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Optimisation of PLA Filament Consumption for 3D Printing Using the Annealing Method in Home Environment

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The idea for this paper came with the outbreak of the Covid-19 pandemic when almost all countries started experiencing shortages of different, previously abundant, materials. As with all other communities, these shortages prompted the 3D printing community to become more involved in the global fight against the Covid-19. This fight was further facilitated by a large number of world-famous companies which provided their 3D models of protective masks, visors, and other aids to medical staff free of charge together with the recommended parameters and open-source files used for their printing. The idea of these companies was to support their countries by providing protective equipment for everyone who sorely needed it, especially at the beginning of the pandemic, but this mass 3D printing led to a shortage of 3D printing filaments. One of the main ideas behind this paper is to show that this problem can be drastically reduced by optimising filament consumption when printing those models. One way of doing this is strengthening the printed element by annealing it, which is the topic of this paper. By strengthening it afterwards, one could reduce filament consumption by reducing the infill percentage in the G code creation procedure. For this research, we opted for a polylactide acid (PLA) filament, because it is the most widely used 3D printing material. By varying its annealing temperature and time, and testing it, the results gave us an optimal procedure for strengthening the PLA prints, as well as an optimal solution for consumption reduction that would be the most suitable during material shortages. These results could be of great significance if applied globally.

Keywords: Covid-19; 3D printing; consumption optimisation; annealing; PLA material; PLA strengthening

Highlights

- *Protective equipment 3D printing is one of the measures against the spread of Covid-19.*
- *The consumption 3D printing PLA filament is optimised by post-print filament baking.*
- *We have determined the optimal baking temperature for the PLA annealing procedure.*
- *Matching annealed model dimensions to the desired one by scaling it before printing.*

0 INTRODUCTION

Additive manufacturing, with its typical representative – three dimensional (3D) printer, has enabled every user to become a small scale manufacturer [1]. Those small-scale manufacturers may not be able to have a huge impact on society in terms of mass-produced items, but united they have the potential and power that exceeds the capacities of factory plants, at least for a short period, in terms of their ultra-rapid adaptation to the market. The typical mass-produced plastic items are produced through the following sequence: designing a product, iterative process between the designer and production engineer to make sure the product is producible, optimising the product, making production plans, moulds, post-production of the moulds etc. [2]. Compared to typical manufacturing, 3D printing is capable of using a trial and error method, where a designer can print a model and try it in real life without any loss (except filament loss). If that design is not capable of performing a wanted task, the designer can continue improving the model, if needed, until it fulfils all the defined goals. This approach came in handy at the start of the Covid-19 pandemic when there was a significant lack of medical protective equipment. [3] and [4].

Soon after the outbreak of the Covid-19 pandemic in Montenegro, protective gear supply of medical equipment approached minimum, meaning there was an insufficient amount of equipment to cover all the hospitals and hospital units' needs. Also, the supply chain from other countries was severely disrupted due to stricter and time-consuming border control which delayed supplies for a long time, causing great problems for our country as well as for the whole world. By looking at the examples of other countries that faced this pandemic before its outbreak in Montenegro, enthusiastic 3D printing communities and hubs in the country started manufacturing everything that could be made on printers and that was desperately needed at that time [5]. Soon after that, at the initiative of the Faculty of Electrical Engineering of the University of Montenegro and the Science and Technology Park of Montenegro, with the support of the Montenegrin Ministry of Science, all 3D printers in the country were clustered (45 functional fused deposition modelling (FDM) printers in Montenegro) and we made a national cluster, which

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altogether resembles a mass production company since all printers printed the same models of protective equipment as per the standards provided by the Institute of Public Health of Montenegro [6]. The most printed equipment were protective visors, together with publicly available models of oxygen masks and tubes for respirators that were manufactured as spare parts for medical units if needed [7].

The exponential growth of infected people increased the demand for protective visors to such a high degree that the 3D printing cluster barely managed to produce sufficient quantities [8]. As mentioned, stricter border controls were hampering imports that soon enough reflected on the manufacturing of visors, as Montenegro does not have its filament production. This “Printing crisis”, that hit 3D printing manufacturers in Montenegro after two weeks into the pandemics, could have been partially postponed by somehow optimising the consumption of filaments until the newly ordered filament crossed the border and became available [9].

This paper aims to precisely describe the process of strengthening the polylactide acid (PLA) 3D printing material, which is performed via the annealing process, which makes it possible to reduce the amount of material used in printing. Annealing of plastic drastically increases its firmness, tensile strength and temperature resistance, and is a well-known procedure in plastic injection moulding, but not so widespread in the post-production of 3D printed parts [10]. This process requires heating a printed element to a temperature between glass transition and melting and waiting for a certain amount of time to harden. By creating a perfect blend of the chosen annealing temperature and time, later tests of the specimens in our experimental equipment, yielded optimal numbers which may be used in optimising 3D models, so that the number of 3D printed elements can be greater for the same amount of the used material [11].

1 METHODOLOGY

1.1 Materials

The goal of this research is to analyse the annealing process of the PLA filament, most commonly used in 3D printing, make tensile strength graphs showing the relation between annealing temperature and time and choose the best annealing process that is suitable for small scale 3D manufacturers who do not have spacious workshops and who are not capable of super-precision “baking”.

The filament used in this research is a standard PLA filament, commercially available in a mid-range quality, printed with standard PLA printing settings (205 °C head temperature, 60 °C bed temperature) on Craftbot FLOW IDEX XL 3D printer [12] and [13]. Since the PLA is a polymer, it has two types of molecular structures: chaotic and partially organised – amorphous and semicrystalline [14]. When the filament is melted, its molecular chains become disorganised (amorphous), flexible and elastic. Due to rapid cooling, its molecular structure remains the same, and its tensile strength, firmness and heat resistance are inferior to the organised chain structure, which is crystalline [15].

Hence, in order to arrange those polymer chains from amorphous to semi-crystalline structure, the temperature needs to be within a certain range for a certain amount of time. “Activation temperature” of organising the chains is called a glass transition temperature [16]. It ranges from the lower temperature point within the annealing process and for the PLA material it is 65 °C, up to the melting temperature, which is around 160 °C – the upper-temperature point. Choosing the right temperature is not that easy to achieve, but the closer the temperature is to the melting point (still in semi-crystalline transition state) the more uniform/merged will be the printed layers. Furthermore, by merging its layers, an object is less likely to “snap” on the printing plane, as shown in Fig. 1, but the printed element will be highly deformed, thus the decision to merge the layer or not depends on the purpose/use of the object [17].

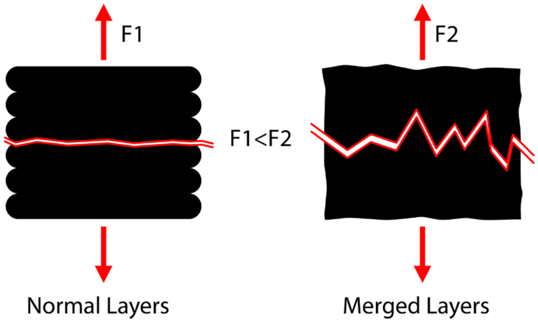


Fig. 1. *Normal and annealed 3D printed element difference – side view*

Tensile strength testing was performed on the testing setup shown in Fig. 2, with the calculated sensor precision of 1 %, using the specimens/samples (also see Fig. 2) divided into 5 batches with 5 different annealing temperatures for 3 different baking times [18].

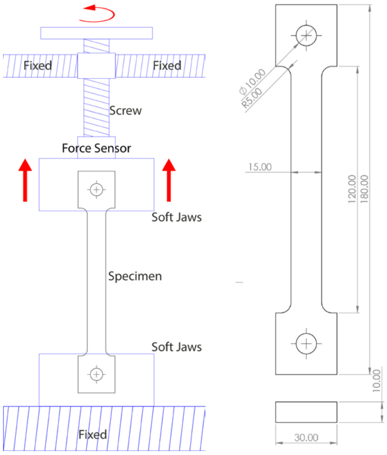


Fig. 2. *Tensile strength tester and specimen dimensions (units in mm)*

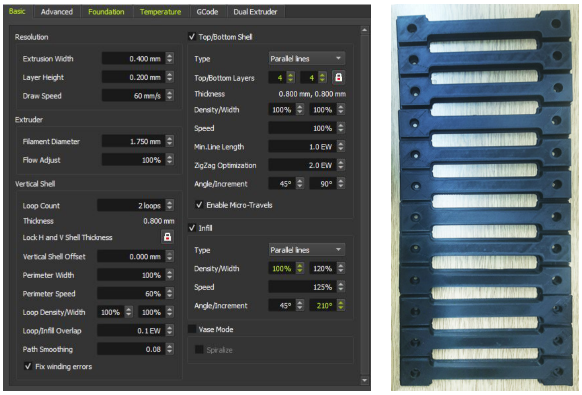
1.2 Process Parameters

Results obtained from the tensile strength tester at different baking temperatures and times were entered in "Force value" fields shown in Table 1, and then averaged for each of the columns in the Table and plotted in graphs for easier readability. Baking times were: (30, 60 and 90) minutes, and baking temperatures were: room temperature (i.e. no baking), (70, 90, 110 and 130) °C [17].

Table 1. *The table used for tensile strength test results*

Test num. 1	Baking time: 30 min / 60 min / 90 min			
	Annealing temperature			
Spec. num.	70	90	110	130
1	Force value	Force value	Force value	Force value
2	Force value	Force value	Force value	Force value
3	Force value	Force value	Force value	Force value
4	Force value	Force value	Force value	Force value
5	Force value	Force value	Force value	Force value
Avg. value	Force value	Force value	Force value	Force value

Specimens shown in Fig. 3 were printed on a Craftbot FLOW IDEX XL 3D printer, as mentioned before, with the following printing parameters – Head temperature 205 °C, bed temperature 60 °C, infill 100 % and Z movement 0.2 mm, as shown in Fig. 4. Computer aided manufacturing (CAM) slicing software used in this G code creation is CraftWare. For the best possible adhesion on the aforementioned 3D printer, we added a "raft" underneath the model, to ensure the specimen was completely parallel to the printing bed and without any warping or layer shifting. Printing was done in sets, with three specimens on each set [19].



Resolution
Extrusion Width 0.400 mm
Layer Height 0.200 mm
Draw Speed 60 mm/s
Extruder
Filament Diameter 1.750 mm
Flow Adjust 100%
Vertical Shell
Loop Count 2 loops
Thickness 0.800 mm
Lock H and V Shell Thickness
Vertical Shell Offset 0.000 mm
Perimeter Width 100%
Perimeter Speed 60%
Loop Density/Width 100% 100%
Loop/Infill Overlap 0.1 EW
Path Smoothing 0.08
☑ Fix winding errors

☑ Top/Bottom Shell
Type Parallel lines
Top/Bottom Layers 4 4
Thickness 0.800 mm, 0.800 mm
Density/Width 100% 100%
Speed 100%
Min.Line Length 1.0 EW
ZigZag Optimization 2.0 EW
Angle/Increment 45° 90°
☑ Enable Micro-Travels
☑ Infill
Type Parallel lines
Density/Width 100% 120%
Speed 125%
Angle/Increment 45° 210°
☐ Vase Mode
☐ Spiralize

Fig. 3. *Printing parameters and the printed model, shown in CraftWare software*

After the printing of all sixty-five specimens, they were classified into two groups. One group of five was used for non-hardened testing and those results were put in a separate table, while the other sixty specimens were separated first into three groups (for different baking times), and then all the mentioned groups were further each divided into four smaller groups intended for different baking temperatures. Since this research is intended for small scale 3D printing manufacturers around the globe (using our data for optimising the filament use), it was not appropriate to "bake" the specimens in expensive laboratory ovens, but rather in a standard, cheap electric kitchen oven, that every house or a small-scale manufacturing facility should have or should be able to easily acquire. The baking was done by first heating the oven to the desired temperature, then letting the temperature settle for ten minutes, then putting five specimens inside the oven, until the selected time elapsed, then letting specimens cool to room temperature outside the oven. All specimens were firstly heat-treated/annealed and exposed to the same standard room temperature/humidity conditions before testing on the tensile strength testing unit, so as to obtain the testing results which would be as objective as possible.

2 EXPERIMENTAL RESULTS

Small irregularities like PLA filament uneven moisture level, various degrees of purity of different filament segments, some external factors like room temperature and humidity may affect each print differently, so the more specimens used for the same test, the better. The results of tensile strength tests are shown in Table 2 (in Newtons) and are visually presented in graphs shown in Fig. 4 [20].

Table 2. *Testing results for baking time, a) 30 min, b) 60 min, and c) 90 min*

a) Test num. 1	Baking time: 30 min			
Specimen num.	Annealing temperature			
	70 °C	90 °C	110 °C	130 °C
1	6509.81 N	6699.16 N	6403.13 N	6342.62 N
2	6505.92 N	6675.30 N	6393.00 N	6336.54 N
3	6565.43 N	6736.34 N	6451.49 N	6394.52 N
4	6525.43 N	6695.32 N	6412.18 N	6355.55 N
5	6606.44 N	6778.40 N	6491.80 N	6434.48 N
Avg. value	6542.61 N	6716.91 N	6430.32 N	6372.74 N

b) Test num. 2	Baking time: 60 min			
Specimen num.	Annealing temperature			
	70 °C	90 °C	110 °C	130 °C
1	6643.88 N	6815.51 N	6529.45 N	6472.24 N
2	6599.76 N	6770.26 N	6486.09 N	6429.25 N
3	6658.08 N	6830.08 N	6543.41 N	6486.07 N
4	6627.71 N	6798.94 N	6513.56 N	6456.49 N
5	6599.45 N	6769.95 N	6485.78 N	6428.95 N
Avg. value	6625.77 N	6796.95 N	6511.66 N	6454.60 N

c) Test num. 3	Baking time: 90 min			
Specimen num.	Annealing temperature			
	70 °C	90 °C	110 °C	130 °C
1	6600.04 N	6769.53 N	6487.05 N	6430.55 N
2	6621.25 N	6791.28 N	6507.89 N	6451.22 N
3	6631.96 N	6802.27 N	6518.42 N	6461.65 N
4	6697.77 N	6869.77 N	6583.11 N	6525.78 N
5	6632.54 N	6802.86 N	6518.99 N	6462.22 N
Avg. value	6636.71 N	6807.14 N	6523.09 N	6466.28 N

Compared to the non-hardened specimens, whose averaged deformation resistance was 5711 N, the annealed ones showed a significantly greater deformation resistance, which was around 20 % greater than before the annealing process. As the annealing temperature exceeds glass transition, the molecular structure of long polymer chains becomes more and more organised, resulting in a stiffer element, but as the temperature rises to the melting temperature, the cross-section area of the specimen shrinks as the elongation of the longitudinal axis increases, thus creating higher pressure on that area, resulting in a slightly lower deformation resistance. Temperatures higher than 130 °C were not taken into consideration both due to the aforementioned problem and the problem with material deformation that would present a big problem when trying to anneal some 3D printed elements intended for mechanical manipulation, such as artistic design elements or something similar [17].

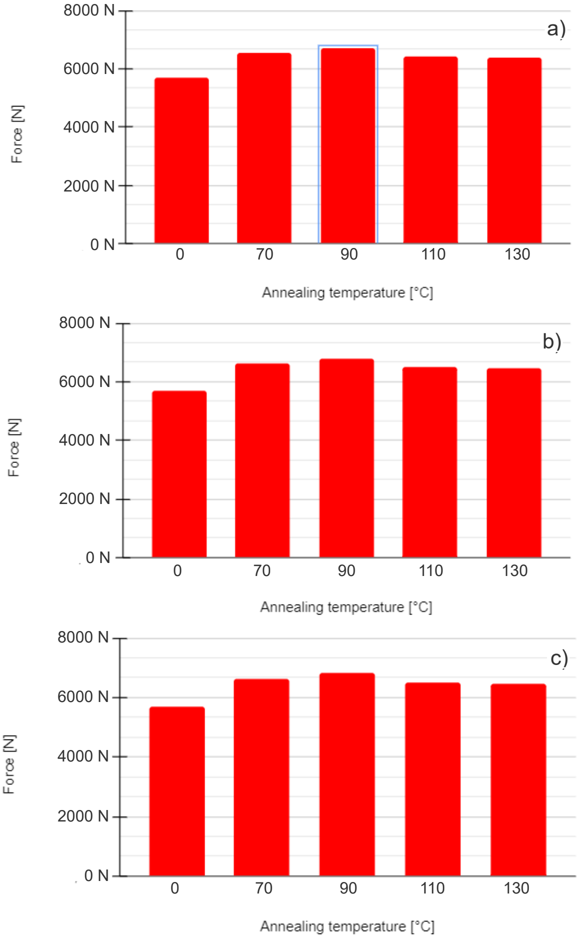


Fig. 4. *Tensile strength graph with annealing time; a) 30 min, b) 60 min, and c) 90 min*

Higher baking temperatures caused deformation of the tensile test material and elongation of around 10 % (x-axis shown in Table 3). Shrinking of the cross-section (y, z-axis in Table 3) is a bit lower than elongation – around 9 % at the mentioned higher baking temperatures, up to the melting point of the specimen when horizontal elongation increases rapidly.

Table 3. *Deformation of the specimens*

Deformation [%]	Baking temperature [°C]				
	0	70	90	110	130
x	0	2	4	6	10
y	0	1	3	5	9
z	0	2	3	4	9

By arranging averaged data in one table and creating a baking temperature-time matrix as shown in Table 4, one can decide if it is prudent to invest more time in annealing the printed elements if the result is only a small difference in tensile strength.

Table 4. *Baking temperature-time matrix*

Baking time [min]	Baking temperature [°C]				
	0	70	90	110	130
30	5711.83	6542.61	6716.91	6430.32	6372.74
60	5711.83	6625.77	6796.95	6511.66	6454.60
90	5711.83	6636.71	6807.14	6523.09	6466.28

In Fig. 5 we can see the normal distribution of the data of the test tube baked most optimally. It gives us information not only on the average value of the force that this sample can withstand, but also gives us the data on the maximum and minimum force measured during the testing as well as the data on the frequency of occurrence of this force. This was done with the testing of one hundred specimens baked for 60 min at 90 °C.

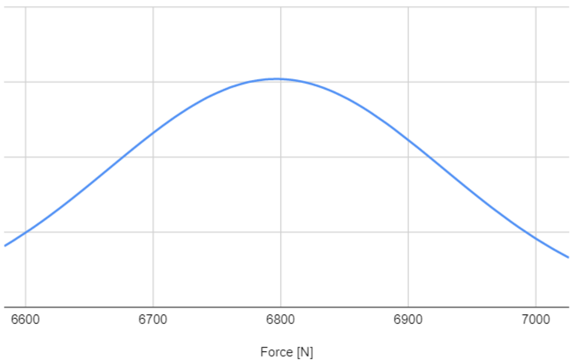


Fig. 5. *Normal distribution of the data of the test tube*

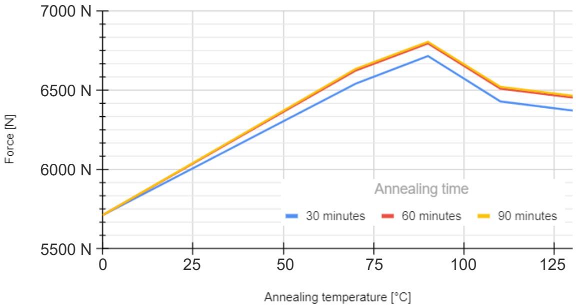


Fig. 6. *Baking temperature-time graph*

Allowing temperature to penetrate through the walls of a printed element to its internal layers, a better semi-crystalline structure can be obtained and the stiffness of the element will be higher, as shown in Fig. 6, but that will take a lot of time for some prints, so it is important to have a plan that will strike a perfect balance between the time spent and the level of obtained tensile strength.

3 CONCLUSIONS

With the aforementioned plan related to the filament strengthening method, one can save a lot of material while mass-producing some elements, but the problem is that a regular home oven would be inadequate for the sheer number of prints. Fixing that just by boiling prints in water instead of baking them in the oven would save a lot of time, as the printed element only needs to be heated to a specific temperature (that happens to match the water boiling temperature). The deformation that occurs at this tested temperature and the annealing time range was measured to be below 5 %, which is quite acceptable for most of the 3D printed elements, and just by simply fixing the scale of the element when creating the G code, that deformation would approach zero after the annealing **[21]**. This study concluded that the material optimisation of 3D printed elements was easily doable using the PLA annealing process explained in this paper. With this kind of optimisation, small scale manufacturers may save a lot of filament material in the long term, which is highly useful for the situations like the one that emerged this year with the Covid-19-related “filament shortage crisis” in Montenegro **[22]**.

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