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THE EFFECT OF DIFFERENT PRINTING PARAMETERS ON MECHANICAL AND THERMAL PROPERTIES OF PLA SPECIMENS

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Abstract
In 3D printing, it is important to choose the right printing parameters because they can influence the mechanical strength of the printed product. Fused Deposition Modelling (FDM) type printer was used to print specimens from poly(lactic-acid) (PLA) fiber. Three printing temperatures, two printing rates, and two building structures were applied. The mechanical properties were measured by tensile and Charpy impact tests, the thermal properties were investigated by Differential Scanning Calorimetry (DSC) and pictures were taken from the fracture surfaces by digital microscope. The results showed that the effect of the fiber orientation was the greatest. The temperature has less impact, but the change is well demonstrated. The effect of printing rate on mechanical strength is not clear, so further studies are required. At slower rate the positive effect of temperature raising is more visible on microscopic images.

1 Introduction

Nowadays rapid prototyping (RP), i.e. 3D printing is not only very popular but also available for a wide audience. At companies 3D printing is used to make visual or functional models, helping also the rapid tool manufacturing [1]. For private one can buy a 3D printer with a lower cost to print decor objects or souvenirs. In both application fields, the good quality of the product is necessary, so it is required to know how the printing parameters and materials change the quality.

The principle of all the 3D printing techniques is that the virtual model of the product is cut into layers by a software and the printer is creating the product by layer to layer [2]. There are many types of RP technics. One of them is FDM (Fused Deposition Modelling) or FFF (Fused Filament Fabrication), which is used both in the industry and in household applications. 3D printers using this method are available in different qualities and prices, therefore their popularity is increasing.

The essence of FDM/FFF technology is that the build and support materials are used from spools. The thermoplastic polymer filament gets to the extruder head by the drive wheels. In the hot printer head, the polymer melts, the nozzle is laying down the melted filament to the working space. After making one layer, the table goes down with the thickness of a layer and the nozzle starts the second layer. The printer head is controlled by NCT (numerical control) codes. There is a possibility to apply more than one extruder head, so material or a support-material with another color can be used.

For most printers, there is a so-called basis setting, which can be applied for most products, but the parameter settings can be rewritten, too. The printing temperature and rate influence the heat diffusion between the layers, which change the welding process, the shrinkage and the crystalline

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structure (in case of semi-crystalline material). Moreover, the orientation of the filaments has the same importance. With the right choice of the parameter set, the quality, the look and mechanical strength of the printed object can be increased.

Several sorts of polymers can be printed by FDM/FFF technique. One of the preferred materials is poly(lactic-acid) (PLA), which is a biodegradable polymer derived from renewable biomass. In industrial circumstances, at high humidity and temperature, it is compostable. The regulation about environmental protection and the fortunate properties of the material helped to spread PLA as a 3D printing material. PLA has a low melting point and good mechanical stability with 60 MPa tensile strength and 3 GPa modulus value [3-5].

PLA is a semi-crystalline, thermoplastic aliphatic polyester. It is made from the fermented plant. L- and D-lactides are its isomers, which have identical formulas, but a different structure. Commercially available PLA types are copolymers, mixtures of the isomers in different proportions. Therefore the properties of the products are changing within a range [4-7].

In this paper, tensile and impact specimens printed from commercially available PLA fibers with different printing parameters were examined. The effect of different printing temperatures, printing speeds, and structural orientations on properties was investigated. In our previous work [8, 9] the focus was on changes in mechanical properties, this has now been supplemented by the analysis of thermal properties and the microscopic study of fracture surfaces, which provide additional important knowledge about understanding the differences [10-13].

2 Experimental

2.1 Material

As printing material, Philament green PLA filament with 1.75 mm diameter was chosen and ordered by Bitshapes Webshop [14].

2.2 Printer

Craftbot PLUS type 3D printer was used (with FFF technique), which belongs to the Department of Innovative Vehicles and Materials at John von Neumann University. Its accuracy in X and Y direction is 4 microns, while in Z direction 2 microns. The thickness of the layers can be set between 50 and 300 microns. The printing zone has 250x200 mm floor area and 200 mm height. The printer is suitable for filaments with 1.7 mm. The maximum printing rate is 200mm/s and the diameter of the printing head nozzle is 0.4 mm. The maximum adjustable temperature is 250°C for the printing head, while 110°C for the printing table [15].

2.3 Printing parameters

For the investigation two types of printing structure (direction), two printing rates and three printing temperature were chosen. In the first structure, the direction of one layer is parallel with the longitudinal axis of the sample, the direction of another layer is perpendicular to the previous one. The name of this structure is 90° orientation. In the case of the second structure, one layer is 45° to the longitudinal axis of the sample, another layer is perpendicular to the previous one. The name of this structure is 45° orientation. The printing rates were 40 and 60 mm/s. The three printing temperatures were 205, 215 and 225°C.

From each parameter set 5-5 samples were measured by tensile and impact test. The investigated cross-section of the samples is 4x10 mm. The name of the parameter set contains the orientation, the printing rate and then the printing temperature in this order. For example, a parameter set with 90° orientation, 60 mm/s printing rate and 225°C printing temperature is signed by 90-60-225; one with 45° orientation, 40 mm/s printing rate and 205°C printing temperature is signed by 45-40-205.

The two types of printing structure can be seen in Figure 1.

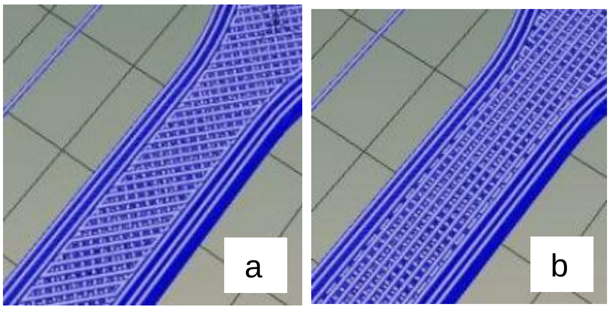

Figure 1. Printing structures, a: 45° orientation, b: 90° orientation

2.4 Methods

The printing samples were investigated by standard tensile [16] and Charpy impact [17] tests at room temperature (23±1°C). The tensile test was performed by Instron 3366 universal testing machine with a 50 mm/min measuring rate. Charpy impact test was performed by Ceast Impactor II with 5 J hammer.

The fracture surfaces were investigated by Keyence VHX-2000 digital microscope.

The thermal behavior of PLA was measured by TA Q200 heat-flux DSC (Differential Scanning Calorimetry [18]) instrument, which was calibrated by Indium. The sample weights were about 5 mg. The applied gas during the DSC scan was nitrogen with 50 mL/min flowing rate. The temperature range was from 30°C to 200°C and the heating rate was 20 °C/min.

The measurements were done in the accredited Material Testing and Measurement Techniques Laboratory at John von Neumann University.

3 Results and discussion

Table 1 introduces the results of the Charpy impact and the tensile tests, including the mean and standard deviation values of the impact strength, tensile modulus, tensile strength, and elongation at break.

Table 1. Results of the Charpy impact and the tensile test

Printing parameters	*Charpy impact strength [kJ/m²]*	*Tensile modulus [MPa]*	*Tensile strength [MPa]*	*Elongation at break [%]*
45-40-205	21.1±1.8	1646±30.8	51.3±3.8	3.9±0.33
45-40-215	22.6±0.9	1684±23.2	55.4±1.9	4±0.07
45-40-225	21.9±1.4	1684±23.2	55±2	4.1±0.09
45-60-205	22.6±1.3	1738±239.3	52.1±1	3.8±0.22
45-60-215	22.3±2.2	1738±239.3	54.8±0.7	3.7±0.07
45-60-225	23.0±3.2	1792±190.9	55.6±1.6	3.9±0.11
90-40-205	19.5±7.6	1952±249.2	48.1±1.5	3.5±0.22
90-40-215	19.4±1.3	2161±66.2	47.4±1.2	3.3±0.12
90-40-225	18.7±2.4	2189±91.7	50±1.4	3.4±0.08
90-60-205	18.7±1.0	2154±65.4	46.5±0.9	3.3±0.07
90-60-215	18.9±0.7	2246±110.5	48.4±1.3	3.4±0.07
90-60-225	18.4±2.2	2362±51.3	48.9±0.7	3.3±0.09

Figure 2 illustrates the variation in impact strength as a function of temperature, orientation, and printing rate. Based on the results, it can be concluded that using the 45° orientation, higher impact strength can be achieved, become more flexible than the 90° orientation, and the two printing structures are well separated from each other. In case of 90° orientation, the increase of temperature and speed slightly reduced the impact strength, while at 45°, the effect of increasing the parameters is not clear, but the tendency is increasing, more tests would be required at different temperatures and rates.

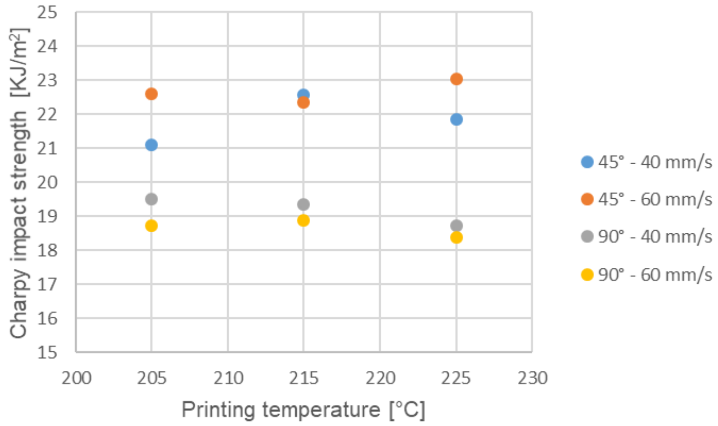

Figure 2. Impact strength as a function of printing settings

Figure 3 displays the change in the tensile modulus as a function of temperature, printing rate, and orientation. The change in the modulus of elasticity fits well with the results of the impact strength. The lower impact strength of the 90° orientation indicates a more rigid behavior, which is confirmed by higher tensile modulus. Increasing the temperature and printing rate the tensile modulus increases.

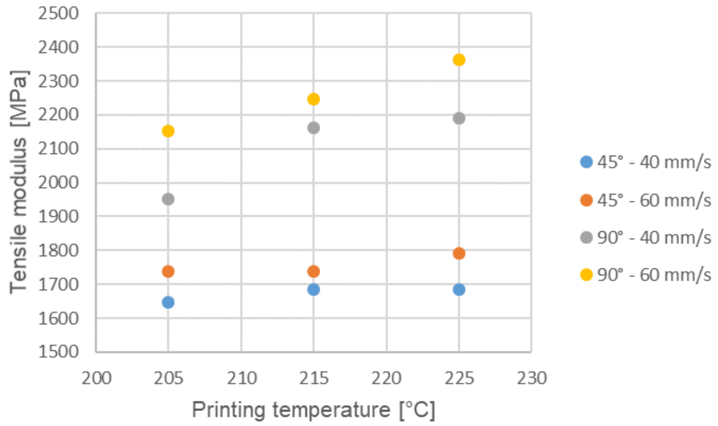

Figure 3. Tensile modulus as a function of printing settings

Figure 4 illustrates the change in tensile strength as a function of temperature, orientation, and printing rate. Based on the results it can be stated that using the 45° orientation, a higher tensile strength can be achieved than in the case of 90°, and the two printing structures are well separated from each other.

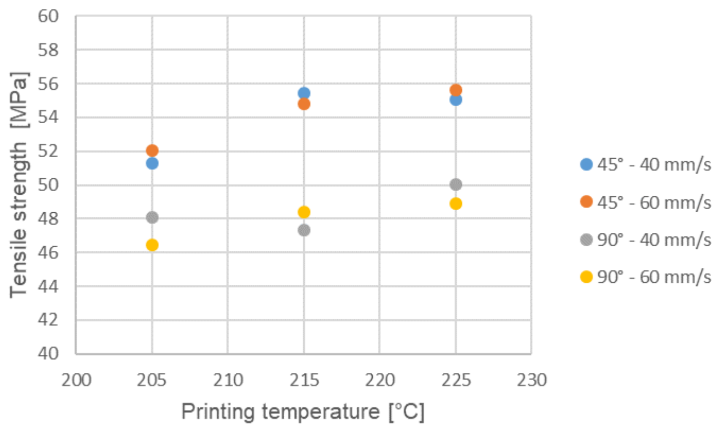

Figure 4. Tensile strength as a function of printing settings

Increasing the temperature in each case, the tensile strength increases, but the effect of the increasing rate is not clear. The results of the specimens printed at 215° C are different from the others; therefore, more tests would be required to demonstrate the effect of the rate.

Figure 5 shows the variation of the elongation at break as a function of temperature, printing rate and orientation. The results concluded that the 45° orientation is also well separated from 90°. The effect of the increasing temperature is small but has an increasing tendency at 45° and practically does not change at 90°. At 45° orientation, the increasing rate reduces the elongation values. It has a reducing effect of 90° but more measuring points would be needed to prove the actual change.

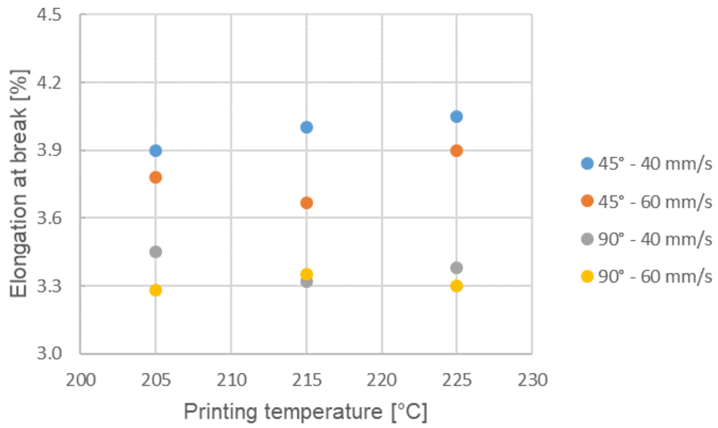

Figure 5. Elongation at break as a function of printing settings

Figure 6 shows a DSC curve during heating. The heating rate was 20 °C/min. The first change is the glass transition temperature around 60°C. Then a cold crystallization occurs, which is the result of too fast cooling rate, the crystals cannot form due to the rapid cooling. Above the T_g temperature, the segment movement starts and the material creates the missing crystals. When it reaches the melting temperature, all crystals, both cold and originals are melted. Universal Analysis software was used to evaluate curves. The software removed the heat of melting of the cold crystallization from the complete heat of melting to obtain the original crystalline phase formed during printing.

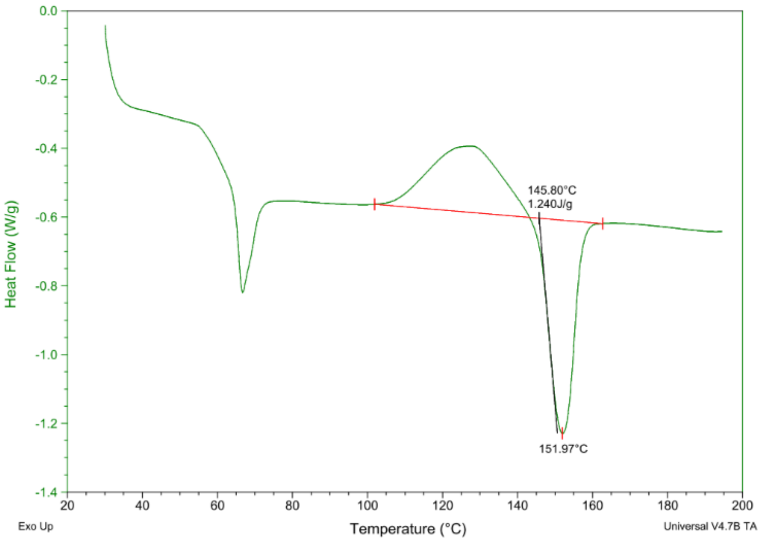

Figure 6. DSC curve of 45-40-205 specimen

The heat of melting is shown in Figure 7 as a function of the printing parameters.

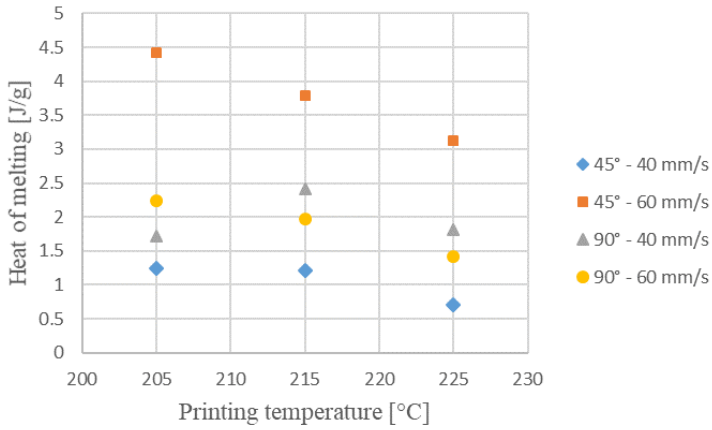

Figure 7. Heat of melting as a function of printing settings

The change in heat of melting is small, so it can be said that the effect of the printing parameters on the crystalline structure is not significant.

The microscopy images are shown in Figures 8 and 9. In both figures the fracture surfaces are visible after the impact tests. The 90 ° orientation was chosen because the changes can be better presented there. Figure 8 illustrates specimens made at the printing rate of 40 mm/s. The images were rotated so that the bottom of the specimen is on the left, and the top is on the right. The adjacent a, b, and c images show the effect of increasing the temperature.

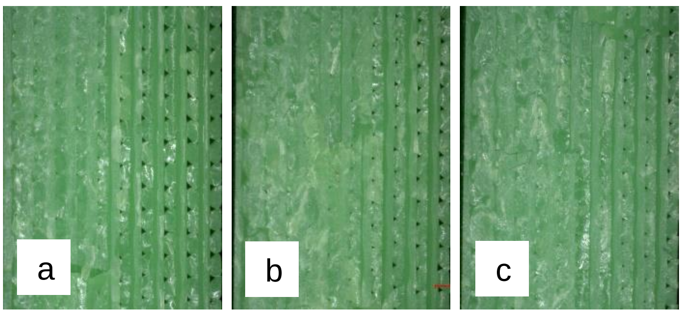

Figure 8. Microscopic picture of 90-40-205(a)-215(b)-225(C) specimen

Microscopic images show that during printing, the fibers at the bottom of the specimen fused. Gaps between the fibers appear from about half of the specimen, and as more and more layers are stacked, the dimensions of the gaps increase. At a print speed of 40 mm/s (Figure 8), the size of the gaps between the fibers gradually decreases as the printing temperature increases. The higher temperature helps the fibers to melt better and thus form a more homogeneous structure.

Figure 9 displays specimens made at the printing rate of 60 mm/s.

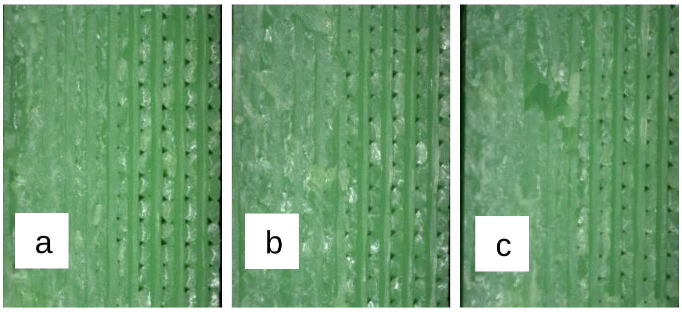

Figure 9. Microscopic picture of 90-60-205(a)-215(b)-225(c) specimen

If the speed is increased to 60 mm/s (Figure 9), the gaps between the fibers are only slightly reduced, so the positive effect of the temperature increase cannot be realized as at a slower speed.

4 Summary and conclusion

From the results of the measurements, it can be concluded that the greatest influence factor is the construction structure from the applied parameter sets. In each case, the 45° fiber orientation had higher impact strength, tensile strength, and elongation, only the tensile modulus decreased.

The effect of temperature was clearly detectable in most cases. Increasing the printing temperature had a positive effect on the results of the tensile test. Higher printing temperatures result an improved bonding of the fibers, this was also visible on the microscopic images, thus allowing the printed product to resist tensile stress. In the 45° orientation, the increase in temperature also had a slight improving effect on the impact strength. Which is also due to the fact that at 45° increasing the temperature shows a decreasing crystallinity on the DSC curves, which results in a decrease in the tensile modulus, i.e. an improvement in the impact strength.

The effect of changing the printing rate was usually not clear. Only in the case of the tensile modulus could it be shown that increasing the printing rate increases the tensile modulus, in other cases further measurements would be needed to prove the exact effect. However, based on the microscopic images, better welding between the fibers is only achieved by using a slower printing rate, or at least this is the only case when the positive effect of the higher printing temperature can take effect.

In general terms, the most important parameters responsible for creating bonding between the fibers, such as temperature and rate, have only slightly changed the mechanical properties, and have a more significant impact on the construction structure and fiber orientation. In the case of a 45° orientation, it is most likely that the fibers can partially absorb the forces parallel to and perpendicular to the longitudinal axis of the specimen. However, in the case of 90° orientation, the fibers perpendicular to the longitudinal axis will be separated sooner in the case of both impact and tensile stress, and the strength of the product is provided by the longitudinal fibers. Further studies are needed to prove this theory.

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