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A Study on the Effects of Test Frequency on the Fatigue Life of PLA Parts Manufactured by Additive Manufacturing

Yusuf Ayan[*a]

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[a,*] Karabuk University, Technology Faculty, Dept. of Mechatronics Engineering 78050 - Karabük, Türkiye
Orcid: 0000-0002-0045-3777
e mail: yusufayan@karabuk.edu.tr

[*]Corresponding author: yusufayan@karabuk.edu.tr

ABSTRACT

Fatigue tests of materials require longer time than most other mechanical tests when the enitre process is considered. One of the most critical factors affecting the test time is the test frequency. In this study, fatigue tests at different test frequencies were applied to the PLA parts produced by the additive manufacturing (AM) technique, and the effects of test frequency were investigated. In the fatigue tests, four different stress levels were applied, and the tests were carried out at four different frequencies: 2 Hz, 4 Hz, 6 Hz, and 8 Hz. The fatigue life of the samples changed according to the applied stress levels at varying test frequencies. There was an approximately 44% decrease in the fatigue life with increasing test frequency at the 1st stress level. Fatigue life showed an increasing trend at and after the 3rd stress level. At the 4th stress level, fatigue life increased by 45% when the test frequency was changed from 2 Hz to 8 Hz. In general, after a specific fatigue life, it was observed that increasing test frequency tended to increase the fatigue life.

Eklemeli İmalat ile Üretilen PLA Parçaların Yorulma Ömründe Test Frekansının Etkileri Üzerine Bir Çalışma

ÖZ

Malzemelerin yorulma testleri, tüm süreç dikkate alındığında diğer birçok mekanik teste göre daha uzun süre gerektirmektedir. Test süresini etkileyen en önemli faktörlerden biri yorulma test frekansıdır. Bu çalışmada Eİ tekniğiyle üretilen PLA parçalara farklı test frekanslarında yorulma testi uygulanmış ve test frekansının etkileri araştırılmıştır. Yorulma testlerinde dört farklı gerilme seviyesi uygulanmış ve testler 2 Hz, 4 Hz, 6 Hz ve 8 Hz olmak üzere dört farklı frekansta gerçekleştirilmiştir. Uygulanan gerilme seviyelerine göre değişen test frekanslarında farklı yorulma ömürleri bulunmuştur. 1. Gerilme seviyesinde artan test frekansıyla yorulma ömründe yaklaşık %44 azalma görülmüştür. 3. Gerilme seviyesi ve sonrası yorulma ömrü artan trend göstermiştir. 4. Gerilme seviyesinde test frekansı 2 Hz'den 8 Hz'e değiştirildiğinde yorulma ömrü %45 artmıştır. Genel olarak, belirli yorulma ömür değerinden sonra artan test frekansının yorulma ömrünü arttırma eğiliminde olduğu görülmüştür.

Anahtar Kelimeler: Polimer, eklemeli imalat, yorulma frekans

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1. Introduction

In recent years, interest in additive manufacturing (AM) systems has increased in academic and industrial fields [1]. The capabilities of the AM method, such as performing fast production, reducing design limitations, and reducing material consumption [2], have contributed to this situation. In today's manufacturing industry, the increasing demand for more specialized and highly complex components has led to advances in AM technologies [3]. Different materials such as polymer, ceramic, metal, and composite can be processed with the AM method. Polymers are a type of material commonly used in the AM process [4]. The development of polymers has led to their use in various structural and load-bearing applications [5]. Polymers have recently been preferred in many industrial applications, and replacing metallic alloys with polymers has become very important in new technological machines and systems [6]. The fact that polymers are light in weight, easy to manufacture, and have good mechanical properties such as abrasion resistance [7] can be shown among the reasons that may contribute to this change.

Different production techniques and methods are used in the AM method. One of them is the fused deposition modeling (FDM) and its use has increased with the widespread use of 3D printers [8]. Poly lactic acid (PLA) is one of the most widely used polymers in FDM [9]. PLA can be used in many sectors, such as medical, biomedical, packaging, agriculture, and automotive industries [10]. Since this material has a common usage area, it is important to determine the mechanical properties of this material to provide the desired working performance. The mechanical properties of the polymer parts produced with AM are highly dependent on the production parameters. Nozzle temperature and speed [11] infill pattern type, build orientation, and raster angle [12] are examples of these parameters. Although a target part produced in different parameters with a 3D printer physically provides the same geometric properties in its final form, mechanical properties may vary due to differences in production parameters. In this respect, studies on the mechanical properties of parts produced with AM have attracted great interest in recent years [13].

Kaygusuz and Özerinç [9] investigated the effect of printing temperature and infill density on the produced PLA structure. Noting that these two printing parameters significantly affect the mechanical properties, they found that increasing printing temperature increased the tensile strength. They attributed this increase to reducing voids in the structure due to high temperature. Kam et al. [14] investigated the effects of vibrations in the 3D printer on the surface roughness of the produced part. They found that the full honeycomb was the best result among the parts produced in six different infill structures. With this study, it is understood that the 3D printer system can also directly affect the properties of the produced part. İstif [7] investigated the wear behavior of PLA parts produced with FDM. Different wear behavior was observed in two different sample types produced in vertical and horizontal orientations, indicating that layer orientation plays a vital role in the wear mechanism. Yavuz et al. [15] applied a three-point bending test to PLA, ABS, and PETG structures produced in different topologies by 3D printing. They stated that the ABS structure is more ductile than the PLA structure, and although the PLA structure can withstand higher loads, it exhibits a more brittle behavior by showing less displacement as a result of bending. In a similar study, Kamer et al. [13] investigated the flexural properties of structures produced with ABS and PLA at different nozzle and bed temperature parameters. While the effect of these two parameters on the flexural strength of the samples produced with ABS is less than in PLA, the table temperature affected the flexural strength very little in the PLA samples. However, the change in the printing temperature affected the flexural strength.

Parts produced with FDM are affected by mechanical failures throughout their service life. Fatigue is one of these failures that can cause the component to crack and fracture even at low cyclic stress values [16]. In addition, fatigue is responsible for 90% of the damage caused by the working of the machine components [17]. If PLA components produced with AM are used in engineering applications, they should provide sufficient accuracy and safety regarding fatigue strength [18]. Considering that PLA components produced with AM can take on a task in structural applications, it is necessary to know these components' fatigue properties. Gomez-Gras et al. [19] applied a fatigue test to PLA samples produced in different parameters with FDM. They stated that infill density had the most significant effect on fatigue performance, followed by nozzle diameter and layer height. They also found that printing speed had little effect. Azadi et al. [20] applied a fatigue test to circular cross-section PLA samples produced with FDM in horizontal and vertical build orientations. They found that at low-stress levels, the effect of the build orientation is greater, and the fatigue life of specimens produced in the vertical orientation is lower. Bakhtiari et al. [16] conducted a review study investigating the effect of 3D printing parameters on fatigue properties. Their study discussed the effects of production parameters according to the fatigue test type. They stated that it is difficult to deduce the overall effect of each parameter due to the few parametric studies on FDM products in the literature. They also mentioned that each production parameter can negatively or positively affect fatigue properties depending on the change in material or load type. Safai et al. [21] stated that the synergy between all printing parameters, such as build orientation, raster angle, layer height, and infill density, makes it difficult to determine the best parameters regarding the best fatigue strength.

When the studies in the literature are evaluated, the effects of 3D printing parameters on mechanical properties have been investigated in general according to the tests applied. Studies about the fatigue properties were found to be less in number than other studies. It was also stated by some researchers that the studies on the fatigue properties of AM and PLA materials are few [18,19,22,23]. Considering the operation of polymer structures under cyclic loading conditions, it is important to determine their fatigue strength. Since the test parameters are directly effective in evaluating the results, the test conditions can be considered another important factor, like 3D printing parameters, in determining mechanical properties. Some basic test parameters applied in fatigue tests are ambient temperature, applied stress level, and test frequency. Each of these parameters is a factor that can directly change the test results. The most critical factor affecting test times is fatigue test frequency. Since varying levels of loads must be applied to the test material in determining the fatigue strength, many samples are used, and thus, the test times can be very long depending on the applied load. This study investigated the effects of fatigue test frequency on the PLA structure produced by 3D printing. Fatigue tests at varying test frequencies were applied to the samples produced under the same conditions. Fatigue tests were carried out with a test machine applying planar bending stress. Investigating the effects of fatigue test frequency and applying the fatigue test are among the differences in this study. This study examined both the effects of fatigue test frequency and the fatigue life of PLA structure at different stress levels.

2. Materials and Methods

The study consist of three stages: specimen production, tensile test, and fatigue test. FDM technique was used in production, and Ender 6 brand-model 3D printer was used. 1.75 diameter white colored ESUN brand PLA+ filament was used. Printing parameters were kept constant in all productions. The printing parameters used in the processes are given in Table 1. Two different types of specimens were printed for tensile and fatigue tests. The printing process is shown schematically in Fig. 1.

Table 1. Printing parameters

Filament diameter (mm)	1.75
Nozzle diameter (mm)	0.4
Nozzle temperature (°C)	205
Bed temperature (°C)	60
Printing speed (mm/s)	80
Layer height (mm)	0.2
Infill density (%)	100
Raster angle (°)	0°

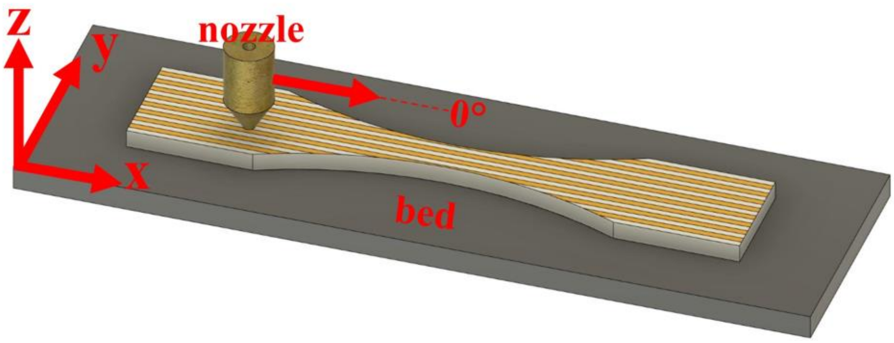


Figure 1. Schematic representation of the printing process

Tensile tests were applied to determine the tensile strength of PLA structures and specify the load levels for fatigue tests. Tensile test specimens were printed according to the ASTM D638 type IV standard [24]. The tests were carried out with a Shimadzu AG 50 kN test machine at a fixed cross head speed of 5 mm/min at room temperature, and three samples were tested. Tensile test specimen dimensions is given in Fig. 2

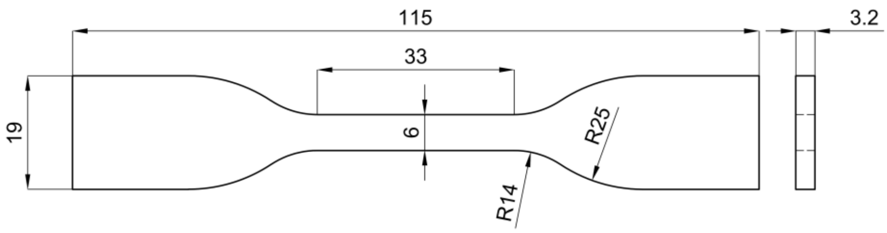


Figure 2. Tensile test specimen dimensions (mm)

Fatigue tests were carried out with a test machine applying planar bending stress. Figure 3 shows the fatigue testing machine and the test scheme. The fatigue test machine is custom designed and manufactured. The test specimen is mounted to one end fixed jaw and the other end movable jaw. The movable jaw moves up and down at a certain frequency (range 0-20 Hz), forcing the specimen to bend. There is a 200 kg capacity load-cell below the fixed jaw. Load cell performs instant load measurement during the test and the measured value is read from the screen on the machine instantly. The machine also has a counter that calculates the total cycle of the sample during testing. By connecting the machine to a computer, instantaneous load changes over time can be monitored and the data obtained throughout the test is recorded. Samples of different dimensions can be tested by changing the jaws on the machine or using the existing jaws. The tests were conducted at room temperature, with all other conditions being the same except for the fatigue test frequency. Since the study aims to investigate the effect of fatigue test frequency, the tests were applied at four different test frequencies: 2 Hz, 4 Hz, 6 Hz, and 8 Hz. Four different stress levels and three specimens for each test frequency were used for each level. A total of 48 fatigue test specimens were tested for four different stress values, four different test frequencies, and three replications. Fatigue test specimen dimensions is given in Fig. 4.

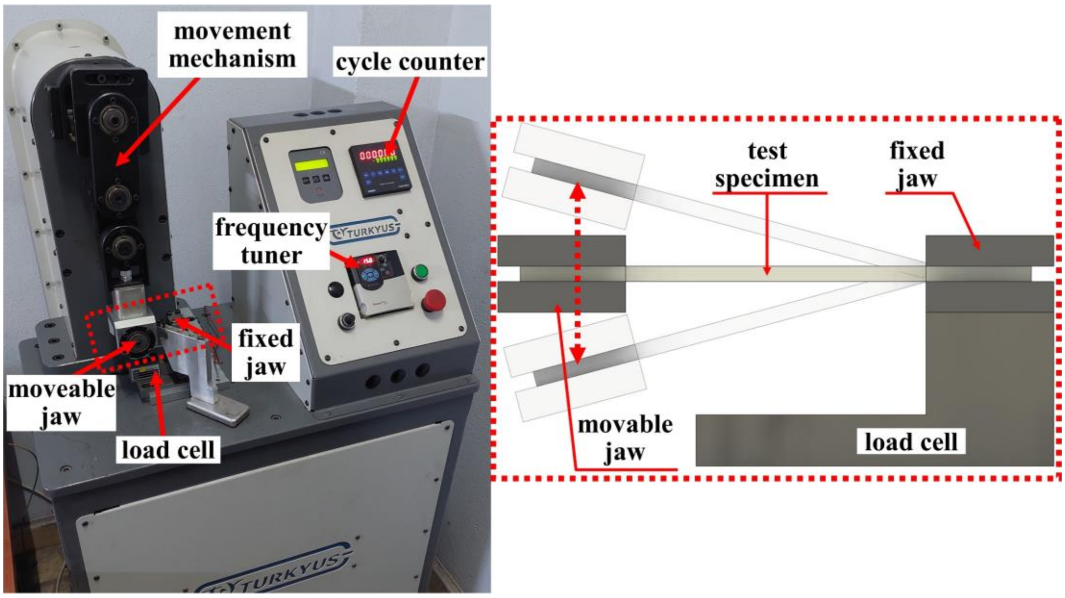


Figure 3. Fatigue test machine and application principle

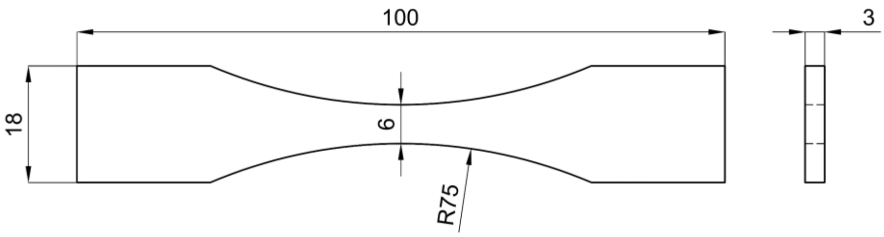


Figure 4. Fatigue test specimen dimensions (mm)

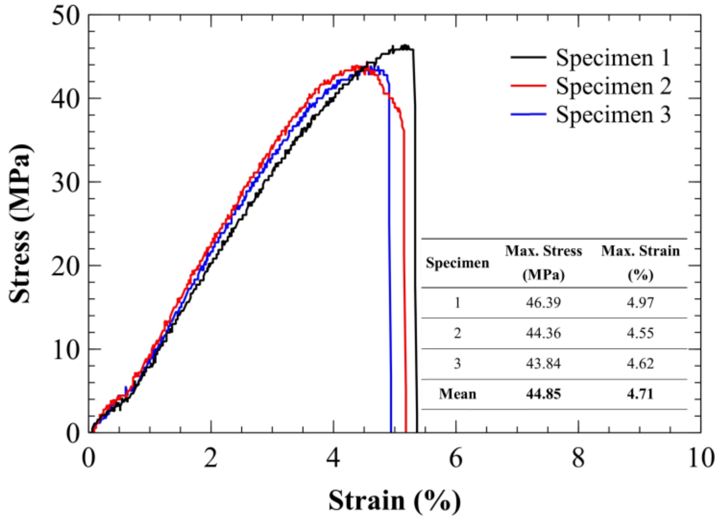
3. Results and Discussions

3.1. Tensile test results

Figure 5 shows the samples after the tensile test. When the rupture regions of the samples are examined, it is seen that all of them were damaged from a similar region. This failure type is the case with specimens printed at a 0° raster angle. In the sample printed at this angle, the orientation of deposited material is in the same direction as the load applied in the tensile test. The stress is concentrated in the region where the flat area on the specimen ends, the rounding begins, and thus, the rupture occurs in this region.

Figure 5. Specimens after the tensile test

The stress-strain curves obtained from the tensile tests are given in Fig. 6. Three specimens subjected to the tensile test showed very similar results in terms of tensile strength and elongation. This situation indicates that the 3D printing process and the applied test are performed correctly under equal conditions. The average tensile strength has been calculated as approximately 45 MPa. The tensile strength of 3D-printed PLA parts is directly related to the printing parameters. In another study, the tensile strength of the PLA part produced with similar parameters was found to be very close [25]. Since the primary purpose of the tensile test is to determine the amount of load to be applied in the fatigue test, there was no need for a more detailed evaluation of the results.



Specimen	Max. Stress (MPa)	Max. Strain (%)
1	46.39	4.97
2	44.36	4.55
3	43.84	4.62
Mean	**44.85**	**4.71**

Figure 6. The stress-strain curves of the specimens

3.1. Fatigue test results

Figure 7 shows the specimens after the fatigue test. Factors such as the applied stress magnitude, temperature, frequency and manufacturing defects in the sample affect the test results [20]. When Figure 7 is examined, it can be seen that the samples were damaged in approximately the same area at all the test frequencies. In this case, when evaluating the test results, it can be said that there is no manufacturing defect that adversely affects the results.

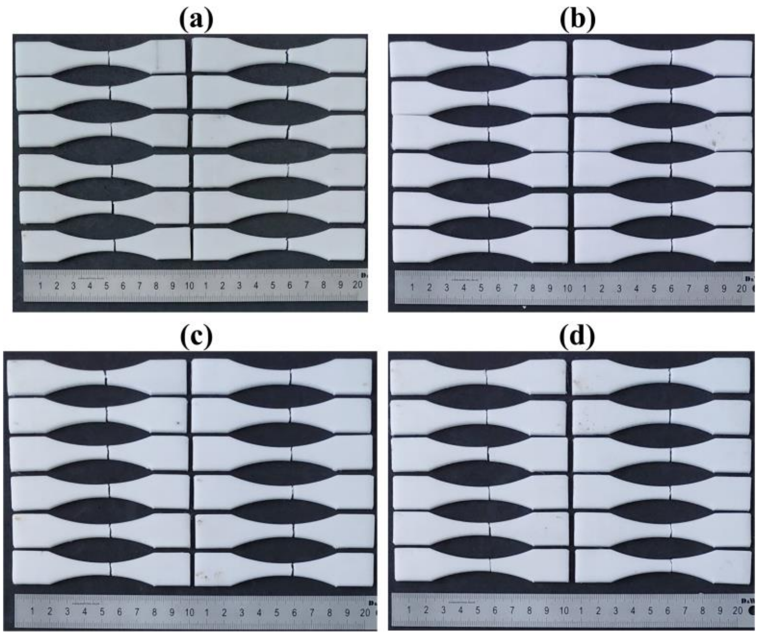


Figure 7. Specimens after the fatigue test a) 2 Hz, b) 4 Hz, c) 6 Hz and d) 8 Hz

In the fatigue tests, four different stress amplitudes of approximately 0.30, 0.45, 0.60, and 0.70 times the average tensile strength (≈45 MPa), calculated according to the results of the tensile tests, were applied. The cycle numbers obtained as a result of the tests at these stress levels are given in Table 2. Two different stress-numbers of cycle graphs were created with these values. The first is the graph obtained with the results of all samples in the fatigue test shown in Figure 8. The graph in Fig. 9 is obtained with the average number of cycles at each fatigue test frequency and each stress level. While calculating the average number of cycles, the total cycle values of the two closest samples were used.

Table 2. Fatigue test results

Stress Level	Applied Stress (MPa)	Test Frequency (Hz)	Specimen	Number of Cycle	Mean Number of Cycle	Stress Level	Applied Stress (MPa)	Test Frequency (Hz)	Specimen	Number of Cycle	Mean Number of Cycle
			1	1072					1	11656	
		2	2	1184	1180			2	2	7552	11024
			3	1176					3	10392	
			1	1136					1	12128	
		4	2	1104	1120			4	2	12176	12152
			3	1368					3	9336	
1	30.2		1	1096		**3**	18.6		1	18096	
		6	2	904	1112			6	2	14424	14952
			3	1128					3	15480	
			1	864					1	15816	
		8	2	624	656			8	2	13200	16004
			3	688					3	16192	
			1	4040					1	27008	
		2	2	2880	2692			2	2	28160	27584
			3	2504					3	31384	
			1	2664					1	34920	
		4	2	2816	2740			4	2	29144	28444
			3	3008					3	27744	
2	25.9		1	2832		**4**	14.3		1	36672	
		6	2	3040	2936			6	2	25624	37576
			3	6016					3	38480	
			1	2656					1	38392	
		8	2	2864	2820			8	2	43424	40908
			3	2776					3	30640	

Note: In calculating the mean number of cycles, the cycle number of the 2 closest samples were used.

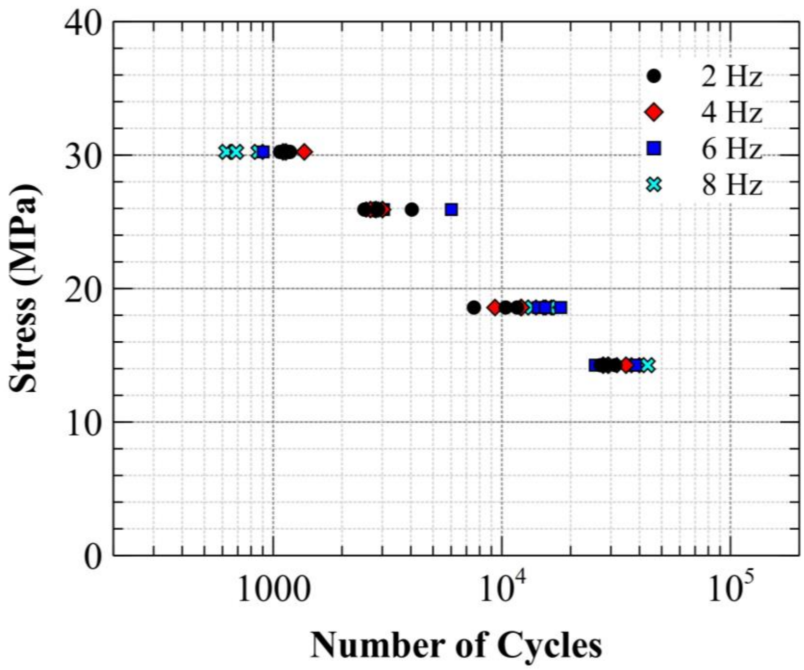


Figure 8. Graph generated by fatigue test results (all samples)

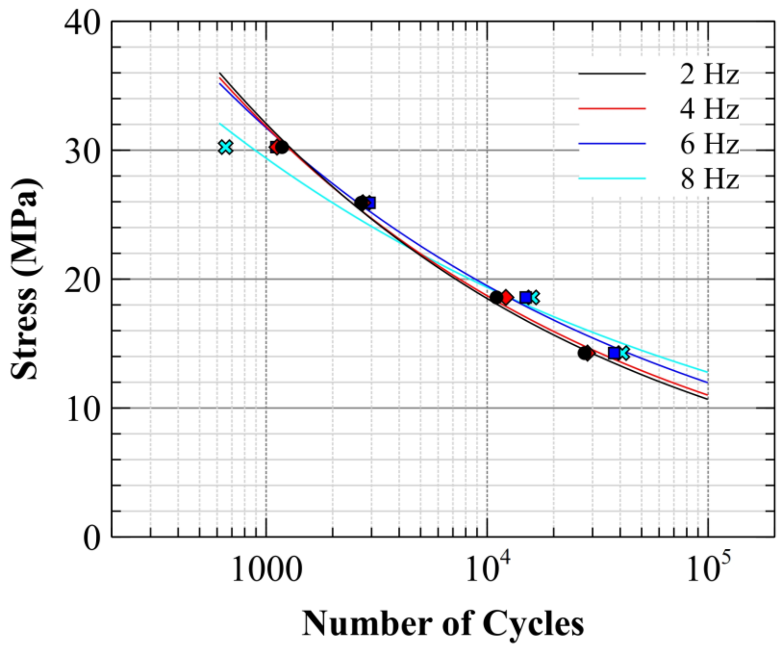


Figure 9. Stress-Average Number of Cycles plot based on test frequency

When the graph shown in Fig. 9 is examined, it is observed that the fatigue life decreases in general with the increase of the fatigue frequency at the highest stress level. At the highest stress level, excluding the 8 Hz test frequency curve, the distance between the curves decreased with increasing test frequency. At the highest stress value, the fatigue life of the specimens applied with a frequency of 8 Hz remained below 1000. With the fatigue test frequency decreasing at the highest stress, the fatigue life exceeded 1000, and the highest fatigue life was obtained at 2 Hz test frequency. When the lowest and highest frequency values are compared at the 1st stress level, approximately a 44% decrease in fatigue life has been calculated.

When Table 2 and Fig. 9 are examined, it is seen that the average fatigue life with the varying test frequency at the 2nd stress level is generally close to each other. However, in the graph in Fig. 9, although the number of cycles at the 2nd stress level is seen to be coincident, a slight difference in the fatigue life was found. At this stress level, the mean fatigue life at 4 different frequencies was calculated as 2797 ± 107. Besides, the lowest fatigue life was found in specimens with a test frequency of 2 Hz and the highest in specimens with a test frequency of 6 Hz. When the test frequencies applied at this level were compared, an approximately 9% difference in fatigue life was found. It was observed that the fatigue life increased with increasing fatigue test frequency at the 3rd stress level. Fatigue life increased by approximately 45% when the test frequency increased from 2 Hz to 8 Hz. When the curves in the graph shown in Fig. 9 are examined, the distances between the curves have increased significantly towards the applied low-stress levels, and it has been observed that the fatigue life tends to increase with increasing test frequency. At the 4th level, where the lowest stress was applied, the highest average fatigue life was 40908 when the test frequency was 8 Hz. The lowest fatigue life was obtained at a test frequency of 2 Hz, with an average of 27584. By increasing the fatigue test frequency by 3 times, an increase of approximately 48% in the fatigue life value was observed. According to the trend of the curves depending on the test frequency, it was deduced that this increase will continue if lower stress is applied.

The above evaluations were based on the fatigue life results obtained at each stress level. When the test results obtained in fatigue tests were generally evaluated, the increased test frequency at high-stress value decreased the fatigue life. When the applied stress value decreases, with increasing test frequency, the fatigue life found intersects at a point on the graph and then shows an increasing trend. It was observed that the linear variation of the fatigue test frequency does not tend to increase/decrease the fatigue life linearly. In the graph in Fig. 9, after the fatigue life of 10^4, the effect of test frequency change on the fatigue life is more apparent.

According to the results obtained in the fatigue test, it has been observed that at high-stress levels (≈0.60-0.70 x σ_{max}) applied, generally close results can be obtained with varying test frequency in fatigue life. At low-stress levels, it was observed that increasing test frequency generally increased the fatigue life. It has been mentioned that high test frequency increases the temperature of the test specimen. In this case, it decreases the fatigue life by causing material flow with increased ductility [26]. Selecting a test frequency of less than 5 Hz is also recommended to reduce high heat generation [21]. Magri et al. [27] applied a tensile-tensile type fatigue test at 10 Hz, 40 Hz, and 80 Hz frequencies to the 3D-produced PLA-Graphen sample. During the test, they measured the sample temperature with a thermal camera and observed a decrease in the fatigue life due to the heating in the material at an 80 Hz frequency. Ueki [28], conducted a study on fatigue testing of composite materials. The researcher stated that if the sample temperature is controlled, close results can be found in the fatigue tests at 1 Hz and 230 Hz frequencies. The researcher also mentioned the possibility of applying external cooling to the sample. Apart from the mentioned literature results, in this study, when the fatigue test results at increasing test frequencies were evaluated, there was no decrease in fatigue life in general. In this case, it was thought that the increased test frequency applied in the study, ranging from 2 Hz to 8 Hz, did not cause a heating that would reduce fatigue life. Increased fatigue life at high frequency compared to low frequency: This could be attributed to prolonging the duration of action of low-frequency repetitive stretching and increasing fatigue damage accumulation under the same stress level [29].

In the literature, it is mentioned that the increasing fatigue test frequency causes heating in polymer materials. Thus, the tests should be carried out at low frequencies. However, within the parameters used in this study, it was not concluded that increasing test frequency influenced reducing fatigue life in general. It has been understood that the frequency values chosen in the study do not cause heating, which reduces the fatigue strength of the samples, or a different adverse effect that will reduce the fatigue life. In a fatigue test where the test frequency is chosen as 2 Hz and 8 Hz, there is a difference of approximately 3 times in the total test time until the same number of cycles is reached. For example, the number of cycles in 4 hours for a test performed at a frequency of 2 Hz will be reached in 1 hour with a frequency of 8 Hz. Considering the conditions, such as the test method and material used in the study, in terms of shortening the fatigue tests: In similar fatigue tests, it has been understood that applying a test frequency of 8 Hz will not have a negative effect and will significantly accelerate the fatigue test process. However, the possibility of frequency variation causing a change in fatigue life should be considered in the fatigue test

3. Conclusions

The general outcomes of this study, in which the bending fatigue test was applied at different test frequencies to the 3D-printed PLA structure produced with AM, are listed below.

- The average tensile strength of the specimens produced at 0° raster angle was calculated as 45 MPa.
- In the fatigue tests, the damage occurred in approximately the same area in all samples; in this case, it was concluded that there was no production-related fault in the samples.
- When the test frequency was increased from 2 Hz to 8 Hz at the highest stress level, a 44% decrease in fatigue life was observed. Depending on the increase in frequency, fatigue life started to increase after the 2nd stress level.
- Fatigue life increased with increasing test frequency, except for the highest stress level applied in fatigue tests since the specimen is subjected to stress in less time at high frequency. When the test frequency was increased from 2 Hz to 8 Hz at the lowest stress level, a 48% increase in fatigue life was observed.
- With increasing fatigue test frequency, there was no decrease in fatigue life due to the heating effect mentioned in the literature.
- It has been concluded that 8 Hz test frequency can be used for tests to be carried out under similar conditions where fatigue tests need to be applied faster or achieve quicker results.

Conflict of Interest Statement

The author declares that there is no conflict of interest.

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