventional heat forming process (Arya & Klenerman, 2008). Using additive manufacturing the manufactured prosthesis can be tailor made for each individual either adult or children. Yet the possibility of the AM manufactured prosthesis to outperform the conventionally made prosthesis is under question.

2.0 MATERIAL AND METHOD

The paper conducted following the below flowchart in figure 2.1

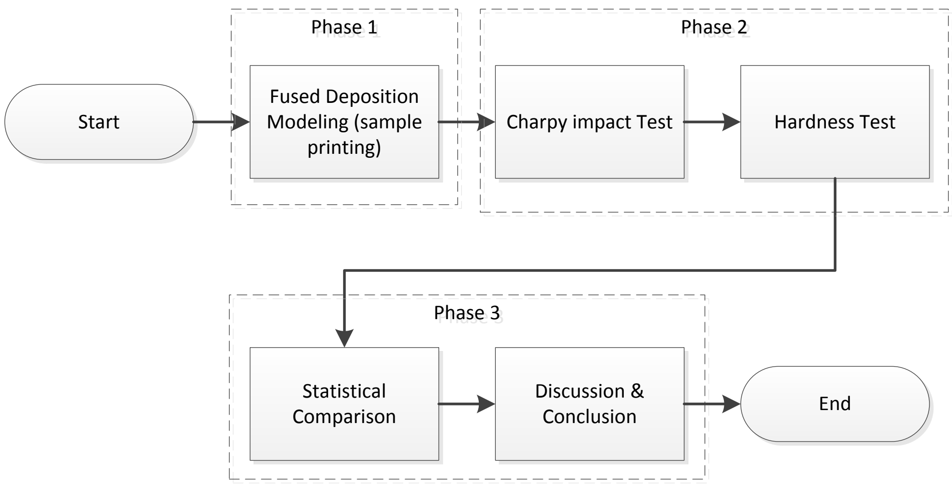


Figure 2.1: Paper Flowchart

2.1 Material

The material used in the experiment is Acrylonitrile Butadiene Styrene (ABS) a widely used material in the injection molding industry. The ABS materials are an excellent choice for making models, prototypes, patterns, tools and end-use parts. Acrylonitrile-butadiene-styrene (ABS)-based plastic is one of the most widely used filament materials for fused deposition modelling (FDM) applications (Singh et al, 2016). ABS is the chosen material due to its excellent mechanical properties in terms of high tensile, impact and flexural strength. Multiple combinations can be made from the original ABS to suit the design needs. The material used is opaque in color with the diameter of 1.75mm locally bought in Malaysia.

Table 1: ABS material specification

Characteristic	Information/values
Material	ABS
Description	Φ 1.75 mm
Tolerance	± 0.03 mm
Printing TEMP	Nozzle 210 ℃ - 230 ℃, Build Plate 50 ℃
Young's modulus	2 - 2.9 GPa
Compressive modulus	1.03 - 2.68 GPa
Poisson's ratio	0.394 - 0.422
Yield strength	29.6 - 44.1 MPa
Elongation	20 - 100 % strain

2.2 Method

Phase 1: Sample Printing

The FDM machine used in this paper is produced by WINBO a China base company. Table 2: shows the FDM printer specification that being used in the project

Table 2.1: FDM machine specification

Model no: WBFDM201515
Printing material: ABS, PLA, PETG, PET
Heated bed: yes, temperature (0 -120^{0}C)
Nozzle: DUAL (0.4mm) (temp 0-260^{0}C)
Build area: 205x155x155mm
Filament: diameter 1.75mm

Table 2.2: The machine setting used in fabricating the pylon

Nozzle temperature: 230^0 C (suggested)
Bed temperature: 110^{0}C
Nozzle speed: 40mm/s

Table 2.3: The parameter used in printing the pylon

Shell (round): 0, 2, 4, 6 and 8
Infill (%); 0, 25, 50 and 75
Dimension: ø20mm x 70mm

Phase 2: Destructive Test

The destructive experiment chosen for the project is Charpy impact test and Rockwell hardness test. The Charpy impact test is one of the basic experimental procedures to determine the object's ability to be subjected to dynamical loads. Charpy test on polymeric material is an impact tests which measure the resistance to failure of a material to a suddenly applied force by measuring the impact energy or the energy absorbed prior to fracture (Raicu, 2012). During the test, a hammer of a known mass is dropped from a specific height on a pendulum and hits the sample placed against supports. The angle of impact is set to 90^0. The test results are amounts of energy absorbed by the material during fracture, which can be used to calculate impact strength with known sample size. The test was performed in the same ambient conditions for all samples.

The Rockwell hardness test conducted on the FDM specimen follows the ASTM D 785 standard. The test uses L scale following the standard. The data are collected from two sides of the specimen, from the top and the side (Figure 2.2). The data collected from three (3) points from each side of the specimen. The purpose of the test is to prove the Charpy result that the FDM process can be used to manufacture prosthesis pylon.

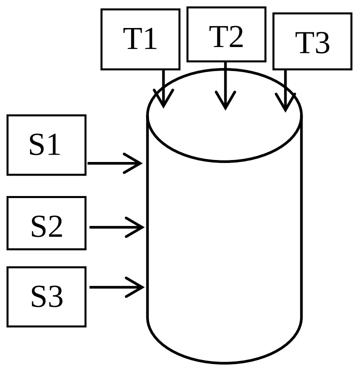


Figure 2.2: Indentation locations for Rockwell test

Phase 3: Comparison & Analysis

Comparing between two data collection will be done using statistical analysis. The impact energy is selected to be compared. The data comparison being done by comparing the histogram constructed from the data collected.

3.0 RESULT AND DISCUSSION

3.1 Result

3.1.1 Specimen, Print time and Weight

The specimen is printed out using an FDM printer using ABS filament material using suggested print temperature by the printer manufacturer. Figure 3.1 shows the specimen printed with 2 shells with 0%, 25%, 50% and 75% infill. Each specimen has different printing time infill of 0% needs 33 minutes, 25% needs 58 minutes, 50% needs 90 minutes and 75% needs 116 minutes.

Figure 3.1: sample of FDM printed Pylon

All of the specimen exhibit the same character which is as the shell thickness and infill increase, the print time also increase proportionally. Table 3.1 below show the relation between the specimen shell, infill percentage and print them.

Table 3.1: Table of FDM specimen shell, infill and print time

Specimen	Shell (no.)	Infill (%)	Print Time (minute)
1	2	0	33
2	2	25	58
3	2	50	90
4	2	75	116
5	4	0	49
6	4	25	76
7	4	50	100
8	4	75	125
9	6	0	68
10	6	25	92

Specimen	Shell (no.)	Infill (%)	Print Time (minute)
11	6	50	110
12	6	75	128
13	8	0	86
14	8	25	103
15	8	50	122
16	8	75	134

Table 3.2 shows the effect of shell and infill volume on weight, the weight of the specimen will increase proportionally with the increasing of shell and infill. Taking the sample with zero percentage of infill, S2I0 (shell =0, infill = 0%), S4I0 (shell = 4, infill = 0%), S6I0 (shell = 6, infill =0%) and (shell =8, infill = 0) an increasing of 86.25%, 174.93%, and 247.7% in weight from S2 to S8. The result data of specimen print time and weight is not the main comparative data; it is recorded as a secondary data to help justify the result of the problem statement.

Table 3.2: Numbers of shell and infill percentage and weight table

Specimen	Shell (no.)	Infill (%)	Weight (g)
1	2	0	3.71
2	2	25	8.7
3	2	50	11.81
4	2	75	14.62
5	4	0	6.9
6	4	25	11.15
7	4	50	14.01
8	4	75	16.16
9	6	0	10.24
10	6	25	14.06
11	6	50	16.22
12	6	75	17.81
13	8	0	12.85
14	8	25	16.13
15	8	50	17.94
16	8	75	18.8

3.1.2 Charpy Impact Test

The test was conducted with an impact angle of 90^0 on all of the specimens. The data of the experiment were recorded in the Table 3.2 below.

Table 3.2: Table specimen shell, Infill Percentage and Impact energy

Specimen	Shell (Nu.)	Infill (%)	IMPACT ENERGY (j)
1	2	0	11.2
2	2	25	32.1
3	2	50	65.8
4	2	75	75.5
5	4	0	16.8
6	4	25	37.9
7	4	50	74.2
8	4	75	84.2
9	6	0	44.8
10	6	25	76.3
11	6	50	111.4
12	6	75	101.8
13	8	0	76.1
14	8	25	120.2
15	8	50	116.8
16	8	75	155.8
HDPE			85.5

Table 3.2 above recorded that as the specimen number of infill and shell increase the specimen impact energy also increases. The HDPE pipe sample tested give the value of 85.5 joule. Few of the specimen showing the impact energy above the HDPE sample. The number of shell and infill plays a major role in absorbing the impact energy, for example specimen 16 with 8 shells and the infill of 75% recorded the highest value of impact energy which is 183.4 J. The table shows that the HDPE pipe recorded only 85.5J impact energy. There are five FDM specimen that exceeds the HDPE impact energy which is S6I50 (111.4J), S6I75 (101.8J), S8I25 (120.2J), S8I50 (116.8J) and S8I75 (155.8J). The sample S4I75 (84.2J) also can be considered as a rival to the HDPE but need some improvement such as increase the shell number from 4 to 5 might increase the impact energy.

3.1.3 Hardness Test

The test was conducted on the specimen at room temperature. Total of six results was collected from the experiment, three from the top and three from the side of the specimen. Table 3.3 shows the Rockwell Hardness test result from the side of the specimen. There 2 specimens S2I0 and S2I25 that the Rockwell hardness test unable to detect the hardness due to the small number of shell and infill percentage. The result from the side test (shell) further shows that the increasing amount of shell increases the hardness number consistently. The specimen S6I0 hardness test result 30.2 HRL is low compared to others in the S6 series of specimen.

Table 3.3: Shows the data result collected from the hardness test on the side of the specimen

Experiment	Shell	Infill (%)	Shell Hardness			Average
			R1	R2	R3	
1	2	0	0	0	0	0
2	2	25	0	0	0	0
3	2	50	50.9	25.3	14.5	30.2
4	2	75	10.9	18.6	83.4	37.6
5	4	0	14	29.7	21.4	21.7
6	4	25	34.1	36.9	19.7	30.2
7	4	50	47.6	29.5	53	43.4
8	4	75	50.3	45.2	56.8	50.8
9	6	0	18.9	57.6	17.5	31.3
10	6	25	60.3	65.3	55.4	60.3
11	6	50	83.7	72.4	60.9	72.3
12	6	75	94.6	44.7	85.4	74.9
13	8	0	51.2	102.1	73.8	75.7
14	8	25	78.4	110	49.4	79.3
15	8	50	85.5	91.6	87	88.0
16	8	75	94.9	95.3	88.7	93.0

Table 3.4 shows the data recorded from the Rockwell hardness test on the top of the specimen, the specimen is vertically setup on the Rockwell anvil. There are 2 specimens S2I0 and S2I25 that the HR value is undetectable or it is out of range due to low shell and infill value. The table shows that the HR number increases consistently as the amount of infill increase. But not for specimen S6I0 and S6I25 where the HR number for S6I0 is higher than S6I25 specimen a specimen that have 6 shells and infill of 25%.

Table 3.4: The data result collected from the hardness test on the top of the specimen

Experiment	Shell	Infill (%)	TOP			Average
			T1	T2	T3	
1	2	0	0	0	0	0.0
2	2	25	0	0	0	0.0
3	2	50	64.8	89.8	52.9	69.2
4	2	75	77.8	95.3	76.2	83.1
5	4	0	0	25	27.8	17.6
6	4	25	40	2.7	91.7	44.8
7	4	50	75.2	102.8	46.3	74.8
8	4	75	53.2	114.3	79.3	82.3
9	6	0	0	105.2	88.2	64.5
10	6	25	3	65.7	48.3	57.0
11	6	50	65	68	76.4	69.8
12	6	75	78.2	73.2	83.4	78.3
13	8	0	0	62	105.2	55.7

14	8	25	78.9	108.2	18.4	68.5
15	8	50	71.6	64.1	85.5	73.7
16	8	75	112.2	50.7	117.7	93.5

3.2 Discussion

FDM is a branch of AM technology where the product is built layer by layer. In this report the specimen is built layer by layer parallel to the Z axis of the printer. The material being used in the building the specimen is ABS filament. The resistance to impact is depended on the fusion or bonding between layer shell thickness and infill percentage. The strength of the FDM part is primarily due to intra-layer bonding, inter-layer bonding and neck growth between filaments (Gurrala & Regalla, 2014). The infill pattern hexagonal is chosen because it is much faster to be produced and it is a pre-set pattern in the slicer software. The impact energy is depended on the number of shell and percentage of infill. From the experiment the highest recorded impact energy is 155.8J for the specimen with eight numbers of shell and 75% of infill. Visual inspection of the specimen, it seems that the infill percentage also unintentionally increases the thickness of the shell. The increase number of infill cause the specimen will be much denser than specimen without or less infill percentage. Higher infill percentage means that more material is used to fill the gap inside the specimen.

FDM technology allows users to control the density of models through parameter which is termed air gap or infill (Lužanin et al, 2014) . Figure 3.2 shows the interaction between specimen against impact energy, print time and weight. Previously identify that specimen S6I50 (111.4J), S6I75 (101.8J), S8I25 (120.2J), S8I50 (116.8J) and S8I75 (155.8J) impact energy exceed the HDPE sample. The entire specimen that exceeds HDPE impact energy exhibited same criteria which are high shell number and high infill percentage. The shell and infill act together to act a one entity to absorb the impact energy. The infill pattern and percentage significantly influence the printing process, as well as physical properties of the printed object and in general, a higher volume percentage leads to a print that is more resistant to external loads, while consuming more material and prolonging the print time(Wu et al, 2016).This shows that the FDM method of manufacturing could be used to produce the prosthetic pylon but to conclude the FDM can be used to produce lower limb prosthetic, it needs to look to the print time and weight of the specimen. A lower limb prosthetic will weight approximately between 1.3 to 1.5 kg (Deshpande, 1994) and from the data collected the pylon specimen printed is only 18.8 gram and adding an artificial foot weighing around 850g, the total assembly weight only 868.8 g still have 631.2g to consider. The longest print time of the specimen is 134 minute in AM the shortest time taken to produce a product will result in profit due to reduction of machine operating cost.

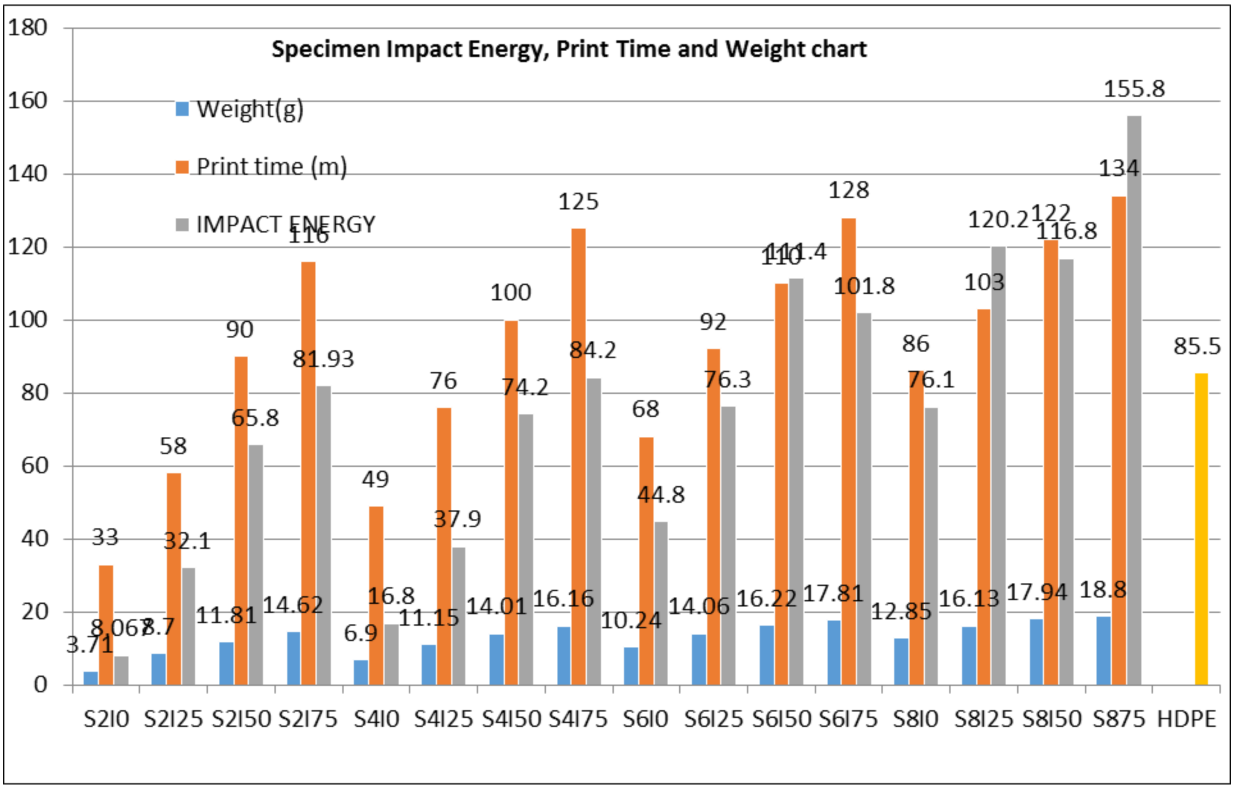
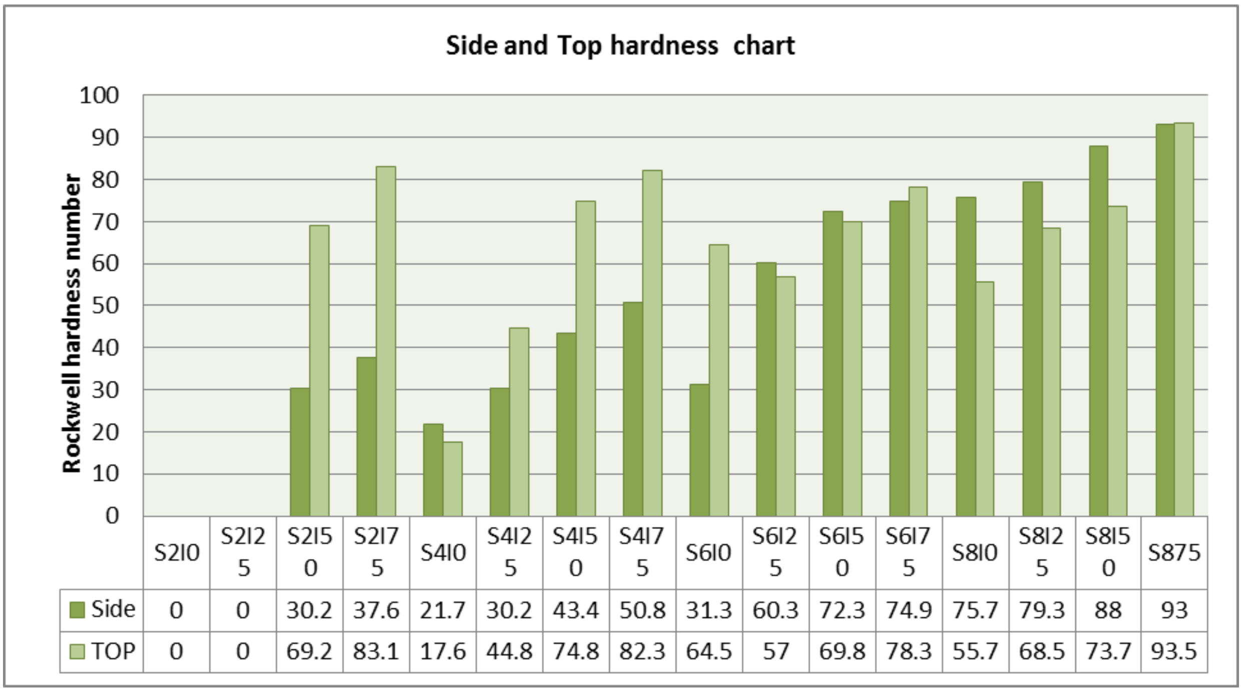


Figure 3.2: Specimen shell and infill against impact energy, print time and weight chart

All of the specimen after the Charpy test are destroyed and broken into mainly three parts. From visual inspection of the broken part, the breakage can be divided into two main categories which are non-union or compound break and simple break. There are white sections on the breakage section shows that a plastic deformation occurs. It is different from the specimen without infill where the breakage is simple and clean. The plastic deformation still occurs but not as much as in the higher shell count and infill percentage. Due to the infill in specimen the Charpy impact energy increase. The increase of infill percentage also increases the weight and print time due to the amount of material extruded increase.

Figure 3.3 shows the Rockwell side (shell) and the top result of the specimen. The chart shows that the specimen with low shell count have a low number of HRL numbers for the side, but high HRL number from the top this indicate that the infill plays a major role in strengthening the structure of the specimen. The specimen with higher shell count S6 and S8 the HRL number for side and top is almost the same. This shows that both of the specimens can be a candidate for the pylon to the support of the Charpy test result. The most important parameter in the FDM is the fusion between the extruded layers. If the layer did not fused together properly the specimen or the part will be weak either from the side or the top. The hardness experimental result shows that almost of the specimen has a good fusion between layers. The two specimen S2I0 and S2I25 result is inconclusive due to the lack of material to withstand the hardest test. The hardness is consistent with the Charpy test where the specimen S6I50, S6I75, S8I2, S8I50 and S8I75 is excel much better than HDPE.



	S210	S2125	S2150	S2175	S410	S4125	S4150	S4175	S610	S6125	S6150	S6175	S810	S8125	S8150	S875
Side	0	0	30.2	37.6	21.7	30.2	43.4	50.8	31.3	60.3	72.3	74.9	75.7	79.3	88	93
TOP	0	0	69.2	83.1	17.6	44.8	74.8	82.3	64.5	57	69.8	78.3	55.7	68.5	73.7	93.5

Figure 3.3: FDM specimen Side and Top hardness Chart

Stated here again, the result of the experiment shows that FDM can be used to fabricate lower limb prosthetic pylon. The result from the Charpy experiment with the support of hardness test there are multiple candidate that can be used to substitute the conventional made pylon use making a prosthetic leg. As long as the shell count is more than six and support with infill the FDM printed pylon will perform as the same the conventionally made pylon.

4.0 CONCLUSION

The main question of this research is to find the possibility of AM to produce prosthetic limb especially lower limb prosthetic. The AM method selected in this paper is Fused Deposition Modelling and focusing on producing lower limb prosthetic pylon. The report finds that in conventional method of producing prosthetic limb, the limb can be produce from aluminium, carbon fibre, wood and polymer (HDPE). The process in producing the prosthetic limb is very labour intensive and some of the pylon is produced from other process such as injection molding, laminating and heat process.

Finding that FDM part builds layer by layer with shell and infill density plays major role in determining the mechanical properties of the part and thus fulfil the objective number two. Fulfilling the objective one and two, the pylon was fabricated using FDM machines with multiple shell various infill density percentages. Then the fabricated specimen is tested using a Charpy impact test to determine the impact energy.

Then the result data are compared to the existing HDPE sample this fulfil the objective three. It is found that from the entire specimen five results exceed the HDPE result. The hardness test also shows that the 5 specimen have a high number of HRL numbers. This shows that it is possible to use FDM to produce pylon for the prosthetic limb. It is much better if the FDM technology is coupled with the latest 3D scanning technology this will produce a highly customized prosthetic. It can be concluded that all of the objectives of the paper have been achieved.

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