INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 12, Issue 2, 2021 pp.115-128
Journal homepage: www.IJEE.IEEFoundation.org

A Study on the Influence of Stress Ratio and Loading Mode on Fatigue Life Characteristics of Porous Functionally Graded Polymeric Materials

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Received 5 Aug. 2021; Received in revised form 28 Sep. 2021; Accepted 2 Oct. 2021; Available online 1 Nov. 2021

Abstract
In this paper, fatigue life tests on 3D printed plain cylindrical specimens made of porous functionally graded polymeric materials (PFGPMs) at room temperature were carried out. Test results are obtained for constant amplitude load in fully reversed bending with mean stress equal to zero with various porosity and gradient index parameters. Fatigue characteristics were evaluated experimentally using the stress life approach. FEA simulations have been performed for smooth specimens using three types of loading modes (Reverse Bending, Reverse Axial, and Reverse Torsional). Numerical Analysis (FEA) and experimental results are used to highlight the effect of stress ratio (R) on fatigue life. Five values of the stress ratio were used in the reversed bending test (R = -1, 0, 0.25, 0.5, and 1). Test results showed that specimens subjected to reversed bending had a greater life than those subjected to axial and torsional loading modes, respectively. According to the results, the specimen's life increased as load ratios increased, and there was a maximum discrepancy of 8% between experimental and numerical work. The fatigue limit value is influenced by both the porosity parameter and the gradient index.

Keywords: Stress life approach; S-N curve; Loading mode; Stress ratio; Fatigue life; FEA.

1. Introduction

Functionally graded materials (FGMs) are a class of advanced materials in which the structural properties are graded in the thickness direction [1]. Porosity gradients are FGMs in which the change in density or pore size of the material through part layers is used to enhance its characteristics. They can be made with various materials using 3D printing technology. PFGM that provides lightweight and sufficient mechanical stability properties can be found in metallic and polymeric foams. Among a variety of other uses, polymers are a versatile and essential material used in energy, aerospace, and biomaterials for their effectiveness in absorbing impact loads and controlling static and dynamic responses, [2].

It has been estimated that 90 % of all service failures of metal parts are caused by fatigue. The fatigue process undergoes several stages and from an engineering point of view, it is convenient to divide the fatigue life of a structure into three stages: fatigue crack initiation, stable crack propagation, and unstable crack propagation [3]. Q. S. Wang et al. [4] studied the fatigue behavior of functionally graded Ti–6Al–4V mesh structure under identical bulk stress conditions. It is found that fatigue cracks first initiated in the lowest strength constituent, and then propagated until structural failure occurred. Saeede et al., [5] investigated the effect of microstructural anisotropy on the fatigue crack growth behaviour of the functionally graded Inconel 718 fabricated through laser powder bed fusion (L-PBF). Different manufacturing parameters, including low and high laser powers, were used to produce a variety of non-graded (NG) and in two build directions, vertical and horizontal. Nezhadfar et al. [6] used experimental and numerical methods to study the thermal fatigue characteristics of additively manufactured Inconel 718 samples subjected to alternating stresses.

Gribbin et al. [7] conducted comprehensives to study the impact of porosity on fatigue behavior of Inconel 718 alloy at room and elevated temperatures. To analyze the influence of selective laser melting defects on the static and fatigue properties of uniformly and porosity-graded materials, Dalia Mahmoud et al. [8] developed a finite element analysis model. According to the results, fatigue strength depends on surface quality and internal defect percentages. Cao et al. [9] investigated the effects of material gradients on crack propagation behavior of titanium alloy FG beams. Various stress intensity factors of cracked samples were determined by modifying the M-integral. Experimental results of crack propagation using the 3D printing technique are employed to validate the theoretical results. An experiment using quasi-static compression and a mathematical model for the mechanical properties of graded Ti-6Al-4V lattice structures fabricated by laser powder bed fusion was conducted by Long Bai et al. [10]. Fatigue failure is identical to static compression in that it produces local brittle crushing and obvious shear band failure. A porous titanium structure produced by selective laser melting was studied by Liu et al. [11]. A porous parameter and the material properties can affect the initiation of fatigue cracks, which in turn can have an impact on fatigue life. Dental implants have been studied using static and fatigue loading by Darwish et al. [12].

The constant amplitude fatigue tests are being carried out on all-on-4 custom-made implant systems to determine which types of implants are better for use under different graded multidirectional forces. Ahmadi et al. [13] investigated the topology and material type characteristics on fatigue performance of additively manufactured meta-biomaterials using various experimental analyses. Razavi et al. [14] examined the impact of geometry properties on quasi-static and fatigue behavior of Ti-6Al-4V produced by electron beam melting and additive manufacturing. Using both experimental and numerical analysis, Krijger et al. [15] investigated how stress ratios affected the fatigue properties of a porous titanium biomaterial produced via 3D printing. Various stress ratios were employed (i.e. R = 0.1, 0.3, 0.5, 0.7, and 0.8) and fatigue constant amplitude was carried out for smooth and notched samples. It is found that in porous structures, the S-N curves move upward with increasing stress ratios. In the references [16-19], fatigue characteristics and mechanical properties of a selective laser melted nickel-base superalloy, Inconel 718, have been assessed based on various analyses. X. Hu et al. [20] investigated the effect of build orientation and stress ratio on the fatigue crack growth behavior of Inconel 625 alloy fabricated by selective laser melting. The results show that the stress ratio plays an important role in identifying the fatigue limit of models selected. The current study aims to investigate the effects of pore size, polymer, and gradient index on the fatigue life characteristics of a porous, functionally graded polymer. The 3D technique was used to create a novel set of fatigue-graded cylindrical samples with varying porosities and polymers. Additionally, a set of non-graded samples with a variety of polymers were manufactured and studied. Further, samples subjected to various load ratios and loading modes were tested and the corresponding data evaluated.

2. Functionally Graded Materials Idealization

In general, four types of schemes are widely used in the representation of functionally graded materials, including (1) Power-law distribution; (2) Exponential law function; (3) Sigmoid function; and (4) Mori-Tanaka form. Each mode has special applications, and in some cases, it can employ more than one scheme for the same model to construct a mathematical idealization. In the current work, the power-law distribution function will be used throughout the material properties. Emad K. et al. [21], presented a method to evaluate the material properties of porous functionally graded materials using a single constituent as indicated below,

$$\mathrm{P(z)} = \mathrm{P_m} - \beta.\mathrm{P_m}\left(\frac{\mathrm{z}}{\mathrm{h}} + \frac{1}{2}\right)^{\mathrm{g}} \tag{1}$$

Here, P_m is the value of the material properties of the metal of the FG part, β is the porosity distribution through-thickness of the FG part, and z is the coordinate drawn from the middle surface in which properties change smoothly via thickness h and g denotes a power-law variation index ($g \leq 0 \leq \infty$)

which describes material property variation in thickness. For the round bar, the term D (diameter of the bar) may be included instead of h in equation 1.

3. Experimental Procedure

3.1 Materials and Sample Preparation

In this work, three types of polymers, including polyethylene, PEEK 30% CF, and Acrylonitrile Butadiene Styrene (ABS) supplied from the international market (China) were employed. Each type has special features distinct from others and is widely used in certain industrial applications. Three-dimensional printing was used to create samples with varying porosities (Beta= 10%, 20%, and 30%).
Various complex shapes that are too complicated to fabricate by ordinary manufacturing processes, such as extrusion, milling, and corrugation, are now possible to manufacture using additive manufacturing (3D printing) and laser cutting [22]. Several advantages over traditional methods can be obtained through the use of additive manufacturing for producing plates, beams, cylinders, and structures. A sample can be made using 3D printing and computer-aided design (CAD) files. The current study utilized a CR-10 Max 3D printer to fabricate all samples for the tensile and fatigue tests.

3.2 Tensile Specimen

Tensile testing is a standard application that was carried out on the microcomputer-controlled universal testing machine type (OLSEN – 50KT) shown in Figure 1. The samples were prepared according to the ASTM D638 standard [23], as shown in Figure 2. The load was applied at a constant rate of 2 mm/min during all tests until failure of the specimen occurred, as in Figure 3. To satisfy an additional accuracy requirement, the average value of six readings for each polymer type was taken, [24-33]; the results are shown in Table 1 and were found to be within standard limits, [34].

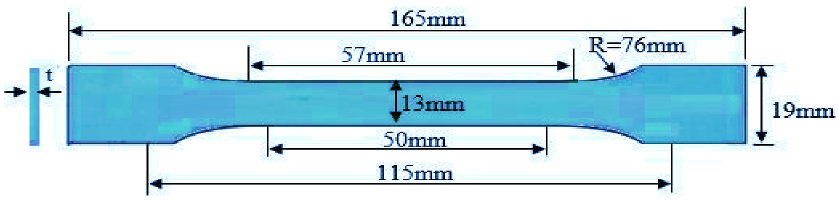


Figure 1. The ASTM D638 dimensions of a tensile specimen.

Figure 2. Tensile specimens manufactured by a 3D printing method.

Figure 3. Tensile test setup.

Table 1. Tensile test results of materials used.

Material	Property		
	σ_u (MPa)	σ_y (MPa)	E (GPa)
Polyethelen	45	38	1.2
Peek 30% CF	130	95	7.7
ABS	64.5	58	3.25

3.3 Fatigue Test

A cantilever bending fixture type WP 140 GUNT was designed to test the specimens based on the critical (i.e. failure) location. A rotating sample is clamped which on one side is loaded with a concentrated force with a maximum capacity of (0.3 KN) with a constant frequency of (50Hz). A sinusoidal cyclic load with a stress ratio R= -1(minimum load/maximum load) is applied throughout the experiment. As a result, alternating bending stress is created in the cylindrical sample following a certain number of load cycles; the sample will rupture as a result of material fatigue. S-N curves are plotted by using software of fatigue instrument presented in PC which is connected directly to fatigue machine, [35-44].

Figures 4 and 5 show the reversed fatigue testing machine and the schematic diagram of the FG specimen. The experiment was conducted by repeating so many similar procedure tests for all specimens. Bending moment values were used to determine the alternating bending stress, which can be determined directly from equation (4). For constant amplitude load, stress ratio (R) can be found by [45],

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad \text{(i.e. R= -1 for reversed bending)} \tag{2}$$

The bending moment M_b is calculated with the load and the lever arm as follows,

$$M_b = F\,.\,a$$
$$W_b = \frac{\pi d^3}{32} \tag{3}$$

By using the section modulus W_b of the sample, it is possible to calculate the alternating stress amplitude as,

$$\sigma_a = \frac{M_b}{W_b} = \frac{32\,F \times a}{\pi d^3} \cong 2F \tag{4}$$

Where, σ_a: is the maximum alternating stress (MPa), F: Applied Force (N), a: bending arm $= 106 \pm 0.1$ mm, d: diameter of the specimen $= 8 \pm 0.1$ mm.

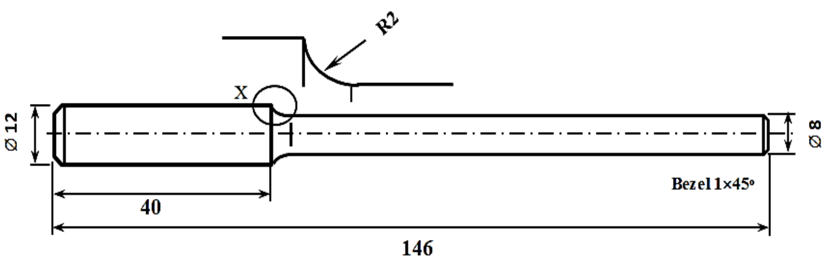


Figure 4. The geometry of test samples according to ASTM specification (all dimensions in mm), [45].

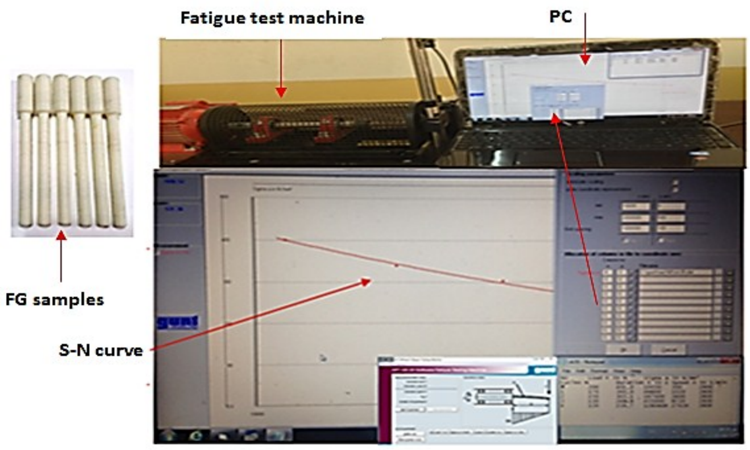


Figure 5. Fatigue experiment setup.

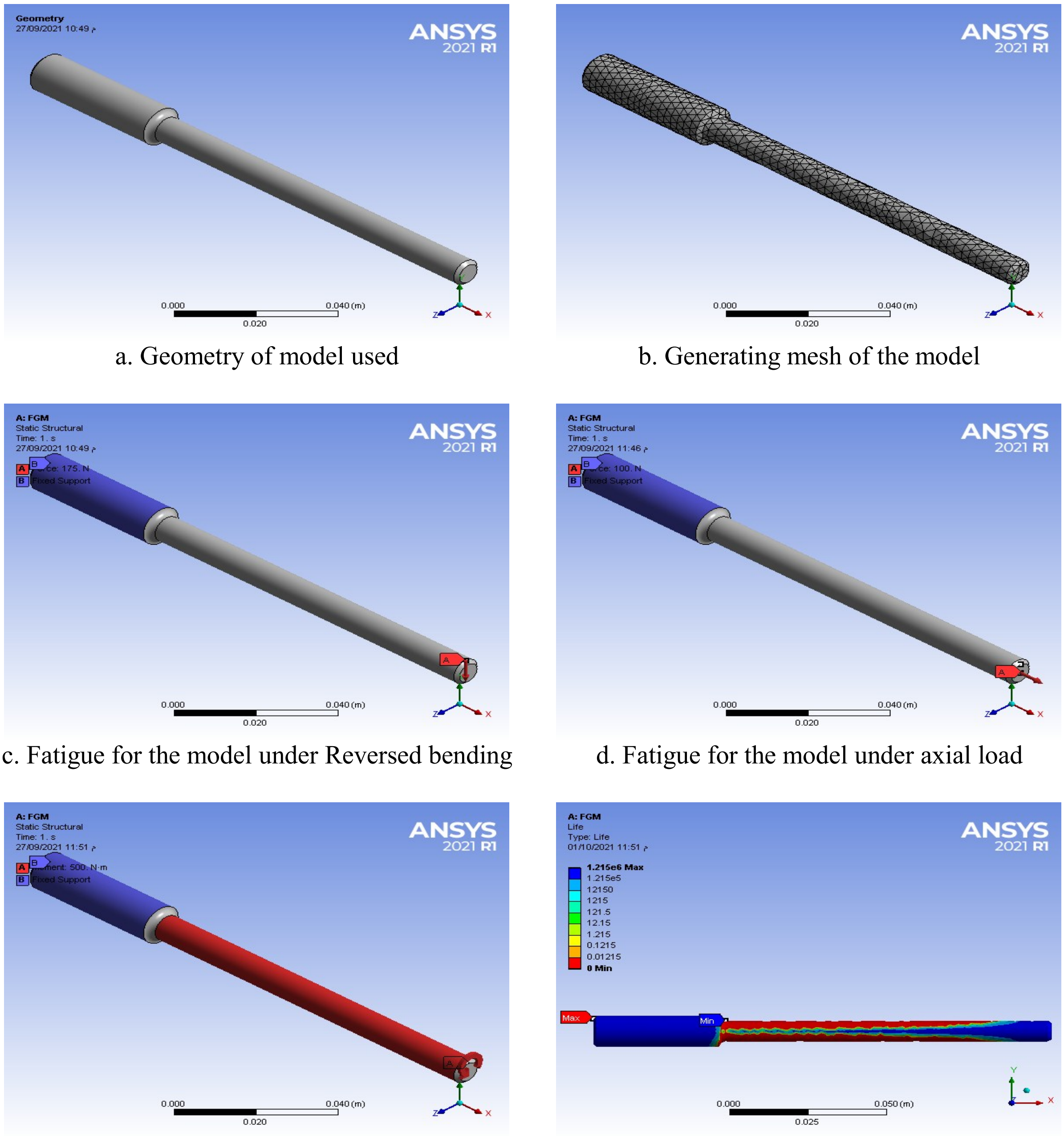
3.4 Fatigue analysis using a stress life model
Data on fatigue is represented graphically by the stress-life curve. A fatigue life function represents the relationship between alternating stress amplitude and cycles to failure. A model known as the Basquin relation is typically used to present an analytical expression of the S-N curve, for finite life (low or high cycle fatigue). It is possible to assess a life prediction using this technique with little information about the material, [46-53]. The Basquin curve can be described as follows, [54],

$$\sigma_a = a\ N_f^{\ b}\ (\mathrm{MPa})$$
$$\tau_a = a\ N_f^{\ b}\ (\mathrm{MPa}) \tag{5}$$

Where, σ_a and τ_a are the fatigue stress and shear stress amplitudes, respectively, n are the number of cycles to failure. Consequently, a and b are constants, and their values depend on the geometry and material. The coefficients a represent the stress-life curve intercept and coefficient b is the fatigue strength exponent. These coefficients can be determined by taking the power law and finding the logarithm of the coefficients. Moreover, the fatigue limit value can be obtained from the fatigue life formula at 10^5 cycles although the value is sometimes not evident on the S-N curve.

4. Numerical Investigation
Using finite element methods (FEM), engineers can simulate various analyses and solve any mechanical problems, including fatigue, creep, and structural analysis [55-62]. ANSYS program was used to perform fatigue analysis where a cylindrical smoothed fatigue specimens with various porosity parameters (Beta= 0.1,0.2 and 0.3) and various volume fraction index (g=0, 0.25, 1, 5) and are modeled and FE simulated results are generated for fatigue three loading modes (Bending, Axial and Torsion) at different stress amplitude by using ANSYS program Version 2020 R1. Solid hexahedral elements (solid187), with 20 nodes were considered. The mechanical properties (Tensile strength, Yield stress, Elastic modulus....etc.) of the selected material and stress life data obtained by experiments on reversed bending machines have been employed in the building model, [63-70], by using Equation 1. The model geometry and element meshes were generated as shown in Figures 6.a and 6.b. The boundary condition for each load type corresponding to the maximum loading condition was given as shown in Figures 6.c, 6.d and 6.e. Through ANSYS results that are common to stress life approach of fatigue analyses include: Fatigue life, Fatigue damage at a specified design life, fatigue factor of safety at a specified design life stress biaxiality, and fatigue sensitivity chart. Figure 6.f shows fatigue life of perfect PEEK 30% CF sample at, under reversed bending load using stress-life approach method.

5. Results and Discussion
In this work, experimental fatigue lives for circumferentially round specimens with various porosities and gradient indices subjected to completely reversed bending loading have been investigated. By using FEA, fatigue analysis based on the stress life approach has been found for cylindrical specimens subjected to completely reversed bending, axial, and torsion. Figure 7 shows the numerical and experimental fatigue life characteristics of Polyethylene porous sample at porosity 10% and gradient index g=0.5. The maximum error between the two methods was found at 9 %. According to the accurate alternating stress corresponding to different amplitude, the S-N curve for the smooth ABS specimens was generated as shown in Figure 8, and the fatigue life equation using the least square method for each type of loading mode was found as shown in Table 2. It is found that specimens subjected to reversed bending exhibit more fatigue life than axial and torsion load respectively. Figure 9 shows the experimental log-log S-N curve for different porosity 10%, power-law index (g=1) for three types of polymers (Polyethylene, ABS, and PEEK 30%CF). From the results, it was found that the fatigue limit of PEEK 30% CF polymer is higher than other types due to high strength, and there is a convergence in fatigue life data between polyethylene and ABS porous polymers. Figure 10-12 shows the shoe fatigue life analysis of the three polymers employed under three types of loading mode, including a porosity ratio of 10% and the gradient index g=1. From FEA results, it is found that the torque loading is less damaging than bending and axial loading in a circumferential bar. On the other hand, it is found that fatigue analysis obtained in torsion and axial loading modes is less affected by porosity compared to bending load.



a. Geometry of model used

b. Generating mesh of the model

c. Fatigue for the model under Reversed bending

d. Fatigue for the model under axial load

e. Fatigue for the model under tension load

f. Fatigue for a perfect model under reversed bending

Figure 6. Numerical procedure for fatigue analysis.

Figure 13 illustrates the S-N curve drawn for three values of porosity parameters (Beta=0.1, 0.2, and 0.3) for cylindrical samples made of PEEK 30% CF polymer at a power-law index (g=0.5). It is observed that S-N curve behavior becomes more significant with a decrease in porosity parameter and there is a convergence in fatigue life data at porosity values of 0.2 and 0.3. Figures 14-16 illustrate the effects of stress ratio on fatigue behaviors for different polymer types using five different stress ratios (R=-1, -0.5, 0, 0.25, and 0.5), for which 0.1 is the porosity parameter and 0.5 is the volume fraction. It is found that a higher stress ratio increases the fatigue limit. According to the results recorded in Table 3, it is noticed that an increase in the stress ratio will increase (a) and (b) (i.e., coefficients of the stress life equation), regardless of the type of polymer used. The accuracy of the predicted life by FEA simulation depends on the selection of an appropriate material model and the accuracy of the value of the material parameters used. It is very important to know that the prediction in this method depends on the correctness of the material total S-N curve generated from experimental results of High Cycle Fatigue data of cylindrical specimens and the accuracy of the simulated value of maximum stress of notched specimens.

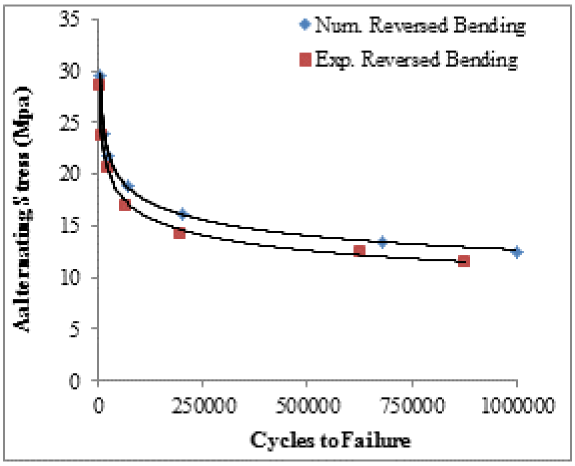


Figure 7. Numerical and Experimental S-N curve at porosity 10%, g=1 for Polyethylene polymer.

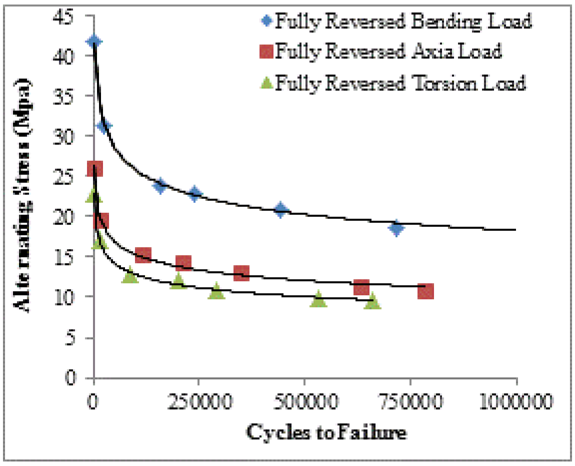


Figure 8. S-N curve perfect ABS polymer under different load modes.

Table 2. Fatigue limit for different loading modes for perfect ABS polymer, Beta=0, numerical analysis.

Case	Fatigue Life Equation	Fatigue limit (Mpa)
Reversed bending	$\sigma_b\ =\ 146.83N^{-0.151}$	25.812
Reversed Axial	$\sigma_a\ ==\ 84.941N^{-0.149}$	15.28
Reversed Torsion	$\tau_a\ =\ 73.818N^{-0.152}$	12.828

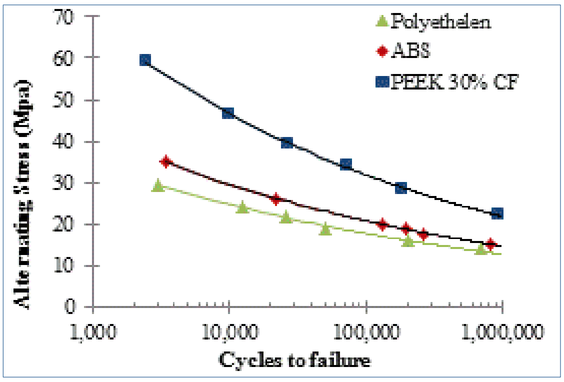


Figure 9. Experimental log-log S-N curve at porosity 10%, g=1 for various polymers.

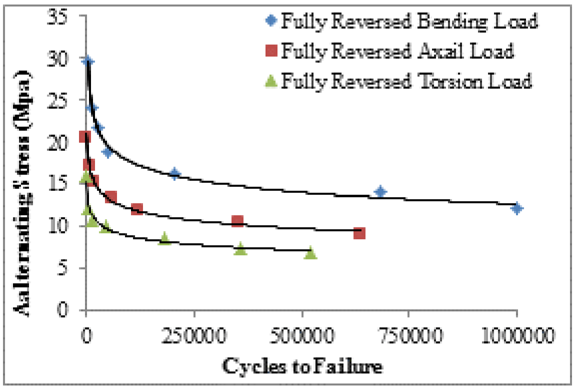


Figure 10. S-N curve for different load conditions at Beta=0.1, g=1, Polyethylene polymer.

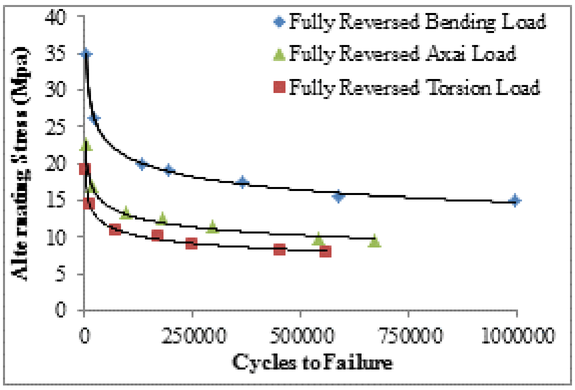


Figure 11. S-N curve for different load conditions at Beta=0.1, g=1, ABS polymer.

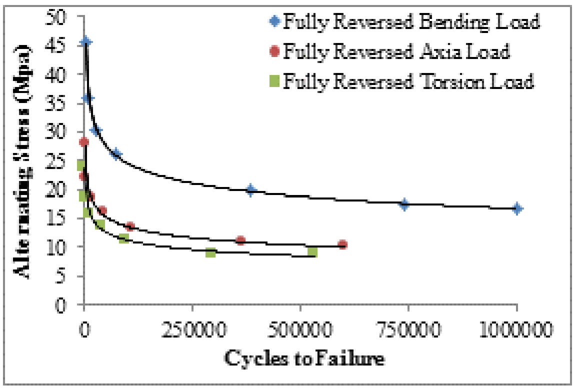


Figure 12. S-N curve for different load conditions at Beta=0.1, g=1, PEEK 30% CF polymer.

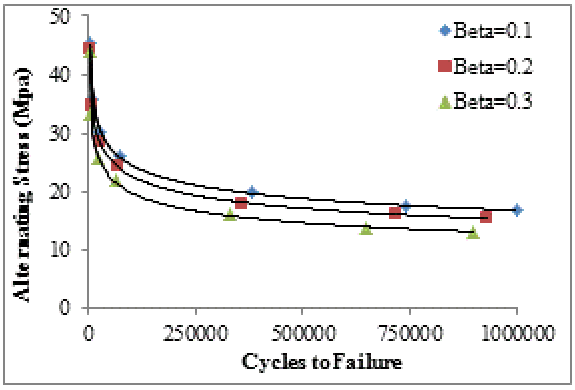


Figure 13. S-N curve for porosity parameters for PEEK 30% CF polymer at g=0.5.

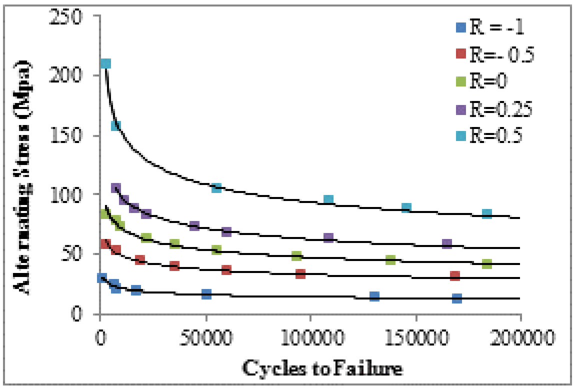


Figure 14. Experimental S-N curve for different R for Polyethylene polymer specimens.

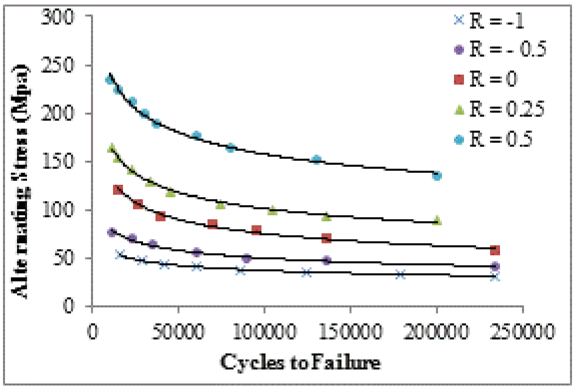


Figure 15. Experimental S-N curve for different R for PEEK 30% CF polymer specimens.

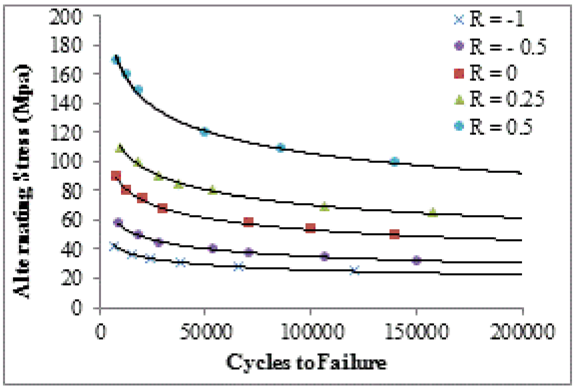


Figure 16. Experimental S-N curve for different R for ABS polymer specimens.

Table 3. The fatigue limit results for different load ratios using numerical investigation, for Porosity=0.1.

Polymer	R	Fatigue Life Equation	Fatigue limit (MPa)
Polyethylene	-1	$\sigma = 111.46N^{-0.18}$	13.994
	-0.5	$\sigma = 246.42N^{-0.176}$	32.484
	0	$\sigma = 393.99N^{-0.185}$	46.825
	0.25	$\sigma = 625.51N^{-0.2}$	62.551
	0.5	$\sigma = 1119N^{-0.216}$	93.07
ABS	-1	$\sigma = 235.63N^{-0.192}$	25.8363
	-0.5	$\sigma = 381.09N^{-0.207}$	35.185
	0	$\sigma = 566.21N^{-0.205}$	53.45
	0.25	$\sigma = 670.38N^{-0.196}$	70.197
	0.5	$\sigma = 1008.6N^{-0.196}$	105.613
PEEK 30%	-1	$\sigma = 348.43N^{-0.194}$	37.334
CF	-0.5	$\sigma = 594.95N^{-0.215}$	50.06
	0	$\sigma = 1463.3N^{-0.257}$	75.916
	0.25	$\sigma = 1268.5N^{-0.219}$	101.927
	0.5	$\sigma = 1417.4N^{-0.191}$	157.214

6. Conclusions

In this work, a novel study of the bending fatigue life of plain specimens of various porosity distributions and gradient exponents under constant amplitude load using stress life load and high cycle fatigue (HCF) was investigated by experiment and the FEA method. The material properties are calculated according to the suggested mixing rules. A comprehensive comparative study was carried out with numerical techniques to verify the accuracy of the experimental solution.

The current work's main conclusions are described:

1. The results show that fatigue limits decrease with increasing porosity factors and increase with increasing gradient indices.
2. According to the study, the fatigue life of samples increases with an increase in tensile strength property at the same ratio as R = 0.5. Consequently, there was an increase in compressing stresses in the region near the fixed end, resulting in an improvement in fatigue strength.
3. It is found that fatigue analysis obtained in torsion and axial loading modes is less affected by the porosity distribution compared to bending load.
4. Under reversed bending conditions, changing the porosity parameter from (Beta =0.1) to (Beta=0.3) reduces the fatigue limit bending load by 19.43% for PEEK 30% CF polymer at g =0.5.
5. From the results, it is also found that fatigue ratio (σL /σu) under reversed bending for Polyethylene sample was equal to 31%, PEEK 30% CF was 19.87%, while for ABS it was 58% respectively.
6. Increasing the stress ratio R from -1 to 0.5 results in an increase in fatigue limit of 76.25 % for PEEK 30% CF, 75.5 % for ABS, and 84.96 % for polyethylene under the same conditions.

Acknowledgment

Both of University of Technology and Kufa University, colleges of engineering, mechanical department, partially supported this research.

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