NTU Journal of Engineering and Technology (2024) 3(4) : 7-16
DOI: https://doi.org/10.56286/ntujet.v3i4.1128

IRAQI Academic Scientific Journals

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

Influence of 3D printing orientations on mechanical properties for polymeric models

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Article Informations

Received: 25-08-2024,
Revised: 22-09-2024,
Accepted: 15-10- 2024,
Published online: 20-12-2024

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Key Words:
3D printing orientation,
polymeric material,
mechanical property,
Phrozen Sonic Mini,

A B S T R A C T

The coming of 3D printing technology has revolutionized the manufacturing process, particularly in the sector of polymeric materials fabricated by LCD printer. Two different designs were selected in study in order to achieve the goal. Their geometry was selected by ASTM to prepare them for the tensile test and compassion test. For tensile tests, three directions were chosen; On-Edge, On-Flat and Up-Right and for compression tests On-Vertical and On-Horizontal directions. Both experimental and FEM were used in this study. Study's findings demonstrated that the printing orientation of the specimens has significantly and decisively impacted the mechanical properties. Tensile specimen (On-Edge) exhibited greater strength due to the smaller printed layer, resulting in improved resolution and less porosity. The tensile specimen (Up-Right) exhibited lower strength due to the perpendicular orientation of the printed layers with respect to the applied tensile force. For compression test, vertical direction own superior strength compared to other.

1. Introduction

Additive manufacturing (AM) is an extraordinary technological advancement, a kind of revolution involved revolutionary design that could completely disrupt the way of designing and manufacturing that has been done for the past two hundred years. AM technology has progressed to the point where it is now possible to create a layer-by-layer 3D object. This technology was first patented in 1986, when 3D printing was first applied with photopolymer resin. Since then, AM technique has improved and developed significantly [1][2].

The utilization of 3D printing technologies is no longer restricted to prototyping, but is increasingly being utilized for the production of a wide range of products. There is no disagreement as to which machine or technology is more effective, as each has its own specific application [3]. Complex topological structures and components, such as porous, lattice, cellular topologies, etc., are extremely challenging to fabricate using traditional manufacturing methods. 3D printing (also known as additive manufacturing) is the nascent technology that enables the creation of complex models layer-by-layer, no matter the geometry [4].

Through a comprehensive literature reviews and experimental analysis various parameters influencing mechanical properties such as printing parameters, polymer type and post processing technique are investigated. Farkas etal.[5] presented a study involved the influence of printing layer directions on tensile and compression tests of printed specimens in (0, 45 and 90 degrees) orientation's through DLP technology. The results showed that, there is a possibility to control the mechanical properties of materials depends on the printed orientation

Caminero etal.[6] have analyzed the effect of build orientation of three different materials in three various axes. Fused filament fabrication (FFF) used to printed the models into three groups: On-Flat, On-Edge and Up-Right by used a (PLA, PLA 3D850 and PLA- Graphene) filaments material. The results showed, through several mechanical tests, that the change in the printing direction had a significant impact on mechanical properties of the samples. For example, through more severe testing, the results just for PLA tensile test, showed the following: On-Flat was 49.5 Mpa, on-edge was 66.5 Mpa and 26.1 Mpa for Up-Right.

Kumar and Narayan [7] have provided a study of the influencing various orientation 3d printing of polymeric material which were printed in FDM technology by printing a ASTM D638 type IV, and they tested the created specimen by using a tensile test, and they supported their results using a simulation technique to provide a comparison between the building material before and after printed structure's.

Jamal [8] has studied the energy absorption (EA) capability of various lattice structures made by ABS polymer and produced through FDM technology. Through his study, he investigated the influence of orientation of three different groups of printed structures presented by: On-Flat, On-Edge and Up-Right. The difference between groups was the printing layers' numbers. The results appeared that the on-edge structure with the smallest area of printing had the best value of EA and the results differed in the other two printing positions.

Keleş et al.[9] they looked and focused at the fracture strength of specimens generated from ABS by FDM with or without a central circular hole under tensile load in three different build orientations - XZ, XY, and C45. The results depend the pervious studied which mentioned before, which made it clear in an unambiguous manner that the mechanical properties will change with the change in the direction of the print.

In the current investigation, the influence of building orientation of 3D-printed models on the mechanical properties is identified as the aim of this study. Vat-Photopolymerization (VPP) technology through 3D-LCD printer was adopted. The study includes two different tracks. The first track is determined by printing models, conducting mechanical tests, and recording the mechanical properties after the printing process. The second track includes the process of designing a model through AUTOCAD in order to analyze the mechanical properties using ANSYS simulation programs. The study will encourage many researchers in the dental industry to understand the optimal method that provides the best strength to their projects by investigating the properties of building material (resin) after curing and becoming a final product**.**

2. Material and Experiential method

2.1 Material used

Material properties of the as received printed building resin are listed in the Table 1, which is provided by the SENERTEK company.

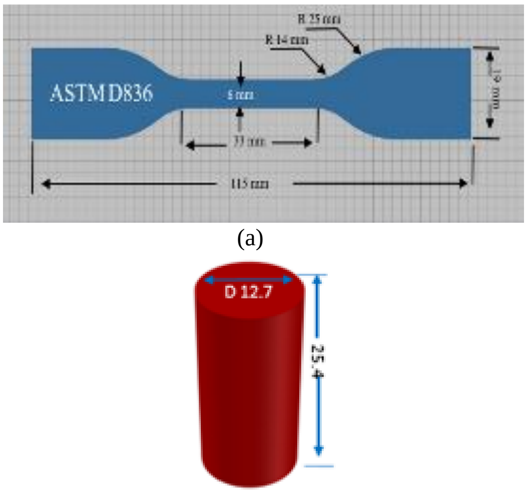
Table 1. Some of the mechanical properties of as-received resin.

Hardness	Viscosity (25ºC)	Ultimate Tensile Strength (Mpa)
≥ 80 Mpa	500~ 600 cP	≥ 50
Tensile Modulus (Mpa)		
≥ 1200		

These mechanical characteristics might be changed after printing, this is due to a variety of factors, including the 3D-printing parameters and conditions, layer orientation, layer thickness and sample size, exposure time, washing and curing steps [10].

2.2 Specimen design

Tensile test specimens were designed according to ASTM D836.The Auto CAD 2022 engineering program was used for the purpose of drawing the model based on the ASTM D836 followed by same producer to print the dog-bone structure and for compression test a specimen ASTM D695, ISO 604 was chosen. Figure 1 show the tensile and compression test specimens respectively.



(a)

(b)

Figure 1. (a) Tensile and (b) compression test specimens.

2.3 Specimes Fabrication

After designing the models according to the required measurements, these designs are export to the (stl) extensions to deal it with (CHITUBOX) program in order to adding supporters and slicing the specimen as an initial step in the process of printing the models in order to the record the specifications of the materials which used in the printing process after printing the models and note any differences before and after the printing process. Figure 3 show the printed tensile specimens at different orientations, (a) On-Edge, (b) On-Flat, and (c) Up-Right.

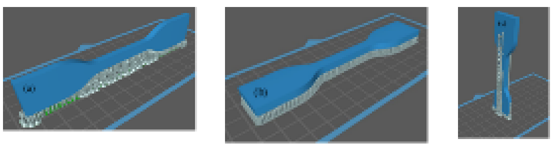


Figure 2. Tensile test specimens ASTM D836 printed at (a) On-Edge, (b) On-Flat and (c) Up-Right directions.

Compression testing explain the behavior of a material under crushing loads. Compression tests are usually carried out on a standardized test specimen (typically a cuboid test specimen or a cylindrical test specimen) using standard platens or specialized fixtures on a standard universal testing machine. Figure 3 show 3D printing compression test specimens at different printing orientations.

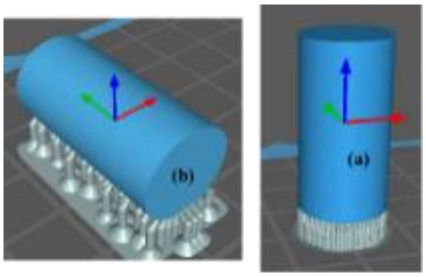


Figure 3. Compression test specimens ASTM D695 printed at; (a) On-Vertical, and (b) On-Horizontal directions.

2.4 3D-printer used

In this study, we used a Phrozen Sonic Mini 8 K $_S$ (CHINA Made-2023) as shown in Fig. 4 with adjustment the original parameter to a suitable parameter according to the instructions of the company that manufactured the printer, the instruction of the company which manufactured the building material (resin), and the printer specification was listed in Table 2.

Table 2. 3D printer Sonic Mini 8K $_S$ Technical specifications

File Format	open-format .PRZ
Slicer Software	Chitubox, Lychee, VoxelDance Tango
Printer Size	L29 x W29 x H43 cm
XY Resolution	22 µm
Printing Volume (L x W x H)	16.5 x 7.2 x 17 cm
Printer Weight	10kg
Rail	Single Linear Rail
USB port	Side
Resin Vat	Metal Vat with FEP Film
Building Plate	Customized Frosted Laser Cut Building Plate

Figure 4. 3D printer Sonic Mini 8K S.

2.5 3D printing preparing steps.

A- Turn on the printer and shake the resin bottle for (1) minute before pouring it into the vat, waiting for a (30) minutes in order to ensure the resin was heated enough. In this paper we used a recommended heat degree (34^{o}). Figure 5 show UA380 Infrared thermometer which used.

Figure 5. UA380 Infrared thermometer.

B- Use a special tool which provide with printer equipment to mix the risen. Special gloves must be used as sjown in Figure 6 below, and it is preferable to use a protective mask (surgical and KN-95) and Transparent Safety Goggles Anti-Splash Impact-Resistant Work Safety Protective Glasses, because these materials which the researcher deals with are toxic material.

Figure 6. Tools and Instruments used.

2.6 Washing and Curing Machine

Once the print is finished, it must be washed to get rid of the uncured resin and then cured to make sure the print is completely cured and stable. Wash and cure machines are specially designed for this purpose and make cleaning and curing the prints much simpler and faster. Figure 7 shows the details of washing and curing components.

Figure 7. Photograph of washing and curing equipment's.

2.7 Testing

Nine specimens were prepared for tensile testing with ASTM D836 - IV, and six other specimens were prepared for compression testing with ASTM D695, ISO 604. The first nine models were distributed into three groups: G1 which printed on-edge, G2 which printed on-flat, and G3 which printed on-upright, three models for each group. Also, six models for compression testing were distributed into two groups as shown in Figure 8 below.

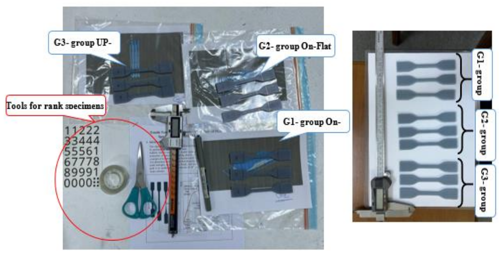


Figure 8. Photograph of Tensile test specimens.

The cross-section of a tensile specimen is defined by two opposing shoulders that are connected by a thinner cross-section, each end of which is tightly gripped in a Tensile testing machine. The tensile test machine will apply tension to the specimen until it breaks. The thinner cross-section of the tensile specimen is intended to be a "predictable failure point" in the tensile test process. A round cross-section or a rectangular cross-section may be used, but in this paper, the flat rectangular cross-section used with American Society for Testing and Materials (ASTM) which was mentioned previously.

Testing started with JJ-Test Universal Testing Machine which located in Salahaddin University-Erbil (SUE) – College of Engineering Mechanical and Mechatronics Engineering.

After marking the center, gauge-length line and the distance between grips, select a tension test from the program operating on the testing device. After that, it was ensured that the device was ready to work through steps that preceded the testing, such as entering testing information such as the name of the testing, the researcher, the date, the dimensions of the piece examined, as well as its standard dimensions, and then making sure to install the grips which contain the grooves that prevent piece from slipping during the process as shows in Figures 9 and 10.

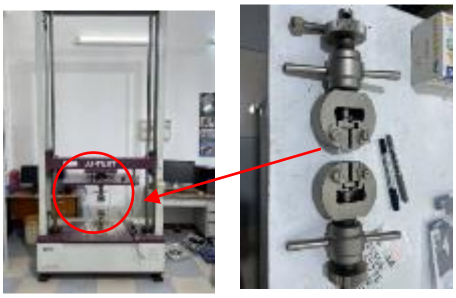


Figure 9. Photograph of JJ-TEST Universal Tensile machine.

Figure 10. Photograph of before and after tested the tensile, dog bone specimen

After replacing the grips with cylinders capable of performing the compression test, calibrating the device, and choosing an examination instead of the tensile test, as well as following the same procedures of numbering the samples according to the groups mentioned previously. Figure 11 show practical producer for compression test

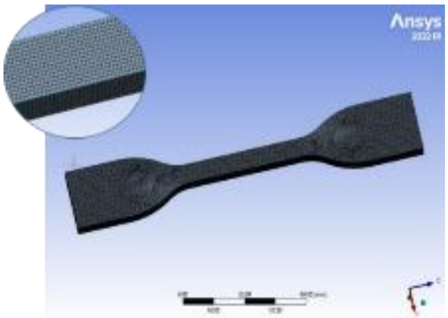
Figure 11.ASTMD695 specimens for compression test.

A hardness test also performed, by measuring the hardness value of the printed structure for tensile a compression test specimens at the workshops and laboratory. Start with Shore Durometer A instrument, which was designed for testing the following materials: soft rubber, elastomers, silicone, neoprin, vinyl, butyl, nitrile, soft plastics, leather, wax, etc. and when the value found more than (100), switch the instrument to ore Durometer D which was designed for testing products from rubber, resin, glass, PCB, fibers, plastics, etc. and re-tested. Figure 12 show the two type of hardness test instrument

Figure 12. Shore Durometer D & A used in the current study.

3. Meshing

For the purpose of obtaining the most accurate details and obtaining the best results that are compatible with the results obtained from the practical side, the size and number of elements which used in the analyzation of the specimen by study the convergence elements size in order to reach a suitable size and number. Figures 13 and 14 show the meshing and mesh convergence of tensile test specimen respectively**.** Hex Dominant element type was selected for this purpose with 0.3 mm elements size and 225592 elements numbers.



Figuer 13. Meshing of tensile test specimen.

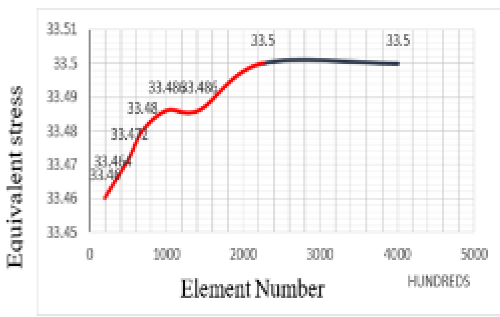


Figure 14. Mesh Convergence study.

4. Simulation

Simulations were carried out in static structural analysis mode with one end fixed in ANSYS 2022 R1 software with Hex Dominant element type and 225592 number elements and size of 0.3 mm. Figure 15 show the simulation results of maximum stress in tensile test specimen, while Figure 16 show the maximum deformation during tensile simulation.

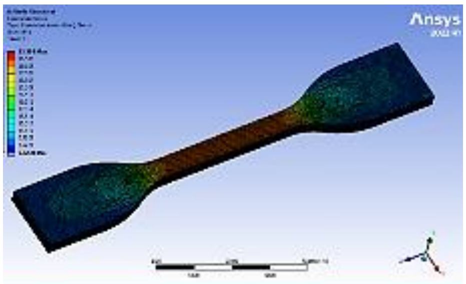


Figure 15. Maximum stress obtained in the tested tensile specimens.

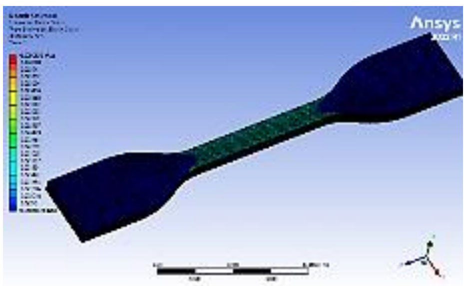


Figure 16. Maximum deformation obtained in the tested tensile specimens.

5. Results and discussion

5.1 Results

One critical factor that influences the mechanical properties such as (strength, hardness, etc.) of 3D printed parts is the orientation of the print. This is because the layer-by-layer construction process of 3D printing which creates anisotropic properties within the printed object. In most 3D printing methods, such as Vat- photopolymerization represent through Liquid Crystal Display (LCD), parts are built layer by layer along the vertical direction. This results in weaker inter-layer bonding compared to the intra-layer bonding within the horizontal direction. This makes parts more susceptible to delamination and lower tensile strength along the vertical axis.

The bonding between layers depends on many factors such as; the temperature, cooling rate, and the type of polymer used. For thermoplastic polymers, insufficient bonding between layers can lead to anisotropic mechanical properties, with lower strength and toughness in the vertical axis.

Studies has shown that the tensile strength of polymeric parts; The tensile specimen (On-Edge) exhibited greater strength due to the smaller printed layer, resulting in improved resolution and less porosity. The tensile specimen (Up-Right) exhibited lower strength due to the fact that the printed layers were oriented perpendicular to the applied tensile force. For compression test (On-Vertical) owned better strength results than (On-Horizontal). The hardness test showed matches for both the tension and compression specimens.

Different application may require different printing orientations based on the specific mechanical property needed. For example, parts that need heightened soil strength in a particular direction should be oriented to maximum layer adhesion in that direction. Tables 3,4,5,6 and 7 shows the study results. Figures 17,18,19,20 and 21illustreated the stress –stain diagram of the tensile and compression tests. Figure 22 show the results of harness test of specimens.

Table 3 Tensile test specimens printed at On-Edge direction G1- Group

	Modulus of Elasticity (MPa)	Avg. (MPa)	Yield Stress (MPa)	Avg. (MPa)	Ultimate Stress (MPa)	Avg. (MPa)
SPECIMEN-01	Neg.		Neg.		Neg.	
SPECIMEN-02	1386.423	1379.09	30.438	30.66	30.481	31.104
SPECIMEN-03	1407.762		30.899		31.726	

Table 4 Tensile test specimens printed at On-Flat direction G2 - Group

	Modulus of Elasticity (MPa)	Avg. (MPa)	Yield Stress (MPa)	Avg. (MPa)	Ultimate Stress (MPa)	Avg. (MPa)
SPECIMEN-01	1376.890		29.531		29.543	
SPECIMEN-02	1148.585	1289.01	29.603	28.10	29.612	28.11
SPECIMEN-03	1341.558		25.170		25.180	

Table 5 Tensile test specimens printed at Up-Right direction G3 - Group

	Modulus of Elasticity (MPa)	Avg. (MPa)	Yield Stress (MPa)	Avg. (MPa)	Ultimate Stress (MPa)	Avg. (MPa)
SPECIMEN-01	1065.201		25.389		25.396	
SPECIMEN-02	1248.870	1163.83	21.861	22.11	21.869	22.99
SPECIMEN-03	1177.416		19.074		21.717	

Table 6 Compression test specimens printed at On-Vertical direction G1-Group

	Max press (KN)	Compress Stress, MPa	Avg. (MPa)
SPECIMEN-01	11.351	89.604	
SPECIMEN-02	11.062	87.324	91.87
SPECIMEN-03	12.504	98.705	

Table 7 Compression test specimens printed at On-Horizontal direction G1-Group

	Modulus of Elasticity (MPa)	Compress Stress, MPa	Avg. (MPa)
SPECIMEN-01	10.758	84.925	
SPECIMEN-02	11.543	91.123	84.53
SPECIMEN-03	9.822	77.534	

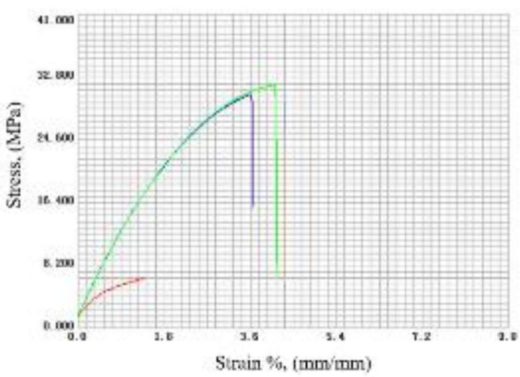


Figure 17. Stress–strain curve for G1.

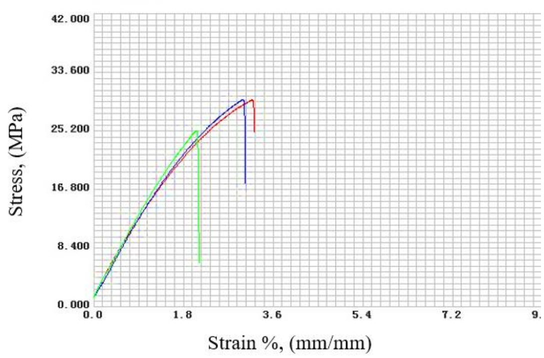


Figure 18. Stress–strain curve for G2.

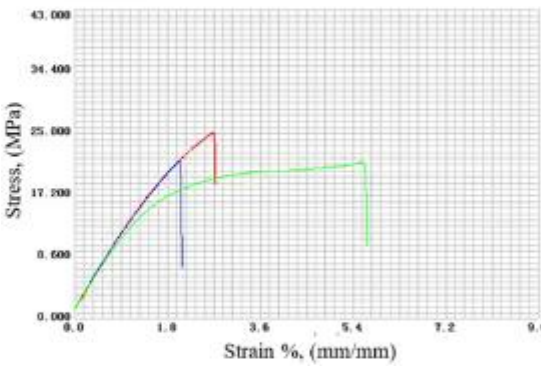


Figure 19. Stress–strain curve for G3.

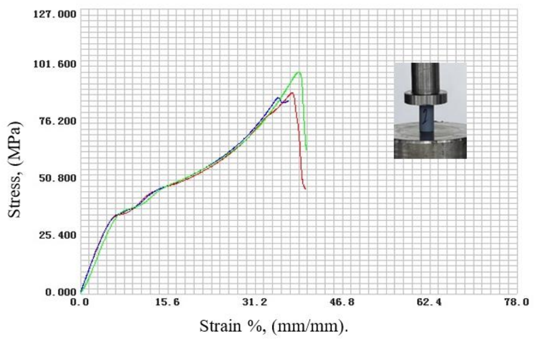


Figure 20. Stress–strain curve for compression

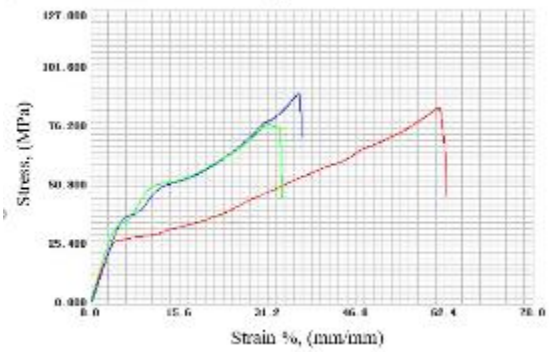


Figure 21. Stress–strain curve for compression test On-Horizontal specimen.

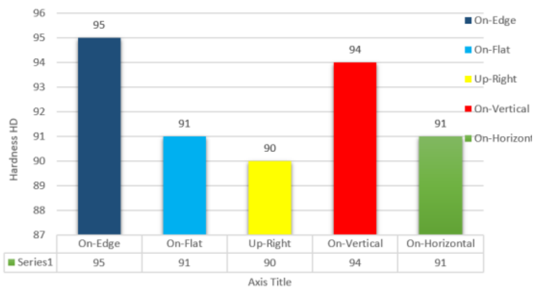


Figure 22. Hardness test results.

5.2 Discussion

The effect of 3D printing orientation, particularly for plastic parts, has great influences on mechanical properties. To investigate the influence of 3D printing direction on mechanical characteristics and properties, a dog bone design was selected and fabricated through a 3D printing technology in a various printing orientation as mentioned before. The results show that in the first group models printed in On-Edge, involved the smallest layer area, which led to increased strength.

In the second, the results showed a decline in the strength tests, as the test results showed a deterioration in the mechanical specifications as a result of the increase in the surface area of the printed layer, which led to an increase in the number of printing problems as porosity which formed a negative factor resulting in a reduction in strength.

In the third group, the difference in printing orientation, form a clear effect of the perpendicularity or parallelism of the layers with the tensile force used in the mechanical tests. Therefore, the results proved that when the layer is perpendicular to the tensile force, this leads to the layers being easily shattered, unlike the case in which the tensile force is parallel to the printing direction of the layers, which requires more force to cause these layers to shatter, and therefore the durability is higher with vice versa in compression to same specimen design. In this study, there was great agreement with many of the studies mentioned before that reinforced this conclusion [12] [8].

In the second group, On-Flat models, the increasing of layer’s area leads to several key which effects the final object: print spent time, object finish and details, model structural strength, support structures, printer calibration to cover all the required area and applications suitability. The results of the study were as anticipated: the maximum stress in the second group decreased by 6% when compared to the first group and recorded 29.612 Mpa. The reason which led to the result was the inverse relationship between the increased surface area of printed models and their mechanical specifications by interact of several parameters such as; layer adhesion: the bonding between layers in large layer area may be weakened by larger layers due to uneven cooling. In particular, the part's strength in the z-axis (the direction perpendicular to the layers) may decrease if the layers don't connect properly. Greater interlayer adhesion and overall strength: smaller areas often cool more uniformly than larger ones. Additionally, Larger layers can involve more internal-stress during the cooling duration, leading to partially or delamination, which weakens the part [13].

In the third group: The results in the third group were the worst. The reason for this is that the printing process involved layering in a direction perpendicular to the force applied during the tension test. Thus, the delamination of the polycarbonate chains was significantly simpler in comparison to the first and second groups. Hence, it is advised against printing in this direction for applications. The reason behind that the layer adhesion vs. material strength, in general, the interlayer adhesion—the link between layers of a 3D printed object—is weaker than the inherent strength of the material. The tension test predominantly strains these interlayer linkages when the layers are perpendicular to the applied force, which may result in an early failure or lesser strength. In this group strength, recorded the worst strength by 25.396 MPa with reducing nearest 20 % if compared with maximum strength in first group

A group of three samples which printed in the vertical direction through 3D printing were layer's perpendicular to the pressure force used in the examination. Polymeric cylinders deform elastically and recover to their original shape after load removal. The cylinder may permanently distort in plastic deformation as load increases. The load at which this transition occurs depends on polymer yield strength. The cylinder was crack when the load exceeds its ultimate compressive strength, anisotropic printed material also affects fracture pattern.

Under a compress load, the load pushing the polymer chains one towards the other and reducing the distances between them, thus achieving the shattering of the chains. In addition, because the printing is in a vertical position, it has small layers and therefore contains short polymeric chains, and therefore it is characterized by a high density and requires force. Too big to break, unlike long chains in a large area which involved a long chain.

The maximum stress was 98.705 Mpa and the average was 91.87 Mpa, indicating harmony amongst the three models tested in this group in the elasticity and plasticity regions.

In Horizontal direction, Polymeric materials frequently undergo plastic deformation prior to failure. The magnitude of this distortion can be impacted by the printing direction, with horizontally printed cylinders potentially exhibiting unequal deformation as a result of weaker connections between layers. When a compressive force is applied to the cylinder, there is a possibility that the layers may separate from each other, especially if the force is delivered in the same direction as the way the layers are stacked. The results showed a clear deterioration in the tests conducted on these models with 14% reduction to up to 84.5 Mpa due a delamination in interior layer.

6 Conclusions

In this paper, various types of polymeric structure are fabricated by 3d-printing in different building layer orientations in order to investigate their mechanical properties. Both experimental and the finite element modeling were performed using ANSYS program. The tensile, compression and hardness tests were used to obtain these results. The results referred to the following: for tensile specimen (On-Edge) had higher strength value due to small printed layer which lead to higher resolution and less porosity. For tensile specimen (Up-Right) had worse strength value due to direction of printed layer were printed perpendicular to the tensile force. For compression test (On-Vertical) owned better strength results than (On-Horizontal). In hardness test, the test results for the tension and compression specimens was in the same manner as for the first tests. The orientation of 3D printing significantly affects the mechanical property of polymeric model. To achieve the best mechanical performance, it's essential to consider the intend use of the parts and optimize the printing of orientation accordingly. Understanding the interplay between layer adhesion, material property, and stress direction is a key to production strong and reliable 3D printed parts.

Acknowledgments

This work was financially supported by Mechanical Engineering Department in Engineering College / Mosul University.

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