Influence processing parameters of FDM 3D printer on the mechanical properties of ABS Parts

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3D printing has been a type of additive manufacturing (AM) that creates parts by adding or printing thin layers of material on top of each other using computer-aided design (CAD) models. Fused deposition modeling (FDM) is a 3D printing process that produces parts by heating, extruding, and depositing the thermoplastic polymers. FDM-fabricated products have been becoming increasingly popular in various industries such as medical, electronics, automobile, pharmaceutical, etc. This study has been carried out on a set of standard samples out of acrylonitrile butadiene styrene (ABS) which have been produced using the FDM process. A comprehensive mechanical property evaluation has been performed to determine the influence of the infill density and layer thickness of ABS (FDM-fabricated) on the ultimate tensile strength, elastic modulus, yield strength, fracture strain, and toughness (energy absorption) using a tensile test. From the result analysis, it has been found that infill density and layer thickness haveimportant effects on the tensile properties. The behavior investigation of ABS-filament freeform fabrication has shown that infill density of 100% and a layer height of 0.1 mm achieve optimized process parameters values.

1 Introduction

Additive manufacturing (AM), commonly referred to as three-dimensional printing (3DP), has been introduced with their manufacturing equipment and materials at the end of the 1980s as rapid prototyping (RP) method[1]. Over the past 30 years, it has developed remarkably, and now it is not only the process for manufacturing models and prototypes but also has considered as a true manufacturing technique for manufacturing complex geometries models[2]. AM has built up three-dimensional parts directly from a virtual Computer-Aided Design (CAD) model by adding materials layer by layer at a time based on a computerized 3D solid model[3]. Contrasting the conventional manufacturing process, it has not needed any tools such as fixtures, cutting tools, or other auxiliary resources. It has been also referred to asthe Layered Manufacturing (LM) technique that CAD geometric data, divided into layer data, which have significantly reduced the time of the product design and manufacturing[4].

Fused Deposition Modeling (FDM) has been Additive Manufacturing (AM) technology that has been the most widely used and has represented the largest installed base of 3D printer technology[5]. FDM is the second most leading commercial layered manufacturing technique[6]. In 1992, the first FDM machine has been developed by Stratasys and named 3D Modeler, and Stratasys has used the 3D printers name for its machines[7]. FDM machines have been based on the extrusion of heated feedstock thermoplastic filaments. Extruder head, extrude semiliquid material through a nozzle tip, and ejects them on the platformto form a layer on the previously deposited layer[8]. The build speed has been thus related to the traversal and extrusion speeds of the print nozzle and platform plate[9]. FDM-built parts have been considered as a laminated composite structure that has been vertically stacked layers of bonded fibers[10]. 3D printers have a lot of applications in industries. For example in the medical sector, it has been used to print organs and cells[11]. Also, it has been used to fabricate a small-diameter vasculature[12]. A large number of thermoplastic polymers have been used for AM such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), polyetherimide (ULTEM), polyether ether ketone (PEEK), and nylon. It has been well-known that polymers have been used extensively for critical

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manufacturing structures in industries. The engineering modeling of polymer structures has needed a thorough knowledge of the mechanical response of polymers[13]. ABS is a thermoplastic polymer have made when 5-30% of styrene and 50% acrylonitrile have been polymerized in the presence of preformed polybutadiene[14]. It has got moldable just below the melting temperature and solidified upon cooling. ABS has got excellent properties such as impact resistance, toughness, stability under load with limited loads, resistance to aqueous acids, etc. A variety of improvements have been made to modify ABS properties like impact resistance, toughness, and heat resistance[15].

Rankouhi et al.[16] have printed ABS parts with different layer thicknesses and have reported parts that printed with 0.2 mm layer thickness, have shown higher elastic modulus and ultimate strength compared with 0.4 mm layer thickness. Fernandez-Vicente et al.[17] have investigated the effect of pattern and density of the infill on the mechanical properties of ABS parts. They have found that the effect of the different printing patterns has caused a variation of less than 5% in the maximum tensile strength. Also, they have shown a rectilinear pattern that has achieved the higher tensile strength which has been about 36.4 Mpa when using 100% infill. Uddin et al.[18] have considered three variables on the FDM printed ABS specimens such as layer thickness (0.09 mm, 0.19 mm, 0.39 mm), printing plane (XY, YZ, ZX), and printing orientation (horizontal, diagonal, and vertical) and have performed on a universal testing machine. Results have shown that the highest failure strength and stiffness specimens have been achieved with a layer thickness of 0.09 mm and printing plane orientation of YZ-H. Farbman et al.[19] have investigated the tensile test results of printed ABS specimens with various infill percentages, infill geometry, load orientation, and strain rate. They have found that specific ultimate tensile strength decreases with decreasing the infill percentage, and the rectilinear infill geometry has been weaker than hexagonal pattern infill. Cwikla et al.[20] have used a DIY 3D printer with ABS parts to obtain the higher tensile strength with different process parameters. They have reported that the best set of parameters to get higher tensile strength obtained with infill percentage of about 40-50%, as hell thickness of 2-3 layers/lines and using the honeycomb pattern. Garrettet et al.[21] have investigated the effects of layer height, infill percentage, and print orientation using a Maker Bot Replicator 2 printer. They have concluded that increasing infill percentage has a significant effect on the ultimate strength and longitudinal elastic modulus of the test specimens that maximizing part strength. Also, it has been reported that layer thickness and print orientation have not had significant effects as infill percentages. Samykano et al.[22] have studied the effect of three process variables such as layer thickness, infill density, and raster angle on the mechanical properties of ABS in FDM technology. They have found that the optimum parameters for printed ABS are 0.5 mm layer height, 80% infill, and 65° raster angle. Cantrell et al.[23] have used the classical laminate theory (CLT) to compare the mechanical behavior of FDM parts which have been ABS and PLA with 0° and 90° raster angles. They have found that ABS has shown more orthotropic behavior than PLA materials. Also, they have shown that the mechanical characteristics of the material decrease with increasing the raster angle.

Anitha et al.[24] have used a 3D printed ABS part to determine the extent of anisotropy using a tensile test. They have printed specimens with different varying raster and build orientations (flat, on-edge, and upright). Their results have shown that changing raster and build orientations have got an insignificant effect on Young's modulus for the ABS material. Also, they have reported that the highest tensile strength (30.8 MPa) and modulus of elasticity (2050 MPa) in ABS specimens have been achieved at flat printing direction with raster angles of 0° and 90°. It has been confirmed that the mechanical properties of the printed parts have changed with different printing variables. Most used printing variables to determine the mechanical properties have been layer height (LH) which has been the thickness between layers, infill density (ID) which has been the amount of filament deposited on the layers or final parts, raster anglewhich is the angle between the nozzle path and the X-axis of the FDM plate, the orientation that is parts position during printing, raster width has referred to the width of the deposited material, and air gap that has been the horizontal space between the beads of deposited FDM material[25-29]. Meanwhile, the discoveries on the ABS properties have been still varied and incomplete, and extra studies have needed to be taken to specify their properties before using them in different applications. Therefore, it has needed to have a complete understanding of their mechanical properties.

The main goal of this investigation has been to determine the correlation between layer thickness and infill percentage with the mechanical properties of AM parts using FDM. In order to calculate mechanical properties such as ultimate tensile strength (UTS), elastic modulus, fracture strain, yield strength, and toughness (energy absorption), tensile tests have been performed on samples made of ABS with different layers thickness and infill percentage.

2 Materials and Methods

The first step for manufacturing FDM samples was preparing the specified designing specimen, according to the standard geometry. This procedure described the preparation of sheet specimens of the Acrylonitrile Butadiene Styrene (ABS). The apparatus used in preparing the specimens should be as specified by ASTM D638–14 standard. This standard is designed to produce tensile property data for the control and specification of plastic materials[30]. In this work, the type IV standard was used. The width and thickness of the cross-section area are 6 mm and 3 mm respectively. Therefore, the original cross-sectional area (A_0) of the specimen was 18 mm^2. The schematic diagram of the sample was presented in Fig. 1. Also, the specifications of the tensile specimen are presented in Table 1.
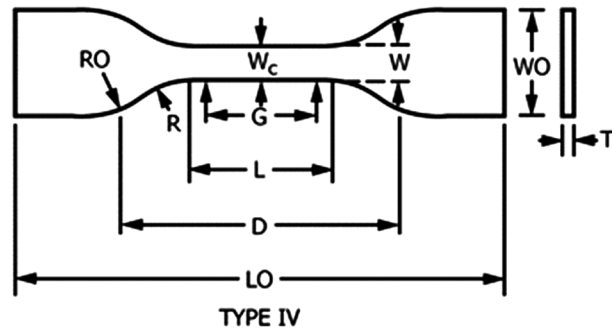

Fig. 1 — Tensile specimen according to ASTM D638 standard.

All the experimental tensile test samples were made from ABS material which is one of the most common filament materials in the FDM process. In this research, ABS polymer filament was use data 1.75 mm diameter at ambient temperature (23°C). The mechanical and physical properties ofused ABS showed in Table 2.

The TOP 3D Printer was used as an open-source FDM printer to build the specimens of the experimental tests. The machine had two nozzles in the extrusion head. The first nozzle was used for deposition of part materials and the second was used to build support structure and alternately work until the making of the specimen was finished. The nozzles were heated to 230°C, just below its ABS filament melting point, to had a semi liquid or softened form of ABS. The filament could extrude through the nozzle tip and deposit on the printing build plate layer by layer. The nozzle could be move-in horizontal directions, and the platform could be movein a vertical direction by using a numerically controlled mechanism. The temperature of the platform plate was much cooler (80°C) than the temperature of the extruder nozzle that the extruded printed materials cool, solidifies, and then bond on contact with it. After the first layer, the process is repeated by injecting a polymer on the adjacent existing layers and so on. All 3D geometries parts were designed using powerful CAD software of Solid Works 2019 (Dassault Systèmes Solid Works Corporation, Waltham, MA 02451) and then stereolithography (STL) format files outputted from the CAD model parts. The standard geometry was designed due to the ASTM D638–14 Type IV standard dimension. STL of the designed part was imported to the 3D printer's software, MakerWare Version 2.4.0.14 (MakerBot Industries, LLC., USA). In this 3D printer's software, the layer thickness, infill percentage, extruders, and

Table 1 — Dimensions of test sample according to ASTM D638–14 standard specifications

W (mm)	L (mm)	WO (mm)	LO (mm)	G (mm)	D (mm)	R (mm)	RO (mm)
Width of a narrow section	Length of narrow section	Width overall, min	Length overall, min	Gage length	Distance between grips	Radius of fillet	Outer radius
6	33	19	115	25	65	14	25

Table 2 — Physical and mechanical properties of ABS

Chemical formula	$(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$	Tensile strength (MPa)	22
Density (g·cm−3)	1.060 – 1.080	Tensile elongation (%)	6
Nozzle temperature (°C)	230 – 250	Tensile modulus (MPa)	1360
Bed temperature (°C)	80 – 110	Glass transition temperature(°C)	105
Thermal conductivity (W/mK)	0.1	Solubility in water	Insoluble in water
Build Surface	Kapton tape, ABS Slurry	Cooling	Part cooling fan not required

build plate temperatures, and the nozzle travel movement speed could be changed. The STL file was converted to X3g format and transferred to an SD card. The printing process was performed considering two different variables simultaneously which were the layer thickness and infill percentage. The manufacturing time and used material weight changed with changes in the input parameters. In this research, the FDM 3D printer of ABS is done at different infill densities of 100%, 50%, and 40%, anddifferent layer thicknesses (0.1 mm, 0.15 mm, 0.2 mm, and 0.3 mm). The combinations of parameters were presented in Table 3. The samples have under gone the slicing process before printing which made the files ready for build with the FDM machine. All the samples were printed in triplicate (n=3).

Samples with different layer thickness and infill percentages were manufacture. Solid works design and the manufactured 3D printed specimen were presented in Fig. 2. All tensile tests were done based on Type IV of ASTM D638–14 standards using the tensile universal machine at room temperature (23°C).

3 Results and Discussion

3.1 Effect of FDM variables on the mechanical properties

As mentioned before the tensile tests were done on the specimens with different layer heights (LH) and infill density (ID). The stress-strain diagrams of tensile tested specimens with different LH and ID values were presented in Fig. 3.

The drawn and fractured specimens with different LH and ID after the tensile tests were shown in Fig. 4.

3.2 Ultimate tensile strength

Ultimate tensile strength (UTS) often shortened to tensile strength or ultimate strength is the maximum stress the material or structure can withstand while being stretched or pulled before failing or breaking. The investigations show that the maximum value of UTS belongs to the specimen with an infill density of
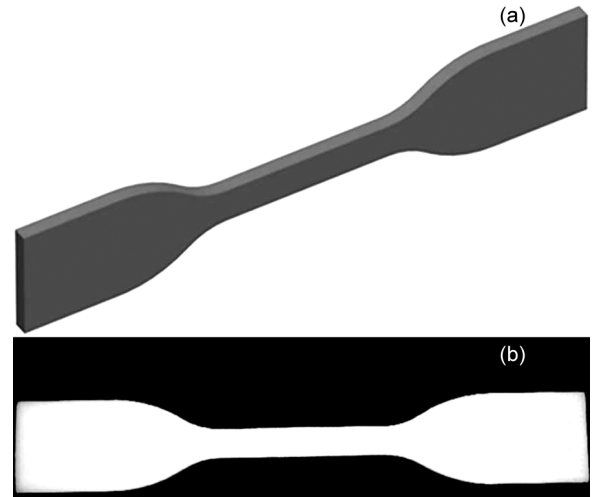

Fig. 2 — (a) Solidworks design, and (b) manufactured tensile specimen based on ASTM D638 – 14 Type IV standards.
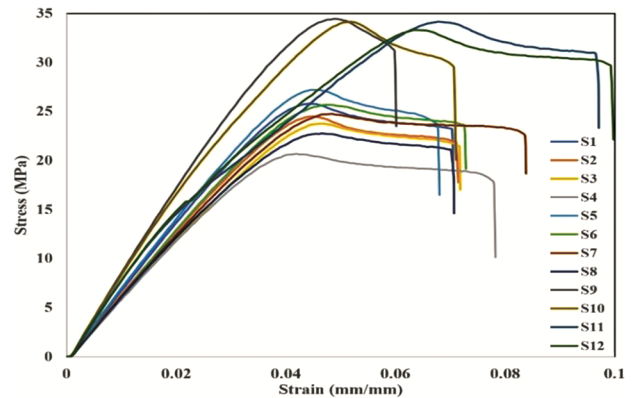

Fig 3 — Stress-strain curves of all 12 samples with different values of LH and ID resulted in tensile tests.

Table 3 — The processing conditions of the 3D printer for test specimens

| Samples	Layer height (mm)	Infill (%)	Speed while travelling (mm/ sec)	Speed while extruding (mm/ sec)	Build Plate (°C)	Extruders Temp (°C)	Number of shells	Weight (g)	Time (min)
S1	0.1	40	150	45	80	230	2	6	40
S2	0.15	40	150	45	80	230	2	7	30
S3	0.2	40	150	45	80	230	2	6	25
S4	0.3	40	150	45	80	230	2	7	20
S5	0.1	50	150	45	80	230	2	6	45
S6	0.15	50	150	45	80	230	2	7	30
S7	0.2	50	150	45	80	230	2	7	20
S8	0.3	50	150	45	80	230	2	7	20
S9	0.1	100	150	45	80	230	2	7	50
S10	0.15	100	150	45	80	230	2	8	60
S11	0.2	100	150	45	80	230	2	8	30
S12	0.3	100	150	45	80	230	2	8	20
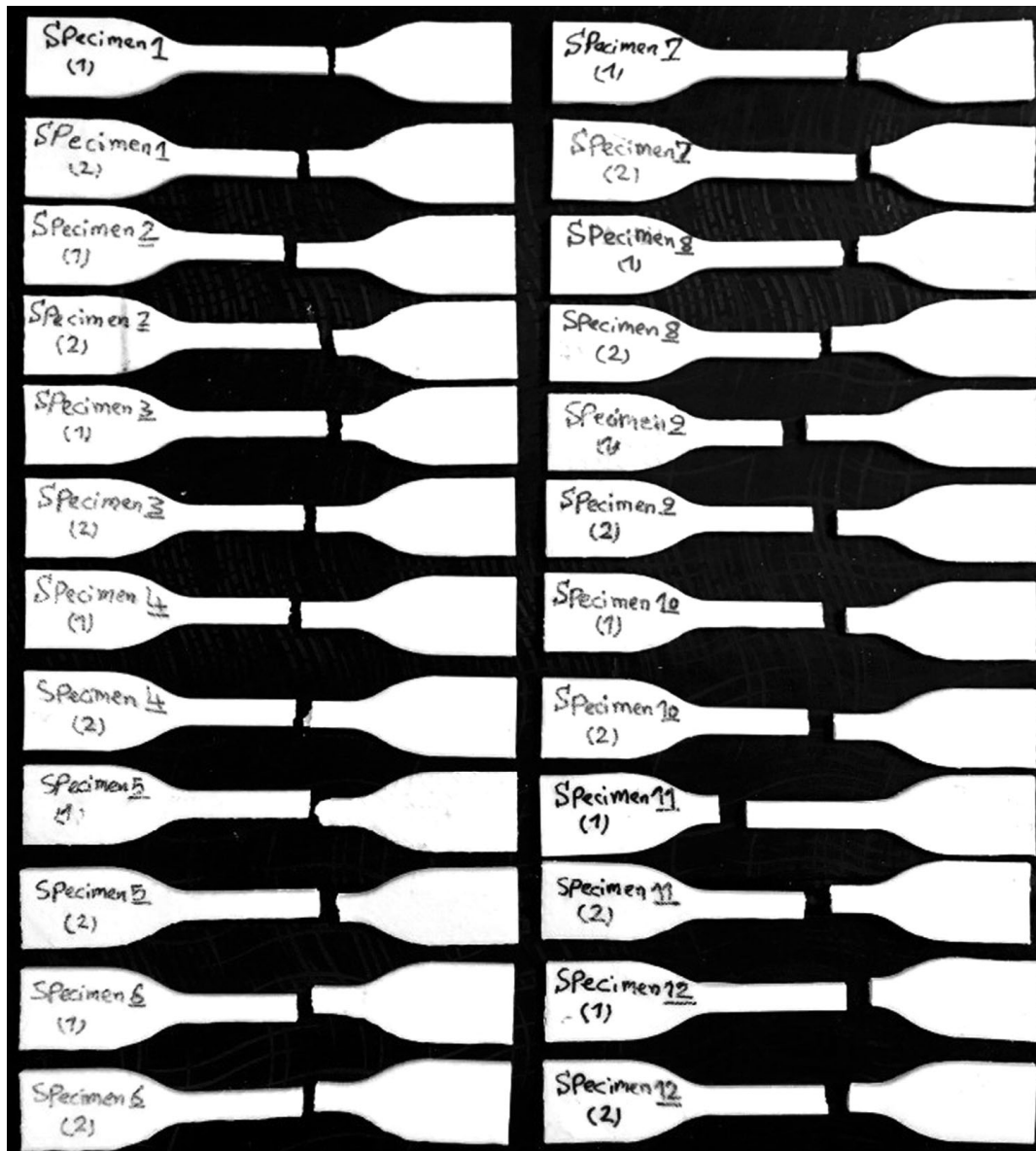
Fig. 4 — Fracture caused on the specimen after the tensile test.

100% and a layer height of 0.1 mm (specimen with No. 6). It was observed in Fig. 5(a) that the UTS increases with increasing the infill density. Also, as was cleared in Fig. 5(b) the UTS values decreased with increasing layer height.

3.3 Elastic modulus

Modulus of Elasticity (E) also known as elastic modulus, is a proportional constant between stress and strain in the elastic portion of the stress-strain curve. In the elastic region after removing the load, materials return to their original shape. E is defined as the slope of the stress-strain curve in the elastic deformation region. Materials with a steep slope in stress-strain curves are resistant to deformation and have a high tensile modulus. On the other hand, the curve of the material with a gentle slope was easily deformed which means it had a low tensile modulus[31]. From the results, the highest elastic modulus was obtained by specimen 9 at 873.4 MPa that has a 100% ID and 0.1 mm LH. S10 has a slightly lower elastic modulus that is 863.03 MPa. The lowest value of elastic modulus had reported in Specimen 4 at 563.1 MPa that had 40% ID and 0.3 mm LH. As it was observed in Fig. 6(a), there was a direct relationship between the infill density and elastic modulus, as the
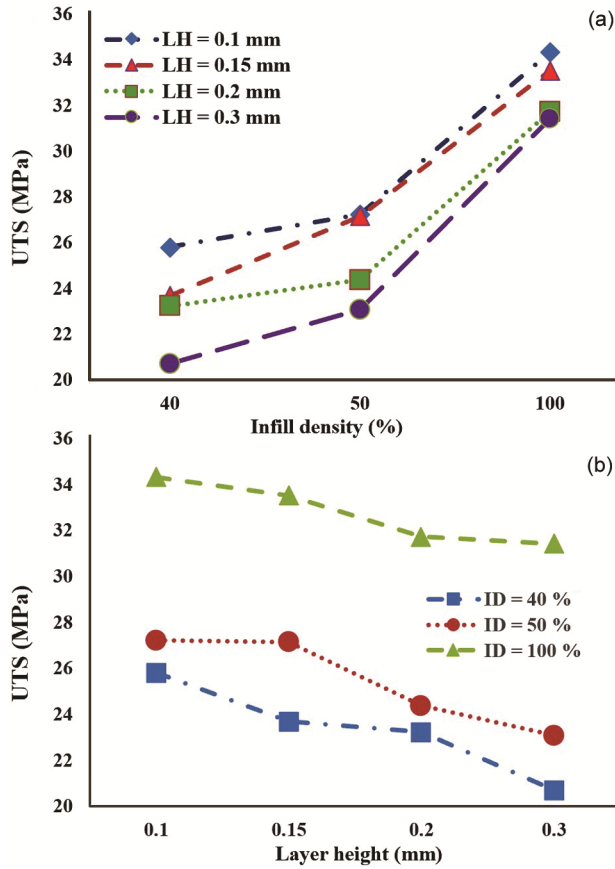
Fig. 5 — Variation of UTS with the variation of (a) infill density, and (b) layer height.

Fig. 6 — Variation of elastic modulus with the variation of (a) infill density, and (b) layer height.

elastic modulus increases with an increase in the infill density. Also, the elastic modulus of the specimen increased with decreasing the layer thickness, as shown in Fig. 6(b).

3.4 Yield strength (0.2% offset)

Yield strength (σ_y) also known as yield stress is the amount of stress needed to produce a small amount of plastic deformation. In the stress-strain curve, yield strengthis the end of the elastic behavior point and the beginning of plastic behavior. In brittle materials like ABS, little or no plastic deformation happens. Aselastic to plastic behavior is not easily detected, it can be defined by the offset method. In this method, a line offset by 0.002 mm/mm (0.2%) from the origin and parallel to the initial portion of the stress-strain curve is achieved. The offset yield stress is the stress that isgot from the intersection of the stress-strain curve and a line parallel to the elastic portion of the curve. The highest yield strength of 29.71 MPa has occurred in specimen 9 that is achieved by 100% ID and 0.1 mm LH. The lowest yield strength of 14.59 MPa has obtained in specimen 12 atthe ID of 100%
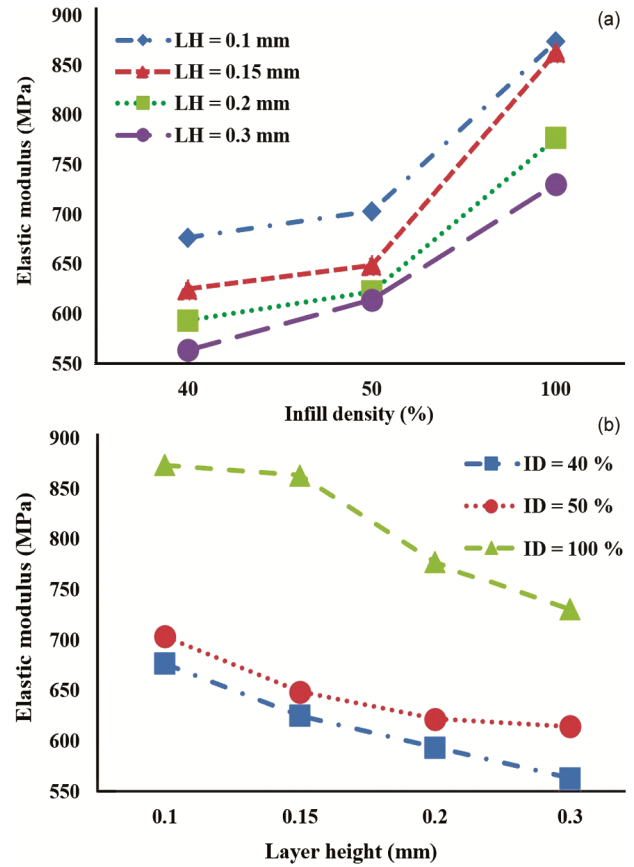
and the LH of 0.3 mm. As it is clear in Fig. 7, there was some instability between the yield strength and infill density, and layer height. As the results have some fluctuation and could not verify the direct relation between the infill density and layer height on the yield strength of materials.

3.5 Fracture strain

Fracture strain is the maximum amount of strain that samples can resist before fractures. It happened when the sample deformed at the maximum amount and no more strain can receive. From the resulted data the highest fracture strain gain by S12 at 0.096 mm/mm with 100% ID and 0.3 mm LH. It was followed by S8 that this value is 0.084 mm/mm. The lowest fracture strain was reported for S9 at 0.058 mm/mm with an ID of 100% and LH of 0.1 mm. The second-lowest fracture strain was achieved by S5 at 0.067 mm/mm. According to Fig. 8, specimens did not show a similar trend that can be understood from the results there was not a specific relation between infill density and layer height with the fracture strain.
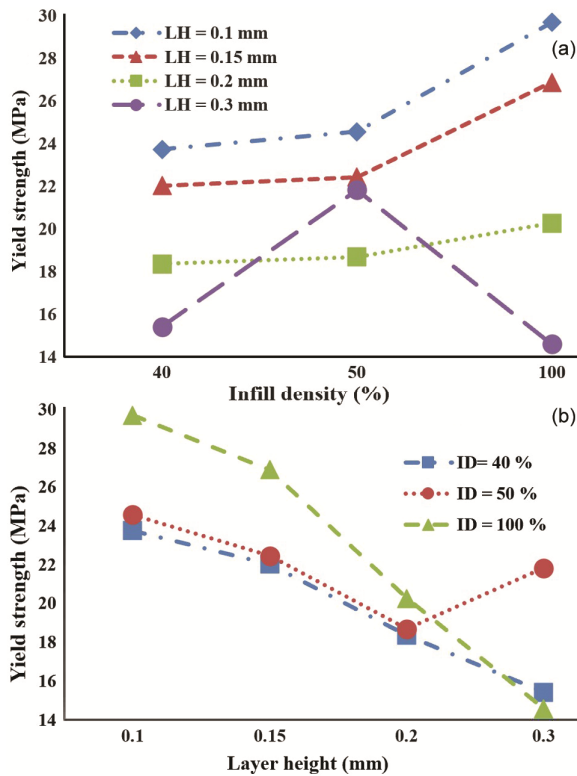
Fig. 7 — Variations of yield strength with the variation of (a) infill density, and (b) layer height of samples.
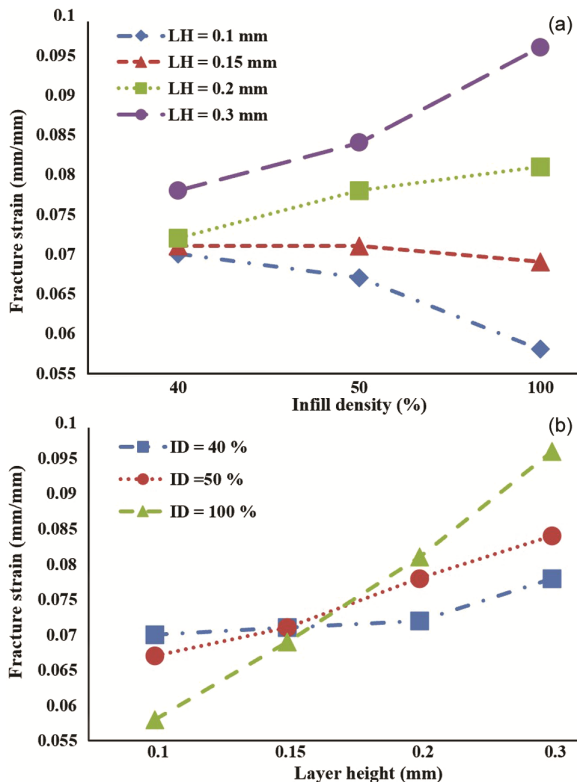

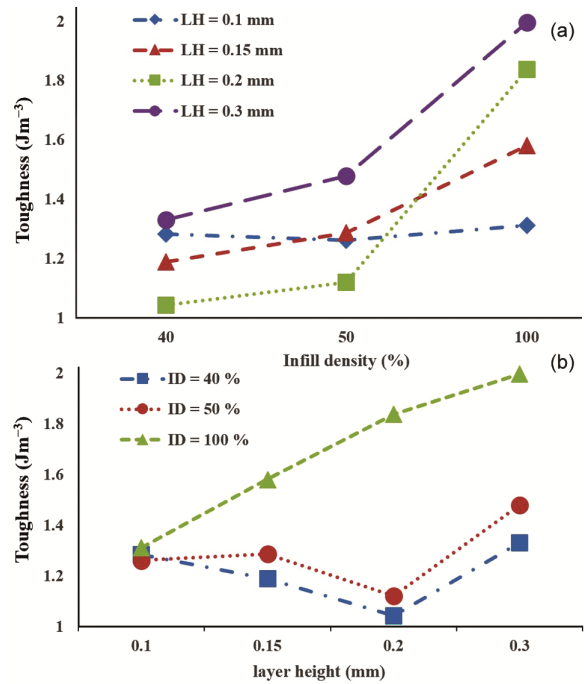Fig. 8 — Variations of fracture strain with the variation of (a) infill density, and (b) layer height of samples.

Fig. 9 — Variations of toughness with the variation of (a) infill density, and (b) layer height of samples.

3.6 Energy absorption (toughness)

Toughness is the ability of a material to plastically deform and absorb energy before rupturing. On the other way, it is the amount of energy per unit volume before fracture. In the stress-strain curve, energy absorption is the area below this curve that is calculated for each sample. The highest toughness got by S12 at 1.99 Jm^{-3} with the ID of 100% and LH of 0.3 mm and it followed by S11 at 1.83 Jm^{-3} which is slightly lower. The lowest toughness was achieved by S3 at 1.04 Jm^{-3} with 40% ID and 0.2 mm LH. It can be interpreted from the deduction of the data, there was not a specific relationship between the ID and LH with toughness. All the data did not show a similar trend which was shown in Fig. 9.

4 Conclusion

In this study, the mechanical properties of ABS specimen FDM printed using an open-source 3D printer have been considered through a standard tensile test to determine the ultimate tensile strength, elastic modulus, yield strength (0.2% offset), fracture strain, and toughness. From the deduction of the data, specimen 9 with an infill density of 100% and a layer height of 0.1 mm has shown the optimum mechanical properties. The ultimate tensile strength, elastic modulus, and yield strength of this sample have been 34.31 MPa, 873.40 MPa, and 29.71 MPa respectively

which has been the highest value compared to another specimen. The layer thickness of 0.1 mm and infill density of 100% have been the ideal parameters for printing ABS polymers. Results have shown that the mechanical properties of printed ABS increase with increasing the infill density. Also, the maximum ultimate tensile strength and elastic modulus have been achieved with the lower-level layer height. On the other hand, the highest value for fracture strain and toughness has been achieved at 0.096 mm/mm and 1.99 Jm^{-3} respectively by specimen 12 that have 100% infill density and 0.3 mm layer height. Finally, the experimental results have shown that infill percentage and layer height did not have a similar trend on the fracture strain and toughness that fluctuation results have been achieved by changing these parameters.

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