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RESEARCH ARTICLE

Experimental study and modeling the tensile strength of 3D-printed aluminium polylactic acid (PLA) parts using artificial neural networks [version 1; peer review: 1 approved with reservations, 1 not approved]

Chockalingam Palanisamy , Hong Kiat Aaron Tay Hong Kiat

Faculty of Engineering and Technology, Multimedia University, Melaka, Melaka, 75450, Malaysia

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Abstract

Background: High quality 3D printed products are in high demand, resulting in an increase in the production of 3D printed parts with precise tolerances, improved surface roughness, and overall durability. The processing parameters of 3D printers have a significant impact on the quality of 3D printed parts. Three-dimensionally printed parts must be durable, especially in terms of tensile strength, and its impact on the printer's process parameters must be investigated.

Methods: Tensile test specimens were printed in the Makerbot 3D printer with aluminium polylactic acid (PLA) material. The three controllable input parameters taken into consideration were layer thickness, infill density and number of shells. The three levels for each of the respective parameters were 0.1mm, 0.2mm and 0.3mm for layer thickness; 2, 3 and 4 for number of shells; 20% 40% and 60% for Infill density. Tensile testing was carried out on the specimens and data was tabulated. Using these data, an artificial neural network model was created using Matlab R2021b software's neural network toolbox (alternatively Scilab can be used).

Results: A high layer thickness (0.3mm) and a 40% infill density were found to be the most effective among all other parameters. The specimen with the lowest layer thickness of 0.1mm, four shells, and a 20% infill density had the highest tensile strength. With the tensile test data, a Matlab ANN model was developed. Validation was done by comparing the values obtained from the model with the experimental data by using random layer thickness, infill density, and number of shells.

Conclusions: In conclusion, higher layer thickness has lower tensile strengths. However, as the number of shells and infill density increases, the tensile strength increases. In summary an ANN model was successfully developed and validated to predict 3D printed aluminium parts.

Open Peer Review

Approval Status

	1	2
version 1
15 Dec 2021	view	view
1. Mahros Darsin , University of Jember, Jember, Indonesia		
2. John Kechagias , University of Thessaly, Karditsa, Greece		

Any reports and responses or comments on the article can be found at the end of the article.

Keywords

3D Printing, ANN, Aluminium PLA, Tensile Strength

This article is included in the **Artificial Intelligence and Machine Learning** gateway.

This article is included in the **Research Synergy Foundation** gateway.

Corresponding author: Chockalingam Palanisamy (palanisamy.chockalingam@mmu.edu.my)

Author roles: **Palanisamy C:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – Review & Editing; **Aaron Tay Hong Kiat HK:** Formal Analysis, Investigation, Writing – Original Draft Preparation

Competing interests: No competing interests were disclosed.

Grant information: The author(s) declared that no grants were involved in supporting this work.

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How to cite this article: Palanisamy C and Aaron Tay Hong Kiat HK. **Experimental study and modeling the tensile strength of 3D-printed aluminium polylactic acid (PLA) parts using artificial neural networks [version 1; peer review: 1 approved with reservations, 1 not approved]** F1000Research 2021, **10**:1286 <https://doi.org/10.12688/f1000research.73796.1>

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Introduction

Additive manufacturing processes such as 3D printing are widely used today in many industries. 3D printing has become more widely used in industries, increasing the number of consumers in need of 3D printed products of high quality.¹ As a result of increased competition, 3D parts with more precise tolerances, better product finish, and overall durability have become increasingly popular. Despite the fact that 3D printing costs are on the decline, part quality issues such as integrity, strength and aesthetics are still a concern.² Because of this, industries have been driven to continuously improve quality control of their products. These quality measures are very important to mechanical parts because it affects the cooperation of parts together, working accuracy, physical properties and chemical properties altogether. 3D printing industries rely on these qualities to produce better-looking and more functional parts while also saving money by reducing the amount of time needed to manufacture the parts.³ The parameters that are taken into considerations are layer thickness, infill density and number of shells.⁴ The product's tensile strength is a critical factor to take into account. In this study, a central composite design experimental plan was developed with three influencing input parameters, namely infill density, layer thickness and number of shells. Aluminium polylactic acid (PLA) materials were used as a work material. Tensile test was conducted on the specimen and recorded. Using the data, an artificial neural network (ANN) model was developed to predict the tensile strength of new combination of parameters, and a validating test carried out on the model.

Methods

This study was conducted in November 2020. A design of experiment (DOE)/Central Composite Design (CCD) experiment plan was designed with three input parameters (layer thickness, infill density and number of shells) shown in [Figure 1](#). There are eight corners, six face centers, and one center, for a total of 15 specimen points.^{4,5} [Table 1](#) shows the three levels of parameters. [Table 2](#) displays the experiment plan as well as the test results.

Tensile test specimens were printed in the Makerbot 3D printer. PLA filament mixed with 15% aluminium powder (Al-PLA- Fabbxible, 1.75 mm diameter) was used as work material. One tensile test was carried out using the Instron 3360 series dual column tabletop equipment. The results were captured using [Instron Bluehill- Universal 3](#) software. American society for testing of materials (ASTM). D-638 standard size was used to prepare the specimen.

Artificial neural networks (ANN) are artificial computing systems that mimic biological neural networks, which are similar to the human brain. The system has self- learning capabilities to perform tasks or produce better results.⁶ Using the

Figure 1. Central composite design.

Table 1. The levels of control parameters.

Parameter	Levels		
Terms	Low	Middle	High
Code	–1	0	1
Layer thickness (mm)	0.1	0.2	0.3
Number of shells	2	3	4
Infill density (%)	20	40	60

Table 2. Experiment plan and tensile test results.

No.	Layer thickness (mm)	No. of shells	Infill density (%)	Tensile strength (kN)
1	0.1	2	20	1.04
2	0.3	2	20	0.68
3	0.1	4	20	1.12
4	0.3	4	20	0.68
5	0.1	2	60	1.11
6	0.3	2	60	0.86
7	0.1	4	60	1.12
8	0.3	4	60	0.91
9	0.1	3	40	0.89
10	0.3	3	40	0.69
11	0.2	2	40	0.49
12	0.2	4	40	0.82
13	0.2	3	20	0.71
14	0.2	3	60	0.77
15	0.2	3	40	0.76

data, an ANN model was developed to predict the tensile strength of newer combinations of input parameters, and a validating test carried out on the model. **Matlab** R2021b neural network software (**Scilab** is an open-source alternative) was used to create a neural network with the printer process parameter and tensile strength data (**Table 2**).

In order to develop the ANN model, the experimental data were imported into Matlab software. With the deep learning toolbox feature, a framework for creating and designing neural networks was made. Whilst giving the option to import, create and export networks and data, it can also generate a neural network system which can be designed, simulated and analysed.

Ethical approval

All procedures used in this project have been approved by Research Ethics Committee (REC) Multimedia University (EA2892021). This work does not involve data collection from human or animal experiments or vulnerable communities.

Results and discussion

There are four specimens in **Figure 2** that stand out as having the highest values of tensile strength. Other specimen includes 1, 3, 5 and 7. They have the same layer of thickness (0.1 mm). This indicate that the lower the layer thickness the higher the tensile strength. As an example, if we look at specimens 13, 14, and 15, they all have the same number of layers (0.3 mm) and three shells, but different infill density levels. Specimen number 13 that has the lowest infill density of 20% appears to have the lowest tensile strength of 0.71 kN. As a result, the breaking load decreases as infill density decreases.

Figure 2. Tensile strength of all specimens.

Figure 3. ANN model.

There are no differences in layer thickness or infill density between specimens 1 and 3, but there is a discrepancy in the shell count between specimens 1 and 3. In spite of the fact that specimen 3 has a much higher number of shells than specimen 1, it has a slightly higher breaking load. The same is true for specimens 2 and 4, which have similar values of layer thickness (0.3 mm) and infill density (20%). Specimen 4 has a very slight increase of breaking load compared to specimen 1, even though specimen 4 has a much higher number of shells compared to specimen 2. Specimens 5 and 7, which have similar values of layer thickness (0.1 mm) and infill density of 60%. Specimen 7 also has a very slight increase of breaking load compared to specimen 5, even though specimen 7 has a much higher number of shells compared to specimen 5. This means that the values of layer thickness and infill density have a significant impact on the value of tensile strength. However, the number of shells does not affect the variation of breaking load in test specimens. The tensile strength increases with decreasing layer thickness. The specimen's tensile strength increases as the infill density increases.⁵

An ANN model was created as shown in [Figure 3](#), by entering input such as layer thickness, number of shells and infill density and tensile strength data as a target data.

Errors in validation and training can be used to gauge a trained network's performance as a whole. Performing a regression plot between the network response and the targeted values, as shown in [Figure 4](#), is one way to achieve this goal. We can tell if the neural network is desirable or not by generating the regression plot. The regression plot depicts the relationship between a network response variable (output) and target variables. If we had a perfect fit, where outputs exactly equal to targets, the slope would be of value "1" and the y-intercept would be at point (0, 0). This condition is considered to be desirable, which means a good correlation of targeted values to output values. Vice versa, if the slope is not close to value "1", then it can be considered as not desirable; such a condition is shown in [Figure 4a](#). If it is not desirable, we can retrain the network by closing the window and clicking on train network again until we get a regression plot's value for all that is close to the value "1" as shown in [Figure 4b](#). As a result of oscillating between input and output values, the neural network learns and repeats the process. This will eventually give a better regression model close to the value "1". It is a good idea to train several networks to ensure that a network with good generalization is found. [Figure 4b](#) shows a good regression plot. According to [Figure 4](#), the open circles represent the values of network output plotted against the goals. The best fitted slope is indicated by the dashed line and the solid line indicates the fitted slope generated by the open circles.

According to [Figure 4a](#), Matlab's first trained network isn't ideal because the regression slope value for all is 0.94767 and the y-intercept isn't close to 0. By retraining the network, we are able to get results such that in [Figure 4b](#), which is our desirable regression. Next simulating by going to the simulate tab, selecting the inputs and clicking simulate network. Using the developed model tensile strength was predicted the new set of input parameters and tabulated in [Table 3](#).

To validate the developed ANN model, 5 new test specimens were fabricated as shown in [Table 3](#). The five test specimens were then subjected to a tensile test, and the results were tabulated. Based on the table, the specimen with the lowest layer thickness has the highest tensile strength with 1.05kN. This can be validating with what we have discussed previously where the lower the layer thickness, the higher the tensile load. The percentage difference of experimental values and theoretical values for all the specimens are less than 5%.

According to [Table 3](#), the percentage difference between experimental data and ANN model predicted data for all specimens is less than 5%, which proves the model's validity and reliability.

Figure 4. (a) Undesirable regression plot, (b) good regression plot.

Table 3. Validity experiment – ANN model predicted data and experiment data.

Parameter No.	Layer thickness	Number of shells	Infill density	Tensile test, kN (ANN predicted)	Tensile test, kN (Experiment)	Percentage difference, %
1	0.12	2	15	1.02	1.05	2.4
2	0.17	2	25	0.60	0.63	4.1
3	0.21	3	35	0.60	0.62	3.9
4	0.24	4	45	1.00	0.98	1.4
5	0.28	4	55	0.76	0.79	4.1

Conclusions

An ANN model was successfully developed and validated using Matlab to predict the 3D printed aluminium part data. The three variables of layer thickness, number of shells, and infill density have been shown to affect the tensile strength of the 3D printed specimens. The specimen with the lowest layer thickness of 0.1 mm, four shells, and a 20 percent infill density had the highest tensile strength of 1.12 kN, based on the results of the tests. In addition, specimen 13 has the lowest tensile strength of 0.71 kN when compared to specimens 14 and 15, which all have the same layer thickness (0.3 mm) and number of shells (3) but different infill density. For this reason, the thicker layers have lower tensile strengths. However, as the number of shells and infill density increases, the tensile strength increases. In summary, the 3D printed part with the lowest layer thickness, highest infill density, and most shells has the highest maximum tensile strength, according to the research. A comparison of predicted and experimental results allowed us to verify the accuracy of the ANN model.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

Acknowledgements

Authors acknowledge Mr. Wan Johannes, Senior lab technician, Faculty of Engineering and Technology, Multimedia University, Melaka, Malaysia for his help during experiments. Furthermore, a thank you to the Research Synergy Foundation for the recommendations and support.

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[Publisher Full Text](#)
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Open Peer Review

Current Peer Review Status: ? ✖

Version 1

Reviewer Report 09 March 2022

<https://doi.org/10.5256/f1000research.77471.r126037>

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John Kechagias

Design and Manufacturing Laboratory, School of Technology, University of Thessaly, Karditsa, Greece

This work presents some new data. The reviewer recommends the following to increase the manuscript quality:

1. Introduction. The literature review is inadequate. This research deals with PLA/aluminium FFF 3D printing process parameters influence on the mechanical response of 3D printed parts. Additionally, an ANN model is adopted to model the effects of the parameters. So, literature should include reference papers like the following articles of mine:

Kechagias *et al.* (2022a)¹, about key parameters of the FFF process.

Kechagias *et al.* (2022b)², about NN parameter optimization.

2. The authors should critically review the used parameters.
3. The same about the ANN topology parameters selection.
4. The authors should also analyze why they keep the other 3D printing parameters constant and why they used the specific values.
5. The authors should present the parameters' effects on mechanical response and generalize the results in other materials.
6. SEM images are needed to see the porosity of the parts. Parts weight should be reported too in table 2 and the strength modulus of elasticity E.

Specific

1. In the 'abstract,' the authors claimed: "*The specimen with the lowest layer thickness of 0.1mm, four shells, and a 20% infill density had the highest tensile strength...*" and then, "*However, as the number of shells and infill density increases, the tensile strength increase...*" - These two sentences are confusing. Which is correct?

2. Proofread the document carefully. E.g., 3D printed parts and not '3D parts.'
3. Use more references in the introduction. Document better each sentence you use.
4. Table 2. Please use the elasticity module E and strain at ϵ_B to better show the specimens' mechanical response.
5. Details of the 3D printing parameters used in the experiment are missing. Please explain why only the LT, NS, and ID are used in this research, as it is critical for the scope of the study.
6. Explain if you used normalization for inputs and outputs (for the ANN model) and, if not, why?
7. Details of ANN training and stop criteria are missing.

References

1. Kechagias J, Chaidas D, Vidakis N, Salonitis K, et al.: Key parameters controlling surface quality and dimensional accuracy: a critical review of FFF process. *Materials and Manufacturing Processes*. 2022. 1-22 [Publisher Full Text](#)
2. Kechagias J, Tsiolikas A, Petousis M, Ninikas K, et al.: A robust methodology for optimizing the topology and the learning parameters of an ANN for accurate predictions of laser-cut edges surface roughness. *Simulation Modelling Practice and Theory*. 2022; **114**. [Publisher Full Text](#)

Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?

Partly

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Materials and manufacturing processes

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 17 Mar 2022

Palanisamy Chockalingam

Reviewer comment:

Introduction. The literature review is inadequate. This research deals with PLA/aluminium FFF 3D printing process parameters influence on the mechanical response of 3D printed parts. Additionally, an ANN model is adopted to model the effects of the parameters. So, literature should include reference papers like the following articles of mine:

Kechagias *et al.* (2022a)¹, about key parameters of the FFF process.
Kechagias *et al.* (2022b)², about NN parameter optimization.

Author's response:

Your feedback is duly noted. My article was written much earlier to the reference materials. I will use these references for future articles.

Reviewer comment:

The authors should critically review the used parameters.

Author's response:

The parameters were selected based on literature (referenced) and machine specifications.

Reviewer comment:

The same about the ANN topology parameters selection.

Author's response:

The parameters were selected based on literature (referenced) and machine specifications.

Reviewer comment:

The authors should also analyze why they keep the other 3D printing parameters constant and why they used the specific values.

Author's response:

The parameters were selected based on literature (referenced) and machine specifications. Experiment plan was designed based on face centred central composite design (FC-CCD). So the parameter combinations have to follow the design.

Reviewer comment:

The authors should present the parameters' effects on mechanical response and generalize the results in other materials.

Author's response:

This research was carried out on specific material and reported, other material comparison was not under the parameters of my research.

Reviewer comment:

SEM images are needed to see the porosity of the parts. Parts weight should be reported too in table 2 and the strength modulus of elasticity E.

Author's response:

This research study was conducted to study the effects of the combination of input parameters on tensile strengths of the material, so, I believe SEM analysis is not necessary.

Specific

Reviewer comment:

In the 'abstract,' the authors claimed: "The specimen with the lowest layer thickness of 0.1mm, four shells, and a 20% infill density had the highest tensile strength..." and then, "However, as the number of shells and infill density increases, the tensile strength increase..." - These two sentences are confusing. Which is correct?

Author's response:

Both are correct, because the study is based on the experiment plan - face centred central composite design.

Reviewer comment:

Proofread the document carefully. E.g., 3D printed parts and not '3D parts.'

Author's response:

Duly noted.

Reviewer comment:

Use more references in the introduction. Document better each sentence you use.

Author's response:

Duly noted for my future articles.

Reviewer comment:

Table 2. Please use the elasticity module E and strain at sB to better show the specimens' mechanical response.

Author's response:

Duly noted for my future articles

Reviewer comment:

Details of the 3D printing parameters used in the experiment are missing. Please explain why only the LT, NS, and ID are used in this research, as it is critical for the scope of the study.

Author's response:

The parameters were selected based on literature (referenced) and machine specifications.

Reviewer comment:

Explain if you used normalization for inputs and outputs (for the ANN model) and, if not, why?

Author's response:

I believe normalization is not necessary because these experiments followed face centred central composite design.

Reviewer comment:

Details of ANN training and stop criteria are missing.

Author's response:

It has been explained in the methods section.

Competing Interests: No competing interests to declare

Reviewer Report 06 January 2022

<https://doi.org/10.5256/f1000research.77471.r115355>

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Mahros Darsin

Department of Mechanical Engineering, University of Jember, Jember, Indonesia

The research is trying to apply an Artificial Neural Network (ANN) to optimize the variable combinations which will result in the highest tensile strength of the 3D printed parts using aluminium-PLA filament. Some useful information is provided in the introduction. However, it lacks references about using ANN by other researchers, such as Yadav *et al.* (2020)¹ and Mahmood *et al.* (2020)².

The presentation of Table 2 needs to be improved, such as by aligning the number at the X-axis to the bar.

There are some errors in the description of results and discussion. For example, the minimum of tensile strength is shown by experiment no. 11 not no. 13. The same error is repeated at the conclusion. The error is also clear when comparing the result of experiments no. 2 and 4. Mistakenly, it is written as experiment no. 1.

Statement regarding either value 1 or 0, which is considered as not desirable needs to be clarified when describing the ANN. I found two statements contradicting regarding it.

References

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Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and is the work technically sound?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Partly

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: FDM 3D printing using metal content filaments

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 17 Mar 2022

Palanisamy Chockalingam

Reviewer comment: The presentation of Table 2 needs to be improved, such as by aligning the number at the X-axis to the bar.

Reply: *Experiment plan is designed with face centered central composite design and table is left aligned.*

Reviewer comment: There are some errors in the description of results and discussion. For example, the minimum of tensile strength is shown by experiment no. 11 not no. 13. The same error is repeated at the conclusion.

Reply: *This comparison for the layer thickness of 0.2 mm, for specimens 13, 14 and 15.*

Reviewer comment: The error is also clear when comparing the result of experiments no. 2 and 4. Mistakenly, it is written as experiment no. 1.

Reply: *Experiment results of 2 and 4 is for layer thickness of 0.3 mm. So the variation is obvious.*

Reviewer comment: Statement regarding either value 1 or 0, which is considered as not desirable needs to be clarified when describing the ANN. I found two statements contradicting regarding it.

Reply: *These statements explain the how to reach the closeness to the desired result and to explain the all procedures followed in this research.*

Competing Interests: In this work no financial/non financial competing interest involved.

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