Fatigue Characterization for Composite Materials used in Artificial Socket Prostheses with the Adding of Nanoparticles

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Abstract. The prostheses sockets use normally composite materials which means that their applications may be related with the human body. Therefore, it was very necessary to improve the mechanical properties of these materials. The prosthetic sockets are subjected to varying stresses in gait cycle scenario which may cause a fatigue damage. Therefore, it is necessary or this work to modify the fatigue behavior of the materials used for manufacturing the prostheses sockets. In this work, different Nano particle materials are used to modify the mechanical properties of the composite materials, and increase the fatigue strength. By using an experimental technique, the effect of using different volume fractions for various types for Nano particle materials on the fatigue behavior for composite materials, and preparing the fatigue samples and tested using the fatigue apparatus. The Nano particles used were (Nano SiO₂ and Nano Al₂O₃) materials with volume fraction as (0% to 2%), for each type of Nano material used. The experimental neural network technique was adopted to have a verification for the experimental results and calculating the fatigue life and strength for composite materials, with the addition of nanoparticles and then, a comparison of the results was achieved. The comparison of the results indicate a maximum error between results calculated by two technique did not exceed about (1%). Then, the results calculated showed that the mechanical properties and fatigue life and strength increase with reinforcement with Nano particle. Also, the results showed that the modified for fatigue limits with materials by (Nano SiO₂) Nano particle was more than the modified for fatigue limits for materials reinforcement with other materials. Finally, it can be concluded that the modified for fatigue strength, by reinforcement with (Nano SiO₂), leads to 60% more than fatigue limit without Nano additive.

Keywords: Fatigue Behavior, Composite Materials, Nano Additive, Prosthetic.

1. Introduction

Rehabilitation centers for people of special needs encourage the development and improvement of prosthetics and orthotics to obtain materials which satisfy the durability and comfort for the amputees patients and present a service to humanity. In this paper will be studying of modify the fatigue characterization by adding Nano particle which are based on the experimental modern methods. As well as use of control system of a kind Artificial neural networks (ANN), which inspired by the
biological neural networks, so that an artificial neuron that receives a signal then processes it and can signal neurons connected to it.

In 2011, M. J. Jweeg et al. [1], studied the dorsiflexion life and angle for foot made from different laminated composite materials. The investigation included the using of an experimental technique to manufacture the samples for foot and testing to calculate the life and angle dorsiflexion for foot, in addition to, use a theoretical technique for verification purposes. In 2012, M. J. Jweeg et al. [2], investigated the fatigue and creep behavior for composite materials used in manufacturing below knee sockets. In 2013, A. M. Takhakh et al. [3] investigated the vibration behavior for ankle foot made from different materials. The materials used to obtain an ankle foot from plastic and metal. Their work included an experimental and numerical techniques to calculate the vibration behavior of the ankle foot. In 2013 many researchers studied different materials and behavior for prosthetic and orthotics, until reached to calculated the best composite materials can be used to made prosthetic and orthotics. In 2017 M. J. Jweeg et al. [4] investigated the stress analysis and materials characterization for syme’s prosthetics. The investigation included the study of different openings on the stress of syme’s prosthetics, in addition to the investigation and characterizations for composite materials used.

Also, at same year, Z. Y. Hussien et al. [5], investigated the modifying for fatigue behavior of below-knee prostheses materials by using ultraviolet radiation with and without heat effect. The study included the using of an experimental technique to calculate the fatigue life-strength for composite materials used. In addition, M. A. Al-Shammari et al. [6] in 2017, investigated the characterizations for composite materials used to manufacture the knee prosthesis sockets, in addition to study the stress analysis for knee prosthesis by using numerical technique. The investigation included the using of an experimental technique to study the mechanical characterizations for composite materials, and numerical technique to calculate the stress for knee prosthesis.

In 2018, many researchers investigated the prosthetic and orthotics by testing and calculating the mechanical properties for different types materials used. The following works showed the same investigation presented in this year, as,

S. M. Abbas et al. [7] studied the mechanical behavior for prosthetic socket, SYMES type. They used an experimental technique to calculate the mechanical properties for materials used to manufacture the SYMES and used numerical technique to calculate the mechanical behavior for SYMES. S. M. Abbas et al. [8] investigated the effect for different composite laminated materials types on the fatigue life and strength for composite material used for manufacturing partial foot. The experimental technique used to calculate both mechanical properties and fatique characterizations for different composite materials types used to manufacture for partial foot. L. E. Yousif et al. [9] studied the effect of a new design for prosthetic foot on the mechanical behavior. In addition, the investigation included the calculation of the effect of temperature on the mechanical behavior for new prosthetic foot. A. M. Takhakh et al. [10] studied the effect of carbon reinforcement fiber on the mechanical properties of composite material used to manufacture the knee ankle foot, in addition to the investigation of the effect for carbon reinforcement finer on the stress analysis of foot structure. The using of the experimental technique to manufacture the foot parts and calculate the mechanical properties for composite materials used, a numerical technique was employed for this purpose. Also, A. M. Takhakh et al. [11], investigated the gait cycle for below-knee socket, in addition to study the mechanical properties for composite materials used. Also, A. M. Takhakh et al. [12] presented an investigation for partial foot by calculating stress analysis and mechanical properties for composite material used in this work. They used the finite element technique to calculate the mechanical behavior of prosthetic and experimental technique.

F. M. Kadhim et al. [13] work was concerned of the smart transfemoral prosthetic by using various composite materials. The investigation included the using of different composite materials and analysis for transfemoral prosthetic in addition to manufacture and design transfemoral prosthetic. A. K. Abdulameer et al. [14] studied the fatigue behavior for syme’s with different composite materials. The study included the prediction of mechanical properties and fatigue behavior for various composite materials used to manufacture syme’s by using an experimental technique. M. J. Jweeg et al. [15] presented a new design for non-articulated foot, in addition to study the mechanical properties for composite materials used for foot. The investigation included the estimation of the temperature effects
on the mechanical characterizations for composite materials used. Also, M. J. Jweeg et al. [16] calculated the optimized design and analysis for trans-tibial sockets. The investigation covered the analysis of different design types for socket to judge on the optimized design of socket by using different types of composite materials. Finally, in 2019, M. J. Jweeg et al. [17] presented a dynamic analysis for below knee prosthesis by calculating for the deformation and stress analysis. The investigation included used dynamic test for below knee prosthesis, in addition to, used numerical technique to calculate the dynamic stress and deformation for prosthesis. In addition, the experimental technique using the CT scan was adopted to predict the dynamic behavior of the below knee prosthesis. F. M. Kadhim et al. [18] investigated the effect for different reinforcement on the mechanical properties for composite materials made of polymer resin materials, in addition to, calculate its effect on the mechanical behavior of prosthetic socket made from its materials. The work predicted the strength and modulus of elasticity for the used materials.

From the previous work, it can be concluded the that using of composite materials in manufacturing prostheses sockets and prosthetics used for people of special needs is increasing in rehabilitation centers in ministry of health in Iraq due to the increased in number of amputees. Therefore, this work is directed to the fatigue characterization of composite materials with Nano particles as additives to improve the fatigue strength. The numerical technique using the artificial neural technique to obtain a validation for the experimental results and have a prediction for the other cases of nanoparticles percentages used in manufacturing the prostheses sockets.

2. Experimental Work

The experimental program includes two parts, first, manufacturing the required sample of the test and second, achieving of testing, tensile and fatigue tests. All the manufactured samples are reinforced by various Nano materials with different volume fractions. The manufacturing of composite sample with Nano materials affects the required mixing the Nano particle with Orthocryl resin materials by using ultrasonic homogenizer, [19-21] as shown in Fig. 1, then, reinforcement is done by mixing the resin by fiber materials by using vacuum technique, [22-24], as shown in Fig. 2. Therefore, the composite materials reinforced by Nano particle can be used to manufacture the Prosthetic socket as presented in Table 1. Two types of Nano materials are used in modifying the composite materials, as, (SiO₂) and (Al₂O₃) with volume fraction from (0 to 2%) for each Nano materials used.

![Fig. 1. Vacuum Machine](image1)

![Fig. 2. Materials Manufacturing](image2)

The tensile samples were prepared according to ASTM standard (ASTM-D638), as shown in Fig. 3, [25], and are tested by using universal tensile machine, [26-28], shown in Fig. 4, to calculate the strength and modulus of elasticity for composite materials presented in Table 1, with various Nanoparticle materials effect, [29-31]. Five samples, for each volume fraction for Nano effect, are
tested to calculate tensile results. Secondary, manufacturing fatigue samples were achieved according to the instructions of the fatigue machine, shown in Fig. 5, [32-34], with dimensions, as shown in Fig. 6, to calculate the fatigue strength for composite materials with various Nano effects, and then, calculating the modified ratio for fatigue characterization for materials by reinforcement with Nano particle. Twelve samples are tested for each volume fraction of Nano effect are to calculate the fatigue limit. In addition, a comparison of the experimental results was achieved with an artificial neural network results to give the validity of the experimental results conducted in this work [35-37].

Table 1. Prosthetic and Orthotics Composite Materials without Reinforcement Nano.

| Sample | Lamination Scheme                                                                 | Perlon | Fiber | Resin |
|--------|-----------------------------------------------------------------------------------|--------|-------|-------|
| S₁     | (3)Perlon+(2)Kevlar+(2)Perlon+(2)Glass+(3)Perlon                                 | 28 %   | 18 %  | 54 %  |
| S₂     | (3)Perlon+(2)Carbon+(2)Perlon+(2)Glass+(3)Perlon                                | 28 %   | 18 %  | 54 %  |
| S₃     | (3)Perlon+(2)Kevlar+(2)Perlon+(2)Carbon+(3)Perlon                              | 28 %   | 18 %  | 54 %  |
| S₄     | (2)Perlon+(2)Kevlar+(1)Perlon+(2)Carbon+(1)Perlon                              | 28 %   | 18 %  | 54 %  |

Fig. 3. Tensile Composite Samples According to ASTM-D638 Standard.

a. ASTM-D638 Standard Tensile Sample.

b. Tensile Sample with Al2O3 Nano.

c. Tensile Sample with SiO2 Nano.

Fig. 3. Tensile Composite Samples According to ASTM-D638 Standard.

Fig. 4. Universal Tensile Machine.
3. Artificial Neural Network Techniques

The artificial neural network (ANN) is an approximant technique used to predict the experimental results using different proportions of the reinforcement. The ANN can be applied to calculate the fatigue behavior and mechanical properties for composite materials with various Nano materials types and volume fraction effect. So, the experimental results can be used as an input data to calculate the approximate formula for ANN, then, the fatigue-number of cycles can be predicted with relative to the mechanical properties (strength and modulus of elasticity) with other Nano volume fraction which were not tested in the experimental program, [38-42]. Thus, the mathematical formulation for ANN can be shown in Fig. 7 in which the mathematical model shows that the ANN can be used with multi input and output variables, in addition to, by ANN the variable parameters can be linear or nonlinear function. Then, the general formulation between input data xᵢ and output parameters y relation can be written as, formulated,

\[ y = \sum_{i=1}^{n}(x_iw_i) + b \]  \hspace{1cm} (1)

Where, wᵢ is the weighted input, and b is the bias term.

To calculate the best formulation, the system must be trained with various input experimental data to predict the approximate output with minimum error as compared with experimental results. In this study, the volume fraction for different Nano materials types (SiO₂ and Al₂O₃) and volume fraction (from 0% to 2%) are used as a input data for neural network and the output for ANN are fatigue with number of cycle and mechanical properties of composite materials. Therefore, by training the data required the error mean squared was about(3.78 x 10⁻⁴), the maximum correlation factor was about(0.99994), and the testing predicating was about (0.99996) at (1200) epochs. Then, after evaluating the best formulation for ANN, to give the fatigue and mechanical properties results, a comparison for ANN results was accomplished with experimental results [43-47] which gave a very good agreement of results with a discrepancy did not exceed (0.54%).
4. Results and Discussion
The results include the characterization of the mechanical and fatigue for composites, used to manufacture the prosthetic sockets as shown in Table 1, with two types of Nano materials effects (SiO$_2$ and Al$_2$O$_3$) using various volume fractions (0% to 2%). The results are divided into two parts, tensile and fatigue results.

4.1. Tensile Results
The tensile experiments are achieved for composites shown in Table 1, for two Nano particle materials effect, with volume fraction (0% to 2%) as shown in Table 2. The calculated mechanical properties include ultimate strength and modulus of elasticity.

| Sample | Nano Volume Fraction (%) | Nano Material Type | Nano SiO$_2$ | Nano Al$_2$O$_3$ |
|--------|--------------------------|--------------------|--------------|------------------|
|        |                          |                    | E (GPa)      | $\sigma_{ult}$ (MPa) | E (GPa) | $\sigma_{ult}$ (MPa) |
| $S_1$  | 0                        |                    | 31.5         | 118.3            | 31.5    | 118.3              |
|        | 0.5                      |                    | 33.2         | 128.9            | 32.6    | 126.9              |
|        | 1                        |                    | 36.8         | 135.4            | 35.1    | 133.7              |
|        | 1.5                      |                    | 39.2         | 146.3            | 37.8    | 145.1              |
|        | 2                        |                    | 42.3         | 158.6            | 41.2    | 156.8              |
| $S_2$  | 0                        |                    | 24.6         | 95.3             | 24.6    | 95.3               |
|        | 0.5                      |                    | 26.4         | 104.5            | 25.3    | 102.8              |
|        | 1                        |                    | 29.7         | 111.7            | 27.9    | 110.2              |
|        | 1.5                      |                    | 33.4         | 120.4            | 31.7    | 118.7              |
|        | 2                        |                    | 36.2         | 130.7            | 35.4    | 128.6              |
| $S_3$  | 0                        |                    | 26.3         | 102.3            | 26.3    | 102.3              |
|        | 0.5                      |                    | 28.3         | 107.8            | 26.8    | 105.4              |
|        | 1                        |                    | 31.2         | 114.6            | 29.7    | 112.7              |
|        | 1.5                      |                    | 35.8         | 125.4            | 34.3    | 123.6              |
|        | 2                        |                    | 38.7         | 136.7            | 37.1    | 134.4              |
| $S_4$  | 0                        |                    | 36.8         | 128.36           | 36.8    | 128.36             |
|        | 0.5                      |                    | 39.2         | 140.3            | 37.8    | 138.2              |
|        | 1                        |                    | 42.3         | 152.3            | 40.8    | 149.6              |
|        | 1.5                      |                    | 45.7         | 165.8            | 43.9    | 162.3              |
|        | 2                        |                    | 48.6         | 176.4            | 46.7    | 172.8              |
The results showed that the mechanical properties are modified with reinforcement by Nano particle materials with a percentage reaches to (50%), with volume fraction of Nano materials did not exceed (2%). Using (SiO₂) Nano materials more than the modifying for its materials with reinforcement by (Al₂O₃) Nano, for same volume fraction, as shown in Figs. 8 and 9. Using the (SiO₂) Nano materials showed more effects than using (Al₂O₃) Nano for the same volume fraction as shown in Figs. 8 and 9. The reinforcements in Nano particles has a more effect than the using fiber reinforcement. The Nano has no effects on weight compared to the using the fibers as additives as these increase the weight of 30%. This is because that the volume fraction used in modifying is not increased than (2%) while the fibers volume fraction is (40% to 60%). The mechanical properties were also calculated using the ANN technique as shown in Figs. 10 and 11. The discrepancy between the experimental and numerical results was not exceed (1%). This will enable the using of the ANN technique to predict other volume fractions not tested experimentally.

Fig. 8. Ultimate Strength for Composite Materials with Various Nano Types Effect.
4.2. Fatigue Results

The fatigue results calculating for various composite materials, shown in Table 1, with various Nano materials types and volume fraction effect, as shown in Table 2. Therefore, the reinforcement by Nano materials lead to modifying the fatigue life and strength with high value with low volume fraction of Nano materials, as shown in Figs. 12 and 13. In addition, as shown in Fig. 14, can be shown that the modifying for fatigue behavior for composite materials reinforcement by SiO$_2$ greater than the modifying for composite reinforcement by Al$_2$O$_3$. So, the modifying for fatigue behavior lead to about (60%) by reinforcement by low volume fraction did not exceed to (2%). In addition, the modifying for composite materials with reinforcement by Nano materials occurred without increase the weight for composite materials, due to low volume fraction for Nano materials.
Therefore, its modifying is considered a good modifying due to increase for fatigue life and strength with high value and without reinforcement with high Nano materials, then, increasing the fatigue behavior for materials without using high reinforcement and without increasing the weight for composite materials. Also, with comparison of modifying for fatigue behavior of composite materials by reinforcement with fiber materials, found that the reinforcement by fiber lead to increasing the weight for materials and the amount for the reinforcement materials, in addition to, the reinforcement with fiber materials lead to increasing the cost to manufacturing the composite materials.

Therefore, after evaluated the fatigue behavior for composite materials reinforcement by Nano materials, comparison the experimental results calculated by ANN technique to given the agreement for results. Thus, from Figs. 15 and 16, can be shown that the discrepancy between experimental and ANN results did not exceed (1%), then, this results shown that the experimental technique is agreement to calculate fatigue behavior for different composite materials with various Nano materials types and volume fraction effect.

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![Graph 1](image1.png)  ![Graph 2](image2.png)

**Fig. 12.** Fatigue Behavior for Different Composite with Various Volume Fraction SiO₂ Nano Effect.

![Graph 3](image3.png)  ![Graph 4](image4.png)
c. Sample $S_3$

d. Sample $S_4$

Fig. 13. Fatigue Behavior for Different Composite with Various Volume Fraction $\text{Al}_2\text{O}_3$ Nano Effect.

a. 0.5% Nano

b. 1% Nano

c. 1.5% Nano

d. 2% Nano

Fig. 14. Fatigue Behavior for Composite Sample $S_4$ with Various Nano Types Effect.

a. 0.5% Nano

b. 1% Nano
5. Conclusions

The modifying for mechanical and fatigue characterizations for same composite used in Prosthetic and Orthotics engineering applications investigation by using experimental and artificial ANN technique. The main conclusions are listed as follows:

1. The experimental program was efficient for estimating the fatigue limits for composites with the presence of Nano materials.
2. The comparison between experimental and ANN gave a good agreement for results with maximum discrepancy did not exceed about (0.54%).
3. The reinforcement of composites by Nanoparticle with a volume fraction not more than (2%) gave a modification in mechanical properties and fatigue approximately 45% keeping the weight of the sample nearly constant.
4. The reinforcement with (Nano SiO$_2$) indicated a better modification than the reinforcement by Al$_2$O$_3$ in mechanical properties and fatigue strength.

5. The ANN technique can be used to predict results irrespective of an experimental program.

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