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Prediction of the mechanical properties for 3D printed rapid prototypes based on artificial neural network

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ABSTRACT

The rapid development of additive manufacturing (AM) technology, especially 3D printing, make it a widespread applicable for prototypes in many industrials, engineering, and biomedical domains. The present work introduced an experimental investigation based on artificial neural network (ANN) and design of experiment (DoE) to identifying and predicate the mechanical properties of the 3D prototypes. The printing temperature, number of top shells, printing speed, and layer height have been studied to determine the influence of such 3D printing parameters on the modulus of elasticity, ultimate tensile strength, and yield strength as a mechanical property of prototypes. Design of experiment for specimens was achieved based on the Taguchi method using a MINITAB software. The CAD/CAM software (solid work) was used to create 3D models of the testing specimens, which were designed according to the ASTM E8M standard. The experimental results of tensile test for the testing specimens proved that the increasing all of the ultimate tensile strength, yield strength, and modules of elasticity can be obtained with raising printing temperature to 220 °C and high number of top shells (4 shells). In turn, decreasing the printing speed belo 100 m/sec. and layer height lower than 0.3 mm will improve the afore-mentioned mechanical properties. The regression of the ANN illustrates that the network learning was appropriate, and it can be applied to effectively prediction the ultimate tensile stress, yield stress, and modulus of elasticity, where the validation, training, test, and all data are about (0.95592-1). Also, it can be concluded that the predicted results obtained from the adopted ANN model were more compatible with the experimental work.

Keywords: 3D printing parameters, rapid prototyping, design of experiments, artificial neural network.

INTRODUCTION

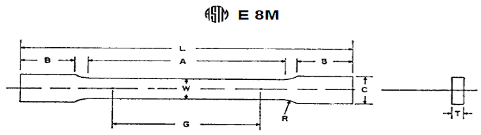
Rapid prototyping is a group of techniques used to quickly fabricate a model of a physical part or assembly using three-dimensional computer-aided design (CAD) data. It is a process of building a prototype in one step by layered the manufacturing process [1]. 3D printing uses CAD data to swiftly and cheaply produce complex shapes without equipment. A solid CAD model is split into layers of preset thickness by specialized slicing software for each 3D printing machine. These sliced sections define the overall shape and geometry of the part collectively when stacked on top of each other [2]. Normally, AM is used to create visualization models for products as they are being developed. These models can be much more helpful than drawings or renderings in fully understanding the intent of the designer when presenting the conceptual design. In addition, 3D printing technology has been used in building, medicine aids, bio printers, organ printing, prosthetics, artificial organs, manufacturing, and others. 3D printing is employed because of its speed, single-step manufacturing, low cost at low volume production, complexity or design flexibility, risk minimization, and sustainability. Therefore, it is necessary to study the printing parameters that influence the quality of the prototypes, which can be done using the testing process for the mechanical properties to determine the proper parameters for the general purpose of prototyping. Many researchers were interested to study the 3D printing technique parameters that influence the resulted prototypes; thus, Ben Wittbrodt et al. [3] studied the effect of color and processing temperature on material properties of PLA in various colors of commercially available filament based on the tensile strength and the microstructure. João Francisco Miranda Fernandes [4] studied the influence of 3D printing parameters on the mechanical properties of PLA, through the printing process. Also, the author found the amount of absorbed water by the PLA, and tried to reduce this amount. Tao Peng [5] studied the energy consumption with regard to the environment through the 3D printing process depending on the process parameters. Ahmed et al. [6] studied the effects of 3D printer parameters on the quality of the surface by manufacturing some part after designing it using free form surface (sculpture surfaces) and found the best parameters that give high quality of surface. Junhui Wu [7] used the melt deposition type (FDM) forming printer to study and optimize the effect of slice height on printing time, consumables, and dimensional accuracy and related parameters. Christin Arnold et al. [8] investigated the effect of resin type, printing resolution, positioning, alignment, target structure, as well as the type and number of support structures on the surface roughness of printed objects. Mostafa et al. [9] investigated the use of fused deposition modeling (FDM) 3D printing to create temporary dental crowns with the highest compressive strength. Using a Taguchi experimental design, key process factors such as infill density, outer shell width, infill pattern, and layer thickness were investigated. The ideal parameters resulted in a maximum compressive strength of 55.488 MPa, with infill density having the greatest influence. Benjamin Maldonado-García et al. [10] focused on the utilization of waste ocean plastics and waste agro-industrial pyrolyzed biomass which were reinforced with filler to develop complex shaped value-added prototypes through additive manufacturing. Also, the authors used the Taguchi method to design the experiments for obtain the defect-free printed specimens during the 3D printing process. Sanglae Kim et al. [11] proposed a constantly variable Infill Pattern for layer stacking to improve mechanical characteristics and print time. The authors noticed increases in ultimate tensile strength, elongation at break, and printing speed compared to the conventional infill pattern within polylactic acid (PLA) filament. Rahmatabadi et al. [12] studied the mechanical properties for the 3D printed specimen using the prepared PLA-TPU from three compounds. Also, Rahmatabadi et al. showed through the results of mechanical tests that by raising the amount of PLA, the strength increased and formability decreased. Mohammad Reza Khosravan et al. [13] discussed the effects raster orientations and printing speeds for 3D printing process on the mechanical behavior of additively manufactured components. The results, which provided by authors showed dependency of the strength, elastic modulus and stiffness of 3D-printed parts on the raster orientation. Mostafa et al. [14] investigated the integration of the Internet of Things (IoT) with 3D printing to improve manufacturing operations and monitoring. The researchers created an IoT application that allows for remote control and real-time monitoring of 3D printers, including printing progress, temperatures, and live observation. The system was evaluated by printing free-form 3D surfaces and comparing them to the original designs, confirming the feasibility of remote 3D printing parameter control and monitoring. The findings emphasize the potential of IoT-based solutions to improve the efficiency and connectivity of contemporary production under the Industry 4.0 principles. In this paper, the effect of each factor used in the rapid manufacturing process on each of the mechanical properties was measured, in addition to predicting the values of the mechanical properties using neural networks.

Design of specimens and the tensile test

In the present work, the adopted tensile test specimen was designed according to the basic geometric parameters that conform to an American National Standard (ASTM) with designation E8M-00b. Figure 1 present the basic dimensions according to the mentioned standard. A steady load was applied in the tensile test, whereas its magnitude and gauge length extension were measured constantly. The obtained results are presented with plotting the load-extension graph [15]. A computer aided design and manufacturing (CAD- CAM) software (Solid work) was used to confirm the design a 3D model of tensile test specimen according to ASTM standard, then the CAD model was exported as (STL. file) to the simulation software.

Design of experiments

The basic type of design of experiments (DoE) that is commonly used in study included:



Dimensions, mm			
Nominal Width	Standard Specimens		Subsize Specimen
	Plate-Type 40 mm	Sheet-Type 12.5 mm	6 mm
G— Gage length (Note 1 and Note 2)	200.0 ± 0.2	50.0 ± 0.1	25.0 ± 0.1
W— Width (Note 3 and Note 4)	40.0 ± 2.0	12.5 ± 0.2	6.0 ± 0.1
T— Thickness (Note 5)		thickness of material	
R— Radius of fillet, min (Note 6)	25	12.5	6
L— Overall length, min (Note 2 and Note 7)	450	200	100
A— Length of reduced section, min	225	57	32
B— Length of grip section, min (Note 8)	75	50	30
C— Width of grip section, approximate (Note 4 and Note 9)	50	20	10

Figure 1. Rectangular tension test specimens according to the ASTM standard

artificial neural network (ANN), and Taguchi method [16, 17]. The Taguchi method was used to design experiments related to the studied parameters of 3D printing as an additive method for fabricating 3D prototypes, arriving at favorable conditions with studied parameters and their influences on the mechanical properties of prototypes, which can be identified by investigating the response under a planned matrix of variables. Table 1 presented these DoE that adopted in the present project.

The DoE in Table 1 displays the L4 (4^4) Taguchi design. That means 4 factors with 4 levels for each. Minitab calculates a response table for each response characteristic [18]. Response tables can indicate which factor has the largest impact on the response and which level of the factor is related to higher or lower response characteristic values [19].

3D printing of the tensile test specimens

The tensile test specimens were fabricated using 3D printing machine called ANYCUBIC machine shown in Figure 2.

Polylactic acid (PLA) filament with diameter 1.75 mm was used to fabricate the adopted tensile test specimens. Table 2 presented the material specifications for the used PLA.

The manufacturing simulation process and the tool path generation

Figure 3 shows the manufacturing simulation process of the tensile test specimens utilizing the Ultimaker Cura software to acquire the right tool path in G-cods and determine production process factors like time, PLA material weight, adhesion, and cooling.

Table 1. Design of experiment according to the Taguchi method

Specimen No.	Printing speed	Printing temp.	Layer height	No. of top shell
1	40	190	0.15	1
2	40	200	0.2	2
3	40	210	0.25	3
4	40	220	0.3	4
5	60	190	0.2	3
6	60	200	0.15	4
7	60	210	0.3	1
8	60	220	0.25	2
9	80	190	0.25	4
10	80	200	0.3	3
11	80	210	0.15	2
12	80	220	0.2	1
13	100	190	0.3	2
14	100	200	0.25	1
15	100	210	0.2	4
16	100	220	0.15	3

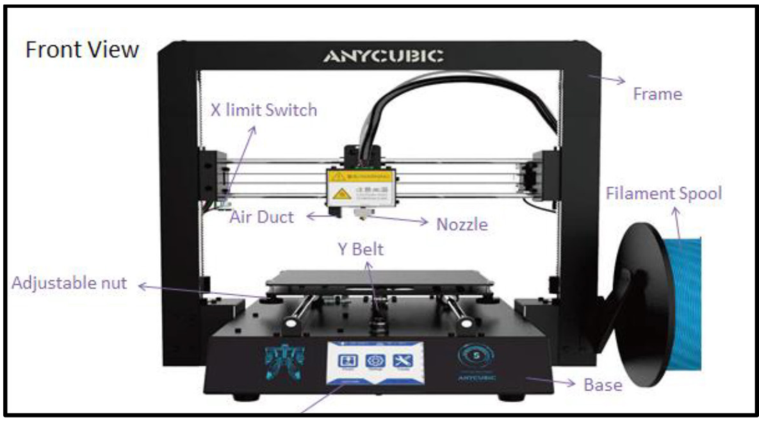


Figure 2. 3D printing machining (ANYCUBIC machine) [20]

Table 2. The material specifications of used PLA [20]

Specification	Value
Strength	88.8 Mpa
Melting temperature	115 °C
Heat resistance	110 °C
Tolerance	± 0.05 mm
Extruded temperature	160–220 °C

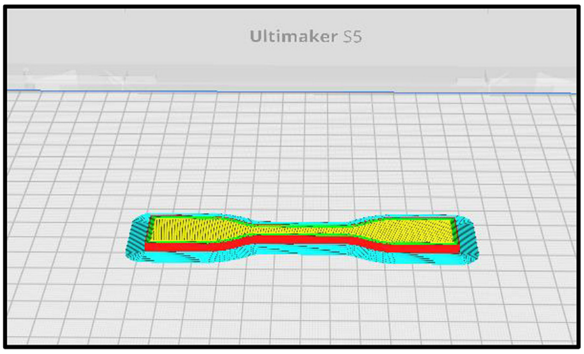


Figure 3. Simulation process of tensile test specimen

Testing process

The tensile test was performed on the universal testing machine WDW-50 (full computer controlled UTM 50KH) that shown in Fig. 4 at a fixed cross-head speed of 1 mm/min. The gauge length of a tensile test specimen was 32 mm. The applying yield load was (40 N). Figure 5 shows the tensile test specimens before and after the testing process. Using various levels of the adopted printing parameter (printing speed, printing temperature, layer height,

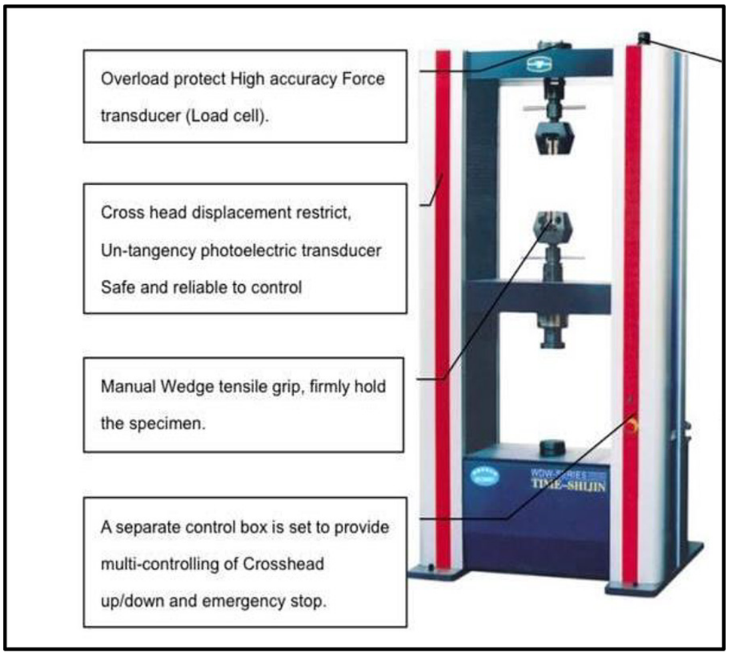


Figure 4. Universal testing machine [21]

and number of top shell), the stress and strain values of PLA were compared to see which was the strongest, as shown in Figure 6 for 16 specimens. Table 3 shows the results of tensile test which indicate the mechanical properties of specimens, such as: tensile (ultimate) strength, yield strength, and Young's modulus. In this table, the stress (strength), strain, and modulus of elasticity of the adopted tensile specimens were calculated.

RESULTS AND DISCUSSION

The adopted 3D printing parameters were accomplished, as results the effect of these parameters were studied for the obtained ultimate stress, yield stress, and modulus of elasticity.

Ultimate tensile stress

From Figure 7, the following can be observed: printing speed, printing temperature, layer height, and the number of shells is some of the process characteristics that may collectively impact the mechanical properties of the printed objects. Fused deposition modeling (3D printing). These process characteristics can impact ultimate tensile stress. On the basis of the ultimate tensile stress, the following are the impacts that certain process parameters have on the goods that are made using FDM printing:

1. Printing speed:
- higher speed – there is a possibility that the final tensile stress will be lowered if the printing speed is increased, since this will result in less interlayer adhesion and poorer bonding between various layers.
- lower speed – it is possible that slower printing rates will result in higher ultimate tensile stress due to increased interlayer bonding. This is because slower printing speeds allow for better material fusion and adhesion.

2. Printing temperature:
- high temperature – the use of higher printing temperatures has the potential to improve the flow of the material and the bond strength, so enhancing the adhesion between the layers and perhaps raising the ultimate tensile stress.

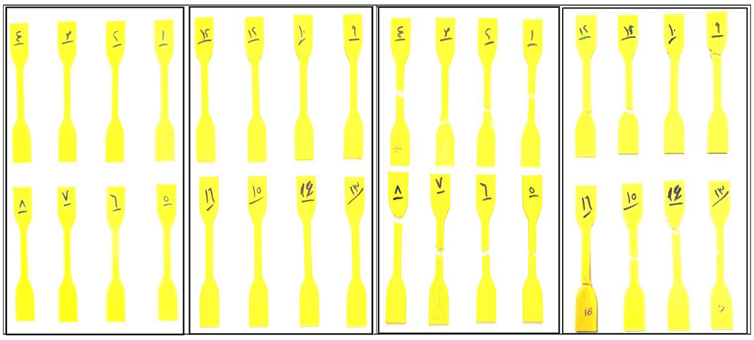


Figure 5. The tested Specimen before and after the test

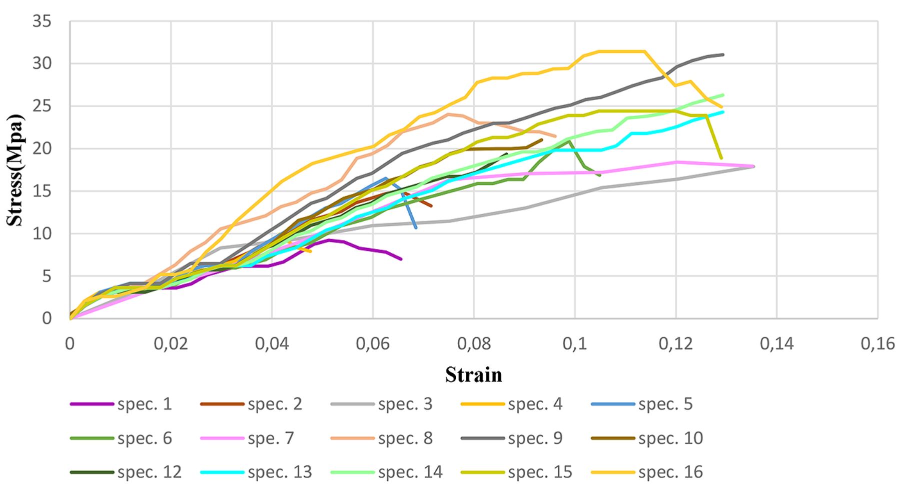


Figure 6. Stress-strain curves

- low temperature – a decrease in temperature can lead to a decrease in ultimate tensile stress and the possibility of delamination. This is because lower temperatures can cause inefficient material flow and weak interlayer bonding.

3. Layer height:

- smaller height – the resolution and surface smoothness can be improved by using finer layer heights; however, this may necessitate the use of more layers, which might potentially improve interlayer adhesion and further increase the final tensile stress.
- larger height – however, the interlayer bonding may be compromised, which will result in a lower final tensile stress due to poorer layer adhesion. Coarser layer heights can minimize the amount of time needed to print the material.

4. Number of shells:

Table 3. The mechanical properties of the tested specimens

Specimen No.	σ_U(MPa)		σ_y(MPa)		E(GPa)	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
1	13.18	12.2844	10.38	10.238	0.692	0.61229
2	18.11	19.0644	11.76	12.283	0.735	0.72698
3	29.85	30.1094	12.39	12.046	0.885	0.96438
4	38.73	38.4119	12.25	12.213	1.113636	1.12199
5	26.50	26.1819	13.64	13.603	0.8525	0.86085
6	28.34	28.5994	13.13	12.786	0.937857	1.01723
7	20.49	21.4444	13.65	14.173	0.6825	0.67448
8	26.20	25.3044	12.52	12.378	0.894286	0.81458
9	30.80	31.7544	13.97	14.493	0.931333	0.92331
10	28.86	27.9644	13.81	13.668	0.986429	0.90672
11	15.96	15.6419	13.35	13.313	0.534	0.54235
12	13.21	13.4694	12.82	12.476	0.427333	0.50671
13	19.04	19.2994	11.728	11.384	0.651556	0.73093
14	11.56	11.2419	9.60	9.563	0.685714	0.69407
15	26.82	25.9244	12.55	12.408	0.965385	0.88567
16	18.26	19.2144	7.22	7.743	0.9025	0.89448

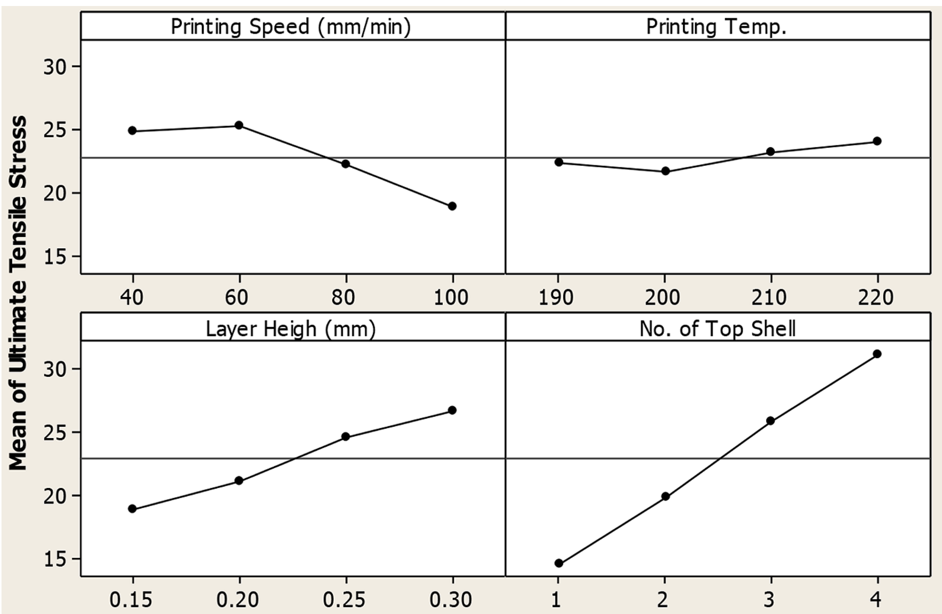


Figure 7. Mean effect plot for ultimate tensile stress

- more shells – in order to strengthen the component and improve its stiffness, increasing the number of shells might be beneficial. This can possibly lead to an increase in the ultimate tensile stress by strengthening the resistance to deformation and the interlayer bonding quality.
- fewer shells – a reduction in the number of shells may minimize the amount of material used and the amount of time required for printing, but it may also affect the strength and interlayer adhesion, which might result in a reduction in the final tensile stress.

Yield stress

From Figure 8, it can be observed that printing speed, temperature, layer height, and number of shells can affect the mechanical characteristics, particularly yield stress, of fused deposition modeling (FDM) 3D printed objects. These process factors affect FDM printing yield stress:

1. Printing speed:
- higher speed – increased printing speed may impair interlayer adhesion and layer bonding, lowering yield stress.
- lower speed – slower printing rates enhance material fusion and adhesion, which may increase yield stress owing to interlayer bonding.

2. Printing temperature:
- high temperature – material flow, bond strength, interlayer adhesion, and yield stress can improve at higher printing temperatures.
- low temperature – delamination and reduced yield stress may occur from inadequate material flow and interlayer bonding at lower temperatures.

3. Layer height:
- smaller height – finer layer heights increase resolution and surface polish but may need more layers, increasing interlayer adhesion and yield stress.
- larger height – coarser layer heights save print time but weaken interlayer bonding, lowering yield stress.

4. Number of shells:
- more shells – by increasing shell count, component strength and stiffness can be enhanced, potentially increasing yield stress through deformation resistance and interlayer bonding.
- fewer shells – reducing shells may minimize material use and print time but weaken strength and interlayer adhesion, decreasing yield stress.

Modulus of elasticity

From Figure 9, the following can be observed: In fused deposition modeling 3D printing, printing speed, temperature, layer height, and shell number can impact mechanical properties like modulus of elasticity. The following process factors have an impact on the modulus of elasticity of FDM printed products:

1. Printing speed:
- higher speed – the interlayer bonding time can be decreased with faster printing speeds,

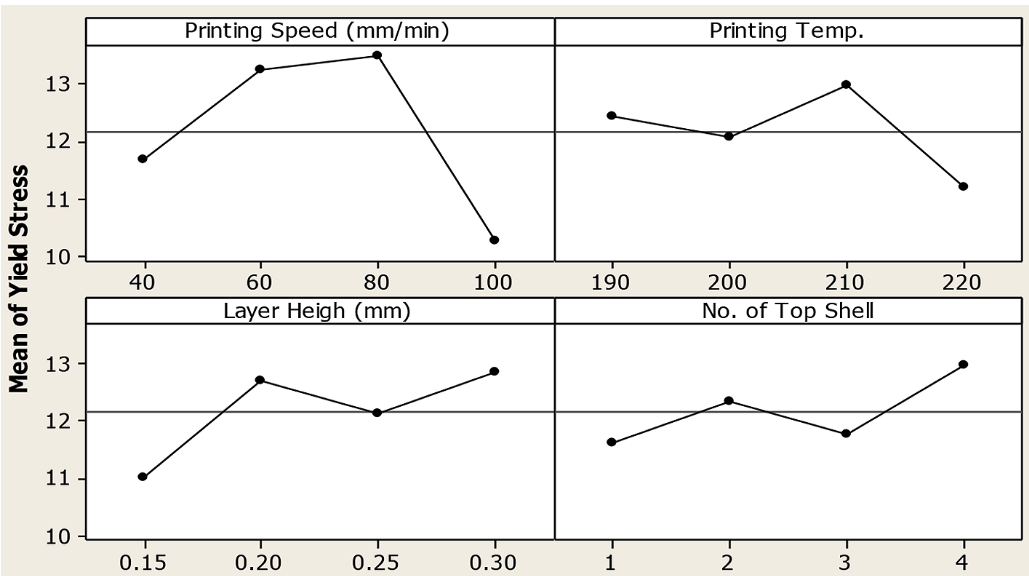


Figure 8. Mean effect plot for yield stress

which could lead to a lower modulus of elasticity, since the adhesion between the layers is weaker.
- lower speed – due to enhanced interlayer adhesion and material continuity, a greater modulus of elasticity may result from using slower printing rates, which allow for better material fusion and bonding.

2. Printing temperature:
- high temperature – the modulus of elasticity may be increased by improved interlayer adhesion and material characteristics brought about by printing at elevated temperatures, which also improve material flow and bonding.
- low temperature – a reduced modulus of elasticity can be the consequence of insufficient material fusion at lower temperatures, which can cause poor flow and weak interlayer bonding.

3. Layer height:
- smaller height – a lower modulus of elasticity can be achieved with finer layer due to increase the risk of interlayer bonding degradation, although a lower layer height may enhance resolution and surface quality.
- larger height – while using coarser layer heights might save print times, which in turn improve the modulus of elasticity they also improved material continuity and greater interlayer adhesion may be achieved with more layers.

4. Number of shells
- more shells – by strengthening the interlayer bonding and making the component more resistant to deformation, adding more shells can increase the part stiffness and strength, which in turn can increase the modulus of elasticity.
- fewer shells – while reducing the number of shells might shorten the print time and save material consumption, it may lower the modulus of elasticity by compromising strength and interlayer adhesion.

Comparison of the results

The obtained results from experimental work were compared with the predicted results obtained from suggested model to verify the theoretical results obtained from this work.

Figures 10, 11 and 12 show the variation of 16 value of ultimate tensile stress, yield stress,

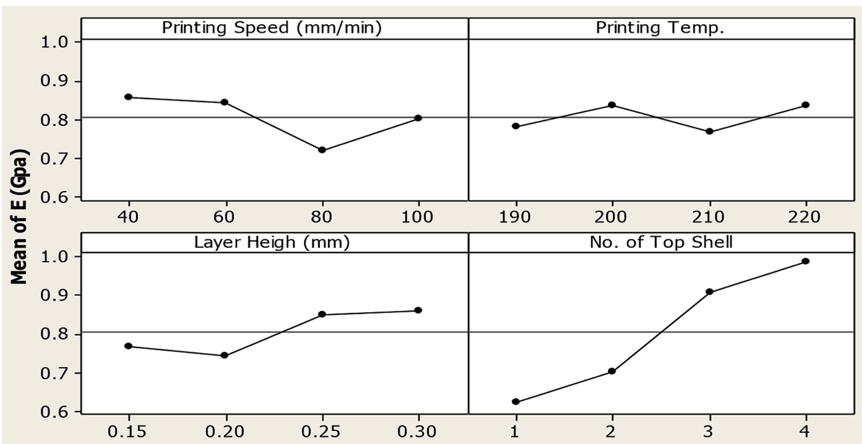


Figure 9. Mean effect plot for modulus of elasticity

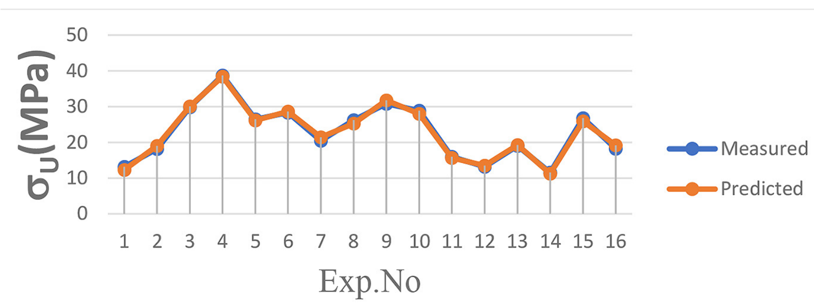


Figure 10. Comparison between the measured and predicted ultimate tensile stress

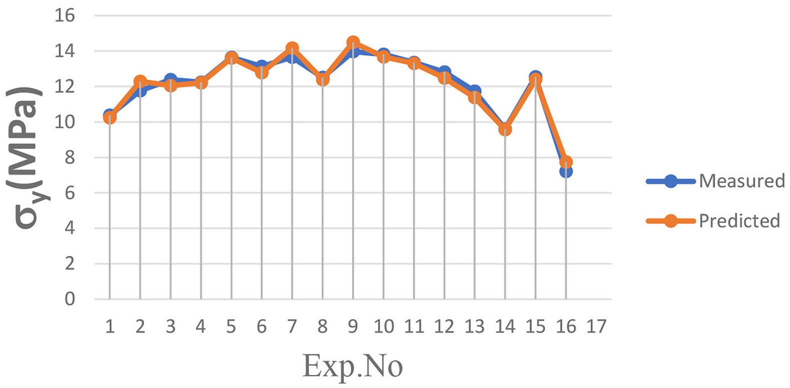


Figure 11. Comparison between the measured and predicted yield stress

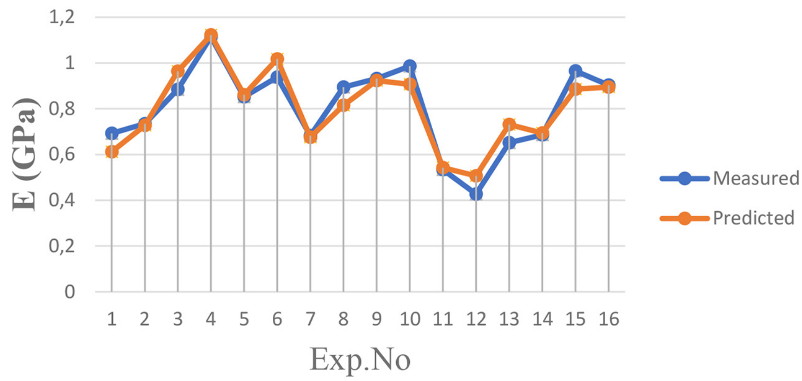


Figure 12. Comparison between measured and predicted modulus of elasticity

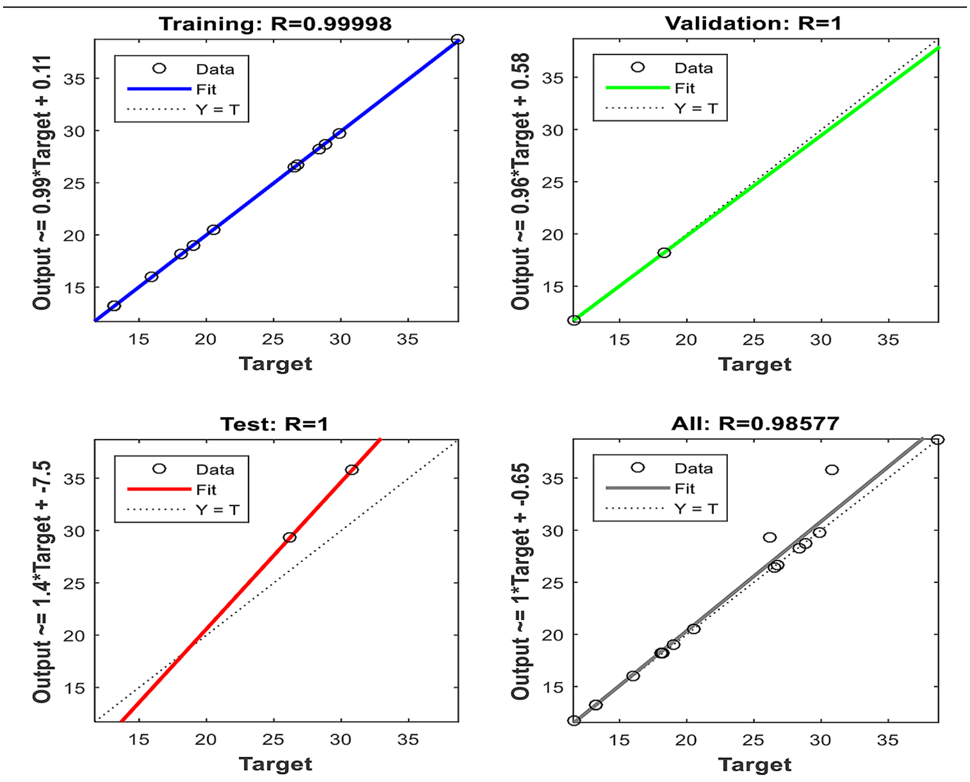


Figure 13. Regression for ultimate tensile stress

and modulus of elasticity, respectively, with the number of experiments. it is seen from this figure that the measured ra values are very close to the predicted ultimate tensile stress, yield stress, and modulus of elasticity values.

Regression graphs for ANN model (ultimate tensile stress, yield stress, and modulus of elasticity)

Regression graph shows the relationship between the targets and the outputs of the network.

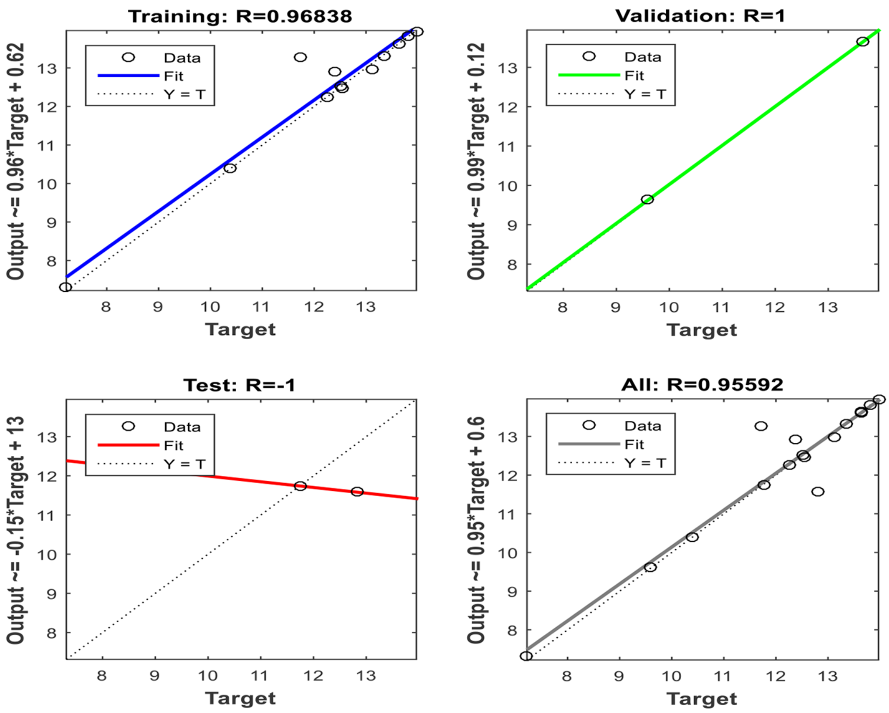


Figure 14. Regression for yield stress

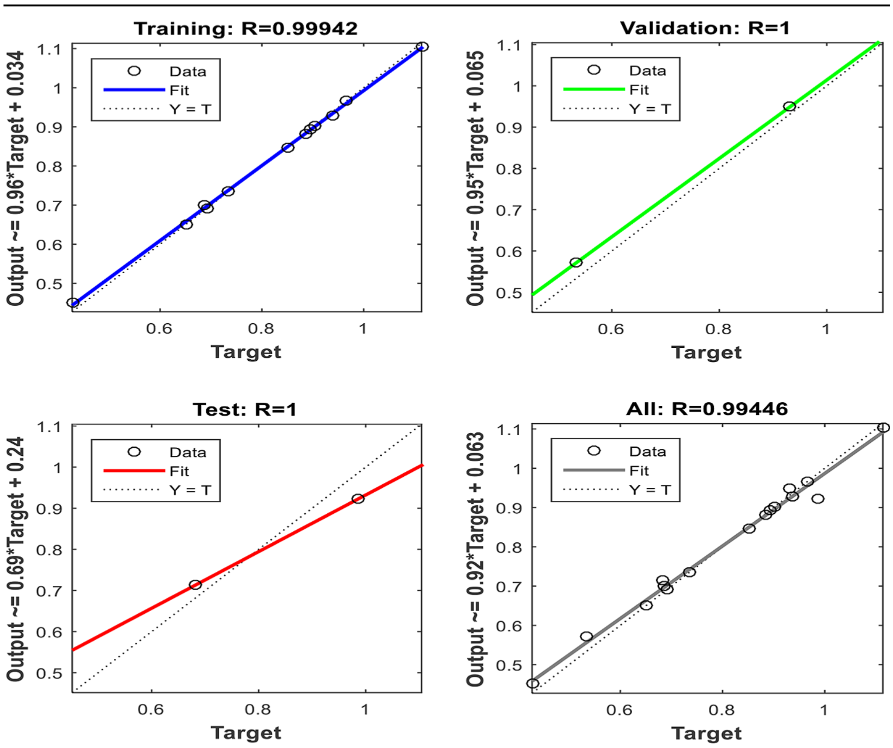


Figure 15. Regression for modulus of elasticity

Table 4. Analysis of variance for ultimate tensile stress (MPa)

Source	DF	Seq SS	Adj MS	P
Printing speed (mm/min)	3	107.014	35.671	11.9
Printing temp.	3	12.997	4.332	1.5
Layer height (mm)	3	146.792	48.931	16.37
No. of top shell	3	621.604	207.201	69.38
Error	3	7.526	2.509	0.84
Total	15	895.933		100

Table 5. Analysis of variance for yield stress (MPa)

Source	DF	Seq SS	Adj MS	P
Printing speed (mm/min)	3	26.7542	8.9	55.7
Printing temp.	3	6.7064	2.233	13.9
Layer height (mm)	3	8.2935	2.763	17.27
No. of top shell	3	4.6062	1.533	9.58
Error	3	1.6536	0.55	3.43
Total	15	48.0139		100

Table 6. Analysis of variance for E (GPa)

Source	DF	Seq SS	Adj MS	P
Printing speed(mm/min)	3	0.04509	0.01503	9
Printing temp.	3	0.01538	0.00513	3.06
Layer height (mm)	3	0.03951	0.01317	7.8
No. of top shell	3	0.34903	0.11634	70
Error	3	0.05115	0.01705	10.22
Total	15	0.50016		100

Figures 13, 14 and 15 show the regression graphs of validation data, learning data, test data and all data. on the basis of the regression coefficients model for training set, validation set, test set and all data sets, it can be observed that the learning of the network is proper and this application can be used to predict the ultimate tensile stress, yield stress, and modulus of elasticity. From Table 4 was found that the most influential factor on ultimate tensile stress is the number of shells, followed by layer height and printing speed, and the least influential factor is temperature. From Table 5 was found that the most influential factor on yield stress is the printing speed, followed by layer height and printing temperature, and the least influential factor is number of shells. From Table 6 was found that the most influential factor on modules of elasticity is the number of sells, followed by layer height and printing speed, and the least influential factor is printing temperature.

CONCLUSIONS

On the basis of the results of tensile test for the fabricated specimens under the levels and values of the selected 3D printing parameters, it can be concluded that increasing the printing temperature up to 220°C, and high number of top shells arriving to 4 shells will increase the ultimate tensile strength, yield strength, and modules of elasticity, which can be noticed in specimen 7, 10 and 4, respectively. In turn, decreasing the printing speed lower than 100 m/sec. and decreasing layer height lower than 0.3 mm will produce a gaining in the mentioned mechanical properties for the same specimen number. Also, from the variance Tables 4, 5, and 6, the effect of the printing parameters on the studied mechanical properties can be illustrated, where the most influential factor on ultimate tensile stress is the number of shells, followed by layer height and printing speed, and the least influential factor is temperature, while relating to yield stress the most influential factor is printing speed, followed by layer height and printing temperature, and the least influential factor is number of shells, finally, modulus of elasticity is highly affected by the number of shells, followed by layer height and printing speed, and the least influential factor is printing temperature. Comparison results of the experimental work and the predicted results obtained from suggested model of ANN provides greater compatibility between these values, the regression of the ANN observed that the learning of the network is proper and can be applied to predict the ultimate tensile stress, yield stress, and modulus of elasticity, where the validation, training, test and all of data are about (0.95592-1).

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