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Original Article

Effects of material, infill pattern and infill density on the tensile strength of products produced by fused filament fabrication method

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ABSTRACT

As a result of the development of additive manufacturing technology and the decrease in device and filament costs, 3D printers have become widespread. The transition from prototype to final product production with a 3D printer is possible by increasing product strength. In many studies where production is carried out with the Fused Filament Fabrication (FFF), it is seen that Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene(ABS) filaments are used. In addition, infill geometry and infill density properties have been examined with limited materials in the literature. The research aims to increase product performance by examining the effects of infill pattern and infill density with different filaments. In this study, in order to investigate the mechanical properties of the product printed with FFF, samples were produced with 2 different infill patterns and 2 different infill densities using 5 different filaments and the tensile test results were examined. As the results, the samples with linear infill pattern and 60% infill density showed the highest strength for PLA, ABS, STH, PETG and Semiflex filaments. The optimum infill pattern was found to be "linear." As infill density increased, tensile strength increased by 4.6% for Semiflex, 5.66% for PLA, 9% for ABS, and 11% for STH.

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INTRODUCTION

All devices, systems and products that we admire for their form, usefulness and technology; it is produced as a result of successful design, correct material selection and appropriate manufacturing method. Manufacturing and design are fields that are constantly open to innovation and improvement. Traditional manufacturing methods can basically be defined under two headings: substractive methods and additive methods [1]. The main advantage of additive manufacturing compared to subtractive manufacturing is the low material loss [2]. Among these methods, additive manufacturing techniques have rapidly developed and become widespread in recent years, not only in the production of advanced technological products, but also in the production of polymer-based products that are frequently used in daily life and can even be produced at home [3]. With 3D printers, beyond the production of prototypes, the commercial product itself is now produced.

Additive manufacturing methods are seen as one of the important "mile stone"s (breaking point) in the manufacturing sector, following the Industrial Revolution [4]. Thanks to 3D printers, which are devices that work with the additive manufacturing method, in addition to rapid prototyping, it has become possible to produce complex shaped products at once, without the restriction of tool geometry. When the working logic of 3D printers is examined, it is seen that the product is manufactured by adding raw mate-

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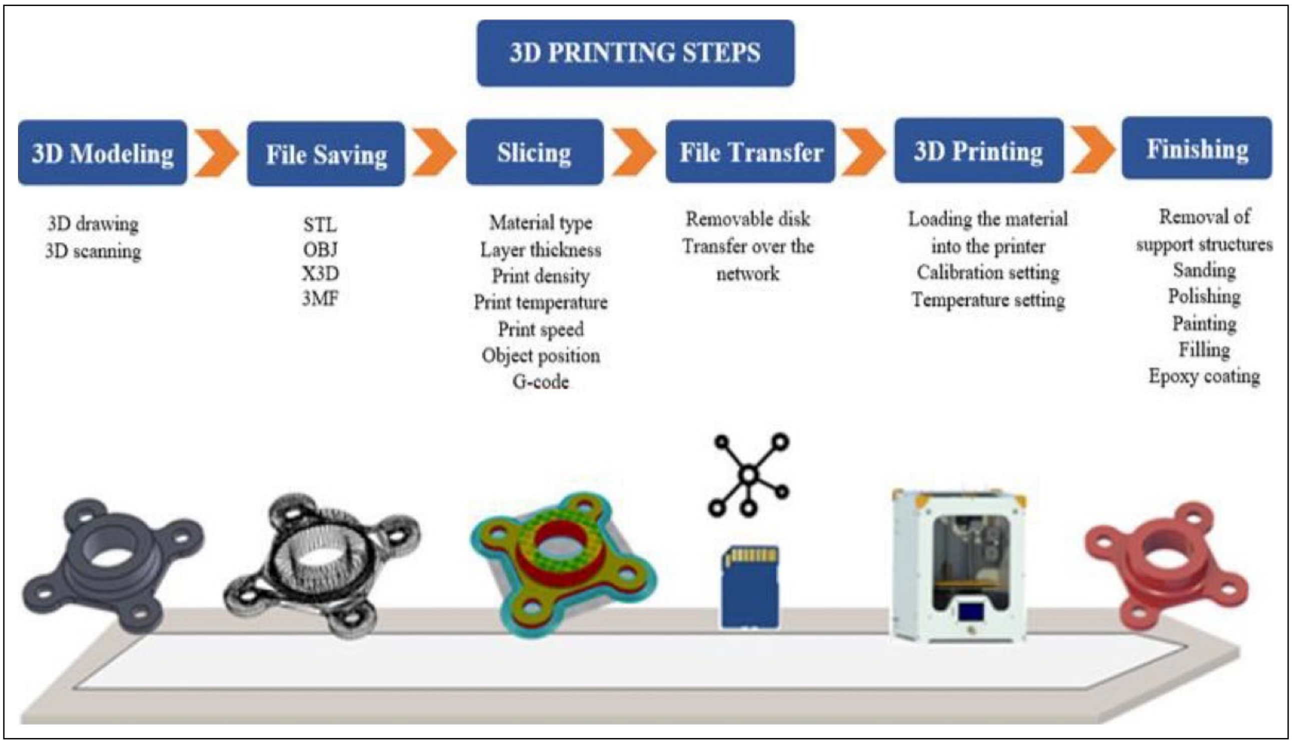

Figure 1. Design and production processes with additive manufacturing [5].

rials one after the other in layers. For this reason, the method is also called "layer manufacturing". Depending on the type of raw material, heating and solidification processes vary during the layer formation phase [4].

Production with the additive manufacturing method includes the following stages, as seen in Figure 1:

Modeling: The design of the product to be printed is carried out with computer-aided drawing programs (CAD).

Slicing: After the drawing is completed with the CAD program, the model is sliced and the layers are determined using the interface program of the three-dimensional printer.

Printing and Production: Before printing, printing settings are made using the interface program. For this purpose, adjustments such as the feature of the filament to be printed, printing speed, nozzle temperature, printing chip temperature, raft settings, support material settings placed in the gaps, main product infill pattern and main product infill density are made.

Secondary Post-Printing Operations: When the printed product has a form with gaps, these gaps are filled with additional parts called supports. After the product is printed, these additional - support parts must be separated from the main product. This can have a negative impact on the surface quality and smoothness of the product. Therefore, secondary processes such as sanding may be needed to ensure surface precision and increase surface quality. In 3D printers with dual nozzles, a support filament can be used in addition to the main filament. In this way, the support filament can be easily separated from the main product after printing. However, when water-soluble support filaments are used, the need to remove the support material in the cavities from the main product is eliminated. When the

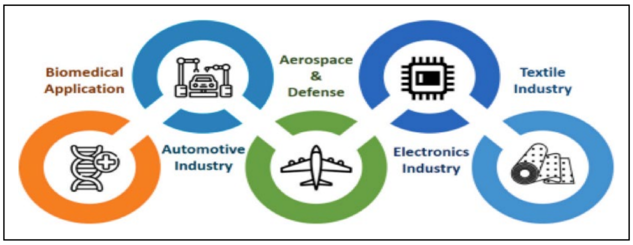

Figure 2. Examples of application areas of polymers shaped by additive manufacturing [9].

product is removed from the printing tray of the 3D printer and placed in water, the support filament melts and the cavity structure is obtained without deteriorating the surface quality of the main product.

Secondary operations are not limited to sanding. Glued assembly can be performed on products that are viewed in multiple parts that cannot be printed individually. This is an application that falls into the class of secondary operations.

As a result of the differentiation of the material structure of the raw material used and the method of operation of the device, the production techniques of 3D printers are separated from each other [5]. Additive manufacturing methods provide designers with greater flexibility and convenience than traditional manufacturing methods, have many advantages, such as low-cost production of complex parts that do not require mass production, which will not be produced in large numbers, fewer assembly requirements, less waste generation, and the ability to update the design and dimensions in the device interface program [5, 6]. Products manufactured by additive manufacturing have lower mechanical strength than the same parts manufactured by traditional

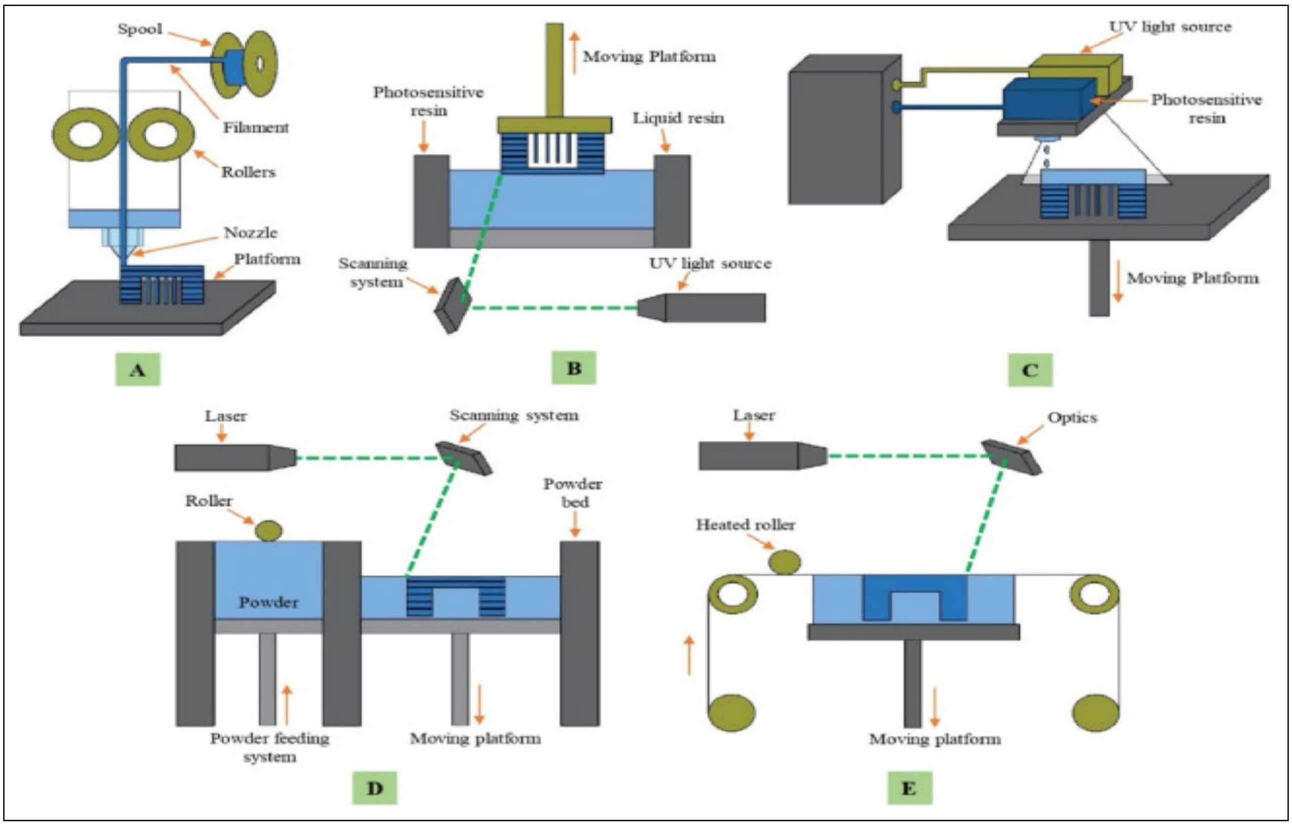

Figure 3. Schematic representation of various additive manufacturing methods **(a)** FFF, **(b)** SLA, **(c)** PolyJet, **(d)** SLS, **(e)** LOM [11].

methods. In addition, ongoing developments in 3D printing technology and filaments used as raw materials for 3D printers allow products to increase their strength and be used in a wider range of applications [6]. Additive manufacturing is widely used in various industries such as energy, automotive, aerospace, construction, machinery, molding, medical, healthcare, design and prototyping (Fig. 2) [7, 8].

The devices used in additive manufacturing have different names in the literature according to the printing techniques. These are methods such as Fused Filament Fabrication (FFF), Selective laser sintering (SLS), Stereolithography (SLA), Sheet Lamination, BinderJet, PolyJet [10]. Figure 3 shows a schematic representation of additive manufacturing methods.

The most well-known method among additive manufacturing methods, which has become so widespread that it can even be used at home, is the FFF technique. Three-dimensional printers, which print with the fused deposited modelling method, are devices that are not limited to manufacturing organizations but also reaching our homes, have a wide range of preferability and widespread use, thanks to their ease of use. In these devices, product printing is carried out by melting the raw material in the form of filaments passing through the heating section called the nozzle and combining the molten filament layer by layer on the table into droplets. The nozzle, which is used to heat the raw material and turn it into a droplet, also moves on the x, y and z axes, allowing the product to be printed on the table in the desired geometry. The raw materials used in this method are polymeric-based filaments. PLA and ABS filaments are the most commonly used raw material types. However, nowadays, as the characteristics of FFF devices have improved, the types of raw materials that they can print have also improved and diversified. The types of raw materials will be discussed in Section 2. In addition to simple, single-nozzle EYM devices with a print volume and raw material area open to the atmosphere, there are also more advanced, double-nozzle EYM devices with a closed print volume, a heated print room, a closed raw material storage area, and protecting the filament from the atmosphere and moisture. In this method, in the printing of parts with gaps, the parts suspended in the air are manufactured by supporting structures. In single-nozzle FFF devices, the support is the layers consisting of the main filament. In dual-nozzle devices, filaments with water melting properties such as high impact polystyrene (HIPS) are used for support. Thus, when the product printing is completed, it is easier to separate the supporting parts from the main part, and the surface smoothness is not disturbed. In addition to supporting material printing, FFF devices with double nozzles can print using two different color filaments on one piece or print two products at the same time. The material to be used as raw material in production with additive manufacturing method has a great influence on both the forming process and the properties of the product [12]. When we look at the most commonly used filament raw material types in the FFF method, we see filament materials such as PLA, ABS, TPU, nylon, HIPS.

Considering the effect of infill density and infil pattern on the mechanical properties of the product, it is obvious that it is necessary to compare various filaments. This comparison will help the designer to design and produce the appropriate filament, appropriate infill density, appropriate infill pattern, appropriate mechanical strength, light weight and economical product. In this context, a systematic evaluation to determine the effects of different filaments on mechanical performance is of great importance for the optimization of products manufactured with the FFF technique. In order to determine the strength of the products, standard size samples are produced and tensile tests are applied. During the tensile test, elastic-plastic deformation behavior is determined by applying axial load to the sample. The transition limit of the elastic and plastic zones reveals the yield strength of the material. Hooke's law ($\sigma = E^* \varepsilon$) is valid within the elastic zone. In the elastic region, since no permanent deformation occurs, when the load applied to the material is removed, the length of the sample returns to its original state. In the plastic region, the yield stress limit is exceeded and permanent deformation occurs. Findings indicating that infill pattern and infill density play a significant role in the durability, flexibility, and overall mechanical properties of the products contribute to research in this field and provide a new perspective for applied engineering practices. Thus, considering the diversity of filaments will enable more comprehensive and effective outcomes in product design processes. In product design and manufacturing processes, material selection is of critical importance in terms of conditions of use and functionality in order to achieve optimum properties. The selection of the appropriate material alone is not enough, because various printing parameters such as infill pattern, infill density, printing temperature, nozzle diameter, table temperature, angle of placement of the product on the table affect the strength of the product manufactured from the material used.

In this study, in order to provide comparison data to the literature, in addition to PLA and ABS filaments, which are widely used in additive manufacturing and FFF techniques, STH, Semiflex and PETG filaments were also used. With these 5 different filaments, tensile samples were produced with 2 different infill patterns and 2 different infill densities. Tensile test results were compared. The results obtained will benefit both designers and manufacturers in choosing appropriate materials, selecting appropriate infill pattern and printing with appropriate infill densities in order to obtain optimum product properties. The proper selection of materials and printing parameters is crucial for designers and manufacturers to produce products with optimal characteristics that exhibit structural and mechanical properties suitable for their intended use. The optimal choice of materials and printing parameters will facilitate the processes for both designers and manufacturers, eliminate uncertainties, and enable the achievement of targeted results.

Raw Material Applications of FFF Printed Products

Today, additive manufacturing technique is used for product printing, beyond prototype production. Preferring additive manufacturing in product printing has gained importance not only in terms of ease of production but also in terms of the features the product will have. The properties of the product such as lightness, flexibility, hardness and brittleness vary depending on the type of filament used, the infill pattern applied during printing, the infill ratio, the placement angle (orientation) on the printing plate, and the device settings such as printing speed and printing temperature. In recent years, various usage areas of products produced by additive manufacturing and the properties of products printed with the most frequently used filament types such as PLA, ABS, TPU, nylon, STH, HIPS have been investigated.

PLA has a thermoplastic polymer structure. PLA, obtained from starch or glucose-based edible sources, is a bioplastic with low toxicity and high biocompatibility. It can be reinforced with other polymers to have different properties. Due to its low melting temperature, it is easy to print products by additive manufacturing method. The low cost of filament has popularized the use of PLA in the FFF method. It is defined as a sustainable and environmentally friendly material due to its recyclability [13, 14]. PLA is a preferred filament material for packaging food, producing biomedical products, producing biodegradable fabrics in the textile industry, printing various kitchen utensils with its biocompatible and biodegradable properties [15–18]. ABS; has hard and brittle structure. Printing with ABS is difficult compared to PLA filament. In addition, the high wear resistance, mechanical strength increases the use of ABS filaments in the production of many industrial products. Polyethylene Terephthalate-glycol modified (PETG); PET used in water bottles, textile fibers, food packages, is not widely used in 3D printers alone as raw material, glycol modified PETG is widely used in 3D printers. PETG is more durable and flexible than PLA. Easier to print than ABS. Due to its high moisture-wicking properties, it exhibits adhesive behavior during printing. STH is a plant-based biopolymer used in the production of various industrial products. Impact resistance, heat resistance and surface quality are high. Like STH, Semi Flex filaments are made of biopolymer and are semi-flexible. Flexible filaments are also called thermoplastic elastomers (TPE) and are soft, flexible and elastic types of filaments. Because of their high flexibility, it is difficult to extrude through FFF, in other words, to press. Thermoplastic polyurethane (TPU) is divided into several subspecies, such as TPC (thermoplastic copolyester). TPU is easier to extrude and is a widely used type of filament. TPC is resistant to chemical types and UV rays. HIPS (High impact polystyrene) is a filament, a mixture of polystyrene and rubber. Soluble in water containing limonene. It is used as backing material in dual extruder printers. It is also ideal for end product, industrial applications, prototypes and mockups due to its high strength, moderate flexibility and low shrinkage tendency. There are also several widely used types of filaments, such as nylon.

Considering the literature studies, PLA filament is generally used in many studies where production is done with the FFF technique [19, 20]. Additionally, studies comparing materials such as PLA and ABS are also seen [21]. However, studies on infill pattern and infill density properties have been limited to a limited number of filament types in the literature. Karakoç and Uzun [22] and Yeşiloğlu [10] investigated the effects of infill pattern and infill density only on PLA filament. Alkhatib et al. [23] compared the effects of filler geometry and filler density on PLA and ABS filaments.

Özmen and Ertek [5] examined the feasibility of personalized production with additive manufacturing, especially in applications such as implants and prostheses, the use of biomaterials, and the use of additive manufacturing in medical product production. They examined the types of materials used for metallic dental implants, ceramic HA/PCL and HA/PEEK orthopedic implants, polymeric stents and prostheses and contributed to the medical field. They predicted that reinforced composite materials will be used more widely in the future for printing products in the medical field with 3D printers. Gonçalves et al. [24], who conducted research on dental protectors, stated that sports mouth guards can be produced faster and more simply with additive manufacturing, which provides advantages for both dentistry and the sports world, instead of traditional production methods. Park et al. [25] conducted a study on the development of fall protection trousers for older women. They have designed a pad with a mesh structure for the hip area of the protective trousers to protect the body by reducing the impact of impact. They printed the protective pad they designed with the FFF technique, using thermoplastic polyurethane (TPU) filament, which is a flexible filament material. Printing flexible and soft TPU filament requires a 3D printer with a dual-gear, direct drive extruder. It was stated that the impact-protected pad developed in the study and produced by the additive manufacturing method was suitable for the body shapes of elderly women and provided ease of daily use. Similarly, Yahaya et al. [26] produced a pad that protects the body from impacts caused by falling using a resin-derived VeroWhite raw material with an SLA type 3D printer. In his study in 2020, Habib examined the energy absorption of thermoplastic honeycomb structures printed using Nylon12 filament with an FFF type 3D printer. It has been demonstrated that honeycomb structures with high energy absorption can be effectively produced with a 3D printer [27].

Narlıoğlu [28] obtained wood-PLA composite filament by adding wood flour to PLA filament. Test samples were printed on FFF type printers using various printing speeds with wood-PLA filament and compared the shrinkage and hardness values depending on the printing speed. They observed that as the printing speed increased, the tensile strength first increased and then decreased. They stated that the mechanical properties of the materials are at optimum values at medium printing speeds.

Özsoy et al. [21] produced tensile and bending samples with PLA and ABS filaments on a 3D printer using the FFF technique and compared the effects of PLA and ABS on the mechanical properties of the product. In their studies, they showed that increasing the infill density increased the mechanical properties of the product and that the mechanical strength of PLA was higher than ABS. In this study, only the occupancy rates of products produced from PLA and ABS filaments were examined. The infill density of other types of filaments and the effects of changing the infill pattern applied during printing have not been examined.

Demir examined the effect of 3D printer parameters on the surface hardness of samples produced with PLA filament. By changing the printer parameters nozzle diameter, nozzle temperature, layer height and mesh angle, samples were produced in 9 different combinations. This study was carried out to determine the most suitable printing parameters for the hardness values of PLA samples to be produced using the fused filament fabrication (FFF) method. According to the results of the hardness tests, it was determined that the most influential variable was the nozzle diameter. It was observed that as the nozzle diameter increased, the surface hardness values of PLA samples also increased. It was found that the effect of mesh angle and nozzle temperature on hardness was low. The highest hardness; it was revealed that it was achieved with the parameters of 210°C nozzle temperature, 0.6mm nozzle diameter, 0.1mm layer thickness and 30° mesh angle [6]. As in Demir's work, Karakoç and Uzun [22] also worked with PLA filaments. Karakoç and Uzun [22] printed tensile samples with the FFF using PLA filament and examined the effects of the infill pattern and the printing direction on the mechanical properties of the samples. In the study, the infill rate was kept constant at 20% and three different infill patterns were applied and straight lines, rotating lines and honeycomb. However, during sample printing, placement angles on the table were chosen in two different ways: horizontal and vertical. In conclusion; they observed that the load resistance of the samples printed by placing them vertically on the table was higher than the samples placed horizontally. Among the horizontally placed samples, it was revealed that the yield strength of the samples printed with straight-line filler geometry was high. However, they determined that the tensile and rupture strengths of the samples printed with the rotational line infill geometry were high. They showed that horizontal samples with straight lines and honeycomb infill pattern had higher elongation rates compared to vertical ones. They found that the filament weight used did not have a direct effect on the mechanical properties of the sample [22].

Aydin et al. [20] printed tensile samples with different writing parameters using PLA filament. Thus, they examined the effects of writing parameters on products produced with PLA filament. According to their findings, they argue that printing processes are more effective at temperatures above 200°C due to low viscosity, the highest hardness value occurs at 220°C at a speed of 70 mm/s, and increasing the printing speed at the same temperature reduces the tensile stress and strength of the material.

Kaygusuz and Özerinç [19] examined the changes in mechanical properties by changing the nozzle temperature and infill density, again using PLA filament. They varied the nozzle temperature between 190–215 °C and the fill density between 10% and 100%. According to their results; they observed that the change in both parameters caused a significant change in the mechanical properties of the sample printed from PLA. It has been stated that as the nozzle temperature increases, the structural voids decrease and the tensile strength increases. It was determined that the yield strength and elasticity modulus decreased by decreasing the infill density. They found that the strength of samples with 20% infill density decreased by half compared to samples with 100% density. However, they stated that low infill density may be preferred in cases where the weight is low and production speed is required to be high, and high infill density may be preferred in cases where ductility and impact resistance are important [19].

Kaya et al. [29] produced samples with 25%, 50%, 75% and 100% infill ratios and triangular - hexagonal infill patterns using PLA filament with the FFF technique. Then, the effects of infill ratio and infill pattern on the mechanical properties of the samples were interpreted by tensile, compression and three-point bending tests. At 25% infill rate, samples produced with triangular infill geometry provided higher specific strength under tensile load than other samples. While samples produced with triangular infill geometry at 50% infill rate showed optimum strength under compressive stress, samples produced with hexagonal infill geometry at 75% infill rate showed optimum strength under three-point bending load. They stated that in both infill patterns, samples produced at 75% infill rate showed better performance than 100% filled samples. As seen in the study by Kaya et al. [29], PLA filaments were evaluated on their own, and the data obtained were not compared with various filaments.

Yeşiloğlu [10] produced samples with 3 different infill patterns and 3 different densities using PLA filament, and examined the mechanical properties of the samples with impact, tensile and compression tests. As a result of the study, it was revealed that the compressive strength of PLA samples decreased as the infill density decreased, the impact strength of the samples with Octet infill pattern was low, the tensile strength was high, and the yield strength in horizontal compression was low.

Taşdelen et al. [30] recycled the residues of PLA and ABS filaments and turned them into filaments again by extrusion method. Thus, their reuse is ensured, contributing to both ecological and economic sustainability. In the study, the products obtained with recycled filament were compared with the products produced with original filament, and the performance of the recycled filament in the 3D printer was evaluated. It has been stated that 3D printed filaments cannot be produced from some thermoplastic materials due to the shrinkage effect that occurs during solidification from the melt, and the strength of products produced from recycled filaments is lower than the products obtained from original filaments.

Özsoy and Kayacan [31] carried out prototyping of a lightweight personalized skull implant using PLA filament using the melt deposition method. According to their results; designing it in personalized shapes and sizes increases the usability of the product. The fact that it is lightweight not only saves material but also increases its preferability due to its low weight. It is expected to be high.

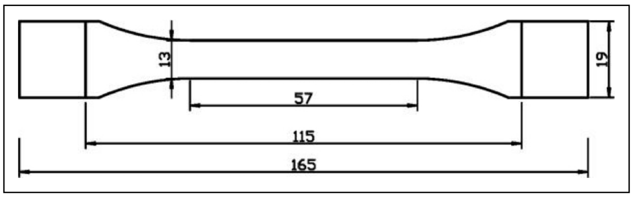

Figure 4. ASTM D638 Type I Tensile Specimen Dimensions [10].

Eryıldız [32] examined the effect of orientation on mechanical strength in products produced using PLA filament with the FFF technique. The effect of orientation was evaluated by printing tensile samples with 5 different placement angles on the table of the 3D printer. According to their results, tensile strength decreased when the printing angle was from 0° to 90°. Samples printed at right angles showed 36% less tensile strength compared to straight ones. He stated that the printing angles of the parts are effective on the tensile strength and printing time.

It can be seen from the literature review that many researches have been carried out on additive manufacturing methods in recent years. Considering the literature studies on filament material comparisons, it has been determined that different infill patterns and different infill densities have been studied and most of these studies have been carried out with PLA filaments. The infill pattern and infill density properties of filaments with different contents have not been examined together and no comprehensive comparison has been made between filament materials. This research article was designed to close the gap in the literature in this field and to provide data to the literature. In this study, samples were produced using filaments with 5 different material contents, 2 different infill patterns and 2 different infill densities, and the mechanical properties of the samples were compared with the tensile test results.

MATERIALS AND METHODS

In this study; the effects of filament properties, infill density and infill patterns on the mechanical properties of the product were observed. In this context, sample design was carried out according to ASTM D638 to determine the tensile behavior of the samples. ASTM-D638 standard; it includes Type I, Type II, Type III, Type IV and Type V samples that can be used for composites, plastics and rigid pipes. In this article, the Type I tensile sample in Figure 4 was used to determine the mechanical properties of the samples. ASTM D638 Type I tensile samples were printed with a Zortrax M200 three-dimensional printer (Fig. 5), which works with the FFF method, has one extruder and has a 0.4 mm diameter nozzle. First, the tensile sample was drawn in the SolidWorks computer-aided design program and saved in .stl format. Then, the .stl file was opened in the Z-Suite interface program and various settings were made such as placement settings on the table of the Zortrax M200 3D printer, assignment of filament material, determination of table temperature and nozzle temperature depending on the material type, selection of infill pattern and infill densi-

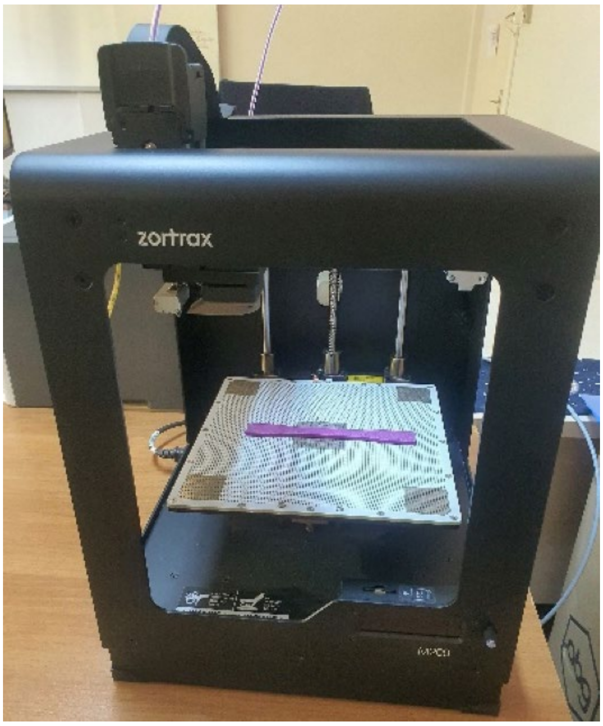

Figure 5. Zortrax M200 FFF type 3D printer.

Figure 6. Shimadzu Ag-Is tensile testing device.

ty, use of raft material on the table. The slicing process of the drawn product was defined in the interface program and a file with the .zcode extension was created. The .zcode file was run on the 3D printer and the product printing was started according to the determined settings.

As materials; five types of filaments with a diameter of 1.75 mm were used: PLA, ABS, STH, PETG and Semiflex. As seen in the literature review, many studies have studied PLA or ABS filaments, and the effects of filler density or filler geometry in these filaments have not been examined. The infill density and infill pattern of the samples produced with PLA and ABS filament have not been compared with each other, nor with other filaments. A gap in this regard was identified in previous studies, and it was decided to use five different filaments in this study in order to provide a source for the literature and to make comparisons with other filaments. Tensile samples were printed at 2 different infill densities, 30% and 60%, and 2 different infill patterns, linear and honeycomb. After the sample printing was completed, a Shimadzu Ag-Is branded 250 kN tensile device (Fig. 6) was used to determine and compare its mechanical properties. During the tests, the pulling speed was applied as 5 mm/minute. Tensile strength was obtained as the "engineering tensile stress" by dividing the maximum force applied during the test by the sample cross-sectional area."Unit elongation" was calculated by dividing the instantaneous length values obtained from the extensometer during the tensile test by the initial length of the sample. The calculated data was used in drawing graphs in the Microsoft Office Excel program. In addition, elasticity modules were calculated under 5MPa tensile value using data comparing samples with 60% infill density and line pattern.

RESULTS AND DISCUSSION

Within the scope of the study, the effects of infill ratios and infill patterns on the tensile strength of products printed with the FFF technique according to the type of filament material were examined. For this purpose, ASTM D638 Type 1 tensile sample was printed on a 3D printer using the FFF technique, using 5 different filament materials. Figure 7 shows photographs of the printing of samples with 30% and 60% infill densities in honeycomb infill pattern on Zortrax M200 branded FFF type 3D printer. Figure 8 shows photographs of the printing of samples with 30% and 60% infill densities in linear infill pattern. 4 different types of tensile samples were produced from 5 different filament types and a total of 60 samples were produced to perform 3 repeated tensile tests. Figure 9 shows labeled photographs of some of the samples after printing and before the tensile test.

Table 1 contains raw data from the Shimadzu Ag-Is tensile device before calculating engineering stresses for each test specimen. The data in question was later processed in the Microsoft Office Excel program. The "engineering tensile stress" was calculated by dividing the maximum force applied during the tensile test by the sample cross-sectional area. The "unit elongation" was calculated by dividing the values obtained from the extensometer by the initial length of the sample. Then, the following curves were drawn in the Microsoft Office Excel program. Then, the tensile curves were drawn in the Microsoft Office Excel program.

Samples with linear infill pattern have a closer, more regular internal structure. Honeycomb structure samples have a hollow geometric structure. Sample weights were measured by precision scales. In addition, sample weights are

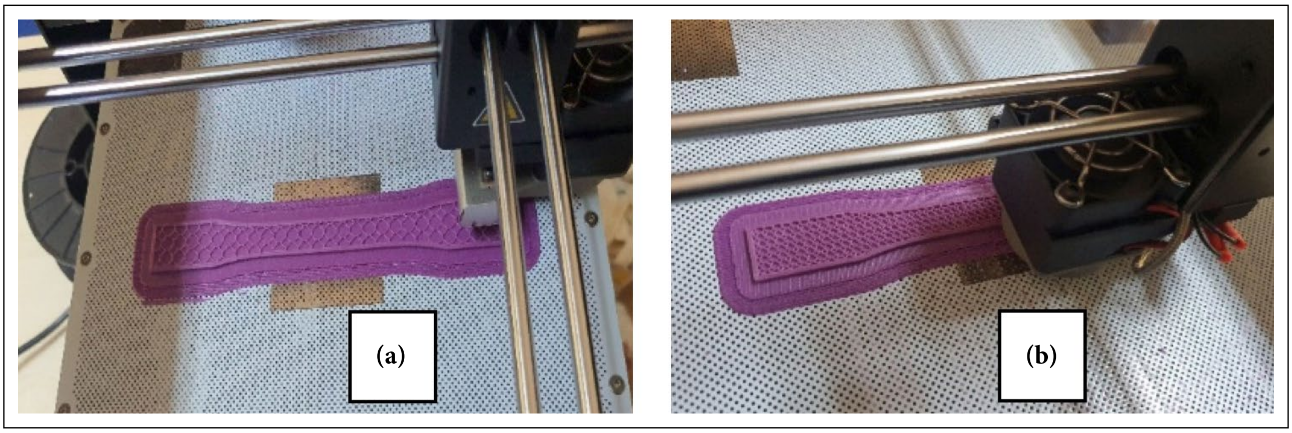

Figure 7. Printing of specimens with honeycomb infill pattern with **(a)** 30 % **(b)** 60 % infill density.

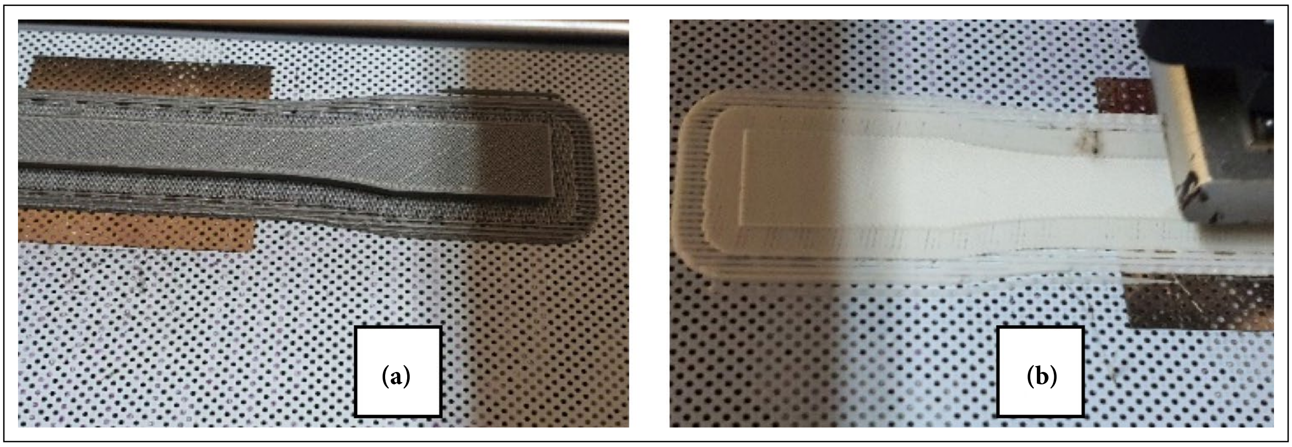

Figure 8. Printing of specimens with linear infill pattern with **(a)** 30 % **(b)** 60 % infill densit.

given on the report page obtained when the printing settings are completed in the Z-Suite interface program. In Table 2, as the infill density increases, an increase of 0.085 grams in PETG, 0.1 grams in STH and Semiflex, 0.2 grams in ABS and 0.5 grams in PLA material was detected in the weight of the honeycomb infill pattern samples. Therefore, it was interpreted that there was no significant change in the weight of the samples with honeycomb infill pattern depending on the infill density. However, in samples with linear pattern, when the infill density increased from 30% to 60%, a weight increase of 0.513 grams was recorded in PETG, 0.588 grams in Semiflex, 0.703 grams in ABS, 1.004 grams in PLA and 1.04 grams in STH. Therefore, it can be said that as the infill density increases in the linear pattern structure, the weight increase is observed more clearly. Depending on the filament materials, printing pattern and printing density, the test results of the tensile samples were plotted by calculating the engineering tensile stresses in the Microsoft Office Excel program and given comparatively below.

As seen in Figure 10, the ABS sample with a 60% infill density and linear infill geometry showed the highest tensile strength and the highest elongation at break compared to other ABS samples. The honeycomb pattern sample with a 60% infill rate ranks second in terms of tensile strength. It is seen that the engineering tensile stress of ABS samples with 30% infill density is lower. According to the interpretations of the graphs in Figure 10; linear infill pattern provides higher strength than the honeycomb structure, however, the decrease in the infill density in ABS filaments also reduced the tensile strength.

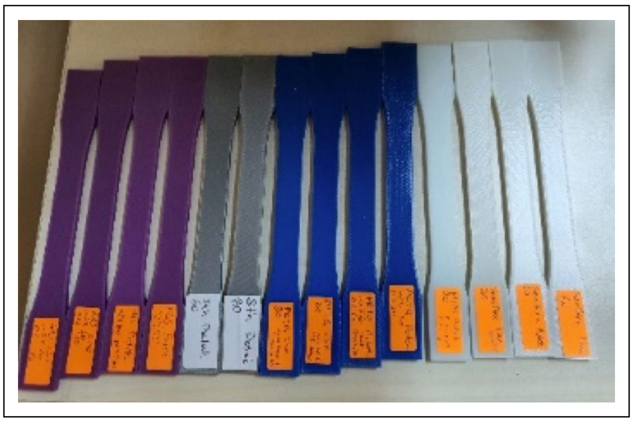

Figure 9. Image of the some printed specimens before tensile test.

When the tensile curves of PLA samples are analyzed, it is seen that samples with a linear infill structure show higher tensile strength compared to the samples with a honeycomb infill structure (Fig. 11). In PLA samples with linear pattern, the tensile strength of the sample with 60% infill

Table 1. Raw data from Shimadzu Ag-Is tensile testing device prior to calculation of engineering stresses

Variable parameters	Filament material	Infill pattern	Infill density (%)	Tensile stress (MPa)	Total elongation at max tension %	Total elongation at breaking stress %
	PLA	Line	30	24.97	2.22	4.27
			60	26.94	2.43	4.5
		Honeycomb	30	23.78	2.16	2.98
			60	23.66	2.08	4.53
	ABS	Line	30	16.14	2.56	7.39
			60	17.47	2.58	7.8
		Honeycomb	30	16.25	2.36	7.67
			60	16.86	2.54	7.18
	Semi flex	Line	30	28.19	2.31	4.59
			60	32.10	2.53	7.84
		Honeycomb	30	20.43	2.29	3.24
			60	29.76	2.11	9.4
	STH	Line	30	19.13	2.31	4.56
			60	21.85	2.1	6.31
		Honeycomb	30	18.87	2.35	4.75
			60	14.1	2.28	4.21
	PETG	Line	30	12.59	2.93	37.56
			60	14.37	3.03	84.62
		Honeycomb	30	20.18	2.99	4.77
			60	13.81	15.22	10.66

PLA: Poly lactic acid; ABS: Acrylonitrile butadiene styrene; STH: Plant based biopolymer; PETG: Polyethylene terephthalate glycol.

Table 2. Weight values of tensile samples

Weight (gr)	Honeycomb pattern, %30 infill density	Honeycomb pattern, %60 infill density	Line pattern, %30 infill density	Line pattern, %60 infill density
PLA	6.989	7.509	6.994	7.998
ABS	6.563	6.792	6.821	7.524
STH	6. 840	6. 948	7.063	8.120
PETG	7.031	7.116	7.267	7.780
Semiflex	7.119	7.246	7.333	7.821

PLA: Poly lactic acid; ABS: Acrylonitrile butadiene styrene; STH: Plant based biopolymer; PETG: Polyethylene terephthalate glycol.

density was higher. When we evaluate the honeycomb patterned PLA samples individually, the tensile strength of the sample with 60% infill density was higher, as in the linear pattern samples. Thus, it is concluded that the infill pattern and infill density behavior of PLA and ABS are similar.

In the PETG samples whose tensile curves are shown in Figure 12, the highest tensile stress value and the lowest elongation at break belong to the honeycomb filled sample with a 30% infill density. The lowest engineering tensile stress is seen in the sample with a linear infill pattern and a 30% infill density. However, the 60% filled sample with a linear infill pattern showed a tensile strength close to the 60% filled sample with a honeycomb infill pattern. Many researchers have stated that PETG has high flexibility due to its chemical composition [33–35]. Supporting the literature data, as seen from the tensile curves, PETG is more ductile than the other 4 types of materials. Since PETG has high flexibility, the amount of elongation before breaking under the applied load in this article is high. It is known that the elongation at break of PETG is approximately 15% higher than PLA [36]. Thus, it is concluded that the flexibility of PETG is higher than the other filaments used in this article and thus its resistance to breakage under impact is also high.

Among the semiflex samples, the sample showing the highest engineering tensile stress is the sample with linear infill pattern and 60% infill density (Fig. 13). This sample is followed by a 30% infill density sample with a line pattern, a 60% infill density sample with a honeycomb pattern, and a 30% infill density sample with a honeycomb pattern. Linear infill pattern has a more dense and closer structure. It is observed that the sample with semiflex honeycomb infill pattern and 60% infill density shows a tensile strength close

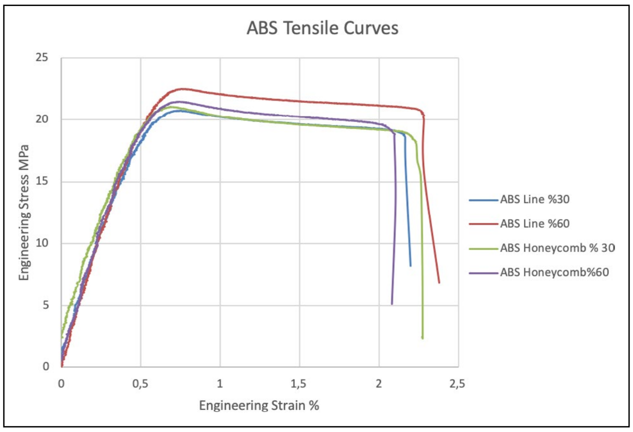

Figure 10. Tensile curves of specimens produced with ABS filament in 2 different infill patterns and 2 different infill densities.

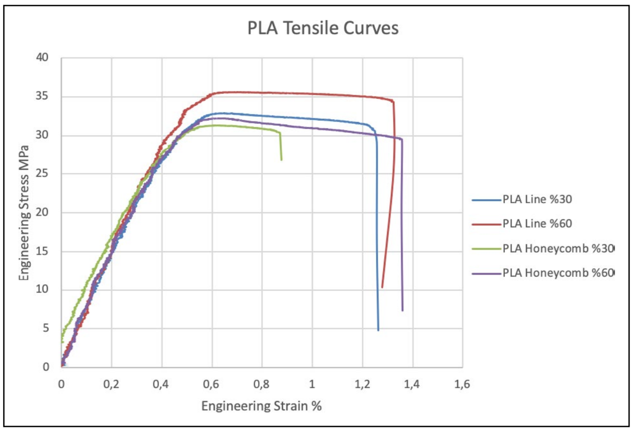

Figure 11. Tensile curves of specimens produced with PLA filament in 2 different infill patterns and 2 different infill densities.

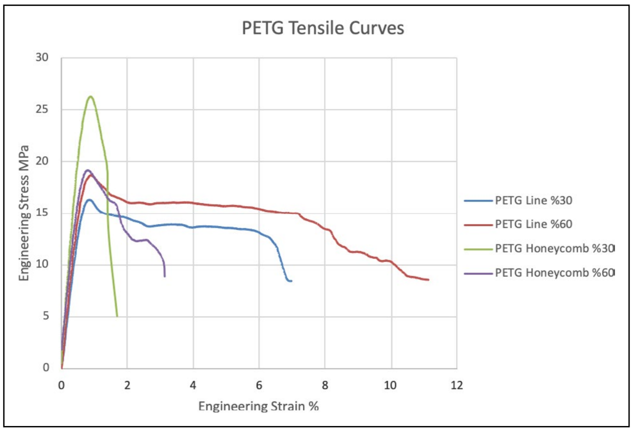

Figure 12. Tensile curves of specimens produced with PETG filament in 2 different infill patterns and 2 different infill densities.

to the sample with linear structure and 30% infill density. As seen in PLA filament, it is seen in Figure 13 that the tensile strengths of the samples with Semiflex honeycomb infill pattern are lower than those with line pattern.

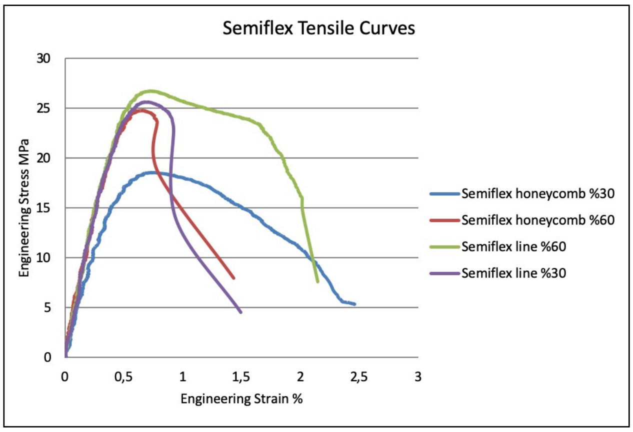

Figure 13. Tensile curves of specimens produced with Semiflex filament in 2 different infill patterns and 2 different infill densities.

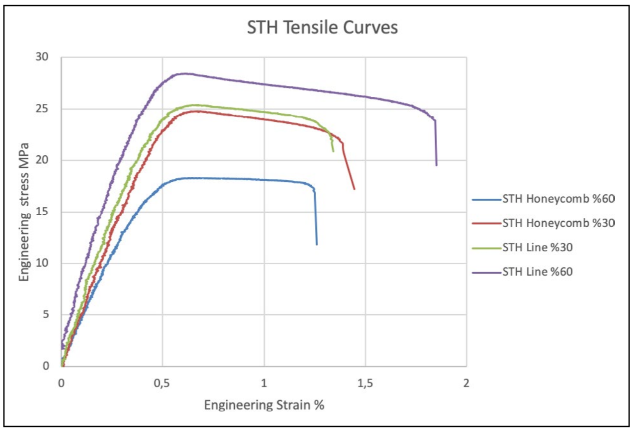

Figure 14. Tensile curves of specimens produced with STH filament in 2 different infill patterns and 2 different infill densities.

Tensile curves of STH samples are shown in Figure 14. The sample with linear infill pattern and 60% infill density is the sample withstanding the highest tensile stress among the STH samples. The sample with a linear pattern and a 30% infill density showed the second highest tensile strength. In honeycomb patterned STH samples, it was observed that the tensile strength of the sample with 60% infill density was lower than the 30% filled sample. As observed in PLA and Semiflex filament, it is seen in Figure 14 that the tensile strengths of the samples with STH honeycomb infill pattern are lower than those with line pattern.

When the results of the tensile tests are examined, the linear infill pattern was determined as the optimum pattern in this study because it showed close or higher tensile strength than the samples with honeycomb infill pattern. Figure 15 shows the comparison of samples with linear infill pattern and 30% infill density. Figure 16 shows the comparison of samples with linear infill pattern and 60% infill density. According to the line pattern comparisons in these figures, PLA with both 30% and 60% infill density showed higher tensile strength than the other samples. In addition, PETG filament showed the lowest tensile strength at both 30% and 60% infill density. According to Figures 15 and 16, it is seen

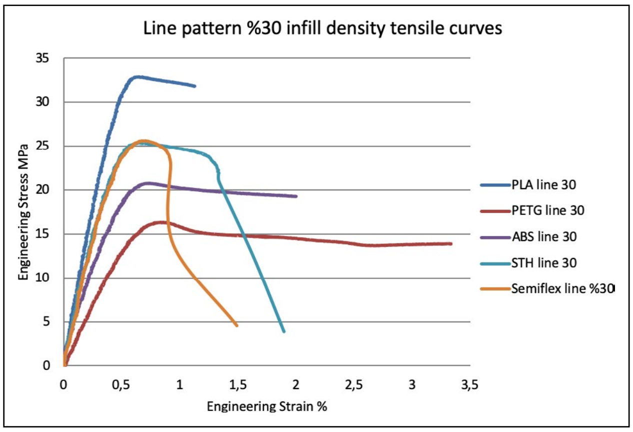

Figure 15. Tensile curves of specimens produced with 5 different filament in line geometry and %30 infill density.

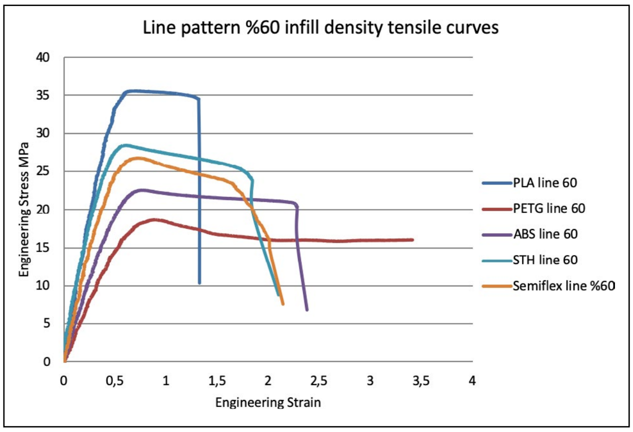

Figure 16. Tensile curves of specimens produced with 5 different filament in line geometry and %60 infill density.

that the tensile strengths increased as the infill density increased from 30% to 60% for all sample types. In addition, it is seen that PETG material is flexible and the amount of creep before rupture is high. According to the comparison of maximum stresses seen in Figures 15 and 16; when the infill density increases from 30% to 60%, the maximum tensile strength increases by 4.6% in Semiflex material, 5.66% in PLA material, 9% in ABS material and 11% in STH material.

Figure 16, where the tensile strengths of samples produced from 5 types of filaments with a line pattern and 60% infill density are compared, was also examined for the purpose of calculating the elasticity modulus. Hooke's law ($\sigma = E * \varepsilon$) is valid in the elastic region up to the yield limit. In Hooke's law, the modulus of elasticity is calculated by dividing the stress value by the unit elognation value. In this study, using the graphical data in Figure 16, the elasticity modulus of PLA, ABS, STH, Semiflex and Petg materials were calculated based on the engineering stress of 5MPa and listed in Table 3. According to the data in Table 3, the highest elastic modulus for a stress value of 5 MPa is shown by the STH material. When looking at Figure 16, it is seen that the slope rates of the curves change as the stress value increases and that PLA is the sample with the highest elastic modulus and that the amount of elongation under load is low.

Kaygusuz and Özerinç [19], printed PLA samples with different infill densities and stated that increasing the infill density increases the mechanical strength of the products. Özsoy et al. [21] compared the effects of PLA and ABS on the mechanical properties of the product. In their studies, they showed that increasing the infill density increased the mechanical properties of the product and that the mechanical strength of PLA was higher than ABS. Similar to the results obtained in the study of both Özsoy et al. [21] and Kaygusuz and Özerin [19], it was revealed in this article that the tensile strength of the sample produced with PLA filament was higher than that of ABS. In addition, except for PETG filament, it has been observed that the tensile strength of the product increases with increasing infill density in samples with the same infill pattern. Similar to the results of the samples produced by Karakoç and Uzun [22] in 2023 using different infill patterns and different placement angles with PLA filament, in this article, it was determined that the infill pattern affected

Table 3. Elasticity modules of filaments according to the Figure 16

Material type	Stress	Strain	Elastisity modulus
STH	5.047	0.051	98.711
PLA	5.021	0.064	77.984
Semiflex	5.067	0.079	63.702
ABS	5.041	0.107	46.697
Petg	5.023	0.153	32.748

PLA: Poly lactic acid; ABS: Acrylonitrile butadiene styrene; STH: Star-triangular honeycomb; PETG: Polyethylene terephthalate glycol.

the tensile strength. Among the 5 types of filaments used in this study, the materials with the most flexible structure are Semiflex and PETG filaments. When the tensile strengths of the samples produced with PETG filament are examined, it is seen that the other 4 types of filaments and the samples with a 30% infill density, show maximum strength.

CONCLUSION

The production of polymeric materials via additive manufacturing is a rapidly expanding topic that has the potential to impact many industries. Due to its customizable, personalizable, sustainable and flexible design and rapid production of complex designs, additive manufacturing has the potential to revolutionize many industries and be an important driving force for innovative approaches.

In numerous manufacturing studies conducted using the FFF method, commonly used materials such as PLA and ABS are typically preferred. However, existing research in the literature has primarily investigated the properties of infill geometry and infill density with a limited variety of filaments. Given the impact of infill density and infill geometry on the mechanical properties of produced products, the necessity for a comparative analysis of various filaments becomes clearly evident. In this study, tensile samples with two different filler densities and two different filler geometries were printed using the FFF technique using PLA, ABS, STH, Semiflex and PETG filaments. By evaluating the data obtained as a result of the tensile test, the following results were reached.

- The change of both infill density and infill pattern caused different behaviors in terms of maximum tensile strength depending on the filament material content.
- Among ABS and PLA materials, which are the most commonly used filament materials in 3D printers today, the sample with a linear infill pattern and a 60% infill density exhibited the highest tensile strength.
- Similar to PLA and ABS, the samples with linear infill pattern and 60% infill density exhibited the highest tensile strength in STH and Semiflex materials.
- The sample with honeycomb infill pattern and 30% infill density exhibited the highest tensile strength in PETG material.
- Considering the tensile test results given in Table 1, it is possible to determine the linear infill pattern as the optimum pattern because it shows close or higher tensile strength than samples with honeycomb infill pattern.
- When the samples with linear infill pattern were compared, when the infill density increased from 30% to 60%, the maximum tensile strength increased by 4.6% in Semiflex material, 5.66% in PLA material, 9% in ABS material and 11% in STH material.
- Material type, infill ratio and infill pattern cause changes in the mechanical properties and lightness of the product. It was observed that there was no significant change in the weight of the samples with honeycomb pattern depending on the infill density. However, in the samples with linear pattern structure, an increase in weight was recorded when the infill density increased from 30% to 60%.
- Correct selection of materials and printing parameters is important for the designer and manufacturer to print products with optimum properties and for the product to exhibit structural and mechanical properties suitable for its intended use. Optimum selection of materials and printing parameters will provide convenience for both the designer and the manufacturer, eliminate uncertainties and ensure target-oriented results. For this reason, in future studies, parameters such as various infill densities, infill pattern, orientation resulting from the placement angle on the table, printing speed, printing temperature, nozzle diameter on various filament materials should be continued to be studied and continue to provide data to the literature.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Use of AI for Writing Assistance

Not declared.

Ethics

There are no ethical issues with the publication of this manuscript.

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