Research Article

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Effect of Dimensional Differences on Tensile Strength in Tensile Test Specimens

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ABSTRACT

Tensile testing is one of the most common mechanical tests performed to understand the properties of materials. Tensile testing is performed to determine elastic and plastic material properties under static load. This method provides helpful information for designers and manufacturers to develop new materials. In tensile tests used for various conditions, there are tensile test specimens of different sizes and shapes. However, in recent years, there has been an increased interest in miniaturized tensile specimens and micro-tensile testing applications instead of standard tensile testing and standard tensile specimens used to determine the mechanical properties of materials. Due to the reduction of test specimen sizes, it is possible to reduce the amount of material, production cost and the time taken for specimen preparation. When the literature is reviewed, it is observed that the downsizing of test specimen dimensions is mostly performed for metal parts. However, in tests conducted to examine the mechanical properties of plastic parts produced by additive manufacturing methods, the amount of material used, and consequently the resulting waste, is also high. In this study, miniature and standard tensile test specimens were produced using additive manufacturing methods (Fused Deposition Modeling and Stereolithography). A mini tensile mold was designed and fabricated for mini tensile tests. The results showed that mini tensile test specimens can be used instead of standard tensile test specimens.

Çekme Testi Numunelerinde Boyutsal Farklılıkların Çekme Dayanımına Etkisi

ÖZ

Malzemelerin özelliklerini anlamak üzere yapılan en yaygın mekanik testlerden biri çekme testidir. Çekme testi; statik yük altındaki elastik ve plastik malzeme davranışlarını belirlemek amacıyla gerçekleştirilir. Tasarımcıların ve üreticilerin yeni malzemeler geliştirmesinde yardımcı bilgi sağlar. Çeşitli şartlar için kullanılan çekme testlerinde, farklı boyut ve şekillerde çekme test numuneleri bulunmaktadır. Bununla birlikte, son yıllarda malzemelerin mekanik özelliklerini belirlemek için kullanılan standart çekme testi ve standart çekme numuneleri yerine minyatür boyutta çekme numunelerine ve mikro çekme testi uygulamalarına ilgi artmıştır. Test numune boyutlarının küçültülmesi sayesinde malzeme miktarını, süreyi ve üretim maliyetini azaltmak mümkündür. Literatür incelendiğinde çoğunlukla metal parçalar için test numune boyutlarını küçültme işleminin gerçekleştirildiği görülmektedir. Bununla birlikte, eklemeli imalat yöntemleriyle üretilen plastik parçaların mekanik özelliklerini incelemek için yapılan testlerde de kullanılan malzeme ve dolayısıyla ortaya çıkan atık miktarı yüksektir. Bu amaçla yapılan çalışmada, eklemeli imalat yöntemleri (Eriyik Yığma Modelleme ve Stereolitografi) kullanılarak minyatür ve standart çekme test numuneleri üretilmiştir. Mini çekme testleri için bir mini çekme kalıbı tasarlanmış ve imal edilmiştir. Sonuçlar, standart çekme test numuneleri yerine mini çekme test numunelerinin kullanılabilir olduğunu göstermiştir.

Anahtar Kelimeler: Standart çekme testi, Minyatür çekme testi, Eriyik yığma modelleme, Stereolitografi, Mekanik özellikler

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1. Introduction

Engineering projects are costly technological works that are often undertaken to solve problems involving people and the environment. If engineering works fail, the negative impact of the consequences will be much greater than the failure of a system used for simple needs in everyday life. For this reason, it is very important to have clear and accurate information about the strength of the materials used in such works. Some mechanical tests are performed to determine the strength of materials and learn their properties. These tests vary widely depending on the load on the material, including tensile, compression, hardness, bending, torsion, notch impact, fatigue and creep tests. One important criterion in these tests is that the test specimen should accurately represent the original material. Additionally, ensuring that the material or part to be tested is subjected to similar conditions as those it will face in its actual use will also increase the reliability of the test results. One of the most basic tests widely used in engineering is the tensile test. Tensile testing is a practical test used to understand the mechanical properties of different material groups such as metals, ceramics, polymers or composites. The tensile testing machine consists of two jaws that can move up and down relative to each other. One of the jaws is moved at a constant speed and a variable amount of tensile force is applied to the test piece and the elongation corresponding to this force is recorded. During the tensile process, the test material is subjected to force in one axis. The tensile test ends when the material is ruptured and fractured.

Tensile testing is a destructive test and therefore it is not possible to use the specimens for any other purpose after the test. The specimens that break or rupture at the end of the tensile test are not reusable. To reduce the amount of material required for this test and to save the time spent in preparing tensile test specimens, the idea of reducing the specimen size has emerged [1]. Non-standard tensile test specimens, called small, mini or miniature, have attracted the attention of researchers because they offer the opportunity for the development of new materials (allowing the production of small quantities of materials in a laboratory environment) and have advantages such as the use of small volumes of material. Mini-tensile testing has been used for localized determination of material properties [2, 3] and as an evaluation tool to validate the results of finite element models [4]. Furthermore, when tensile testing of radioactively irradiated material is required, it has become almost mandatory to use small or miniaturized specimens instead of using conventional tensile specimens [5, 6]. Whereas the first standard for conventional tensile testing and tensile test specimens was published in 1904 [7], there is yet no standard for miniature tensile testing and specimens. Nevertheless, the fabrication of miniature tensile test specimens, appropriate test methodologies and test results have been extensively discussed in various research [8].

Kumar et al. [9] compared the mechanical properties of miniature and sub-size tensile test specimens with the test results obtained from a conventional size specimen. They supported their tests with finite element analysis to determine the geometrical design of the miniature specimen and its behavior under tensile loading.

Kihara et al. [10] evaluated micro specimens by micro tensile testing. In their study, the micro-tensile test method was performed using specimens with two different crystal orientations. They stated that the results they presented suggest that their proposed micro-tensile test can be applied to evaluate the crystal anisotropy of micro-components composed of nickel or other non-crystalline materials.

Konopik et al. [11] investigated the applicability of micro-tensile testing for DC01 steel material characterization, the results of micro-tensile test specimens were compared with standard sized specimens. The results showed good agreement between the values obtained using standard and micro-tensile test specimens for all parameters and conditions considered in the experiments.

In another study [12], the dynamic mechanical properties of S355JR, S235JR and 1.4301 (X5CrNi18-10) steel sheet materials were compared with the results obtained from miniaturized tensile tests and standard tensile tests. In a similar study [13], the use of miniaturized tensile specimens was evaluated to understand the mechanical properties of DP800, DP600 and 316L stainless steel alloys developed by rapid alloy prototyping. The study concluded that miniaturized tensile testing can be safely used as a highly efficient tool for predicting standard mechanical properties of various steels.

In this study, two different types of mini tensile test specimens were produced using two different 3D printing techniques, Stereolithography (SLA) and Fused Deposition Modeling (FDM). According to a review of the literature, it has been observed that studies have been focused on reducing the size of standard tensile test specimens for metal-based materials in generally [14, 15]. However, no reference studies have been found related to modifying the tensile specimen dimensions for plastic materials in this field. Nowadays, for all material groups, specimen preparation time and the cost impact of specimens are important. The absence of a specific standard defining the dimensions of mini tensile test specimens has led to experiments being conducted with miniature specimens of varying sizes, determined based on user requirements and the availability of the material to be tested. Researchers, particularly in cases involving valuable and scarce materials, are working to reduce tensile specimen sizes to minimize material waste. Mini-tensile tests are particularly advantageous for testing parts produced using new manufacturing techniques such as additive manufacturing. SLA and FDM 3D printers primarily utilize plastic materials. Reducing the amount of material used in test specimens produced by these methods will not only decrease waste but also lower production costs. For this reason, reducing the amount of material consumed is of great importance. Thus, tensile test specimens are produced in the form of small-sized parts, significantly reducing material consumption and specimen preparation time. In this study, the applicability of mini tensile testing was evaluated by comparing the mini tensile test results of materials produced using 3D manufacturing technologies with standard tensile test results.

2. Material and Methods

The steps followed in the study are shown step by step in the flowchart given in Figure 1. The first step of the study was to recognize the problem through literature research and then to decide on the methods of the processes to be applied. After determining the method of the study, the printing process of standard and mini tensile bars was realized. A mini mold was designed and manufactured to connect the mini tensile bars to the tensile testing machine. Finally, the tensile process was completed, and the fracture surfaces of the specimens were examined. The usability of the mini tensile test was investigated by comparing the mini tensile test results with the standard tensile test results.

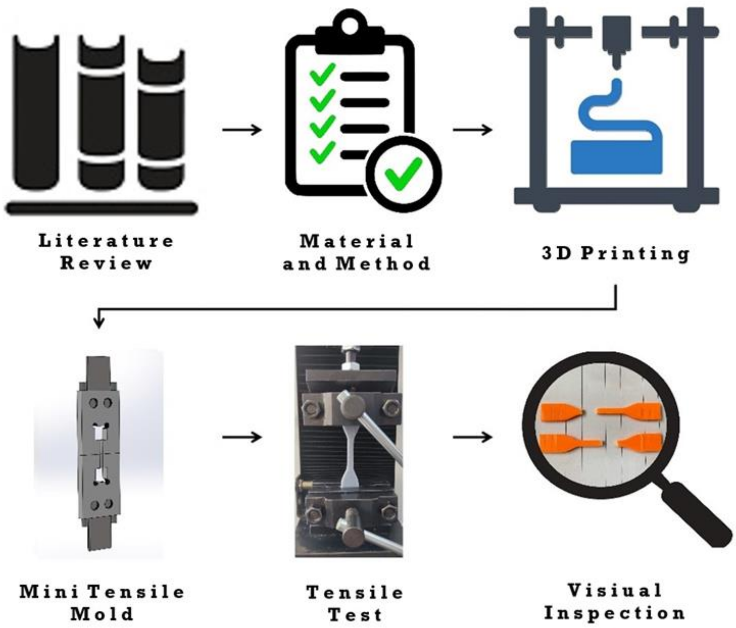


Figure 1. Flowchart of the experiment

2.1. Material

In the study, PLA + (PLA Plus) filament material produced by ESUN brand with a diameter of 1.75 mm and UV liquid resin produced by Anycubic brand were used. Table 1 shows the mechanical properties of PLA Plus and Table 2 shows the mechanical properties of UV liquid resin.

PLA (polylactic acid) is one of the most widely used filament types in 3D printers. This is due to its ease of production, affordable price, and easy availability. PLA material is manufactured from organic materials such as corn starch and sugar cane. It is not harmful to human health and is biodegradable [16, 17]. Since PLA has good compatibility with filler materials, many derivatives such as PLA Plus 2% calcium carbonate containing polylactic acid), PLA Tough, PLA CF (carbon fibre-reinforced polylactic acid) and PLA GF (glass fibre-reinforced polylactic acid) are produced. PLA types are variations of standard PLA with enhanced mechanical properties. They are produced to meet the needs of different applications. For example, the PLA Plus material has a higher toughness and better adhesion between the layers than PLA. PLA Plus improves PLA's weaknesses such as moisture absorption and brittleness. Because of these advantages, PLA Plus material was chosen for the parts produced on the 3D printer.

Table 1. Mechanical properties of PLA Plus material [18]

Mechanical Properties	PLA Plus
Filament diameter (mm)	1.75
Color	Orange
Tensile strength (MPa)	63
Elongation at Break (%)	20
Density (g/cm^3)	1.23

The UV resin used in the study has low odor, high dimensional accuracy, excellent adhesion, low shrinkage, high printing resolution, and high surface roughness. This type of resin is used for the production of designs such as figures, detailed models, prototypes, and structures with a good appearance [15].

Table 2. Mechanical properties of UV liquid resin [19]

Mechanical Properties	UV Resin
Wavelength (nm)	405
Viscosity (mPa.s) 25°C	150-200
Elongation (%)	8-12
Density (g/cm^3)	1.05-1.25
Tensile strength (MPa)	36-45
Hardness (Shore D)	82
Volumetric shrinkage (%)	4.5-5.5

2.2. Printing Process and Printing Parameters

The tensile specimens used in the study were produced using two different additive manufacturing methods. The first additive manufacturing method is Fused Deposition Modeling. FDM is an extrusion-based manufacturing method that creates 3D geometries layer by layer using thermoplastic polymers as consumables [20]. The second additive manufacturing method is Stereolithography, which uses liquid, photosensitive(photopolymer) resin as a consumable material and solidifies the 3D designed part on top of each other with the photopolymerization technique of the resin and has high dimensional accuracy [21, 22].

For the FDM method, 3D printing was performed using the Ender-3 S1 model printers produced by Creality. For the SLA method, Photon Mono X 6K printer manufactured by Anycubic was used. Both devices used in the study are shown in Figure 2. Since the parts produced with the SLA method needed to be subjected to an extra post-processing, they were exposed to UV light in the curing device. For the curing process, the Anycubic Wash & Cure device was operated for 10 minutes for both surfaces of the part.

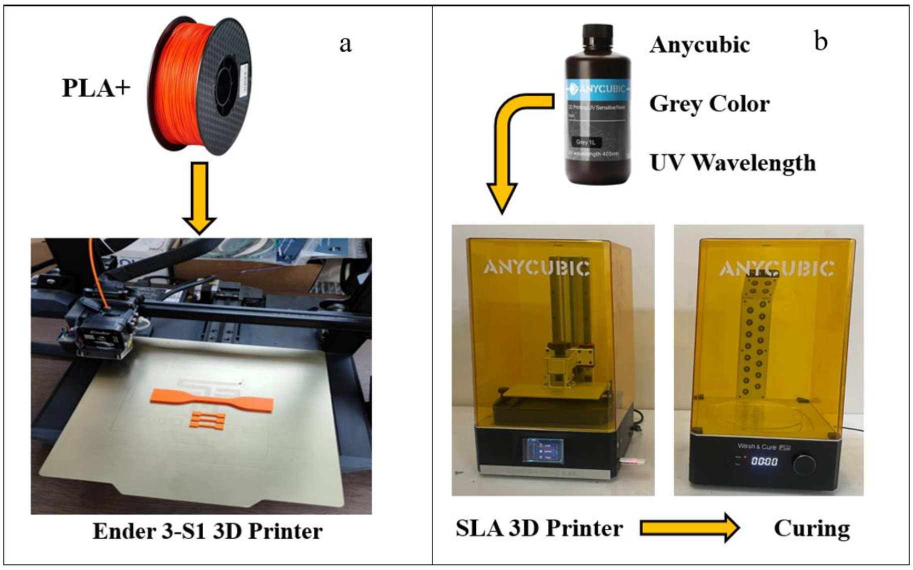


Figure 2. a) Ender 3 S-1, b) Anycubic Photon Mono X 6K and Anycubic Wash & Cure

In the parts produced by the FDM method, the printing parameters were adjusted by considering the recommendation of the filament manufacturer before printing from the 3D printer. Printing parameters of the process are as given in Table 3.

Table 3. Printing parameters for FDM method

Printing Parameters (FDM)	
Printing speed (mm/s)	50
Plate temperature (°C)	60
Printing temperature (°C)	207
Layer thickness (mm)	0.1
Infill percentage (%)	100

For the SLA method, gray standard UV resin of Anycubic brand was used. The parameters used for SLA printing are given in Table 4. The 3D drawings of the specimens were made by using the "SolidWorks" software and then saved in STL file format. Using the "Chitubox" slicing software for SLA prints and "Cura" slicing software for FDM prints, G codes of the samples were extracted in accordance with the parameters used during printing.

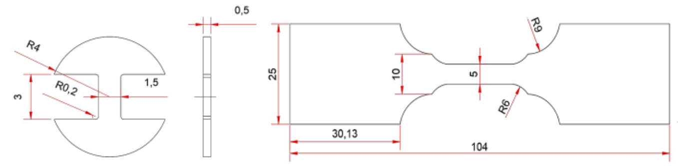
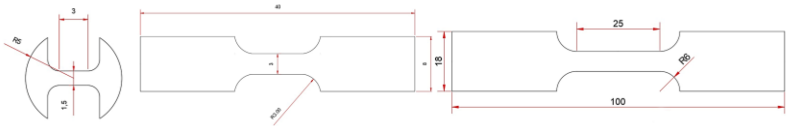
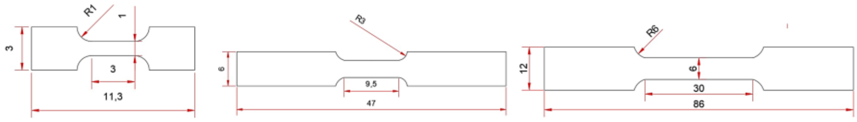
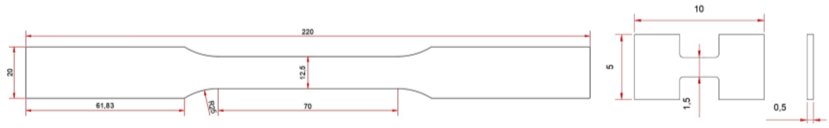
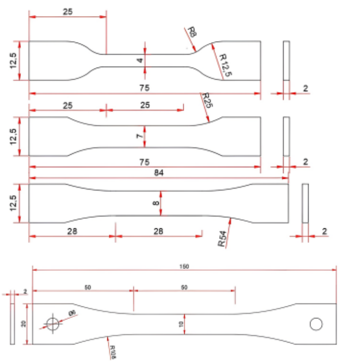
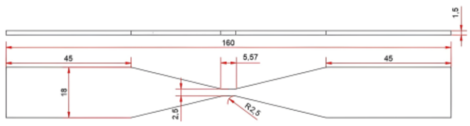
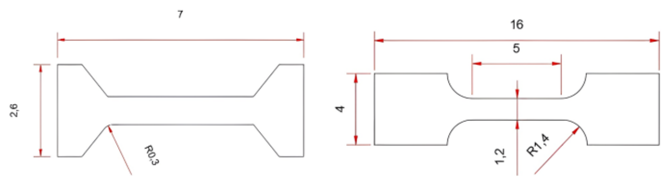
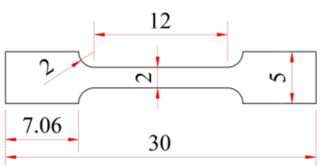
Table 4. Printing parameters for SLA method

Printing Parameters (SLA)	
Exposure time (s)	2
Layer thickness (mm)	0.05
Lifting distance (mm)	2
Lifting speed (mm/min)	60
Infill percentage (%)	100

2.3. Tensile Test Standards

The dimensions of mini tensile test specimens encountered in various studies in the literature are given in Table 5 and the dimensions of mini tensile and standard tensile specimens used in this study are given in Figure 3. As seen in Table 5, researchers have prepared mini and standard tensile test specimens of various sizes from metal materials. It has been observed that the dimensions of mini specimens were determined in a way that allows sampling regionally from parts used in applications. The reason for the dimensional differences in these studies is the absence of a standard for mini tensile testing and the researchers' aim to investigate the relationship between specimen size and strength. In the literature, ASTM D638 Type IV tensile test specimens are generally preferred for mechanical testing of polymer materials produced by additive manufacturing [23-25]. Therefore, ASTM D638 Type IV standards were used for the dimensions of standard specimens in this study. However, since no definite standard is defined for additively manufactured polymer mini-tensile specimens, other studies in the literature were taken into consideration. Figure 3a shows the dimensions of the [26] standard tensile specimen and Figure 3b shows the dimensions of the mini tensile bar. In the study, five standard tensile specimens and five mini tensile specimens were produced for each of the FDM and SLA methods. In total, 10 tensile specimens made from PLA and 10 tensile specimens made from UV resin were subjected to tensile testing. In the FDM method, 2.77 m of filament material was used to produce standard tensile bars and 0.11 m of filament material was used to produce mini tensile bars. In the specimens produced by SLA method, 0.30 g of resin was used in mini tensile bars and 8.30 g of resin was used in standard tensile bars. Approximately 25 times more filament was used between the mini and standard tensile specimens for the FDM method and approximately 27 times more resin was used for the SLA method.

Table 5. Dimensions of different mini tensile test specimens in the literature (all dimensions are in mm)

Material	Dimension
S355JR, S235JR and 1.4301 [12, 27]	
Stainless Steel 316 [5]	
20MnNiMo55 CrMoV SS304 LN [9]	
Steel sheet made of DC01[3]	
Nagase XNR 6852-1 and SikaPower 4720 [28]	
Steel [4]	
6061 Al Alloy 304 L FeCrAl Alloy 718-Alloy Tungsten [6]	
Stainless Steel 316L [29]	

The thickness of the mini-sized specimens was reduced compared to the standard specimens. This can be attributed to the fact that all dimensions of the model were reduced. In addition to the reductions in length and width, the thickness also decreased. Since the material used in the study can be enlarged and reduced according to the practical application area, the thicknesses may change in the application part. In addition, the distribution of the forces acting on the material in the cross-sectional area and the stress distribution on the material with reduced size are closer than the standard specimen.

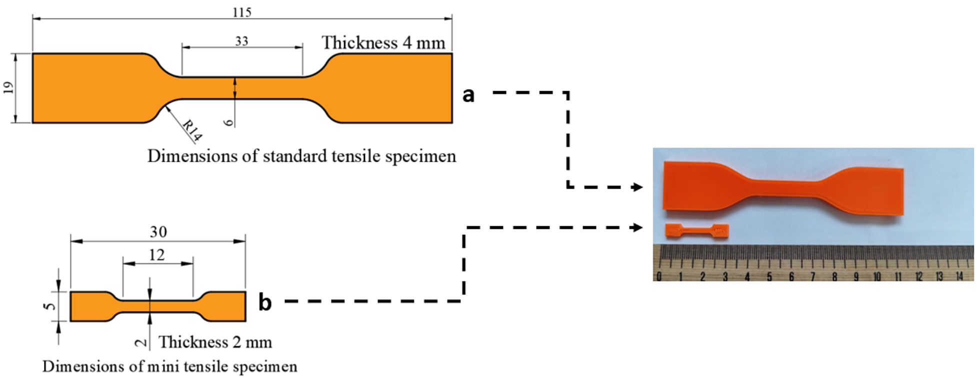


Figure 3. a) Dimensions of standard tensile specimens, b) Dimensions of mini tensile specimens

2.4. Design and Manufacturing of Mini Tensile Mold

Tensile testing machines and their fixtures are designed for standard tensile specimens. Therefore, a different fixture is needed to mount mini tensile specimens to the tensile testing machine. For this reason, a mini tensile test mold was designed for the study and this mold is shown in Figure 4. The mini tensile mold consists of two centering pins and two connection flat bars at the top and bottom. The profile in which the tensile bar will be placed on the upper and lower parts was cut using a wire EDM machine. Flat bars are used for connecting the mini tensile test mold to the tensile machine.

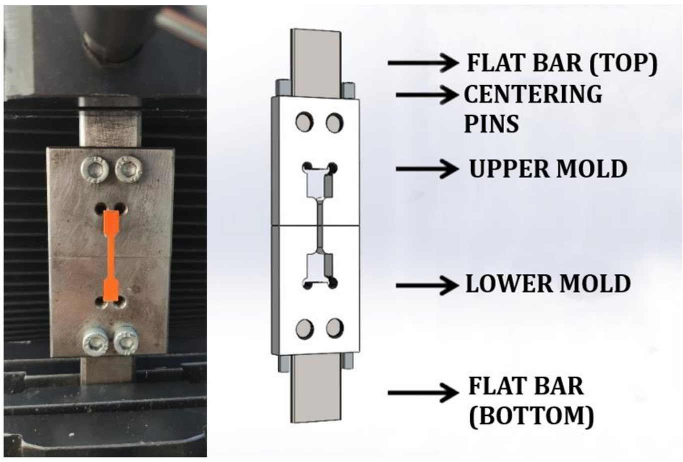


Figure 4. Mini tensile mold

2.5. Tensile Testing Machine

WDW-5 model universal tensile machine (Figure 5) with a capacity of 5 kN was used for the tensile tests performed in the study. Tensile tests were performed at room temperature at a tensile speed of 2 mm/min. While no extra equipment was used for the standard tensile test bars, the mini tensile bars were pulled using a mini tensile mold.

Figure 5. WDW-5 model universal tensile machine

3. Results and Discussion

When the results of the tensile test were analyzed (Figure 6), the average mini tensile strength value for PLA Plus was 49.68 ±3.64 (MPa), while the average tensile strength of the standard tensile specimens was 47.83 ±4.82 (MPa). The percentage error between the results of the average tensile strength of the mini and standard tensile bars using PLA Plus is calculated as 3.8%. When the percentage elongation is evaluated in Figure 7, the average of the mini tensile bars is 4.7 ±1.02% while the average of the standard tensile bars is 8.20 ±1.89%. The difference between the average of mini and standard tensile bars in percent elongation was calculated as 57.31%.

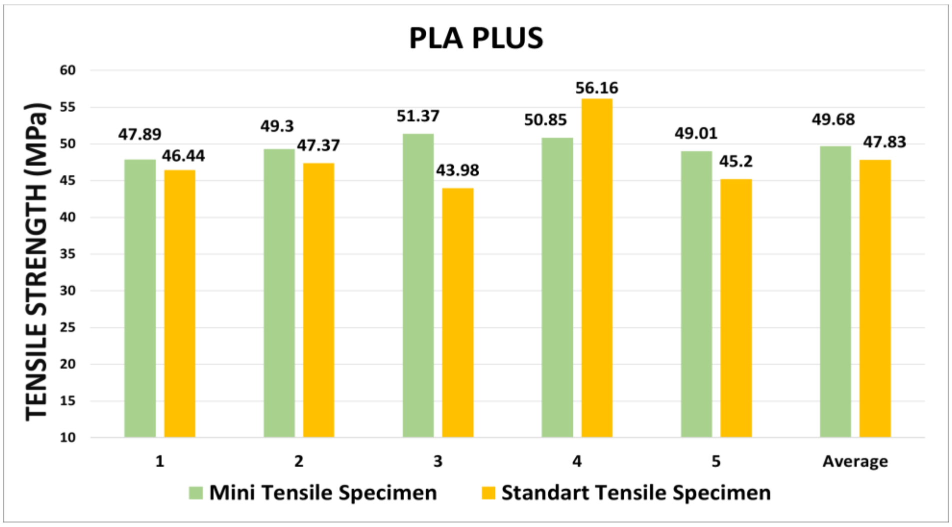


Figure 6. Tensile strength results of PLA Plus specimens

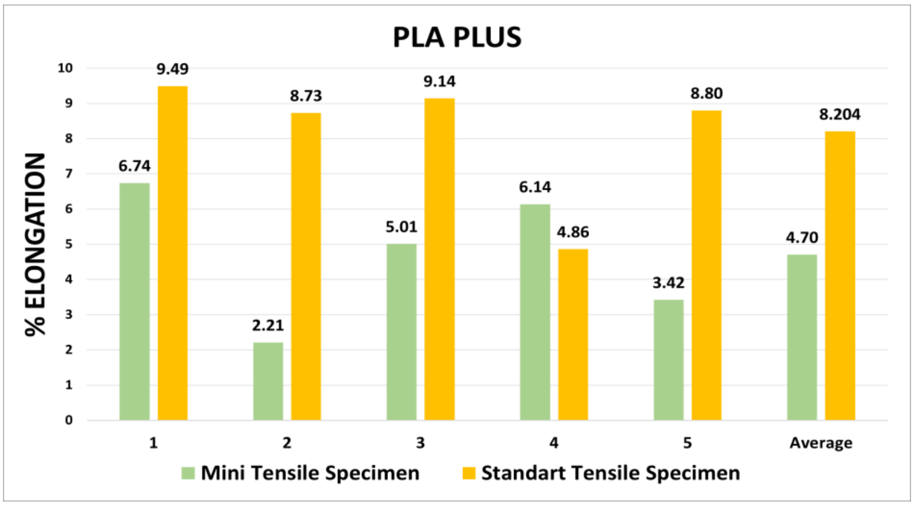


Figure 7. Percent elongation results of PLA Plus

In Figure 8, the average tensile strength of the mini tensile bars produced by the SLA method was 21.06 ±4.96 MPa, while the average tensile strength of the standard tensile specimens was 20.28 ±2.42 MPa. The percent error between them was calculated as 3.8%. When the percent elongation was analyzed in Figure 9, the average of the mini SLA tensile bars was 1.29 ± 0.71% while the average of the standard tensile bars was 4.5 ± 0.43%.

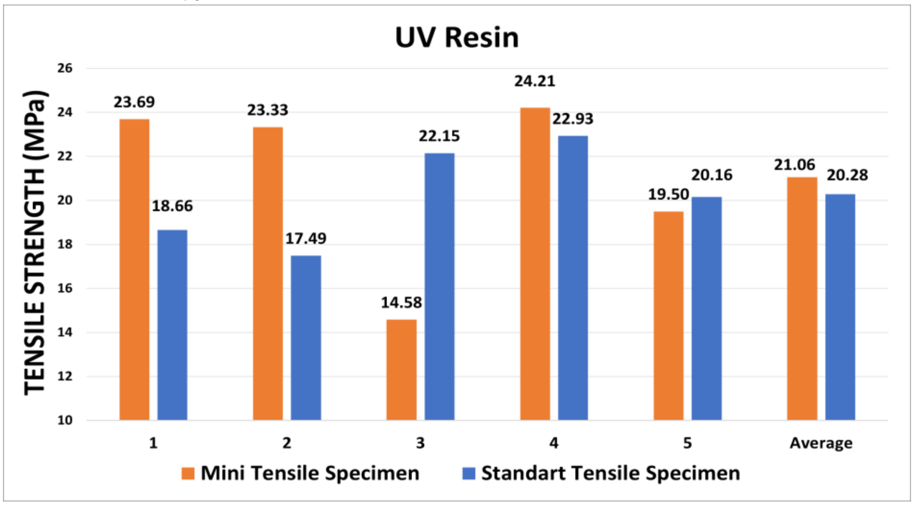


Figure 8. Tensile strength results of UV Resin specimens

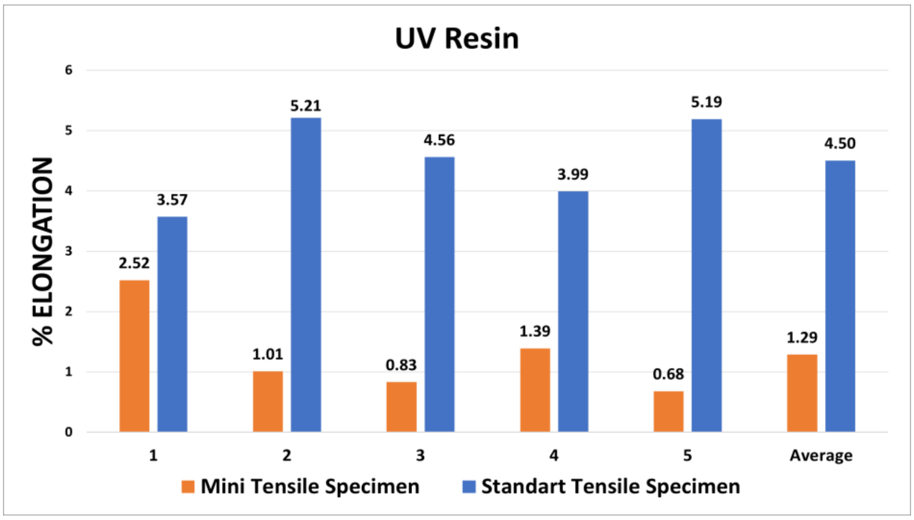


Figure 9. Percent elongation results of UV Resin specimens

The maximum, minimum and standard deviation values obtained as tensile stress and % elongation of mini and standard tensile specimens produced by FDM and SLA methods are given in Table 6. The elongation values obtained from the mini specimens are less than the standard specimens for both materials. This is assumed to be due to both material and geometrical inhomogeneity (thickness) [30].

Table 6. Maximum and minimum tensile strength results

		PLA Plus		UV Resin	
		Mini	**Standard**	**Mini**	**Standard**
Tensile strength	**Maximum**	51.37	56.16	24.21	22.93
	Minumum	47.89	43.98	14.58	17.49
	Standard Dev.	1.42	4.83	4.07	0.74
%Elongation	**Maximum**	6.74	9.49	2.52	5.21
	Minumum	2.21	4.86	0.68	3.57
	Standard Dev.	1.88	1.89	2.89	1.56

3.1. Visual Inspection Results

The standard and mini tensile test SLA specimen samples are shown in Figure 10. It was observed that the standard and mini tensile bars ruptured in the central zone. When the fracture surfaces of the tensile specimens are observed, the specimens are brittle. When the fracture surfaces of the standard and mini tensile bars are compared, it can be said that the fracture surfaces are similar.

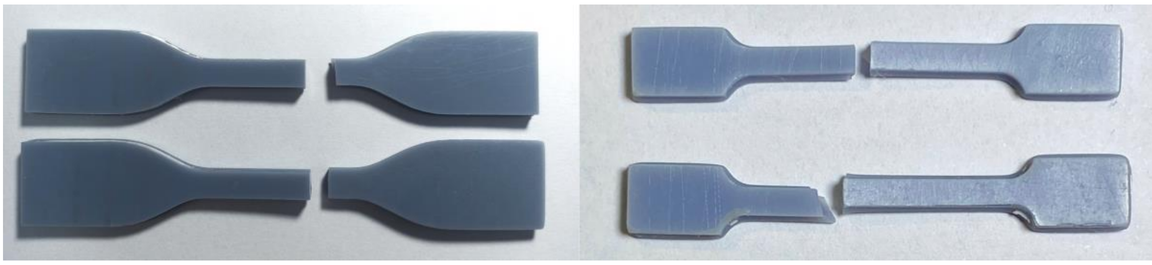


Figure 10. Standard and mini SLA tensile test specimens

The standard and mini PLA plus tensile test specimens are shown in Figure 11. When the specimens are examined, it is noteworthy that the rupture points and fracture surfaces of the specimens in both sizes are similar. When the rupture points are evaluated, it is understood that the materials have a ductile structure due to the visible necking in the tensile specimens of both sizes.

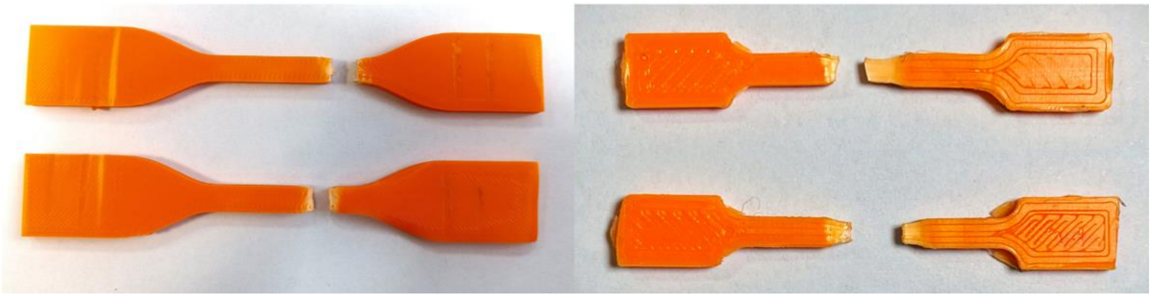


Figure 11. Standard and mini PLA Plus tensile test specimens

4. Conclusion and Suggestions

In order to assess the applicability of mini-tensile specimens as a substitute for standard tensile specimens in tensile testing, tensile strength and elongation values must be comparable. For this reason, there is an international standardization effort of miniature specimen technology. Due to the small dimensions of the mini-tensile specimen, elongation measurements are often performed using the cross-head movement of the instrument instead of an extensometer. It is possible that specimens with different dimensions, such as mini and standard tensile specimens, are geometrically similar, thus reducing the difference in elongation properties [9]. Nevertheless, the difference between the total elongation values may be due to the fact that the thickness/width ratio of the specimens is not the same

[3,9]. It is also possible to obtain accurate results by controlling the surface quality and size of the tensile test specimens or by taking more precise elongation measurements.

In this study, it was observed that the dimensional difference between mini tensile test specimens and standard tensile test specimens had minor effect on tensile strength. The difference in the mean tensile strengths of the mini and standard tensile test bars produced by the FDM method is 3.8%, while the difference in the mean tensile strengths of the tensile test bars produced by the SLA method is 3.8%. In the parts produced by the FDM method, it was observed that the fracture surfaces were similar and the mini and standard tensile test specimens fractured in a ductile manner. In the specimens produced by the SLA method, it was observed that the fracture surfaces were similar and the mini and standard tensile test specimens fractured in a brittle manner.

Mini tensile test specimens are generally preferred for metal-based materials with small geometries, such as those used in fusion reactor applications in nuclear plants or laser welding [31, 32]. However, the application areas of mini tensile specimens for plastic materials are not yet well-defined. Nevertheless, it is believed that mini tensile specimens printed using SLA and 3D printers could provide significant advantages in terms of cost and project duration, especially for budget-constrained research. Additionally, it is anticipated that obtaining reliable results from mini tensile tests could lead to discussions about reducing specimen sizes for other mechanical tests in the future.
The existence of a standard for tensile test specimens makes it possible to compare studies in literature. However, the high cost of specimen preparation and the limitations of specimen dimensions do not allow easy testing in all cases. In the mini-tensile test, the specimens can be compared in terms of their mechanical properties, but it is not very efficient to compare them with other studies. This is because the mini-tensile test is becoming more widespread, but it is not fully standardized. Therefore, researchers should consider the advantages and disadvantages of both specimen sizes and choose the appropriate one.
Today, the production of parts using 3D printers and SLA technology is highly popular for both industrial and everyday use. The continuous development of filament and resin materials has significantly contributed to this rise. However, the costs of SLA resins (particularly those used in medical applications) and engineering-grade filaments remain very high. Reducing the amount of material consumed during production would lower costs, making it beneficial to focus on standardization in this area in the long term. To outline steps toward standardization in the mini tensile testing process for plastic materials, it is first necessary to increase the number of studies conducted with these materials. To achieve this, the initial step should involve identifying the relevant industries and the key polymer materials used in these sectors. The next step would be to decide on the production method for the material. This entire process should be planned and executed collaboratively with relevant institutions and scientists.

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Conflict of Interest Statement

There are no declared conflicts of interest or common interests.

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