第 49 卷 第 7 期
2022 年 7 月

湖南大学学报（自然科学版）
Journal of Hunan University (Natural Sciences）

Vol. 49 No. 7
July 2022

Open Access Article https://doi.org/10.55463/issn.1674-2974.49.7.17

The Effect of FDM Process Parameters on the Compressive Property of ABS Prints

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Abstract: Most 3D-printed FDM items are not solid-printed because printing solids requires a large amount of material and a relatively long printing time, both of which result in higher printing costs. Most items are printed with a hard shell and proper infill density to optimize the printing process. The shell width, the filling density, the infill pattern, and the thickness of the layer all play an important role in the quality of the printed items. This new work aims to characterize the FDM process to apply this technology in printing parts to withstand stresses by focusing on the most important process parameters that contribute to improving the bearing of parts when exposed to compression. For this purpose, the effects of four main parameters of the FDM, which are: infill density, outer shell width, infill pattern, and layer thickness, with different levels of each parameter, were investigated, and the effect of each of these parameters on the compressive property of the printed parts was also examined. The Taguchi method was used to design the experiments so that all parameter levels were tested in the fewest possible number of tests. The signal-to-noise ratio (S/N) was also used to clarify and measure the effect of the process variables on the compressive property. The compression test was adopted as the basis for analyzing test results, which confirmed that the effect of the infill density on the compressive resistance can be classified at a strong level (rank 1), and that of the outer shell width on the compressive resistance can be classified at a level ranging from medium to strong (rank 2), while that of the infill pattern on the compressive resistance can be classified at a range from weak to medium level (rank 3), and the effect of the layer thickness on the compressive resistance can be classified as weak (rank 4). This work provides an opportunity to improve the functionality of the multipurpose FDM process, which can be used to reduce the number of raw materials required, efficiently shorten printing times, and enhance the compressive properties to meet the needs of FDM print design better.

Keywords: fused deposition modeling, acrylonitrile butadiene styrene, outer shell width, infill density, infill pattern, layer thickness, compressive strength.

FDM 工艺参数对 ABS 印刷品压缩性能的影响

摘要：大多数 3D 打印的 FDM 物品都不是实体打印的,因为打印实体需要大量的材料和相对较长的打印时间,这两者都会导致更高的打印成本。大多数物品都印有硬壳和适当的填充密度,以优化打印过程。外壳宽度、填充密度、填充图案和层厚都对打印件的质量起着重要作用。这项新工作旨在描述 FDM 工艺,通过关注有助于改善部件承受压力时的轴承的最重要的工艺参数,将该技术应用于打印部件以承受应力。为此目的,研究了 FDM 的四个主要参数,即填充密度、外壳宽度、填充图案和层厚,每个参数的水平不同,并且这些参数中的每一个对还检查了打印部件的压缩性能。田口方法用于设计实验,以便在尽可能少的测试次数中测试所有参数水平。信噪比(序列号)也用于阐明和测量过程变量对压缩性能的影响。采用压缩试验作为分析试验结果的依据,证实填充密度对抗压强度的影响可归为强等级(等级 1),外壳宽度对抗压强度的影响可分为中等至强(等级 2),而填充图案对抗压强度的影响可分为中等(等级 3),层厚对抗压强度的影响抗压性可以归类为弱(等级 4)。这项工作为改进多用途 FDM 工艺的功能提供了机会,可用于减少所需原材料的数量,有效缩短打印时间,并增强压缩性能,以更好地满足 FDM

Received: April 1, 2022 / Revised: May 4, 2022 / Accepted: June 2, 2022 / Published: July 30, 2022

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打印设计的需求。

关键词：熔融沉积建模、丙烯 成盒二烯苯乙烯、外壳宽度、填充密度、填充图案、层厚、抗压强度.

1. Introduction

Fused Deposition Modelling (FDM) technology is classified as one of the Additive Manufacturing (AM) technologies. It shares the idea of its work with other such technologies, which is to build its products within a single production process by transforming computer-aided design (CAD) into several layers built one on top of the other, starting from the base and ending at the top. While all additive manufacturing techniques share the same idea, they differ among themselves according to the shape of the raw material used (solid, liquid, powder) and the energy used to form the raw material (laser, thermal) [1]. FDM technology uses solid raw materials (thermoplastics) as a filament and thermal energy (electrical heaters) to melt the raw material. This technology is considered one of the cheapest manufacturing techniques. In addition, it is easy to adjust and use. It is also classified as environmentally friendly, as it does not produce any harmful substances or fumes [2]. FDM builds 3D solid models from a digital file of computer-aided design. The working idea of this technique is based on building models in the form of layers superimposed on each other based on the slicing software, where this software determines all the paths that the extruder must take when building each layer [3].

The printer builds the first layer directly on the surface of the working platform. Upon completion of construction of all the design details through this layer, the work platform descends by an amount equal to the desired layer thickness, which is determined according to the user's specification when adjusting program settings dissection. Then, the extruder builds the second layer the same way as before. The building process continues similarly until it is finished at the top. Figure 1 illustrates the main components of the 3D printer. The 3D printer contains feed wheels that feed the thermoplastic filament to the heating chamber, which is heated to a specific temperature to convert the solid material into a molten structure extruded through a nozzle. The extruder often moves in the X-Y plane, which means that it is free to move in the direction of the X axis and the Y axis, while the movement of the working platform is towards the Z axis. Thus, the printer can move in three axes.

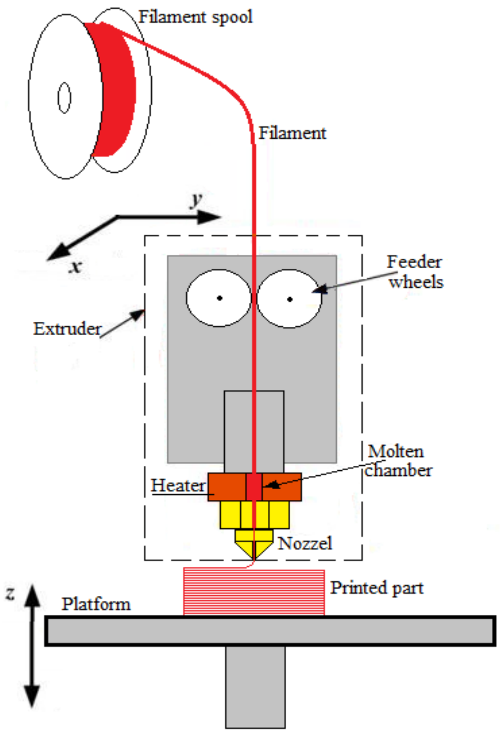


Fig. 1 Schematic diagram of the FDM printer

Several research investigations have been conducted to enhance the quality of technology products from several aspects, the most important of which is regarding the improvement of the mechanical properties of the raw materials previously used by mixing them with materials with high mechanical properties. This improvement has clearly helped support these materials and produce finished products rather than just models. [4], [5]. Other researchers have sought to enhance the product quality by optimizing the process parameters to achieve the best results for the model mechanical properties (tensile strength, compressive strength, impact resistance, bending resistance, stiffness), physical external surface roughness, and dimensional accuracy. Many advanced statistical methods have been used (Design of Experiment, DOE) to improve the tuning of the process parameters to achieve the best possible output by designing combinations of multiple variable values and testing their impact on the process outputs. This has aimed to maximize or minimize the values of the process outputs according to their natural outputs [6], [7].

From reviewing the previous research, it is clear that the process variables for FDM significantly impact the mechanical properties of the printed parts in that they can be optimized through the appropriate selection and modification of these variables. Therefore, this study aims to evaluate the effect of four variables (infill density, outer shell width, infill pattern, and layer thickness) on the compressive property of 3D printed samples using ABS as a building material.

2. Material in the FDM Process

The FDM technique started with a very limited number of raw materials, Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) being the most widely used. This was one of the most important challenges that faced this technology at the beginning. However, the high technology capabilities and low cost have impressed many researchers to find new choices of raw materials. This matter contributed to the widespread and developed new technology applications that did not exist before [8]. As a result, on the market, there are numerous FDM filament manufacturers. In the FDM printing process, filaments are made of thermoplastic materials such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), polyether-ether-ketone (PEEK), nylon, and other composites. ABS and PLA are still two of the most commonly used thermoplastics for FDM 3D printers [9]. ABS is a thermoplastic copolymer based on acrylonitrile butadiene styrene. Its three structural units ensure a balance of properties, with the acrylonitrile providing heat resistance, the butadiene providing good impact strength, and the styrene providing rigidity to the copolymer. Due to its good properties such as resistance to chemicals, heat, and physical effects, ABS is a good base material for a variety of applications in a wide range of industries, including automobiles, medical appliances, electrical appliances, sports equipment, and construction applications [10, 11].

3. Related Studies

The research carried out in this area has varied according to the diversity of the impact of process parameters on five key aspects involved in achieving quality in the totality of the process outputs: mechanical properties, dynamic properties, surface roughness, dimensional accuracy, and modeling time. Researchers are working to improve mechanical properties as one of the most important features of products, as it is the main way that enables technology to produce final products that can be used directly and not be limited only to representative modeling.

FDM technology has several parameters that control how it works, and changes in the values of these parameters directly affect the quality of its outputs. Unfortunately, due to a large number of these variables, it has become difficult to understand their impact, especially since their effects have overlapped.

As presented in [8], the FDM technique was used to study the infill pattern effect on the mechanical properties (tensile, compressive, and flexural) of samples made of ABS material. In compression tests, the research results showed a large variation in the values of the compressive elastic modulus between the patterns, which indicates that this characteristic strongly depends on the filling pattern in which the sample core is filled. The researchers also concluded that the compression resistance increases with the increased complexity of the filling pattern design. The effects of infill density, infill pattern, and raster angle on the mechanical properties (tensile strength) of FDM products manufactured from ABS were evaluated in [12]. The effect of the raster angle was tested at 100% infill density using a rectilinear pattern. The results indicated that 0° is the angle that achieves the highest value, with an improvement rate of 31% for tensile strength, compared to the lowest being recorded at 45°. At 90°, no effect was recorded for the raster angle on the modulus of elasticity. Cho et al. [13] conducted a laboratory study in 2019 on the effect of the type of filling pattern and layer thickness on the tensile strength of samples made of PLA material using the FDM technique.

Prior FDM research was carried out to investigate the effects on compressive characteristics. Printing orientation, raster angle, width, air gap, and layer thickness were the most prevalent printing variables found in prior FDM research. However, only a few studies investigated the impact of outer shell thickness. Therefore, this study aims to see how specific variables, such as the outer shell thickness, affect the compressive property of ABS prints.

4. Process Parameters

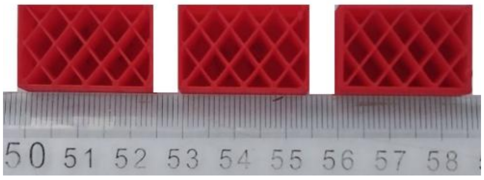
The process of building models using FDM technology is controlled by several printing parameters that set how to build the infill pattern, infill density, outer shell, layer thickness, temperature, and many other parameters related to the process, either directly or indirectly. The effect of these variables on the process is not the same. This finding means in the field that some variables have an effect on tensile strength and have little effect on dimensional accuracy [14]. Also, the variables interact with each other, resulting in different effects than if they were acting alone. Therefore, the effects of these variables are not simple and must be considered. Performing any printing operation with random values for process variables is unacceptable. Rational control of these variables achieves a noticeable improvement in most outputs while working with random values results in defective products [15].

4.1. Testing Parameters

Many parameters in the FDM extrusion process can be modified to improve the properties of the prints. In this research work, four parameters of the fused deposition modeling process, namely: outer shell width, layer thickness, infill pattern, and infill density, with different levels of each, were adopted, and their effect on the compressive properties of the ABS printed samples were investigated.

4.1.1. Outer Shell Thickness

Three different outer shell thicknesses, 0.4 mm, 0.6 mm, and 0.8 mm, were adopted in this research work to investigate their impact on compression properties. Figure 2 illustrates these levels.

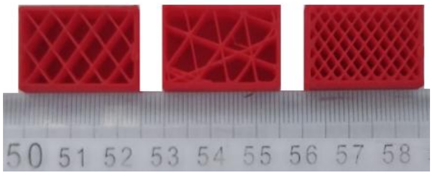


(a) (b) (c)

Fig. 2 Outer shell thickness: (a) 0.4 mm, (b) 0.6 mm, (c) 0.8 mm

4.1.2. Infill Pattern

The Ultimaker Cura software used in this research work allows for changing the fill pattern of the printed structure. Three different patterns (grid, triangle, and line) were adopted to investigate their impact on the compression properties of ABS print. The adopted patterns are illustrated in Figure 3.



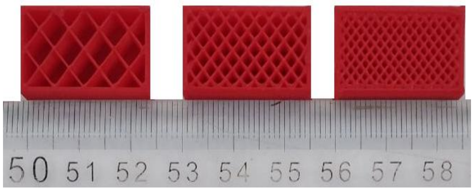
(a) (b) (c)

Fig. 3 Infill patterns: (a) grid, (b) triangle, (c) line

4.1.3. Infill Density

The density of the filler determines the number of thermoplastics used within the printed structure. A higher fill density means more thermoplastic material is inside the prints, thus resulting in a somewhat stronger part. Infill density is the amount of material to be printed inside the outer shell of the printed part.

Infill density is measured as a percentage rather than a unit of measurement. Three levels of filling density (20%, 40%, and 60%) were adopted for the models to investigate their effects on the compression properties of the print, as shown in Figure 4.



(a) (b) (c)

Fig. 4 Infill density percentage: (a) 20%, (b) 40%, (c) 60%

4.1.4. Layer Thickness

Layer thickness is the height of each printed layer in print. When a layer with less thickness is chosen, successive layers tend to blend with each other. Moreover, the thinner the layer, the more time it will take to print the part, as there will be more layers to print. When prototypes are to be printed, a higher layer thickness is often chosen, saving time. Three levels of layer thickness were adopted in this research work: 0.2, 0.25, and 0.3 mm, to investigate their impacts on the compression properties of the printed part.

5. Methodology

The CAD model is created after selecting the sample geometry (12.7 x 12.7 x 25.4 mm) and then converting this model into an STL file format, approximating the model surface with triangles. This format is usually required for Cura post-processing software, commonly used software in 3D printing. Seven steps were adopted in this research work to prepare and print samples:

1. Creating a CAD model is the first step in the 3D printing process. Solid modeling of the model is the most popular representation for creating a digital model. In the CAD software, a standard specimen design was created;
2. The second stage was to convert the digital model into a Standard Triangle Language (STL) format file that approximated the model's surfaces with triangles;
3. After creating an STL file for the digital model, the third stage was loading the STL file into slicer software to slice the digital model into successive layers and export the new files in STL format;
4. In stage four, these STL files were run with the Cura software, and the 3D printer build parameters were specified;
5. The STL file was then converted in stage five to G-code to operate automated 3D printers to print specimens;
6. The specimen was printed using the Ultimaker 2+ printing machine;
7. The specimens were compression tested, and measurements were taken.

Table (1) illustrates the process parameters and the adopted levels. Printing parameters were set using the Taguchi method to design the experiment (Table 1).

Table 1 Process parameters and their levels

Levels	**Outer Shell [mm]**	**Layer Thickness [mm]**	**Infill Pattern**	**Infill Density [%]**
Level 1	0.4	0.2	Line	20
Level 2	0.6	0.25	Grid	40
Level 3	0.8	0.3	Triangle	60

5.1. Design Summary

Table (2) shows the design of the experiments adopted in this research according to the Taguchi method.

Taguchi Array L9 (3^4), Factors: 4. Levels: 3, and Runs: 9.

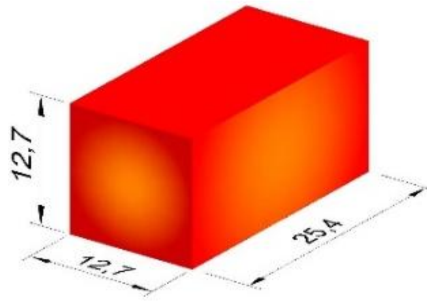
Table 2 Design of the experiments

Run Order	Outer Shell	Layer Thickness	Infill Pattern	Infill Density
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

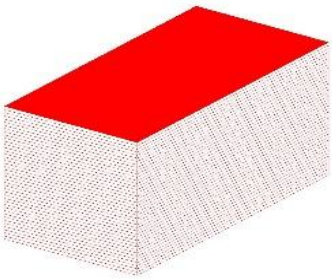
6. Experimental Work

6.1. Compression Specimen

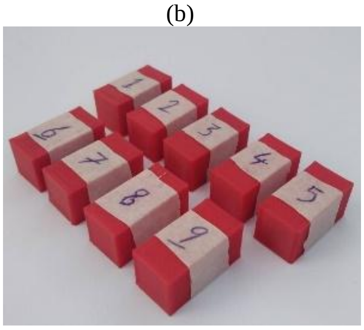
The compression specimen was selected for the tests because of the simplicity of its preparation and its suitability for FDM. The 3D compressive specimen was designed according to ASTM D638-03 [14], and it can be either a cylinder or a block. For ASTM, the typical block specimen dimension is 12.7 mm in height, 12.7 mm in width, and 25.4 mm in length, while the cylinder specimen is 12.7 mm in diameter and 25.4 mm in height. Therefore, block specimens were used for compressive testing in this research. The specimen dimension is illustrated in Figure 5a, while the printed specimens according to the Taguchi DOE are illustrated in Figure 5b.



(a)



(b)



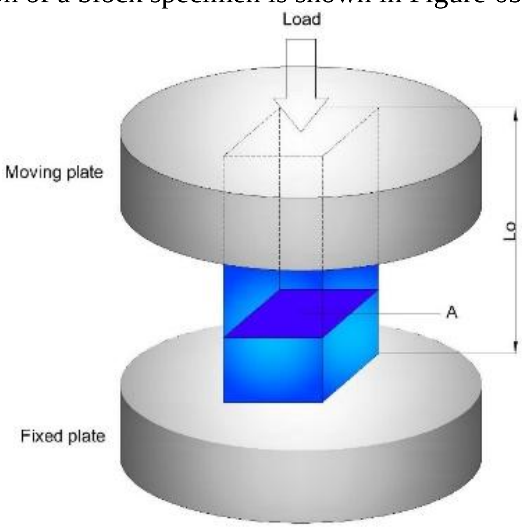
(c)

Fig. 5 Compression specimen: (a) CAD model; (b) Sliced model; (c) Printed specimens

6.2. Test for Compression

The behavior of a material, when subjected to a compressive load at a relatively low and uniform loading rate, is described by its compressive properties. Even though plastic products are subjected to compressive loads in various applications, the compressive strength of plastics has limited design value. Compression tests are a common method of obtaining data for research and development, quality control, acceptance or rejection under specifications, and other special purposes. Compressive strength, compressive strain, yield stress, and modulus of elasticity exemplify compressive properties.

Compressive strength is the most commonly used and specified design parameter. Compression occurs when two antiparallel forces of equal magnitude act on an object along only one of its dimensions, causing the object to remain stationary Figure 6a. A pair of forces acting along the length and perpendicular to the cross-section of a block specimen is shown in Figure 6b.



(a)

(b)

Fig. 6 Experimental set for compression tests: (a) A pair of forces in compression; (b) Specimen under load

The net effect of such forces is that the block's length changes from the original length L_0 that it had before the forces are applied to a new length L that it has as a result of the forces action, as calculated by Eq. 1.

$$\Delta L = L - L_0 \quad (1)$$

In a compression test, the stress is defined as the test sample being performed at any moment under compression load per unit of cross-sectional area. This is expressed in the force unit area, as shown in Eq. 2.

$$y = \frac{F}{A} \quad (2)$$

where:
y - compressive stress (MPa);
F - applied load (N);
A - cross-sectional area of the test specimen (mm^2).

7. Results and Discussion

There were two types of results obtained during this research work, one relating to the compression tests and the other to the mean of signal-to-noise analysis.

7.1. Compressive Strength

The compressive strength of the ABS samples was investigated using a compression test, the results of which are listed in Table 3. At the same time, Figure 7 illustrates the compressive stress-strain curves of the tested specimens.

Table 3 Compressive strength of the tested specimens

Run order	Outer shell width [mm]	Layer thickness [mm]	Infill pattern	Infill density [%]	Compressive strength [MPa]
1	0.4	0.2	Line	20	8.8
2	0.4	0.25	Grid	40	14.3
3	0.4	0.3	Triangle	60	34.0
4	0.6	0.2	Grid	60	25.3
5	0.6	0.25	Triangle	20	12.8
6	0.6	0.3	Line	40	14.5
7	0.8	0.2	Triangle	40	30.1
8	0.8	0.25	Line	60	33.8
9	0.8	0.3	Grid	20	21.8

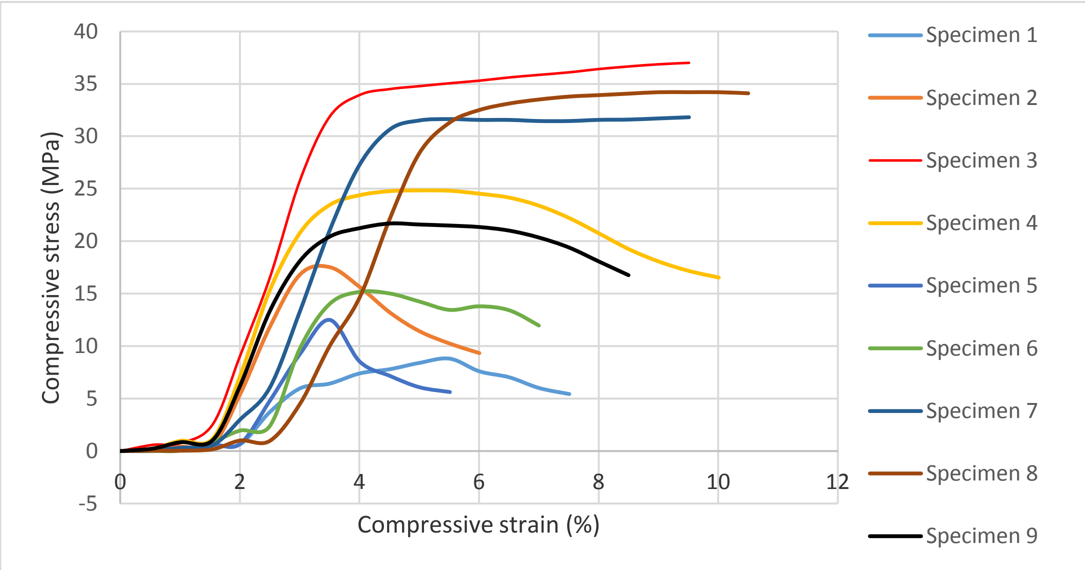


Fig. 7 Compressive stress-strain curves of the tested specimens

7.2. Mean of the Signal to Noise (S/N) Ratio

A response table for each factor can be generated using Minitab (signal-to-noise ratio). These tables show which factor has the most influence on the response and which level of the factor correlates with higher or lower response characteristic values. Minitab provides three S/N ratios: bigger is better, smaller is better, and nominal is best, where the appropriate type of these ratios to be used depends on the type of application. For example, S/N values for bigger is better Eq. 3 were utilized to indicate which factor influences compressive strength (response) most.

$$S/_N = -10\ log\left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i}\right)^2\right] \quad (3)$$

Table 4 illustrates the response values for the signal-to-noise ratio for compressive strength.

Table 4 Response for S/N ratio for compressive strength

Levels	Outer shell	Layer thickness	Infill pattern	Infill density
Level 1	24.21	25.51	24.23	22.60
Level 2	24.48	25.28	25.98	25.30
Level 3	28.97	26.88	27.45	29.76
Delta	4.76	1.60	3.22	7.16
Rank	2	4	3	1

The statistical analysis of the data in Table 4 shows that the infill density variable has the most influence (rank 1) on compressive strength. The outer shell width is the second most effective variable (rank 2), the infill pattern variable is the third (rank 3), and the layer thickness variable is the least influential (rank 4). Figure 8 indicates the signal-to-noise ratios of the main effects of the process parameters in Minitab, which can be used to optimize a set of variables for increasing the compressive strength of the specimen.

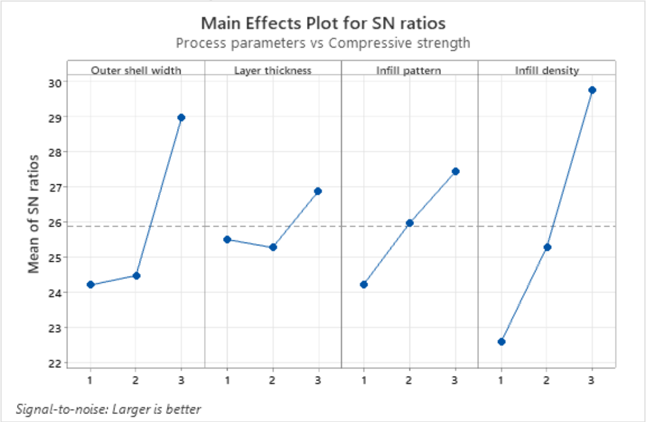


Fig. 8 S/N ratio for compressive strength

From the graph of the S/N ratios in Figure 8, it can be seen that infill density has the greatest influence on the compressive strength of the four considered factors. The outer shell width is the second most effective factor for tensile strength, the infill pattern is the third, and the layer thickness is the least influential.

8. Analysis of the Results

The results obtained from this research work determined the effect of the printing process variables on the compressive strength and the level of importance of each variable, which is summarized as follows.

The effect of the infill density: high infill density enhances the compressive property of the model, which is due to the dependence of the resistive forces on the mass of the material contained in the unit volume. The effect of the infill density on the compressive resistance can be classified as being at a strong level (rank 1) when compared with the other three process parameters.

The effect of the outer shell thickness: The effect of the outer shell thickness variable on the compressive resistance can be classified at a level ranging from medium to strong (rank 2) compared to the other three process parameters.

The effect of the infill pattern: The filling pattern variable has a noticeable effect on the compressive strength due to the number of points it reaches between the tissues and adjacent layers. The effect of the filling pattern on the compressive resistance can be classified as ranging from weak to medium level (rank 3) when compared with the other three process parameters.

The effect of layer thickness: The effect of layer thickness varies with the property under its influence. It is noticed that the compressive strength property is enhanced by decreasing the layer thickness level due to the approach of the extruder nozzle to the level of the previous layer, which generates a pressure force on the material being subtracted that causes it to flatten. This approach reduces the presence of spaces between the material paths and increases the area of contact with adjacent ones. Compressive strength depends on the strength of the bonding between adjacent tissues in one layer and between the layers with each other. The effect of the layer thickness on the compressive resistance can be classified as weak (rank 4) when compared with the other three process parameters.

9. Conclusion

This work represents a step toward improving the functionality of the multipurpose FDM process for ABS prints to obtain good compression properties from a sustainable perspective by reducing raw materials, efficiently shortening printing time, and reducing energy consumed to print parts meeting required engineering specifications. Simultaneous analysis and evaluation enabled the determination of the effects of four important parameters at different levels of each FDM process parameter on the print compressive properties and the rank of the influence of each of these parameters on the compressive properties of the prints.

Increasing the infill density increases the mass of the material per unit volume, which enhances the strength of the resistance, provided that the appropriate infill pattern is chosen.

Strength can be added by increasing shell thickness, which enables the production of a somewhat more durable print without increasing the quantity of material needed for filling.

If a print is to be finished by chemical smoothing or sanding, however, increasing shell thickness is typically required because post-processing processes diminish the thickness of the model's surface.

Working with a thin layer provides many points of contact between the tissues, thus increasing the bond strength and compressive resistance.

Strength can also be added by increasing shell thickness.

This work can be improved by recommending some directions for future work, such as investigating other mechanical properties such as fatigue and torsion and performing the microstructural examination and failure analysis.

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