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Effect of 3D printing speed on mechanical and thermal properties of wood-PLA composite filament

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ABSTRACT: This study was carried out to examine the effect of the change in printing speed on the material properties of printing wood flour-filled filaments on a 3D printer. First, hornbeam wood flour was added to the Polylactic acid (PLA) polymer and then mixed in a twin-screw extruder, and then a wood-PLA composite filament with a diameter of 1.75 mm was produced. Then, test samples were printed from the produced wood-PLA composite filament at different printing speeds (40-50-60 mm/s) using a 3D printer. Tensile strength and hardness tests were performed to determine the mechanical properties of the 3D printed samples. According to the tensile strength test results, the tensile strengths of the 3D printed samples exhibited different values with the change in printing speed. The highest tensile strength value was determined as 23.02 MPa at a printing speed of 50 mm/s, and the lowest tensile strength value was 22.14 MPa at a printing speed of 40 mm/s. According to the Shore D test results, the lowest hardness value was measured as 85.33 at a printing speed of 40 mm/s, and the highest value was measured as 86.1 at a printing speed of 60 mm/s. The crystallinity percentage of PLA first increased and then decreased with the increase in 3D printing speed according to the Differential Scanning Calorimetry (DSC) results. In addition, 3D printing speed did not have much effect on the melting temperatures of PLA.

Keywords: Wood flour, composite, 3D printing speed, tensile strength, DSC analysis

3B baskı hızının odun-PLA kompozit filamentin mekanik ve termal özelliklerine etkisi

ÖZ: Bu çalışma, odun unu dolgulu filamentlerin 3 boyut (3B) yazıcıda yazdırılmasında, baskı hızındaki değişikliğin malzeme özellikleri üzerindeki etkisini incelenmek amacıyla yapılmıştır. İlk önce gürgen odun unu Polilaktik asit (PLA) polimerine ilave edildikten sonra çift vidalı ekstruderde karıştırılmış ve ardından 1.75 mm çapında odun-PLA kompozit filamenti üretilmiştir. Daha sonra, üretilen odun-PLA kompozit filamentinden 3B yazıcı kullanılarak farklı baskı hızlarında (40-50-60 mm/s) test numuneleri yazdırılmıştır. 3B yazdırılmış numunelerin mekanik özelliklerini belirlemek için çekme mukavemeti ve sertlik testleri yapılmıştır. Çekme mukavemeti testi sonuçlarına göre 3B yazdırılmış örneklerin çekme mukavemetleri baskı hızındaki değişiklik ile farklı değerler sergilemiştir. En yüksek çekme mukavemeti değeri 50 mm/s baskı hızında 23.02 MPa, en düşük çekme mukavemeti değeri ise 40 mm/s baskı hızında 22.14 MPa olarak tespit edilmiştir. Shore D testi sonuçlarına göre en düşük sertlik değeri 40 mm/s baskı hızında 85.33 olarak, en yüksek değer ise 60 mm/s baskı hızında 86.1 olarak ölçülmüştür. Diferaniyel Taramalı Kalorimetre (DSC) sonuçlarına göre 3B baskı hızı artışı ile PLA'nın kristallik yüzdesi önce artmış, sonra azalmıştır. Buna ek olarak, 3B baskı hızının PLA'nın erime sıcaklıklarına çok fazla etkisi olmamıştır.

Anahtar kelimeler: Odun unu, kompozit, 3B baskı hızı, çekme direnci, DSC analizi

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1 Introduction

The impact of technological developments that can be seen in many areas has also manifested itself in manufacturing methods. Nowadays, the mechanized systems of the past have been replaced by modern production systems. One of these production systems is additive manufacturing and it has become increasingly widespread with technological developments and has become accessible to many users including amateur users. Developments in manufacturing methods have also been felt clearly in production methods such as rapid prototyping. A common type of rapid prototyping fused deposition model (FDM) 3D printer has attracted the attention of material scientists and manufacturers with their ease of use and reasonable prices. Biopolymers such as Polylactic acid (PLA) and PHB (Polyhydroxybuturate) are widely used as polymers in FDM type 3D printers. Improving material properties and reducing production costs have recently aroused the interest of researchers by adding various organic and inorganic filler/reinforcement materials to polymers.

3D printing known as additive manufacturing or rapid prototyping is the process of obtaining objects from 3D models drawn with computer-aided design (CAD) or similar programs. There are many 3D printing methods with different working principles. Among these methods, the most common 3D printing methodology is FDM in which suitable polymers (such as PLA and ABS) are generally melted from a hot nozzle and constructed in a stack on top of each other. The FDM method is preferred because it is reliable, simple, affordable and requires minimal material waste. 3D structures are printed layer by layer by depositing filament heated to the melting temperature region and extruded through the extrusion nozzle (Tao et al., 2017; Tümer et al., 2021). This technique allows complex shapes to be made with a degree of design freedom unattainable through traditional manufacturing methods (Blok et al., 2018). The properties of the parts depend on the correct selection of process parameters in the FDM method (Alkahari et al., 2021). In the FDM method, the mechanical strength and surface quality of printed parts can be controlled by changing the properties of polymeric filaments as well as printing parameters such as nozzle temperature, polymer flow, layer thickness and scanning angle (Khosravani et al., 2020).

The integration of wood materials into additive manufacturing is interesting due to their positive impact on the environment and better properties (Tao et al., 2017). Wood-filled PLA is preferable to solid wood considering the cost-strength balance (Karabağ et al., 2023). In recent years, great attention has been paid to the development of 3D printing materials including the use of biodegradable, natural or recycled materials such as wood fibers, cellulose and lignin. Wood waste is an interesting and relatively inexpensive material that can be processed and used as a 3D printing material (Wimmer et al., 2015; Kuo et al., 2016; Kariz et al., 2018). The low price of waste wood particles is one reason why they are used in wood plastic composites (WPC) which limits the use of more costly thermoplastic polymers. Using natural materials such as wood helps reduce the use of petroleum-based plastics and reduces environmental impact (Kim and Pal 2010). Composite materials have been produced by mixing wood flour with waste and neat polymers (Bal 2023; Bal et al., 2023). In addition, it has been stated that the produced composite materials can be used in some application areas where high rigidity and low strength are required (Bal et al., 2023).

PLA composite filaments can be used in 3D printing due to the good interfacial bond between biomaterials and PLA matrix (Tisserat et al., 2015). PLA is a promising biopolymer that can replace traditional petroleum-based polymers due to its renewability, recyclability and biodegradability. Additionally, PLA has excellent fabrication capability as it is suitable for processing by various methods. The excellent mechanical properties of PLA can be used in the production of biomaterials suitable for a variety of applications. PLA is one of the most produced biopolymers among the biopolymers available in the world. Therefore, the effectiveness of PLA composites has been examined by researchers as an alternative material to replace non-renewable petroleum-based materials (Ilyas et al., 2021).

The biggest disadvantage of the FDM method, which is a common technique of the additive manufacturing method, is that it takes more time for the production of 3D materials than traditional manufacturing methods (such as machining and welded manufacturing). A few scientific studies have been conducted to determine the effect of printing speed on the properties of materials in the FDM method. However, commercial filaments were used in all previous studies. In previous studies, it has been observed that there are limited studies on converting wood flour and other lignocellulosic materials into filaments after mixing them with PLA and then examining the effect of printing speed on material properties from 3D printing parameters. In this study, wood-PLA composite filament was produced by mixing wood flour with PLA polymer. After, test samples were printed from wood-PLA composite filament using a 3D printer working according to the FDM method. Then, the mechanical and thermal properties of the 3D printed test samples were examined.

2 Material and Method

2.1 Material

In this study, hornbeam (*Carpinus betulus* L.) wood flour was used to produce wood-PLA composite filament (Figure 1a). The hornbeam tree is a broad-leaved tree species seen in mountainous and hill forests of Europe and Asia. They are widespread in Romania, Croatia, France, Iran and Turkey (Fodor et al., 2018). Hornbeam wood was obtained from local timber producers in İzmir Türkiye. PLA polymer (FKUR Bioflex® 3D Clear) was used as the polymer matrix (Figure 1b). PLA polymer was obtained through purchase. Bio-Flex® 3D Clear is a biodegradable polymer compound suitable for the production of 3D printing filaments. The biobased carbon content is 90%. Melt flow rate (190 °C/2.16 kg) is 10 (g/10 min) and density is 1.25 g/cm^3.

Figure 1. Wood flour (a) and PLA (b)

2.2 Method

2.2.1 The production of wood-PLA composite filament

Hornbeam wood was ground in a laboratory type grinder (Loyka LKD 100) and then sieved in a shaker sieve and the wood flour remaining under an 80 mesh sieve (149 to 177 µm) was used for the production of composite filament. Wood flour was dried in an oven set at 103±2 °C until it reached full dry weight before the production of composite filament.

25% wood flour by weight was added to the PLA polymer and mixed in a twin-screw extruder with a mold opening of 1.75 mm and an L/D ratio of 20 for the production of wood-PLA composite filament. The extruder temperature profile was adjusted to 90-120-150-165-180 degrees from the feeding section to the exit section, respectively, and the screw speed was adjusted to 50 rpm. Extruded 1.75 mm diameter wood PLA composite filament was produced in the desired length with a filament winder (Figure 2).

Figure 2. Wood-PLA composite filament

2.2.2 Printing wood-PLA composite filament on a 3D printer

Extruded wood-PLA composite filament with a diameter of 1.75 mm was printed using an open source 3D printer (Sigma 3D printer) with a 0.6 mm nozzle. A 0.3 mm layer thickness, 100% print infill density, 50°C printing bed temperature, 190 °C nozzle temperature, and 30° raster angle parameters were selected to print the tensile test samples.. Test samples were produced at printing speeds of 40, 50 and 60 mm/s using the same printing parameters to determine the effect of 3D printing speed on the properties of composite materials (Figure 3).

Figure 3. 3D printed tensile test sample

2.2.3 Mechanical properties

Tensile test specimens were printed according to ASTM D638 (Type-IV). Tensile strength tests were carried out with an electromechanical universal mechanical testing device (AL-UN 20; Alarge) with a capacity of 20 kN. The clamp movement speed was set to 2 mm/min in the tensile test. The hardness tests were carried out according to ASTM D2240 using the Shore D hardness device to determine the hardness of 3D printed composite samples.

2.2.4 Thermal properties

Differential Scanning Calorimetry (DSC) analyzes were performed between 30 °C and 200 °C using the Shimadzu DSC-60 device set to 100 ml/min nitrogen gas flow rate and 10 °C/min heating rate. All samples were weighed to about 10 mg for DSC analyses.

3 Results and Discussion

Tensile strengths of 3D printed wood-PLA filaments at different printing speeds are given in Figure 4. The tensile strength first increased slightly and then decreased as the printing speed increased. The tensile strength values of the test samples printed at 40-50 and 60 mm/s printing speeds were determined as 22.14, 23.02 and 22.21 MPa, respectively. Yang and Yeh (2020) examined the properties of 3D printed composites using commercial WPC filament (40% wood fiber and 60% PLA). In the study, they reported that the printing speed did not have a significant effect on the tensile strength properties of the composites.

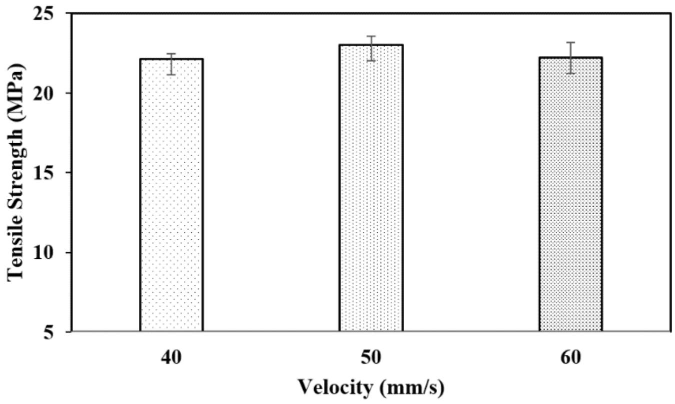

Figure 4. Tensile strengths of 3D printed samples

The Young's modulus of the 3D printed wood-PLA composite samples is shown in Figure 5. The effect of 3D printer printing speed on Young's modulus of wood-PLA composites was parallel to the tensile strength values. The lowest Young's modulus was determined as 1344 MPa in the test sample printed at 40 mm/s printing speed, and the highest Young's modulus was determined as 1410 MPa in the test sample printed at 50 mm/s printing speed. In addition, the Young's modulus of the test sample printed at a printing speed of 60 mm/s was calculated as 1369 MPa. As a result of comparing the Young's modulus of 3D printed composites from commercial filament, it was reported that the Young's modulus values of composites produced at 30-50 and 70 mm/s printing speed were 1731, 1650 and 1682 MPa, respectively (Yang and Yeh 2020). This study determined that Young's modulus of 3D printed test samples first increased and then decreased with the increase in printing speed.

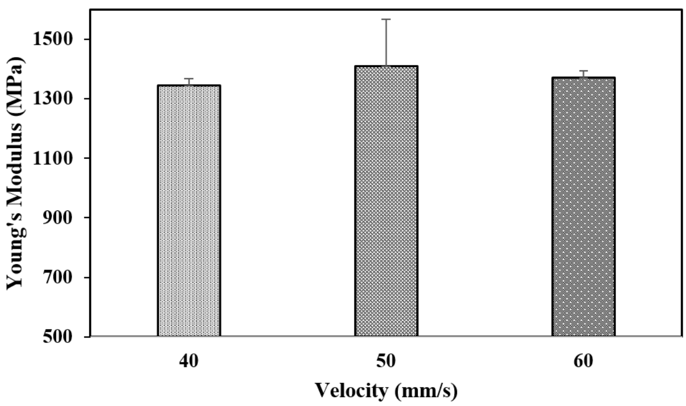

Figure 5. Young's modulus of 3D printed samples

The elongation at break values obtained from the tensile strength test results of 3D printed test samples from wood-PLA composite filaments are shown in Figure 6. The highest elongation at break was determined as 2.17% in the test sample printed at 50 mm/s printing speed among 3D printed wood-PLA composite samples. The lowest elongation at break was determined as 1.98% in the test sample printed at 40 mm/s printing speed. In addition, the elongation at break of the test sample printed at a printing speed of 60 mm/s was determined as 2.01%.

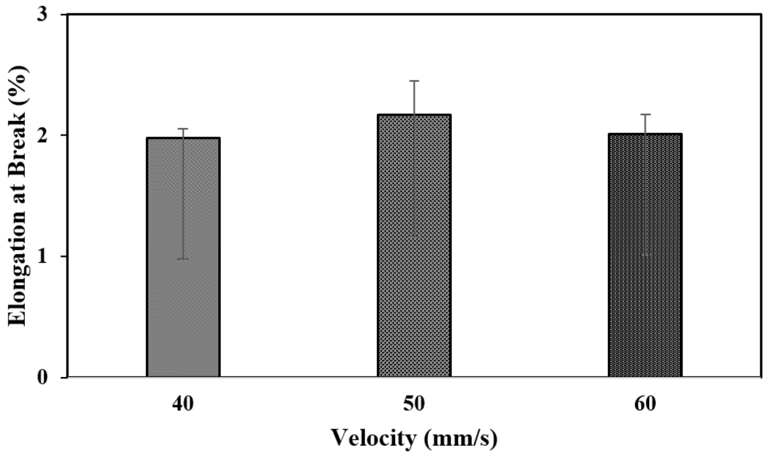

Figure 6. Elongation at break of 3D printed samples

Figure 7 shows the effect of printing speed on the hardness of 3D printed wood-PLA composites. The effect of printing speed on the hardness of composites was different from the tensile strength. Shore D hardness of the test sample printed at 40 mm/s printing speed was measured as 85.33. Shore D hardness of the test samples printed at 50 mm/s and 60 mm/s printing speeds were calculated as 85.6 and 86.1, respectively. The hardness of the composites increased slightly by increasing the 3D printing speed as seen from the Shore D results.

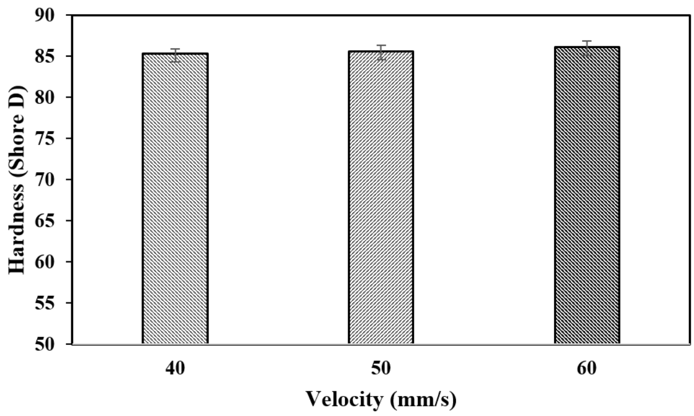

Figure 7. Shore D hardness of 3D printed samples

DSC curves of samples printed at different printing speeds using wood-PLA composite filaments are shown in Figure 8. DSC analysis is a type of thermal analysis that shows the change of the material according to the flow rate of heat under the programmed temperature. Typical DSC curve represents the endothermic and exothermic performance of the sample with varying temperature and heat flow rate (Höhne et al., 2003). The glass transition refers to the segmental movement of amorphous polymer chains that begin to freeze or unfreeze for polymers (Forrest and Veress 2001). The curves similar to the characteristic DSC curve of PLA composites were revealed as a result of the DSC analysis of 3D printed samples. Three different DSC peaks namely glass transition temperature (T_g), crystallization temperature (T_c)

and melting temperatures (T_m) were observed as distinct endothermic and exothermic peaks in all DSC curves.

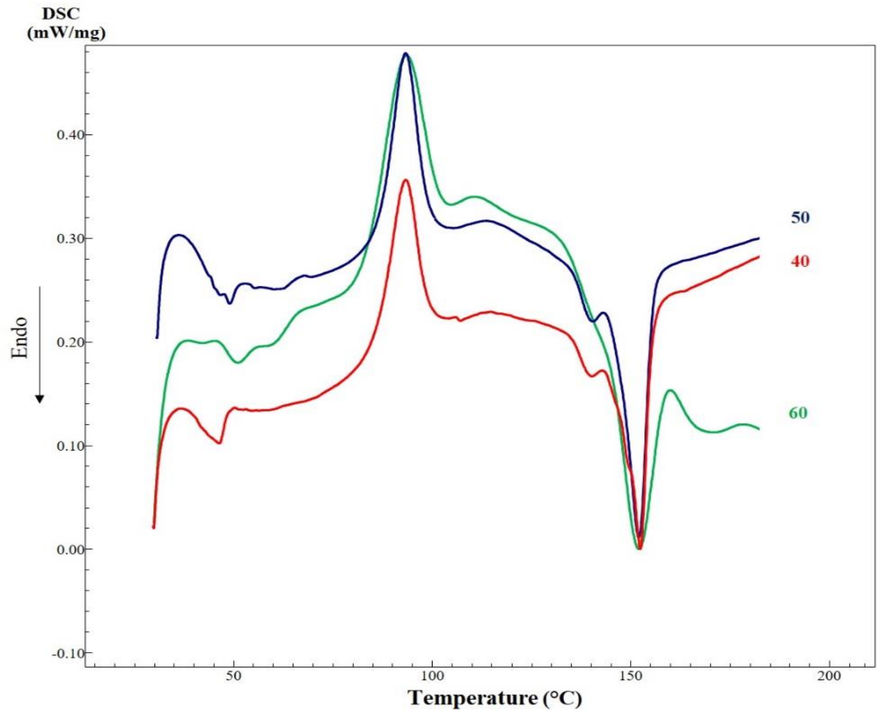

Figure 8. DSC curves of 3D printed samples

In addition to the T_g, T_c and T_m obtained as a result of DSC analysis of 3D printed test samples, enthalpy values (Δ_{hm} and Δ_{cc}) recorded as a result of endothermic and exothermic reactions and DSC crystallite percentages (X_{cr}) calculated from these values are given in Table 1. The T_g increased slightly with the increase in the 3D printing speed of wood-PLA composites. The highest T_g was measured as 47.80 °C in the sample printed at 50 mm/s printing speed, and the lowest T_g was 46.02 °C at 40 mm/s printing speed. T_g depends on the molecular properties, composition and compatibility of the components in the composite (Chung et al., 2002). The effect of changing printing speed on T_c and T_m is similar. It was determined that as the printing speed increased, both temperature values (T_c and T_m) first decreased and then increased. There were significant changes in the X_{cr} with the change in the printing speed of 3D printed wood-PLA composites. The highest X_{cr} value was calculated as 38.37% in the test sample printed at 50 mm/s printing speed, and the lowest X_{cr} value was calculated as 30.02% in the sample printed at 60 mm/s printing speed among the samples.

Table 1. DSC values of 3D printed samples

Velocity (mm/s)	T_g (°C)	T_c (°C)	T_m (°C)	Δ_{hm} (j/g)	Δ_{cc} (j/g)	X_{cr} (%)
40	46.02	92.59	151.21	-10.60	13.14	34.04
50	47.80	91.70	149.89	-12.05	14.71	38.37
60	47.28	92.83	151.27	-9.17	11.77	30.02

4 Conclusion

In this study, wood flour-filled PLA filament was produced and research was conducted on optimizing and characterizing the 3D printing processes of the produced filament. Among these studies, the effect of 3D printing speed on the mechanical and thermal properties of materials has aroused curiosity, and as a result, the necessary investigations have been carried out using relevant tests and analysis methods. The results obtained from the research and investigations are summarized below.

- It has been determined that the printing speed in the 3D printing process affects the tensile strength properties of the materials. It was observed that tensile strength properties first increased and then decreased with increasing printing speed.
- As a result of mechanical tests, changes in the properties of the materials were observed when the printing speed was low or high. The mechanical properties of the materials exhibited optimum values at speeds between the two printing speeds, low and high.
- The increase in 3D printing speed had a significant effect on DSC values according to the thermal analysis results. In general, it was observed that the test sample printed at medium speed had a higher crystallite ratio.
- In future studies, significant contributions can be made to this research field by producing PLA composite filaments reinforced with different wood flour or fibers to optimize the 3D printing of biocomposites and then printing them by changing the printing parameters (such as temperature, nozzle tip diameter, printing angle) in the 3D printer.

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Author Contributions

Nasır Narlıoğlu: Conceptualization (developing the research idea and objectives), Investigation, Determining the methodology, Resources, Visualization, Conducting Research, Performing Analyses, Validation, Drafting Manuscript, Manuscript Writing, Review and Editing.

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Conflict of interest statement

The author declares no conflict of interest.

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