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AN INVESTIGATION AND OPTIMIZATION PARAMETER FOR THE MECHANICAL STRENGTH OF ACRYLIC BUTADIAIENE STYRENE (ABS) PRINTED PART IN 3D PRINTING

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Abstrak: *3D printing is Additive Manufacturing (AM) technology that capable of realizing virtual solid models into physical models through a fast and easy process. In the industry of automotive, aerospace and household appliance, there is great demand for polymeric material in term of strength and toughness. This study to investigate effect of process parameter on tensile, flexural, and impact strength of Acrylonitrile Butadiene Styrene (ABS) printed part. Design of Experiment (DoE) Taguchi in Minitab 17 software was used to find the optimum parameter setting for infill pattern, layer thickness and printing speed, in order to achieve maximum tensile, flexural and impact strength of 3D printed part. Testing specimens were prepared by Ultimaker Cura 3.4.1 slicing software and fabricated by Ultimaker 3D printer. The tensile, flexural and impact test were conducted according to the standard and procedures ASTM D638-14, ASTM D790-03 and ASTM D6110-04. The optimum process parameter setting for tensile strength is* A_1 B_1 C_2 *(Grid, 0.1 mm, 50 mm/s), flexural strength* A_3 B_2 C_3 *(Cross, 0.2 mm, 70 mm/s) and impact strength* A_1 B_1 C_2 *(Grid, 0.1 mm, 50 mm/s). After optimization, the experimental result show tensile strength 26.4710 MPa (12.45%), flexural strength 53.7866 MPa (0.41%), impact strength 1.95 Joule (0.98%). The errors between the predicted and experimental values are less than 15%. From this percentage it can be concluded that predicted and experimental result has agreed each other and good as a reasonable result.*

Keyword: *3D printing, Acrylonitrile Butadiene Styrene (ABS), Design of Experiment (DoE) Taguchi, Mechanical Strength.*

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Introduction

The application of additive manufacturing (AM) in rapid prototyping such as 3D printers has started to grow since the 1990s. Since then, extrusion technique is introduced through Fused Deposition Modeling (FDM) to produce 3D objects using layer-by-layer methods. The production is based on a 3D model which is digitally sliced into layers (Gebhardt & Jan-Steffen, 2016). In the manufacturing industry sector, 3D printers help to produce concept model and functional prototype as a preliminary or mock up model in engineering design. In addition, 3D printers are also capable of generating complex geometrical without any investment in mould and die or tooling. At the same time enable to eliminate number of assemblies by printing consolidated functional part (Mohamed et al., 2016). Today, 3D printer technology has improved so much by applying rapid manufacturing. The perspective of industry player has switched to rapid manufacturing because this technology shown a potentially to minimum the cost and cycle time of product development. This clearly demonstrates some of the features that are available in 3D printers compared to today's conventional manufacturing (Durgun & Ertan, 2014). Acrylonitrile-Butadiene-Styrene known as ABS is thermoplastics that commonly used in 3D printing for build models, prototypes, patterns, tools and end-use parts. ABS is a low-cost engineering plastic and has a low melting temperature making it easy to machine and fabricate. However, there is a deficiency of precise understanding about influence of process parameter especially infill pattern on mechanical properties, dimensional accuracy and building time of final part (Alafaghani *et al*., 2017). Thus, it is significant to study mechanical properties of 3D printed part and conduct the optimization process parameter such as infill pattern, layer thickness and printing speed so that optimum performance can be decide through selection of best setting.

Literature Review

There are several different methods of 3D printing, but the most extensively used is a fused deposition modeling. FDM use a thermoplastic filament, which is heated until reach to melting point and then extruded layer by layer to create 3D object. The object created with FDM technique start from computer aided design (CAD) files. Before the object can be printed, CAD files must be converted to a format that a 3D printer can understand, normally stereolithography format (.stl). When the 3D printer begins printing, the raw material is extruded as a thin filament through the heated nozzle. It is deposited at the top of the printer platform, where it solidifies. The next layer that is extruded fuses with the layer blow, creating the object from the bottom-up layer by layer. (Yeong, 2017).

Process Parameter 3D Printer

Infill Pattern refer to the structure that is printed inside an object. It is extruded in a designated percentage and pattern, which is set in the slicing software. There are several considerations when choosing an infill pattern; object strength, time and material, personal preference (Dudescu *et al.*, 2017). It can be inferred that a more complex pattern will require more movement, and hence take more printing time and material usage (Baich *et al.*, 2015). Figure 1 shows the different infill pattern.

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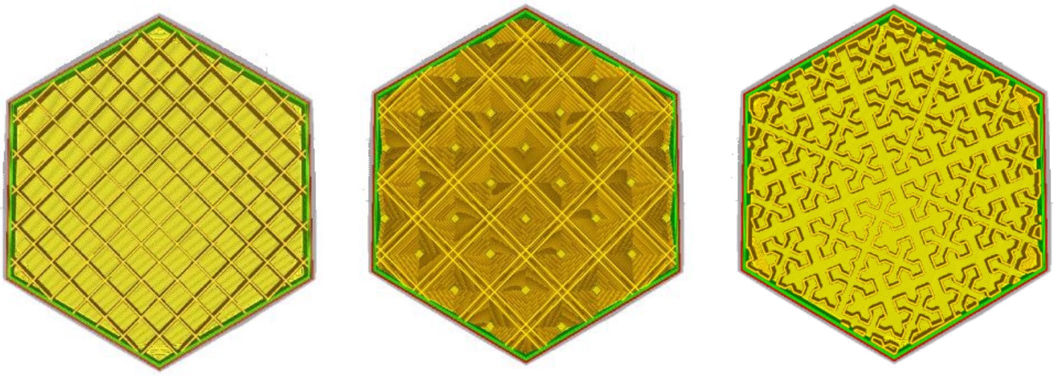

Figure 1: From left to right - variation infill pattern Grid, Octet and Cross
Source: Ultimaker Cura 3.4.1 Software

Layer Thickness recognized as the height of each layer that is being printed. This thickness of layer is referring to the nozzle head or bed that travelled in the z-axis between successive layers. The layer thickness is the most significance element in FDM for build cost of 3D printed part. As the layer thickness increase, will be a smaller number of layer needs to create up the part and consequences reducing build cost (Mohamed *et al.,* 2016).

Printing Speed is defined as speed of printer's head or extruder move during printing. If printing speed is increased it will shorten the print time. However, keep in mind that increasing printing speed should be consistently with the increment temperature so that the filament 3D printer will properly melt. Otherwise, it will affect the bonding arrangement between each layer, consequently also effect on tensile strength printed part (Sukindar et al., 2017).

Effect of Process Parameter on Mechanical Strength

Previous studies show that many researchers emphasize the role of process parameters 3D printer on mechanical strength. There are several studies that investigated the behavior of mechanical properties such as tensile, flexural, impact and compressive strength for ABS and Polylactic Acid (PLA) by manipulating the process parameter.

Dudescu *et al.* studied the effect of raster orientation, infill rate and infill pattern on tensile strength. The specimens of ABS were printed with 100% infill and 6 variations of infill pattern including rectilinear 0^o and 90^o, grid 0^o -90^o and 45^o -45^o, fast honeycomb, full honeycomb, triangular (60^o) and wiggle. The results showed that the ultimate tensile strength is largest for wiggle compared to the others pattern. Additionally, orienting of the raster along printing direction contributed to the largest tensile strength of ABS

Alafaghani *et al*. studied the experimental optimization of FDM processing parameter: a design for manufacturing approach. The spesimens of PLA were printed by manupulating 6 parameters ie building direction, printing speed, extrusion temperature, layer thickness, infill percent and infill pattern. The results showed that printing speed and infill patern does not hightly influence on tensile strength. In addition, by used larger layer thickness from 0.30 mm to 0.40 mm will be improved tensile strength and Young's modulus. This studied also recommended to print bigger size specimen with lower infill percentage; in order to allocate bigger space for the infill pattern, so that the significance of infill patern can be highlited.

Christiyan *et al.* studied on the influence of process parameter on the mechanical properties of 3D printed ABS composite. The specimen of ABS + hydrous magnesium silicate composite

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were printed by selecting various value of layer thickness and printing speed. The observation while produced the specimen, indicates that there is a difference in printing time due to the different process parameters selected. The results showed maximum tensile strength (28.5 Mpa) and flextural load (43 N) and displacement (14 mm); when part is printed used layer thickness 0.2mm and printing speed 30 mm/s.

Alvarez C. e*t al.* investigated the influence of infill percentage on the mechanical properties of fused deposition modelled ABS parts. The specimens were printed with raise 5% increase in infill percentage, beginning at 0% until 100%. The results showed maximum tensile force 1438 N and tensile stress 34.57 Mpa for 100% infill percentage. Meanwhile, the result from charpy test also showed that maximum impact resistance is 155 J (Joule) for 100% infill percentage.

Material and Method

Fused Deposition Modeling is a technique used to print Acrylonitrile Butadiene Styrene (ABS) 3D printed part for the purpose of providing specimen experiments. The specimens are fabricating using Ultimaker 3D printer. Before that, the specimens are design according to ASTM standard test methods for plastic properties. Figure 2, 3 and 4 shows the dimensional of tensile, flexural and impact test specimen.

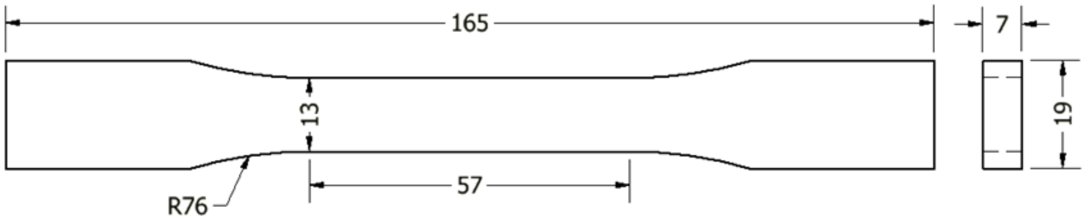

Figure 2: Dimensional of Tensile Test Specimen (mm)
Source: ASTM D638-14

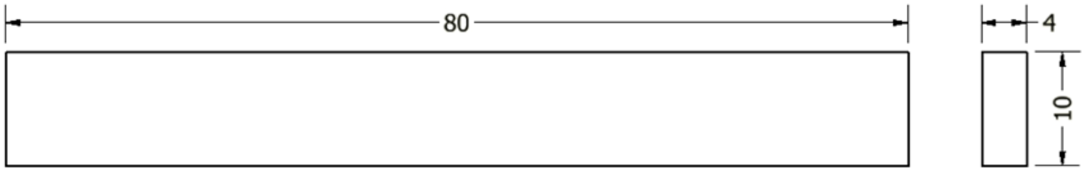

Figure 3: Dimensional of Flexural Test Specimen (mm)
Source: ASTM D790-03

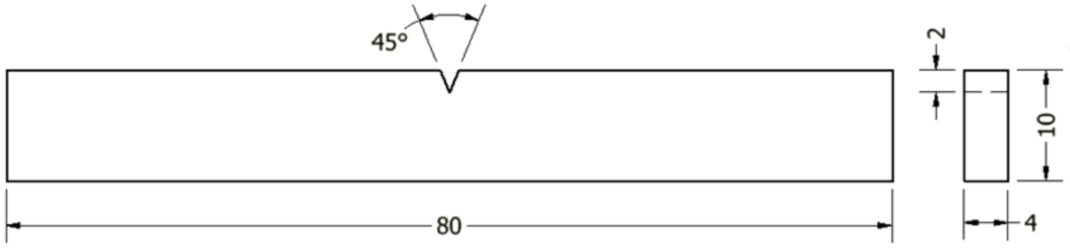

Figure 4: Dimensional of Impact Test Specimen (mm)
Source: ASTM D6110-04

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Design of Experiment Taguchi Method

Taguchi recommends experimental arrangement in term of Orthogonal Array (OA) that allow various combinations of process parameter and level for each experiment. Three (3) process parameters are considered as independent variables (factor) namely infill pattern, layer thickness (mm) and printing speed (mm/s). These process parameters were set as a factor with level of three (3). The effect on tensile, flexural, impact strength is considered as response characteristic. Table 1 shows process parameter and level of the experiment. Minitab software version 17 was used as aided software to analyses and optimize the process parameter. Based on Taguchi design approach, the orthogonal array L_9 (3^3) is selected to run experimental. Table 2 shows that L_9 orthogonal array intended to be nine experiments will be run by manipulating three process parameters (factor) with three levels of value, (3^3). To perform tensile, flexural and impact tests, it required a total amount of 27 samples as shown in figure 5, where each test is required 9 samples.

Table 1: Process Parameter and Levels

No	Process Parameter (factor)	Coding Factor	Unit	Level		
				1	2	3
1	Infill Pattern	A	-	Grid	Octet	Cross
2	Layer Thickness	B	mm	0.1	0.2	0.3
3	Printing Speed	C	mm/s	30	50	70

Table 2: L_9 Orthogonal Array

No. of Run	Process Parameter (Factor) / Level		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

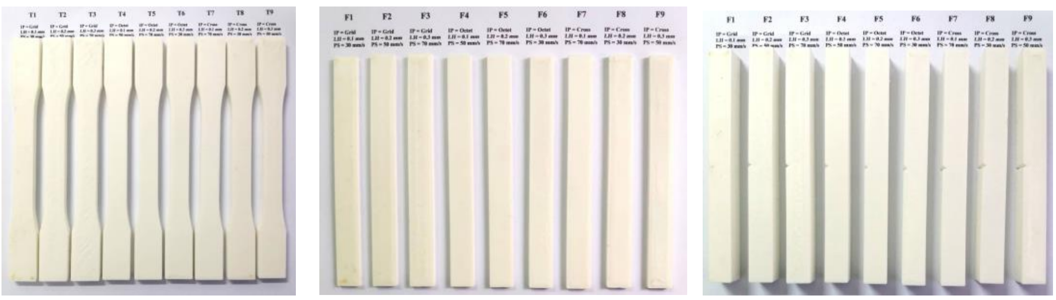

Figure 5: Specimens Preparation Using L_9 Orthogonal Array

Mechanical Testing on Specimen

The tensile test was conducted according to the ASTM D638-14 Type I standard on Shimadzu Universal Tensile Machine (UTM) AG-1 series with load capacity 10kN is shown in Figure 6. The loading speed of this machine is 5 mm/min and the test was stopped once the specimens

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broken. The flexural test was conducted according to the ASTM D790-03 and the experiment uses the same machine equipment as tensile test and it is distinguished by the position and shape of the specimen, as well as the support device called jigs. The loading speed of this machine is 2 mm/min and length between lower support refer to span to depth (thickness) ratio of 16:1 is 51.2 mm. The Figure 7 shows that the material is placed horizontally on two contact points (lower support span) and then the force is applied to the top of the material through either one or two points of contact (the upper load span) until the specimen fails. Meanwhile, the Charpy test was conducted according to the ASTM D6110-04 is used to determine the amount of energy that material can absorb when impacted by sudden load. The specimen is placed across parallel jaws in the impact testing machine as shown in Figure 8. The hammer pendulum with weight 1 kg is released from the initial height downward towards the sample. Once the hammer pendulum striking to the specimen, the value of energy absorbed is recorded.

Figure 6: Overview of Tensile Test

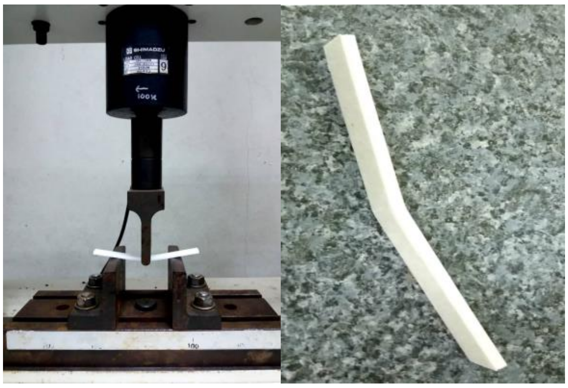

Figure 7: Overview of Flexural Test

Figure 8: Overview of Impact or Charpy Test

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Result and Discussion

The experimental result for the tensile, flexural and impact strength are obtained after conducting three (3) different type of testing for all twenty seven (27) specimens. The result shows that maximum tensile strength 22.3747 MPa (specimen 2), flexural strength 53.1161 MPa (specimen 7) and impact strength 1.92 Joule (specimen 4). The overall experimental result for tensile, flexural and impact strength with S/N ratio was summarized in Table 3.

Table 3: Experimental Result on Mechanical Strength with S/N Ratio

Exp. No	Tensile Strength (Mpa)	Flexural Strength (Mpa)	Impact Strength (Joule)	S/N Ratio Tensile Strength	S/N Ratio Flexural Strength	S/N Ratio Impact Strength
1	22.3197	47.0595	1.68	26.9738	33.4529	4.50619
2	**22.3747**	51.1672	1.70	26.9951	34.1798	4.60898
3	22.1524	48.5509	1.66	26.9084	33.7239	4.40216
4	21.3583	41.0802	**1.92**	26.5913	32.2727	5.66602
5	19.4176	41.6188	1.50	25.7639	32.3858	3.52183
6	19.4938	40.9660	1.56	25.7979	32.2485	3.86249
7	20.2006	**53.1161**	1.70	26.1073	34.5045	4.60898
8	18.1202	52.9732	1.44	25.1633	34.4811	3.16725
9	19.2469	49.7664	1.82	25.6872	33.9387	5.20143

The analysis effect on tensile, flexural and impact strength, larger is better was chosen because the aim to identified optimum process parameter for increase mechanical strength. Delta value was calculated based on the difference between the highest and lowest average response values of that each parameter (factor). The Analysis of Variance (ANOVA) used to determine the significant effect of parameter on tensile, flexural and impact strength show. If the p-value is less than 0.05 ($P<0.05$) to the significant level, it is can be concluded that there is statistically significant. Based on Table 4, results show that infill pattern has major influence factor on tensile strength with p-value 0.013 (76.703%) with R^2 and R^2 adjusted are 99.00% and 95.99%. Meanwhile, Table 5 show that infill pattern has major influence factor on flexural strength with p-value 0.041 (91.956%) with R^2 and R^2 adjusted are 96.07% and 84.29%. Table 6 show that printing speed and layer thickness has major influence factor on impact strength with p-value 0.006 (58.219%) and 0.008 (40.797%) with R^2 and R^2 adjusted are 99.66% and 98.62%. The value of R^2 and R^2 adjusted for ANOVA analysis tensile, flexural and impact strength are more than 84% which indicated high reliability result.

Table 4: Result of ANOVA for Tensile Strength

Variance Source	Degree of Freedom (DoF)	Sum of Squares (SS)	Mean of Square (MS)	F Ratio	P Value	% Contribute
Infill Pattern, A	2	15.1845	7.59226	76.46	0.013	76.703
Layer Thickness, B	2	2.8450	1.42249	14.33	0.065	14.371
Printing Speed, C	2	1.5684	0.78422	7.90	0.112	7.923
Error	2	0.1986	0.09929	-	-	1.003
Total	8	19.7965	-	-	-	100.00
S = 0.315106 R-sq = 99.00% R-sq (adj) = 95.99% R-sq (pred) = 79.69%						

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Table 5: Result of ANOVA for Flexural Strength

Variance Source	Degree of Freedom (DoF)	Sum of Squares (SS)	Mean of Square (MS)	F Ratio	P Value	% Contribute
Infill Pattern, A	2	183.649	91.8247	23.41	0.041	91.956
Layer Thickness, B	2	7.345	3.6727	0.94	0.516	3.678
Printing Speed, C	2	0.875	0.4377	0.11	0.900	0.438
Error	2	7.845	3.9223	-	-	3.928
Total	8	199.715	-	-	-	100.00
S = 1.98047 R-sq = 96.07% R-sq (adj) = 84.29% R-sq (pred) = 20.46%						

Table 6: Result of ANOVA for Impact Strength

Variance Source	Degree of Freedom (DoF)	Sum of Squares (SS)	Mean of Square (MS)	F Ratio	P Value	% Contribute
Infill Pattern, A	2	0.001156	0.000578	1.86	0.350	0.640
Layer Thickness, B	2	0.073689	0.036844	118.43	0.008	40.797
Printing Speed, C	2	0.105156	0.052578	169.00	0.006	58.219
Error	2	0.000622	0.000311	-	-	0.344
Total	8	0.180622	-	-	-	100.00
S = 0.0176383 R-sq = 99.66% R-sq (adj) = 98.62% R-sq (pred) = 93.02%						

After ANOVA procedure, the main effect plot for S/N ratio of tensile, flexural and impact strength has been plotted as shown Figure 9. As mechanical strength is the larger is better type characteristic, Figure 9 suggested that optimum parameter setting of infill pattern at level 1 (A_1 - Grid), layer thickness at level 1 (B_1 - 0.1 mm) and printing speed at level 2 (C_2 - 50 mm/s) gives maximum tensile strength. The interaction of infill pattern and layer thickness gives some evident that infill pattern of Grid with lower layer thickness 0.1 mm contributes better tensile strength compare with others infill pattern and layer thickness. Similar finding have been observed in other research Nidagundi et al., (2015) and Divyathej et al., (2016) which states that the layer thickness 0.1 mm gives a high tensile strength. It is due to the high molecular orientation and the both within strip. In addition, the thinner layer thickness gives better bonding strength and provides good capability to axial load. This is in accordance with the finding of Shubham et al., (2016) which indicated that smaller layer thickness creating better inter layer bonding due to the each layer thickness are closely stacked together. Meanwhile, the higher layer thickness causes a weak internal layer bonding and creates micro voids, thus contributed the lower tensile strength. Furthermore, Fernandez-Vicente et al., (2016) observed that lower density in infill pattern were increased total of voids and directly affect the decrease in tensile strength. Meanwhile, the optimum parameter setting of infill pattern at level 3 (A_3 - Cross), layer thickness at level 2 (B_2 - 0.2 mm) and printing speed at level 3 (C_3 - 70 mm/s) gives maximum flexural strength. The interaction of infill pattern and layer thickness gives some evident that infill pattern of Cross with layer thickness 0.2 mm contributes better flexural strength compare with others infill pattern and layer thickness. Similar finding have been observed in other research Christiyan *et al.*, (2016) and Divyathej *et al.*, (2016) which stated that the layer thickness 0.2 mm gives a high flexural strength. In addition, Sood, *et al.*, (2010) observed maximum flexural strength will be at minimum layer thickness. Meanwhile, due to the stepped effect of deposition layer, some portion is vacant between layers. This vacant is lead to the weakness of flexural strength when layer thickness increased. However, with higher

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density in infill pattern has reduced vacant portion and increase capability of infill fiber to absorb the stress before break (Fernandez-Vicente *et al*., 2016). Lastly, the optimum parameter setting of infill pattern at level 1 (A_1 - Grid), layer thickness at level 1 (B_1 - 0.1 mm) and printing speed at level 2 (C_2 - 50 mm/s) gives maximum impact strength. The interaction of layer thickness gives some evident that lower layer thickness 0.1 mm with printing speed 50 mm/s contributes better impact strength compare with others layer thickness and printing speed. Similar finding have been observed in other research Shubham et al., (2016) which stated that impact strength gradually decreased as the layer thickness increased. Thus, increasing layer thickness exhibited more brittle and poor bonding between layers. This condition causes an ineffective of stress transfer, hence decrease the material toughness. Moreover, thinner layer thickness will increase in number of layers; it is resulted in high temperature gradient approach the bottom of part. This is increased the diffusion between neighboring raster and improved the strength (Sood et al., 2010). Furthermore, Fernandez-Vicente et al., (2016) observed that lower density in infill pattern were increased total of voids and directly affect the decrease in tensile strength.

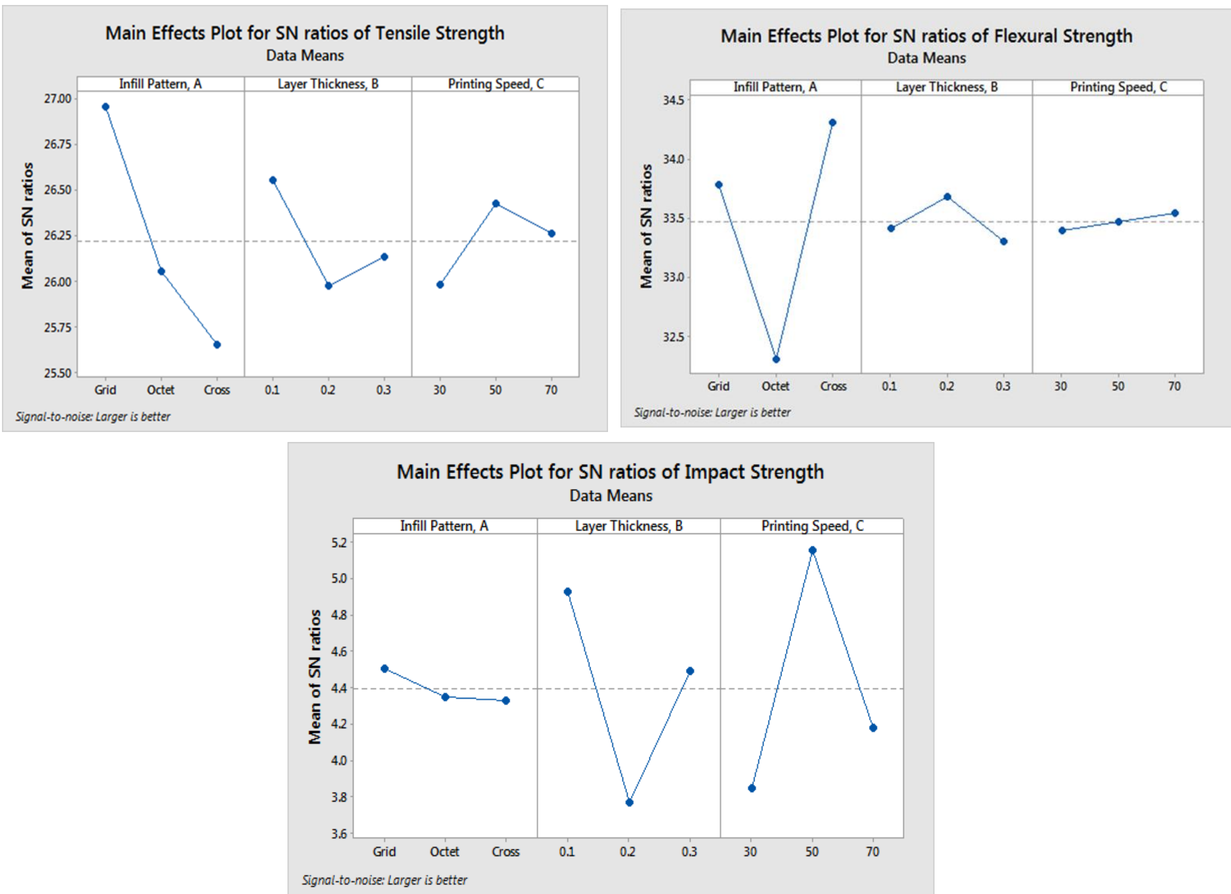

Figure 9: Main effect plot for S/N ratio of Tensile, Flexural and Impact Strength

In order to validate the performance of optimum process parameter, confirmation experiment of tensile, flexural and impact for strength was carried out. For validation tensile, flexural and impact strength were measured by the corresponding test machine. Three specimens are provided for each test performed. The average readings are obtained as shown in Table 7.

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Table 7: Confirmation Experiment Result

Confirmation Experiment	Optimum Process Parameter Level	Experimental Result			Average
		Reading 1	Reading 2	Reading 3	
Tensile Test (MPa)	$A_1 B_1 C_2$	26.8750	25.5632	26.9748	26.4710
Flexural Test (MPa)	$A_3 B_2 C_3$	54.1461	53.1496	54.0641	53.7866
Impact Test (MPa)	$A_1 B_1 C_2$	1.84	1.90	2.12	1.95

The Table 8 shows the comparison experiment result between initial and optimum process parameter level for prediction and experiment.

Table 8: Comparison Experiment Result

Response Characteristic	Initial Process Parameter	Optimum process parameter level		Error %
		Prediction	Experiment	
Tensile Test (MPa)	$A_1 B_2 C_2$ 22.3747	$A_1 B_1 C_2$ 23.5275	$A_1 B_1 C_2$ 26.4710	12.45
Flexural Test (MPa)	$A_3 B_1 C_3$ 53.1161	$A_3 B_2 C_3$ 53.5673	$A_3 B_2 C_3$ 53.7866	0.41
Impact Test (MPa)	$A_2 B_1 C_2$ 1.92	$A_1 B_1 C_2$ 1.93111	$A_1 B_1 C_2$ 1.95	0.98

Conclusion

The optimum process parameter settings are predicted and confirmed for each response characteristics. The errors between the predicted and experimental values are less than 15%. From this percentage it can be concluded that predicted and experimental result has agreed each other and good. The optimum parameter setting of 3D printer on response characteristics can be used for unskilled operator as a guidance and reference when operating 3D printer without any trial and error method. The effect of layer thickness on tensile, flexural and impact strength, clearly states that strength of 3D printed part has increased when layer thickness is thinner. The smaller layer thickness creating better inter layer bonding due to each layer thickness are closely stacked together and reduce micro voids between layers. The effect of printing speed on tensile, flexural and impact strength, clearly states that strength of 3D printed part has increased when printing speed is fast. The higher printing speed will ensure that current layer bonding together with previous layer in melting temperature. The effect of infill pattern on tensile, flexural and impact strength, clearly states that strength of 3D printed part has increased when density in infill pattern is higher. The higher density of infill pattern was reducing total of voids and directly affect the higher in mechanical strength. This trend can be seen at the main effect plot of S/N ratio for tensile and impact strength, where infill pattern Grid is the best optimum condition and for flexural strength use infill pattern Cross.

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