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Research Article

A Comparative Study for High-Cycle Bending Fatigue Lifetime and Fracture Behavior of Extruded and Additive-Manufactured 3D-Printed Acrylonitrile Butadiene Styrene Polymers

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Abstract

Objective: In this research, the built orientation in additive manufacturing on high-cycle bending fatigue properties for the acrylonitrile butadiene styrene (ABS) polymer, manufactured by fused deposition modeling, has been investigated. Then, fatigue lifetime and the fracture behavior were compared to the extruded ABS material. Fatigue properties included the fatigue strength coefficient, the fatigue strength exponent, and the fatigue lifetime, as the general parameter.

Methods: Cylindrical standard samples for fatigue testing were made by the 3D-printer device, in two directions of longitudinal and transverse. Bending fatigue tests were done under stress levels of 5-25MPa, and then, the stress-lifetime curve was calculated.

Results: Obtained experimental results indicated that the fatigue lifetime was lower for specimens, which were 3D-printed in the transverse direction, compared to those printed in the longitudinal direction. The investigation of the fracture surface by scanning electron microscopy demonstrated that the failure plane was flat in standard samples, which were printed in the longitudinal direction. However, in the fracture surface of the specimen, 3D-printed in the transverse direction, cleavage planes could be observed which illustrated the brittle fracture of the material. The ABS sample, 3D-printed in the transverse direction had a higher fatigue strength coefficient, compared to the specimen 3D-printed in the longitudinal direction. Moreover, its fatigue strength exponent was more negative. Consequently, the effect of the build orientation was significant on the fatigue lifetime of the ABS polymer. Moreover, under high-stress levels, bending fatigue properties of two sample types, in both transverse and longitudinal directions, were approximately similar to each other.

Conclusion: Generally, the fatigue lifetime of the extruded ABS sample was higher than those of 3D-printed specimens. However, the fracture behavior was also brittle, similar to 3D-printed ones. Considering the specimen weight as an objective, the fatigue behavior was closer to the extruded ABS sample.

Keywords: Bending fatigue lifetime, Fracture behavior, ABS polymer, Additive manufacturing, 3D-printing

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1 INTRODUCTION

Polymeric components, made by the additive manufacturing (AM) technique, have different applications in various fields of engineering. Today, parts with complex geometries are produced by the AM, without the need for conventional tools in the traditional fabrication method and based on a three-dimensional (3D) computer model. Therefore, flexibility in design, rapid conversion of design ideas into prototypes, and significant reduction of material waste are the advantages of this technology[1].

AM systems were first introduced in 1986 with stereolithography technology. In the early 1990s, other technologies such as fused deposition modeling (FDM), laminated object manufacturing (LOM), and selective laser sintering (SLS) were introduced commercially. FDM technology is the most popular and widespread method of FDM, in which the parts are produced in layers and by extrusion of thermoplastic materials. Ease of fabrication of complex geometries, lightness, and low cost are the factors of rapid development of thermoplastic parts made by FDM in various fields of engineering and medicine. Today, due to the importance of the mechanical properties of these materials, many studies have been performed on various thermoplastics such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) polymers to estimate mechanical properties[1-6].

These AMed materials could be widely used in aerospace and automotive industries besides the biomechanics application, especially in the case of composite materials[6-7]. Therefore, predicting mechanical properties and the fatigue lifetime in these parts, which are fabricated by 3D-printing, is important for designers. Especially they should know knowledge of the quality of 3D-printed materials, which is one of the most problems in the AM technique[1,4].

Afrose et al.[8] investigated the effects of fabrication orientation on the fatigue behavior of PLA materials produced by FDM. The results showed that in static loading, X orientation had more tensile stress but in terms of 45° tensile cycle loading, it investigated longer fatigue lifetime. Letcher et al.[9] performed material properties tests on 3D-printed samples of PLA polymer. They produced samples of tension, bending, and fatigue in the 0, 45, and 90° layered directions. The results indicated that the 45° laminate had the highest final tensile strength. Zero-grade laminate also had the highest bending stress, and no behavior was evident in the fatigue tests. Lee et al.[10] performed fatigue analysis on materials produced by FDM for ABS. They studied fatigue lifetime at different stress levels for ABS and ABS+ by utilizing the S-N curve for the comparison of two materials. Miller et al.[11] studied the fatigue behavior of urethane polycarbonate produced by a 3D-printer, and found that the FDM method had better properties in tensile, compressive, shear, and tensile fatigue than the injection molding method. Ziemian et al.[12] studied the tensile behavior and fatigue of ABS laminate. Tensile and tensile-tensile tests were performed on standard samples produced by FDM in different directions (90, 75, 60, 50, or 45). The results illustrated that the best performance at the final tensile strength is for zero degrees orientation, while the fatigue lifetime was reported to be higher for specimens with the 45° angle. Ziemian et al.[13] reported the characteristics of stiffness degradation due to fatigue damage in multilayer parts made by the FDM method. It was shown that the zero-angle parts had a completely different pattern of damage. They also presented a nonlinear model of cumulative damage.

Senatov et al.[14] studied the fatigue behavior of porous scaffolds made of PLA with a 3D-printer, in which decreased height, pore loss, delamination, bending and shear cutting, crack growth, and propagation were observed during cyclic loading. Jerez-Mesa et al.[15] studied the fatigue lifetime of PLA components based on sensitivity analysis, and revealed that the filling density, nozzle diameter, and layer height had the greatest effect on fatigue lifetime. Safai et al.[16] reviewed the fatigue behavior of polymers produced with 3D-printers. They indicated that for fatigue resistance, there is a relationship between print parameters and material properties, and that printing in the direction of 45 degrees and higher material density in the parts also led to better fatigue resistance. Arbeiter et al.[17] presented the characteristics of fracture mechanics and lifetime estimation of samples produced by the FDM method, and argued that the direction of fabrication has no effect on the number of cycles leading to crack formation and crack growth and the Paris relation can be used for such parts. Ezeh et al.[18] studied the fatigue strength of PLA, which was effective in making the material. They indicated that such materials, which are made from AM techniques, could be considered homogeneous isotropic materials.

The mechanical properties of a built part depend on several process parameters[19]. Some researches have been performed recently to characterize the effect of these parameters such as the extruder temperature[20-21], the platform temperature[22], the print speed[22], and the print orientation[23] on the mechanical performance of AMed parts. Gomez-Gras et al. [24] studied the fatigue performance of PLA samples. They examined the parameters of layer height, filling density, nozzle diameter, and velocity on fatigue lifetime and investigated that the filling density of the material is the most effective parameter during fatigue lifetime, followed by nozzle diameter and layer height. Dezianian et al.[25] investigated the effect of layering direction on bending fatigue lifetime and fracture levels in PLA material, made by AM technique, at specific stress. The results depicted that the fatigue lifetime of the hollow specimen printed in the transverse direction was longer than the specimen printed in the longitudinal direction. Examination of the fracture surfaces also showed that the presence of defects between the printed layers was evident in both samples. In addition, the fracture surface in the sample printed in the longitudinal direction was a flat plate, while in the fracture surface of the sample printed in the transverse direction, there were plates such as cleavage planes, which indicated the brittle fracture in the material. Azadi et al.[26] presented a study of the fabricating direction by FDM on the bending fatigue properties of the PLA polymer. The properties of bending fatigue were investigated at three stress levels and a stress-lifetime diagram was drawn. The results illustrated that the fatigue lifetime of printed parts in the transverse direction was longer than the samples printed in the longitudinal direction.

As the ABS polymer has been widely used in the automotive industry, a comparative study was done on fatigue properties of 3D-printed and extruded ABS polymers. The common fabrication method in the industry is the extrusion process, which could be substituted with the AM technique[27].

In this research, the influence of the FDM fabricating direction on the high-cycle bending fatigue properties of 3D-printed ABS polymer was investigated. Therefore, dog-bone specimens were tested under cyclic bending loadings. It is worth noting that testing on dog-bone shape as the standard specimen, compared to flat-shaped or hollow ones, can be the novelty of this article. The sample shape will affect the performance of the 3D-printed materials, especially for smart structures[1]. Moreover, the results of 3D-printed samples were compared to the fatigue lifetime and the fracture behavior of the extruded ABS polymers, as another innovation.

2 MATERIALS AND METHODS

2.1 Fabrications Process

One of the most important and widely used commercially produced polymers is the ABS polymer, which is a thermosetting copolymer with an amorphous structure consisting of three Acrylonitrile, Butadiene, and Styrene monomers. As mentioned in the introduction, balanced mechanical, thermal, and chemical properties render this inexpensive plastic one of the most widely used plastic raw materials in various fields such as pipes and fittings, electronic equipment, enclosures and coatings, vehicle components and it is useful to build prototype models[28].

Standard dog-bone fatigue test specimens were fabricated by a 3D-printer using FDM. Samples were fabricated in both longitudinal and transverse directions and made of ABS. The sample dimensions and 3D-model were given to the 3D-printer are shown in Figure 1. This dimension was selected based on the ISO-1143 standard (2010); however, it was for metallic materials-rotating bar bending fatigue testing. In the FDM 3D-printer, the sample is fabricated by depositing the molten raw material, in a predetermined path, by computer and layer by layer. The raw materials used in this type of printer are thermoset polymers in the form of filaments. The 3D-printer used in this research was the Author-M-Pro model (3DPE Company).

The nozzle temperature of the device was 245°C and the bed temperature was considered to increase the print quality, 60°C. The density of the samples in the two initial and final layers was 100% and in the inner part, 50% (with a square pattern). The perimeter speed of the device and the infilling speed inside the part were 50 and 60mm/s, respectively. These process parameters were selected based on the literature[23,25,26,28,29].

For extruded parts, initial ABS extruded rods with a diameter of 20mm and a length of 100cm were provided from the ASP Company with TEPHLON® brand. Then, the rods were machined to have 9mm of diameter and lastly, the final geometry of the fatigue testing sample was fabricated with the CNC machine.

In addition, the nozzle diameter was 0.4mm and the layer was 0.15mm. The actual image of the standard dog-bone samples of the fatigue test and print direction is shown in Figure 2. According to Figure 2, at the bottom of the samples, a separator (raft) was included to prevent the sample from sticking to the print plate (bed). Moreover, to increase the fabrication accuracy, in the middle part of the sample printed in the transverse direction, a holder (support) was included which was not used in the longitudinal sample. Notably, both the support and the raft were removed before testing.

2.2 Fatigue Testing

In this research, a rotary bending fatigue device with the trade name “SFT-600” from Santam Company (shown in Figure 3) has been used to perform cyclic tests through a high-cycle fatigue regime. The sample with standard dimensions was clamped between the two fixtures of the

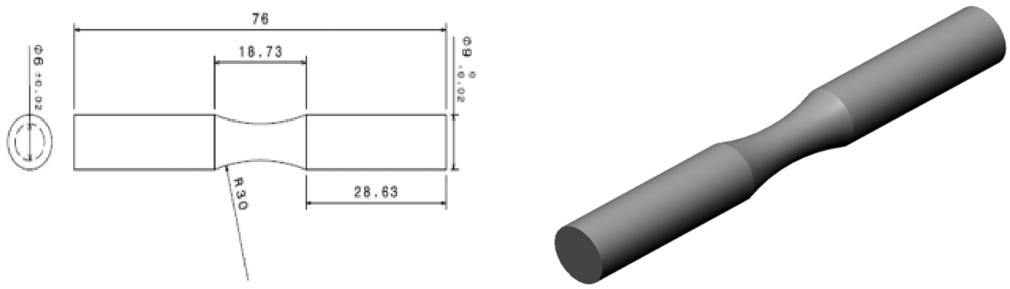

Figure 1. The dimension of the dog-bone sample for fatigue testing and the 3D-model for 3D-printing.

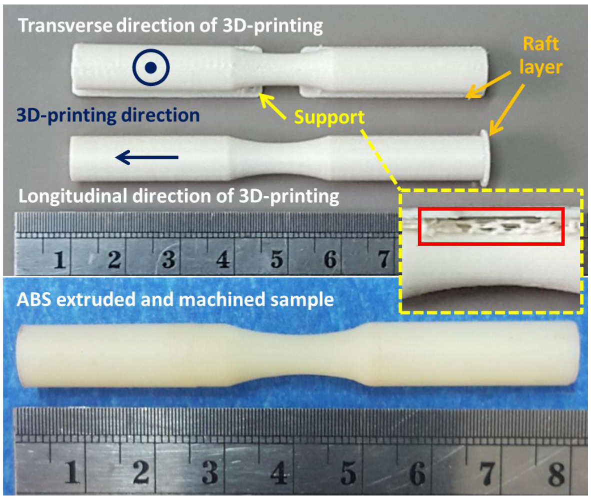

Figure 2. Extruded and 3D-printed standard samples for fatigue testing.

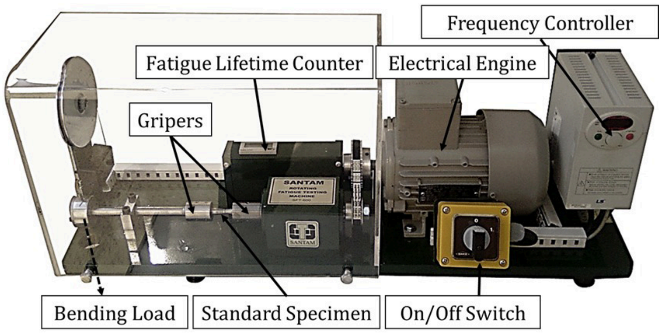

Figure 3. Rotary bending fatigue testing device.

device and was fastened by 6 screws. In the fatigue testing machine, the sample was subjected to a fully-reversed bending load under stress-control conditions, in which the ratio of minimum stress to maximum applied stress was equal to -1. All fatigue tests were performed at 100Hz of loading frequency at room temperature. The bending fatigue test was performed at the stress levels of 5-25MPa, and for the repeatability, at least 3 tests were performed at each stress level.

In order to derive fatigue parameters such as coefficient and strength of fatigue strength, Equation 1 has been used[30].

$$\sigma_a = \acute{\sigma}_f (N_f)^b \qquad (1)$$

where the amplitude of the stress represents σ_a in MPa, N_f is the number of cycles leading to failure, and b and $\acute{\sigma}_f$ as well as the exponent and the coefficient of fatigue strength. Using the fitting of the curve at the logarithmic scale, the stress-lifetime curve characteristics are obtained.

2.3 Morphological Examination

After performing the fatigue test, failure mechanisms were observed in two standard test specimens in the longitudinal and transverse directions and at a stress level of 10MPa. Moreover, the fracture surface was examined at 17.5MPa for the extruded sample. Since the samples are not conductive, the fracture surfaces were coated with gold before observation. The image of the samples was observed by scanning electron microscopy.

3 RESULTS AND DISCUSSION

3.1 Fatigue Experimental Data

As the first important issue, the infill effect is significant on the strength, the fatigue lifetime, and the weight of 3D-printed materials[29,31]. Therefore, to eliminate the direct effect of the infill parameter, it is better to consider the ratio of material properties to the weight of the sample, as also mentioned in the literature[31].

Based on the experimental data obtained from the high-cycle bending fatigue test, the stress-lifetime diagram, on a logarithmic scale, was obtained for the samples printed in both longitudinal and transverse directions (with the 50% infill), plus the extruded ABS material. This diagram is shown once for all test data and again for the mean data at each stress level, in Figures 4 and 5, respectively. It should be noted that similar S-N curves were reported for ABS polymers by the literature[10].

Moreover, the strength and fatigue strength coefficient for longitudinal and transverse ABS samples with the minimum coefficient of determination (R^2), 88% is calculated and shown in Table 1. The amount of fatigue strength for the longitudinally printed sample was more negative than the transverse position. The fatigue strength coefficient was also calculated for the longitudinal sample more than the transverse sample. These two fatigue strength coefficients were higher than the values for the extruded ABS polymer. However, the fatigue lifetime of the extruded samples was higher than those of 3D-printed specimens. As another interesting result, the scatter-band for the extruded sample was wider than the printed specimens, which showed the quality of the 3D-printing process was similar for all samples but the fabrication variation was higher through the extrusion of ABS polymers. It should be noted that the infill percentage was 50% for 3D-printing.

Notably, as it could be seen in Figure 4, the stress levels for 3D-printed and extruded samples were different, since the fatigue strength was different. Under lower stresses for extruded materials, the lifetime increased more than 3 million cycles, which was time-consuming. Therefore, higher levels were considered for the extruded sample. Moreover, when the objective is the stress-to-weight ratio, data for both types of materials would be in a similar range, as shown in Figure 6.

According to Figures 4 and 5, the bending fatigue lifetime of transversely printed specimens was longer than that of longitudinal specimens. It is important to note that as the stress level increased, the fatigue lifetime of the specimens approached. For example, at the stress levels of 5 and 10MPa, the average fatigue lifetime of the transverse specimens improved by 73% and 70% compared to the longitudinal specimens, respectively. While at high stresses such as 15MPa, the high-cycle bending fatigue behavior was almost similar for both print directions.

The result of research by Ezeh et al.[18] showed that the fatigue strength of materials was effective in terms of material fabrication. In this research, it has been effective on the properties of fatigue for fabrication. Consistently, a similar effect could be seen in this research. Studies by Lee et al.[10] and Ziemian et al.[12] also investigated that in ABS polymer, transverse specimens printed in the transverse direction had a longer fatigue lifetime than longitudinal specimens, which is consistent with the results of this study. In addition, the results from Azadi et al.[26] demonstrated that the lifetime of bending fatigue for dog-bone and hollow PLA samples printed in the transverse direction was longer than the sample printed in the longitudinal direction. In another study conducted by Letcher et al.[9], for PLA polymers, the fatigue lifetime of transversely printed specimens was longer than that of longitudinal specimens. These results are in an agreement with the presented results.

Notably, if the samples would have 3D-printed at 100% infill, it would have increased the mass of the specimen, which might have changed the fatigue properties and increased the lifetime. Therefore, 50% infill was considered to reduce the excess amount of material used. The weight of samples was 3.3 and 4.4 gram for 3D-printed and extruded ones, respectively. This parameter could be considered as another objective for normalizing the experimental data. If the objectives were selected as the ratio of the stress and the weight and also the ratio of the fatigue lifetime and the weight, Figure 4 would be changed to Figure 6. In this case, experimental results for extruded and 3D-printed specimens were closer, since the weight was reduced in 3D-printed samples by about 33%, compared to extruded ones. Due to the higher density of extruded parts (without any porosities), the performance is better, as expected. In the extruded ABS, the material becomes denser and therefore, it is stronger. Here, the air gap (or the infill percentage) and also the print direction are crucial parameters. Under static testing, it can make the effect of changing the print direction insignificant, as mentioned in the literature[32]. Moreover, considering the ratio of stress to weight, the infill percentage has no direct effect on the material behavior[31].

3.2 Microscopic Investigations

Fracture surface images with scanning electron microscopy for two samples in the longitudinal and transverse directions with a magnification of 200 microns are shown in Figure 7. The printing schedule, the layer direction, and the square pattern used in fabricating the samples can also be seen in this image. Figure 8 depicts the fracture surface with two types of magnification for the sample printed in the longitudinal direction.

The failure surface in this example was a flat plate, which was the interface between the two layers. In other

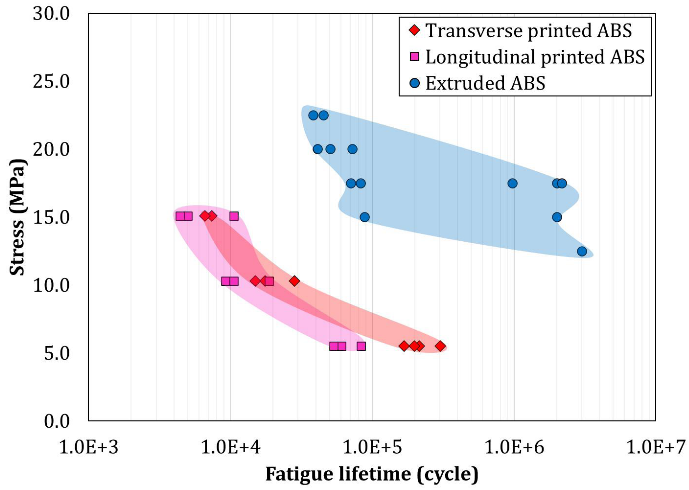

Figure 4. The stress-lifetime diagram for all experimental data.

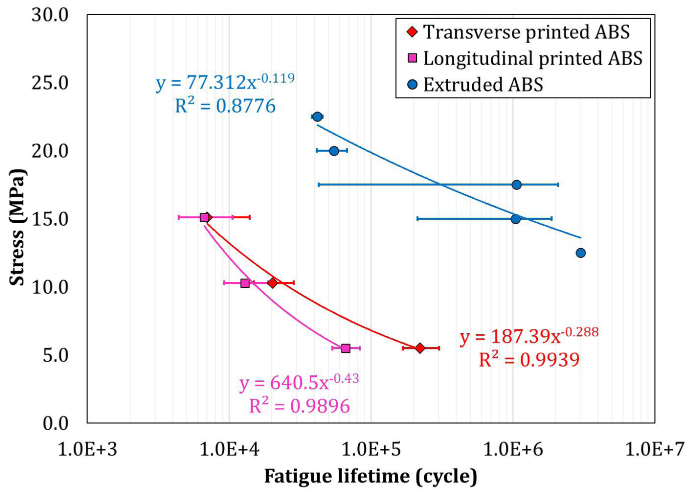

Figure 5. The stress-lifetime diagram for average data.

Table 1. Material Constants for High-cycle Fatigue of ABS Polymers Based on Average Data

Sample Type	$\acute{\sigma}_f$	b
Transverse printed ABS	187.39	-0.288
Longitudinal printed ABS	640.47	-0.430
Extruded ABS	77.31	-0.119

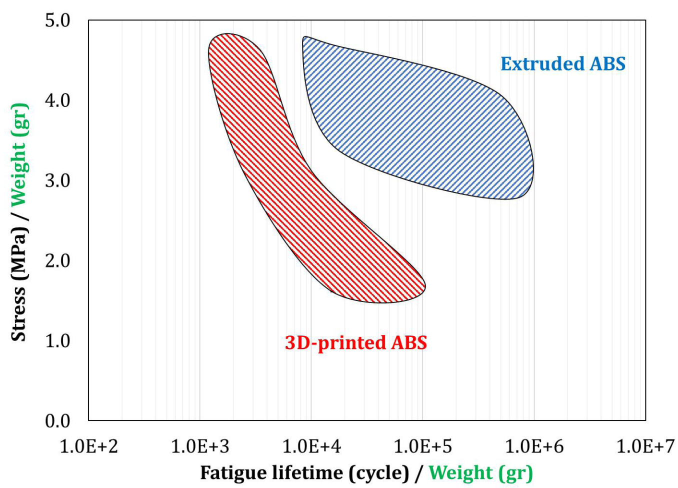

Figure 6. The stress-lifetime diagram for all experimental data considering the sample weight.

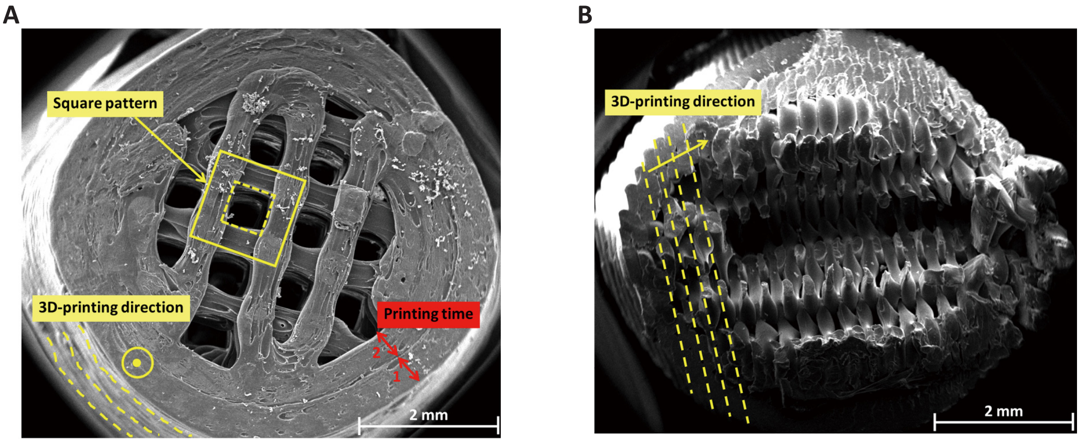

Figure 7. Printing direction, layer direction, and the square pattern in A the sample printed in the longitudinal direction and B the sample printed in the transverse direction.

words, this sample failed based on a smaller number of fatigue lifetime cycles, which is consistent with the results of the fatigue test. Azadi et al.[23] also obtained similar results for PLA samples under a load of high-cycle fatigue. In the figure at higher magnification, defects are seen between the printed layers. These defects can be classified into two categories of pores and unmelted areas. The presence of pores is mainly due to the formation of vapor during the fabrication of the part and they are spherical and the unmelted areas are due to poor metallurgical bonding between the layers, or so-called lack of fusion and have an irregular and grooved shape. These defects are visible in Figure 8. Ghasemi Ghalebahman et al.[33] have observed these defects for polymer composite parts. Sayar et al.[34] also observed various defects in glass/epoxy fiber composites. Analysis of fatigue failure surfaces in these samples demonstrated that the failure was caused by cavities located near the surface of the parts. Such gaps provide the concentration level of stress necessary to initiate cracks in a smaller number of fatigue cycles. Although the mechanisms of crack initiation depend on the applied stress level, defects (pores and non-melted areas) with a larger size, irregular shape, and closer to the surface, have more effects on the fatigue lifetime of the parts.

Yadollahi et al.[35] in a study investigated the low-cycle lifetime for ABS components. They have observed these defects at the failure levels and have achieved a similar result. Senato et al.[14] investigated fatigue lifetime for PLA/hydroxyapatite porous scaffolds. They also observed the destruction from points adjacent to the abutment and close to the surface. Moreover, failure level studies demonstrated that the failure occurred as a flat plate and in the joint between the printed layers, which is consistent with the results of this study.

In a different result for non-polymeric materials, Bagheri et al.[36] in fatigue tests on nitinol indicated that regardless of the location, shape, and size of the defect, the fatigue lifetime for this sample with a higher stress level was always shorter. Observations have shown that the maximum stress level may be the most influential factor in the fatigue behavior of nitinol, fabricated by AM techniques.

Figure 9 depicts the fracture surface with two types of magnification for the sample printed in the transverse direction. According to this figure, pages such as cleavage planes are seen on the failure level. This type of failure is related to brittle failure in the material. According to this figure, inside each of the cleavage plates, there are shaped beach marks that indicate cyclic loading. The distance between these lines can estimate the fatigue lifetime of the sample. Serra et al.[37] also observed such plates for PLA-based composites. Gomez-Gras et al.[24] observed brittle fractures in the inner layers and ductile fractures in the outer layers for PLA samples with a density of 25%. They attribute this to more space between the strands, which causes the outer layers to deform plastic before breaking.

In the samples used in this study, a density of 100% has been considered for the outer layers, which according to observations of Gomez-Gras et al.[24] can be a reason for the brittle failure of the part. Kulshreshitha et al.[38] investigated the failure levels for impact-fractured ABS/Polyvinyl chloride. They also observed two types of ductile and brittle behavior at the failure level.

In Figure 10, the fracture surface of the extruded ABS sample could be seen, which was exactly different from 3D-printed specimens in the longitudinal direction. The fracture surface was flat and only severe plastic strains could be observed in a small region of the sample, similar to the 3D-printed specimen in the transverse direction. Therefore, the fracture behavior is brittle for the extruded ABS material. Such a flat surface and brittle behavior were also reported by the literature[39]. Mura et al.[39] presented 12MPa for the fatigue limit of ABS polymers (fabricated by the mold injection) at room temperature, which was similar to data in Figure 5 (10-15MPa at 3×10^6 cycles for the extruded sample).

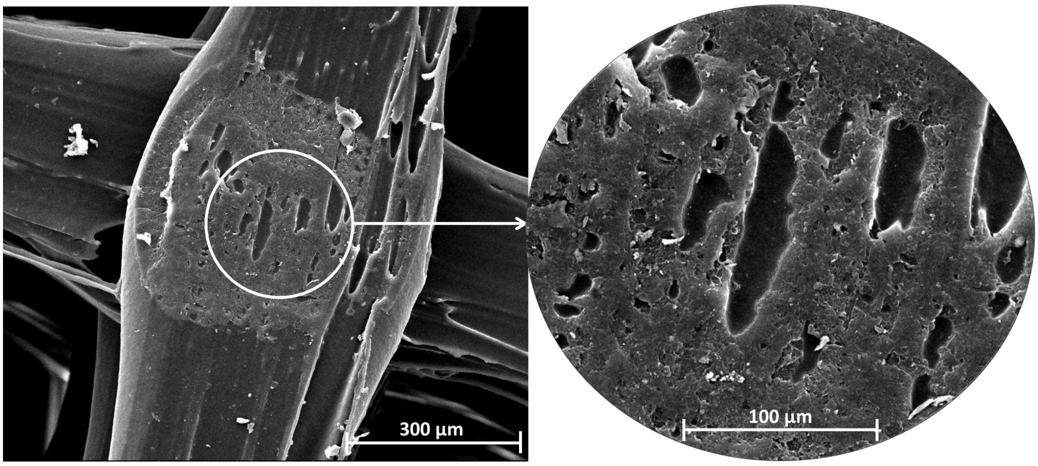

Figure 8. Fracture surface images in the sample printed in the longitudinal direction with more magnification.

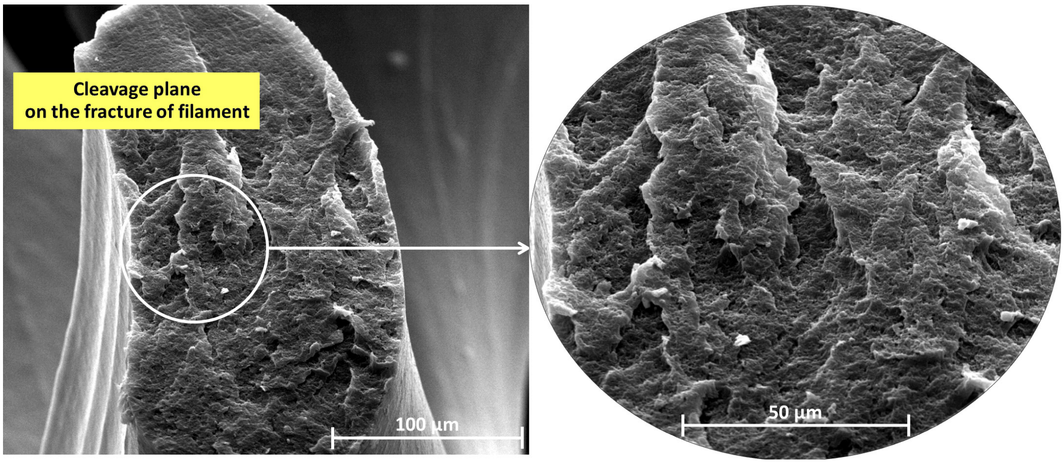

Figure 9. Fracture surface images in the sample printed in the transverse direction with more magnification.

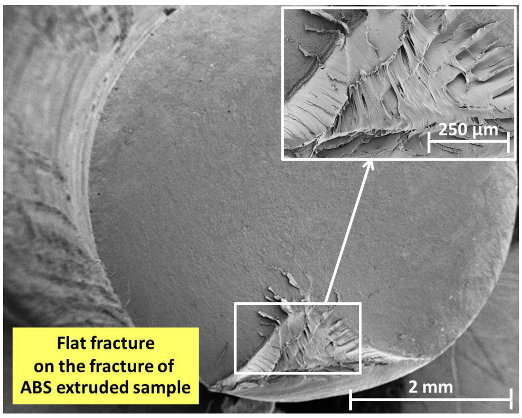

Figure 10. Fracture surface images in the extruded ABS sample.

Based on Figure 10, as mentioned, some plastic zones could be seen on the final fracture rougher region of the extruded ABS specimen. They are similar, but not exactly, to the fibrillation or Hackle marks in some cases for 3D-printed ABS samples[40]. Hackle marks with the mirror-like appearance are the reason for the poor adhesion between the filaments through the crack growth. Moreover, crack propagation leads to the fibrillation of the filaments at the crack tip[40].

4 CONCLUSIONS

In this study, the effect of printing direction in FDM on the high-cycle bending fatigue properties for ABS polymer fabricated with a 3D-printer was investigated and compared with the extruded ABS. For this purpose, cylindrical standard samples were fabricated in two directions of longitudinal and transverse by the 3D-printer device, and the stress-lifetime curve was calculated after performing bending fatigue tests under stress levels of 5-25MPa.

Experimental results showed:

- Dog-bone ABS polymer samples printed in the longitudinal direction had a more negative fatigue strength, higher fatigue strength coefficient, and shorter high-cycle bending fatigue lifetime than the transverse samples.
- The effect of the print direction is less pronounced at lower stresses, while at higher stresses, the high-cycle bending fatigue behavior of both ABS polymer dog-bone specimens printed in the longitudinal and transverse directions was almost the same. Such a conclusion could not be described for the extruded ABS under either low- or high-cycle fatigue regimes.
- The fracture surface in the sample printed in the longitudinal direction was a flat plate and included a joint between the two layers. On the fracture surface of the transversely printed specimen, there were plates such as the cleavage markings, indicating the brittle fracture of the material. In addition, the fracture behavior of the extruded ABS polymer is brittle with a flat surface and severe plastic strains in a small zone.
- Considering the weight of 3D-printed samples as an objective, the scatter-band of normalized fatigue testing data was close to those of the extruded ABS material.

For future works, it is suggested to obtain similar mechanical behaviors (strength, fatigue lifetime, etc.) to extruded samples by the 3D-printed parts with lower weight be an objective. Such metamaterials merit applications in automotive and aerospace industries, besides biomechanics issues.

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Conflicts of Interest

The authors declared that there is no conflict of interest for this research. Moreover, Dr. Mohammad Azadi, as one of the authors in this article, has declared that he is also the Editor-in-Chief of the International Journal of Additive-Manufactured Structures (IJAMS, ISSN 2789-5017). Therefore, for this manuscript, another editorial board member is assigned and handled the editor's responsibility for overseeing the peer-review process and the final decision.

Author Contribution

Azadi M conceptualization, methodology, validation, investigation, resources, writing-review & editing, supervision, project administration, funding acquisition; Dezianian S software, formal analysis, investigation, data curation, writing-original draft; Parast MSA software, validation, investigation, data curation, writing-original draft; Bagheri A investigation, resources, visualization, funding acquisition; Kami A conceptualization, investigation, resources, visualization, funding acquisition; Dadashi A software, formal analysis, investigation, data curation, writing-original draft; Kianifar M software, formal analysis, investigation, data curation, writing - original draft; Asghari V investigation, resources, visualization, funding acquisition.

Abbreviation List

ABS, Acrylonitrile butadiene styrene
AM, Additive manufacturing
FDM, Fused deposition modeling
LOM, Laminated object manufacturing
PLA, Polylactic acid
SLS, Selective laser sintering
b, Exponent of fatigue strength
$\acute{\sigma}_f$, Coefficient of fatigue strength in MPa
σ_a, Stress amplitude in MPa
N_f, Cycles to failure
3D, Three-dimensional

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