Çukurova Üniversitesi Mühendislik Fakültesi Dergisi
Çukurova University Journal of the Faculty of Engineering
ISSN: 2757-9255 CİLT/VOLUME: 39 SAYI/ISSUE: 3 EYLÜL/SEPTEMBER 2024

Investigation of The Effect of CNC Milling Cutting Process on The Tensile Test of PLA Samples Produced Using Two Different 3D Printers with The FDM Method

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Article Info

Received : 08.05.2024
Accepted : 27.09.2024
DOI: 10.21605/cukurovaumfd.1559927

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Keywords

Additive manufacturing
3D printer
PLA
Filament diameter
CNC milling
Tensile test

How to cite: *KAMER, M.S., UZAY, Ç., (2024). Investigation of The Effect of CNC Milling Cutting Process on The Tensile Test of PLA Samples Produced Using Two Different 3D Printers with The FDM Method. Cukurova University, Journal of the Faculty of Engineering, 39(3), 599-608.*

ABSTRACT

One of the most commonly used materials in additive manufacturing with the fused deposition modeling (FDM) method is polylactic acid (PLA) filaments. In 3-dimensional (3D) printed products, an external wall is also used in addition to the internal structure pattern. The exterior wall pattern differs from the interior structure pattern. The 3D products obtained by this method contain two different pattern structures, which is not desired when determining the mechanical properties. In this study, tensile test specimens were produced with two different 3D printers using 1.75 mm and 2.85 mm diameter PLA filaments. Some tensile test specimens were directly produced in ASTM D638-14 Type 1 dimensions and subjected to tensile testing. The rest of the specimens were produced in a rectangular shape with 19 mm x 165 mm dimensions and the side edges of those specimens, produced in rectangular shape, were cut with CNC milling to bring their dimensions to ASTM D638-14 Type 1. All tensile test specimens were manufactured with a thickness of 4 mm. The test specimens cut with CNC milling after 3D printing were compared with the specimens tested only by 3D printing. The effects of CNC milling cutting on the tensile test properties of specimens produced on two different 3D printers using 1.75 mm and 2.85 mm diameter PLA filaments were investigated. Consequently, it was observed that cutting the side edges with CNC milling eliminated irregularities caused by 3D printing due to the tensile stress in those areas and allowed for more regular and consistent fractures of test specimens. When compared with only the 3D-printed specimens, the elongation at break of the tensile test specimens whose side edges were cut with CNC milling resulted in 13.45% and 33.55% higher using 1.75 mm and 2.85 mm PLA filaments, respectively. It was determined that the toughness of the samples cut by CNC milling was higher than the test samples that were only 3D printed.

EYM Yöntemiyle İki Farklı 3B Yazıcı Kullanılarak Üretilen PLA Numunelerde CNC Freze ile Kesme İşleminin Çekme Testi Üzerindeki Etkisinin İncelenmesi

Makale Bilgileri

Geliş : 08.05.2024
Kabul : 27.09.2024
DOI: 10.21605/cukurovaumfd.1559927

Sorumlu Yazar

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Anahtar Kelimeler

Eklemeli imalat
3B yazıcı
PLA
Filament çapı
CNC freze
Çekme testi

Atıf şekli: *KAMER, M.S., UZAY, Ç., (2024). Investigation of The Effect of CNC Milling Cutting Process on The Tensile Test of PLA Samples Produced Using Two Different 3D Printers with The FDM Method. Cukurova University, Journal of the Faculty of Engineering, 39(3), 599-608.*

ÖZ

Eriyik yığın modelleme (EYM) yöntemi ile eklemeli imalatta en çok kullanılan malzemelerden biri polilaktik asit (PLA) malzemedir. 3-boyutlu (3B) yazdırılan ürünlerde iç yapı deseninin haricinde bir de dış duvar kullanılmaktadır. Dış duvar deseni, iç yapı deseninden farklılıklar göstermektedir. Bu yöntemle üretilen ürünler iki farklı desen yapısı içermekte olup, bu durum 3B yazdırılmış ürünlerin mekanik özelliklerinin belirlenmesinde istenen bir durum değildir. Bu çalışmada, 1,75 mm çapında ve 2,85 mm çapında PLA filamentler kullanılarak iki farklı 3B yazıcıda çekme test numuneleri üretilmiştir. Çekme test numunelerinin bir kısmı ASTM D638-14 Tip1 boyutlarında üretilmiş olup, numunelere çekme testi uygulanmıştır. Çekme test numunelerinin bir kısmı da 19 mm x 165 mm boyutlarında dikdörtgen şeklide üretilmiştir. dikdörtgen şeklinde üretilen numunelerin yan kenarları CNC freze ile kesilerek numuneler ASTM D638-14 Tip1 boyutlarına getirilmiştir. Çekme test numunelerinin tamamının kalınlığı 4 mm olacak şekilde üretimler gerçekleştirilmiştir. 3B yazdırıldıktan sonra CNC freze ile kesilen test numuneleri, sadece 3B yazdırılarak test edilen numunelerle karşılaştırılmıştır. CNC freze ile kesme işleminin, 1,75 mm çapında ve 2,85 mm çapında PLA filamentler kullanılarak iki farklı 3B yazıcıda üretilen numunelerin çekme testi özellikleri üzerindeki etkileri araştırılmıştır. Çalışma sonucunda, 3B yazdırılmış çekme test numunelerinin çekmeye maruz kalan yan kenararının CNC freze ile kesilmesi sonucunda, bu bölgelerde 3B yazdırmadan kaynaklanan düzensizliklerin ortadan kaldırıldığı, test numunelerinde daha düzenli ve tutarlı kopmaların gerçekleştiği tespit edilmiştir. 1,75 mm PLA filament kullanılarak üretilen ve yan kenarları CNC freze ile kesilen çekme test numunesinin kopma uzamasında, 3D-printed çekme test numunesinin kopma uzamasına kıyasla %13,45 artış olduğu belirlenmiştir. 2,85 mm PLA filament kullanılarak üretilen ve yan kenarları CNC freze ile kesilen çekme test numunesinin kopma uzamasında, 3D-printed çekme test numunesinin kopma uzamasına kıyasla %33,55 artış olduğu belirlenmiştir. CNC freze ile kesilen numunelerin tokluğunun 3D-printed test numunelerine göre daha yüksek olduğu belirlenmiştir.

1. INTRODUCTION

Today, additive manufacturing is widely used with one of the most commonly applied 3D production methods being Fused Deposition Modeling (FDM). FDM involves layer-by-layer production in additive manufacturing. Determining the mechanical properties of products produced with this method is important for assessing their suitability for various applications. In FDM additive manufacturing, products typically have both an infill pattern and an outer wall pattern. Therefore, test specimens, produced to determine the mechanical properties of the materials manufactured with this method, naturally exhibit two different infill pattern structures. This makes it difficult to determine the actual mechanical properties of the produced materials. Various methods (such as producing without outer walls, production by cutting specimens from a 3D produced sheet, etc.) are applied to eliminate this issue, with the most common being the production of test specimen dimensions slightly larger and then cutting these parts using various methods [1-4]. This eliminates the infill pattern differences in the outer walls of the produced product, ensuring that only a single infill pattern remains in the test region of the specimen. One of the most commonly used materials in additive manufacturing with the FDM method is PLA material. Two different diameters of PLA filaments, 1.75 mm, and 2.85 mm, are used in 3D printers. The filament diameter is determined depending on the 3D printer. Just as there may be differences in the mechanical properties of PLA filaments of these two different diameters, there may also be differences in the mechanical properties of 3D printed products using these filaments. Many studies have been conducted in the literature to determine the mechanical properties of 3D-printed PLA materials, some of which are introduced below.

Tunçel and Tutar [5] examined the effects of different edge widths on the compressive strength of face-centered cubic structured specimens produced using PLA material with the FDM method. They determined that increasing the edge width also increased the compressive strength. Demirci et al. [6] investigated the effects of nozzle diameter and layer thickness parameters on the mechanical behavior of 3D-printed PLA lattice structures under quasi-static loading. They found that a combination of small nozzle diameter and high layer thickness led to a decrease in compressive strength in both types of lattice structures. Şahin et al. [7] exposed tensile test specimens produced using PLA material on a 3D printer and the PLA filaments used in production to 80% relative humidity for different durations. They investigated the changes in mechanical properties as a result of the test specimens being exposed to a humid environment. Their study revealed that the tensile strengths of filament and tensile test specimens exposed to a humid environment decreased by 6.8% on the twentieth day. Bolat and Ergene [8] investigated the dimensional accuracy of tensile test specimens produced using PLA, PET-G, and ABS materials with different layer heights with a 3D printer. They determined that the most accurate dimensional measurement results for length and height were obtained from PET-G test specimens, while the most accurate dimensional measurement results for width were obtained from PLA test specimens.

The authors have previously experimentally investigated various aspects of additive manufacturing and material properties. They examined the mechanical properties of tensile test specimens produced with ABS and PLA materials using different table and nozzle temperatures [1], the mechanical properties of bending test specimens produced with different printing parameters on a 3D printer [2], the mechanical properties of tensile test specimens produced with ABS and PLA materials in different colors and infill patterns [3], the creep behavior of PLA test specimens produced with different printing parameters using the FDM [9], the mechanical properties of tensile test specimens produced with ABS and PLA materials at different printing speeds on a 3D printer [10,11], the tensile and shear strengths of bolts created by threading the polymer shafts produced with PLA material at different printing orientations using a 3D printer [12], the bending strengths of honeycomb sandwich structures with different cell diameters produced using a 3D printer [13], and the mechanical properties of tensile test specimens produced with PLA filaments of different diameters on a 3D printer [14].

In this study, tensile test specimens were produced using PLA filaments with diameters of 1.75 mm and 2.85 mm on two different 3D printers. Some of the tensile test specimens were directly produced in ASTM D638-14 [15] Type 1 dimensions and subjected to tensile testing. The rest of the test specimens were produced in rectangular shapes with 19 mm x 165 mm dimensions, and then the side edges of the specimens produced in rectangular shapes were cut using CNC milling to size them into ASTM D638-14 Type 1 dimensions. All tensile test specimens were produced to have a thickness of 4 mm. Tensile test specimens that were 3D printed and then cut with CNC milling to obtain specified dimensions were compared with the specimens that were tested after being solely 3D printed. The effects of the CNC milling process on the tensile test properties of specimens, produced with two different 3D printers using 1.75 mm and 2.85 mm diameter PLA filaments, were investigated.

2. MATERIAL AND METHOD

Table 1. The 3D printing parameters for manufacturing test specimens

Nozzle temperature	208°C
Bed temperature	60°C
Printing speed	70 mm/s
Travel speed	150 mm/s
Nozzle diameter	0.4 mm
Layer thickness	0.2 mm
Wall thickness	0.4 mm
Wall number	1
Infill density	%100
Infill pattern	Zig Zag
Applied standard	ASTM D638-14 Type-1 – 4mm thickness

In this study, tensile test specimens were produced using PLA filaments with diameters of 1.75 mm (Raise3D Premium PLA Blue [16]) and 2.85 mm (Ultimaker PLA Pearl White [17]) on two different 3D printers (Zaxe Z1 Plus 3D printer [18] and Ultimaker S5 3D printer [19]). Test specimens were produced using Raise3D Premium PLA Blue filament with a diameter of 1.75 mm on the Zaxe Z1 Plus 3D printer. On the Ultimaker S5 3D printer, test specimens were produced using Ultimaker PLA Pearl White filament with a diameter of 2.85 mm. The parameters given in Table 1 were used for 3D printing of the tensile test specimens on both printers.

Six tensile test specimens, based on ASTM D638-14 Type-1 dimensions, each having a thickness of 4 mm were produced using 1.75 mm and 2.85 mm diameter PLA filaments, respectively (Figures 1a and 1c). Additionally, six rectangular specimens of 19 mm x 165 mm in size and 4 mm in thickness were produced using PLA filaments of two different diameters (Figures 1b and 1d). The images of all produced specimens after 3D printing are shown in Figure 1.

(a) Raise3D PLA dog-bone samples (c) Ultimaker PLA dog-bone samples

(b) Raise3D PLA rectangular samples (d) Ultimaker PLA rectangular samples

Figure 1. 3D-printed test samples

A two-stage cutting process was performed with a CNC milling machine to size the rectangular specimens into ASTM D638-14 Type-1 dimensions in the form of a dog-bone shape. The cutting with CNC milling operations were performed in two stages. In the first stage, one side of the rectangular specimen was cut. Then it was turned to cut the other side. At this stage, the test specimen was brought to ASTM D638-14 Type-1 dimensions. The images, illustrating the CNC milling stages of the rectangular specimens, are shown in Figure 2. A 6 mm diameter, 4-flute, flat-end mill cutter was used in CNC milling operations. Initially, a rough cutting operation was applied with a depth of 0.8 mm and a lateral feed of 0.9 mm to leave a 0.30 mm finishing allowance. Then, two passes of finish cutting with a lateral feed of 0.15 mm were conducted with cutting depths are to be equal to the material thickness, followed by one final pass of idle cutting without lateral feed. First, the cutting was performed on one edge of the specimen (Figures 2b and 2e) which was placed on the CNC milling machine (Figures 2a and 2d). Then, the test specimen was rotated 180° along the vertical axis and placed on the CNC milling machine, and cutting was performed on the other edge of the test specimen (Figures 2c and 2f). In all CNC milling operations, a spindle speed of 3500 rpm, a cutting axis speed of 500 mm/min, an idle axis speed of 1500 mm/min, and a conventional cutting direction were used. A Hattech 3-axis CNC milling machine was used for milling the side edges of the test specimens. No cooling system was used in CNC milling cutting processes and dry milling was done. In order to prevent the chips formed during cutting with the CNC milling machine from sticking to the workpiece or tool, the chips were removed by air blasting once in each round-trip period.

Figure 2. Converting rectangular samples into dog-bone shape with CNC milling

Tensile test specimens produced in two different ways (3D-printed samples and milled samples) using 1.75 mm and 2.85 mm diameter PLA filaments were measured for their dimensions, masses, hardness, and surface roughness values, and all specimens were subjected to tensile testing. Additionally, four pieces of 165 mm long filaments, prepared individually from 1.75 mm and 2.85 mm diameter PLA filaments, respectively, were subjected to the tensile tests. A digital caliper with a precision of 0.01 mm was used to measure the dimensions of the test specimens. KERN PLS 6200-2A precision balance with 0.01g sensitivity was used to measure the masses of the test specimens. The hardness values of the test specimens were measured using an MITECH MH210 portable hardness tester. Hardness measurements were performed on the bottom surfaces of the test specimens using a Shore D probe, and average values were determined by taking measurements from five different regions of each specimen. Surface roughness values of the test specimens were measured using a JENOPTIK Hommel-Etamic W5 surface roughness measurement device with parameters set at a measurement length of 4.8 mm, measurement speed of 0.5 mm/s, and wavelength of 0.8 mm. Surface roughness measurements were performed parallel to the tensile direction on the top surfaces of the test specimens, and average values were determined by taking measurements from three different regions of each specimen. Tensile tests were conducted using a Zwick/Roell Z100 tensile testing machine, equipped with a long-stroke extensometer mounted on the machine frame. Tensile tests were performed at a speed of 5 mm/min, with an extensometer gauge length set to 50 mm. The sample codes and production parameters for the test specimens in all tested parameters are provided in Table 2. The test specimens will be referenced by these codes in the paper henceforth.

Table 2. Sample codes of test specimens and production parameters

Sample code	Production method	Production parameters		
		Filament	3D printer	CNC milling machine
R-F.1~4	Filament	1.75 mm Raise3D Premium PLA Blue	-	-
R-5.1~6	3D-printed		Zaxe Z1 Plus 3D printer	-
R-CNC-1.1~6	Milled			Hattech 3-Axis CNC Milling Machine
U-F.1~4	Filament	2.85 mm Ultimaker PLA Pearl White	-	-
U-6.1~6	3D-printed		Ultimaker S5 3D printer	-
U-CNC-3.1~6	Milled			Hattech 3-Axis CNC Milling Machine

3. RESULTS AND DISCUSSION

Spider graphs generated from measurements of all tensile test specimens produced using two different diameters of PLA filament (1.75 mm, 2.85 mm) and two different methods (3D-printed, Milled) are shown in Figure 3. When the figure is examined, it can be seen that the measurement data of the test specimens for each parameter are very close to each other within each graph.

The average values of tensile test specimens' measurements, taken from four different production types, were used to create the spider graph, as shown in Figure 4. When the graph is examined, it can be revealed that the highest dimensional values are generally found in the U-6 3D-printed test specimens, the highest mass values are in the R-5 3D-printed test specimens, the highest hardness values are in the R-CNC-1 Milled test specimens, and the lowest arithmetic mean surface roughness values are in the U-CNC-3 Milled test specimens.

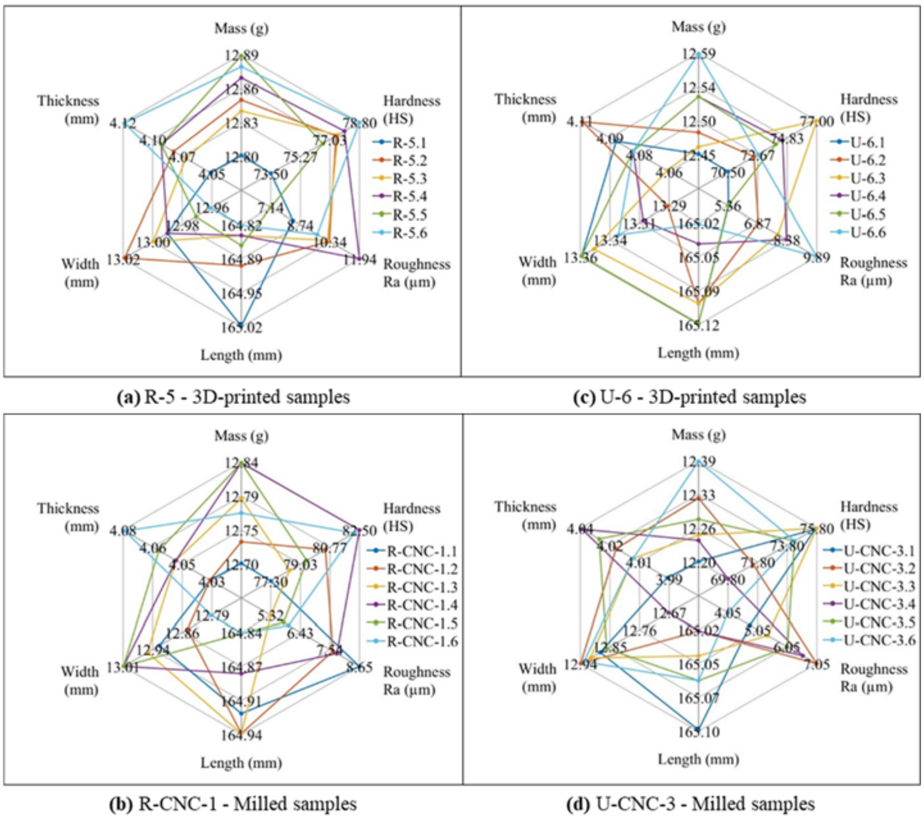

Figure 3. Spider graphs created with data obtained from measurements

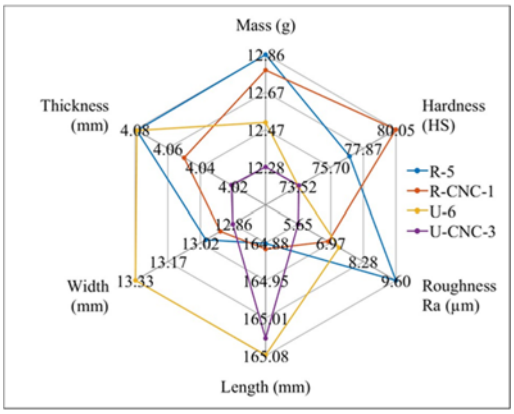

Figure 4. Spider graph created with average values of parameters

The failures of the tensile test samples for all parameters are shown in Figure 5. Since an error was observed during the tensile test of the R-CNC-1.1 Milled test specimen, the results of this test specimen are not included in the paper. In some of the R-5 3D-printed tensile test specimens (Figure 5a), fractures occurred from the neck region during the tensile test (R-5.1, R-5.4). However, such a situation was not encountered in the R-CNC-1 Milled tensile test specimens, whose side edges were cut with a CNC milling machine (Figure 5b), and the fractures were generally observed in the middle regions of the test specimens. Similar to the failures of R-5 3D-printed and R-CNC-1 Milled tensile test specimens, respectively, in some of the U-6 3D-printed tensile test specimens (Figure 5c), the fractures occurred in the neck region during the tensile test (U-6.1, U-6.3). However, such occurrences were not observed in the U-CNC-3 Milled tensile test specimens, whose side edges were cut with CNC milling (Figure 5d), and the fractures were observed in the middle regions of all test specimens. It was found that cutting the side edges of the specimens with CNC milling operations eliminated the irregularities, where those regions were exposed to tensile forces, caused by 3D printing, and resulted in more regular and consistent fractures in the test specimens.

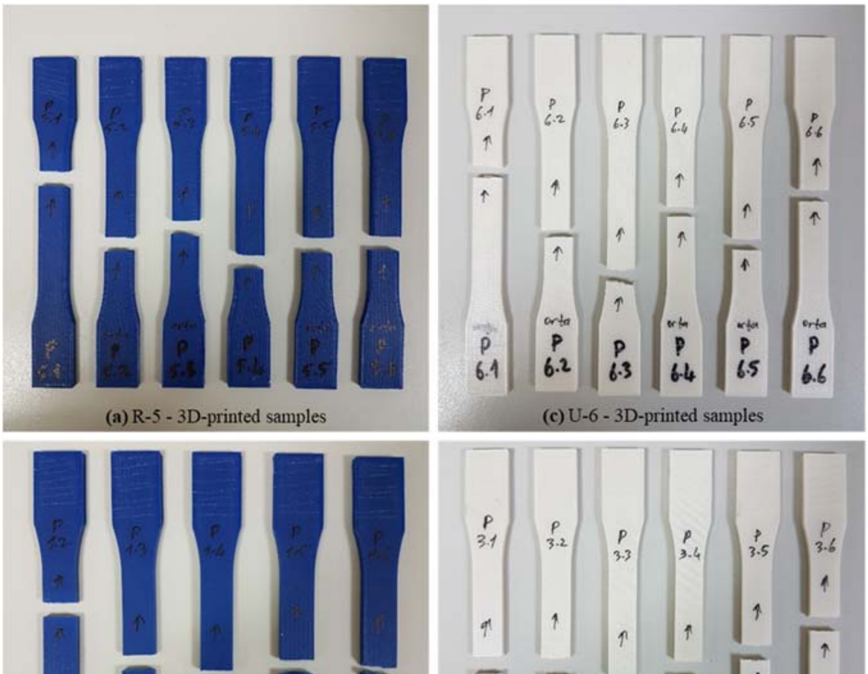

Figure 5. Images of broken samples

Stress-strain curves obtained from all tensile tests are shown in Figure 6. It is observed that the stress-strain curves of R-F 1.75 mm PLA filament (Figure 6a) and U-F 2.85 mm PLA filament (Figure 6d) are generally very close to each other. Although the tensile strengths of the tensile test curves of the R-5 3D-printed test specimens (Figure 6b) and the U-6 3D-printed test specimens (Figure 6e) are close to each other, it is seen that there are irregularities in their elongation at break values. It has been determined that the stress-strain curves of R-CNC-1 milled test specimens (Figure 6c) and U-CNC-3 milled test specimens (Figure 6f) exhibit much closer and more consistent results among themselves.

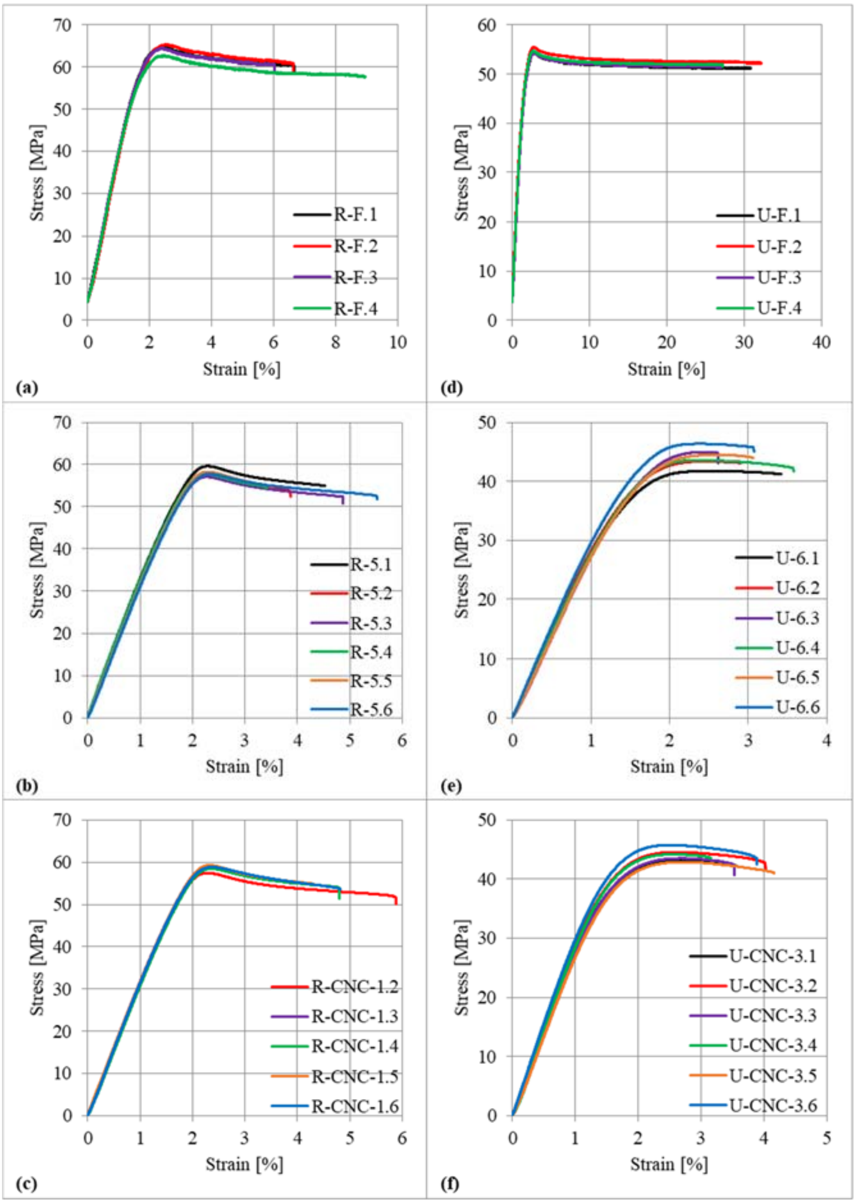

Figure 6. Tensile test stress-strain graphs
(a) R-F 1.75 mm filament, **(b)** R-5 3D-printed specimens, **(c)** R-CNC-1 milled specimens,
(d) U-F 2.85 mm filament, **(e)** U-6 3D-printed specimens, **(f)** U-CNC-3 milled specimens

Figure 7 was created by selecting a curve that can be represented as an average from each parameter shown in Figure 6. It was determined that the tensile strength of the R-5.2 3D-printed tensile test specimen is 11.3% lower than that of the R-F.2 1.75 mm filament (Figure 7a). Similarly, it was determined that the tensile strength of the U-6.5 3D-printed tensile test specimen is 17.8% lower than that of the U-F4 2.85 mm filament (Figure 7a). Since voids are formed within the specimens produced during 3D printing, it can be concluded that 3D-printed tensile test specimens have a porous structure. Therefore, it is expected that the tensile strength values of 3D-printed tensile test specimens can be lower than the tensile strength of the filaments used in 3D printing. It was determined that the elongation at break value of the R-5.2 3D-printed tensile test specimen is 36.5% lower than that of the R-F.2 filament (Figure 7a). Similarly, the elongation at break value of the U-6.5 3D-printed tensile test specimen is 89.4% lower than that of the U-F4 filament (Figure 7a). Based on these results, it can be inferred that there is a significant decrease in the toughness of 3D-printed products compared to the filaments used in 3D printing. Similar results were also encountered in the literature [7].

When Figure 7b is examined, it can be seen that there is almost no change in the tensile strength as a result of cutting the side edges of the 3D-printed test specimens with a CNC milling machine. However, there was a 13.45% increase in the elongation at break value of the R-CNC-1.4 milled tensile test specimens, whose side edges were cut with a CNC milling machine, compared to that of R-5.2 3D-printed tensile test specimens. Similarly, it was determined that there was a 33.55% increase in the elongation at break value of the U-CNC-3.2 milled tensile test specimens, whose side edges were cut with a CNC milling machine, compared to that of the U-6.5 3D-printed tensile test specimens. As a result, it can be concluded that cutting the side edges of the 3D-printed test specimens with CNC milling reduces the possible notching effects that may occur during 3D printing, and reveals the stress-strain curves that the test specimens should exhibit.

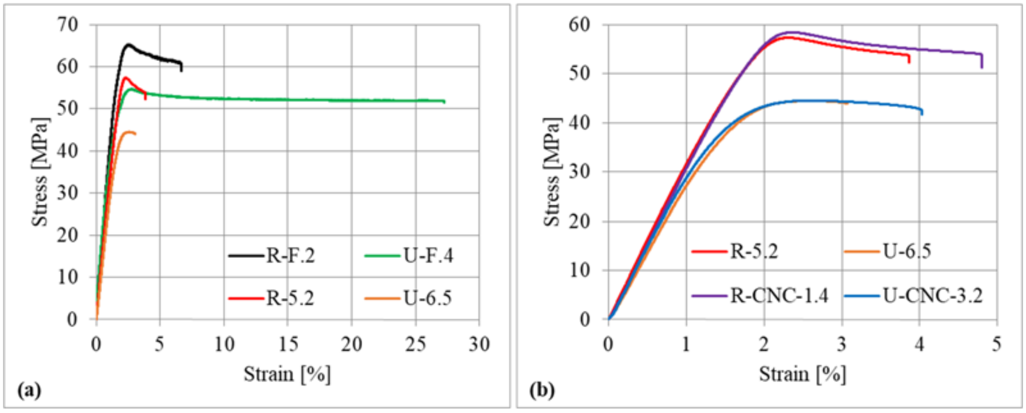

Figure 7. Comparison graph **(a)** filament vs 3D-printed, **(b)** 3D-printed vs milled

Figure 8 presents the comparison of the average tensile strength and elongation at break values for samples using 1.75 mm and 2.85 mm PLA filaments. When Figure 8a is examined, it is determined that the tensile strengths of the specimens using 2.85 mm filament are consistently lower than those using 1.75 mm filament in all cases (filament, 3D-printed, milled). It is determined that the tensile strength of the 1.75 mm filament is approximately 19% higher than the tensile strength of the 2.85 mm filament. The elongation at break value of the 2.85 mm filament is approximately 4.39 times higher than that of the 1.75 mm filament as seen in Figure 8b. Contrarily, in other cases (3D-printed, milled), it is found that the elongation at break value of the samples using 2.85 mm filament is slightly lower than that of the samples using 1.75 mm filament.

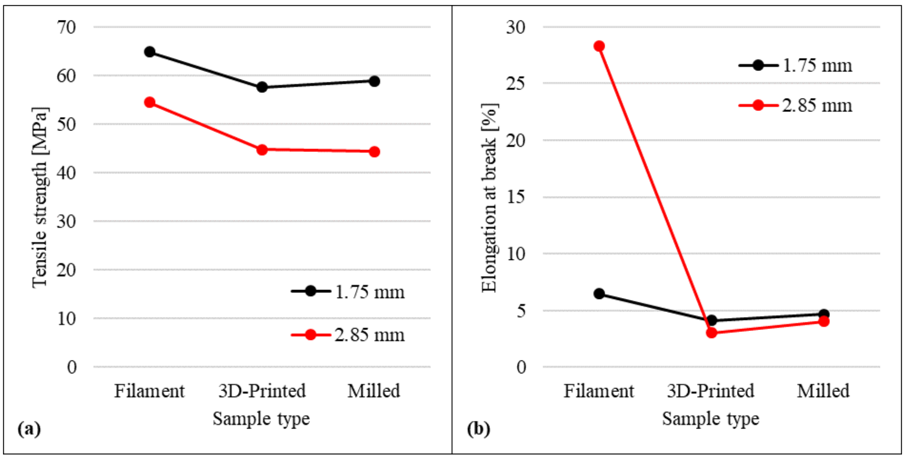

Figure 8. Variation of **(a)** tensile strength and **(b)** elongation at break according to sample type

4. CONCLUSIONS

In this study, tensile test specimens were produced on two different 3D printers using 1.75 mm and 2.85 mm diameter PLA filaments. Some of the tensile test specimens were directly produced according to ASTM D638-14 Type 1 dimensions and subjected to tensile testing. The remaining specimens were produced in a rectangular shape with 19 mm x 165 mm dimensions. The side edges of the specimens, produced in a rectangular shape, were cut using CNC milling to bring the specimens into ASTM D638-14 Type 1 dimensions. All tensile test specimens were manufactured with a thickness of 4 mm. The results of test specimens cut by CNC milling after 3D printing were compared to those produced by only 3D printing. The results obtained from the study are listed below.

- Cutting the side edges of the 3D printed tensile test specimens, which were exposed to tension, with a CNC milling machine eliminated the irregularities caused by 3D printing in those areas, leading to obtaining more uniform and consistent fractures in the test specimens.
- Tensile strength and elongation at break values of the 3D-printed tensile test specimens were lower than those of the filaments used in 3D printing. Accordingly, a significant decrease in the toughness of the 3D-printed products compared to the filaments, used in 3D printing, was observed.
- There was almost no change in the tensile strength of the 3D-printed test specimens as a result of cutting the side edges with CNC milling.
- A 13.45% increase was obtained in the elongation at break value of the R-CNC-1.4 milled tensile test specimen, produced using 1.75 mm PLA filament and with side edges cut by CNC milling, compared to that of the R-5.2 3D-printed tensile test specimen.
- A 33.55% increase was obtained in the elongation at break value of the U-CNC-3.2 milled tensile test specimen, produced using 2.85 mm PLA filament and with side edges cut by CNC milling, compared to that of the U-6.5 3D-printed tensile test specimen.
- Cutting the side edges of 3D printed test samples with a CNC milling machine, the notch effects that could occur in 3D printing were reduced, and the stress-strain curves expected for the test specimens were revealed.
- Tensile strengths of the specimens using 2.85 mm filament were consistently lower than those using 1.75 mm filament in all cases (filament, 3D-printed, milled).
- Elongation at break values of 2.85 mm diameter filament was significantly higher than that of 1.75 mm diameter filament. Conversely, in other cases (3D-printed, milled), it was observed that the elongation at break values of the test specimens using 2.85 mm filament was slightly lower than that of the specimens using 1.75 mm filament.

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