UDC 678
DOI: 10.15587/1729-4061.2023.274573

IDENTIFYING SOME REGULARITIES OF THE FATIGUE BEHAVIOR OF THE REINFORCED CARBON-FIBER WITH AL_2O_3 NANOPARTICLES COMPOSITE STRUCTURE OF THE PROSTHESIS FOOT

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In this research Carbon-Fiber with AL_2O_3 Nanoparticles Composite Structure of the Prosthesis foot has been examined and analysed numerically explain the fatigue behaviour of the prosthesis. Nanoparticles made of AL_2O_3 were incorporated into the production process of the composite structure of the prosthesis foot in the appropriate manner. The life forecast, the damage indicator, and the Biaxiliray indexation were the three primary considerations that went into the process of studying the composite construction of the prosthesis foot. The life prediction was the most important factor. Experiments on the phenomena of fatigue have been carried out with the stress being entirely reversed as the variable in order to ensure that the findings are in keeping with the theory that was proposed by GoodMan. In order to develop an estimate for these characteristics, the dynamic load that was applied, which was 1000 N, was utilised. It used the dynamic load that was applied in order to produce an estimate for these characteristics so that we could better understand them. The results of the computational research showed that the life prediction could be increased to 106 cycles by applying a primary force of 1000 N. This was shown by the findings of the studyThis was demonstrated by the findings. While the same load application was being carried out, the Biaxiliray indexation attained a value of 0.99. In addition to the research that was done on the damage indicator, the numerical findings demonstrated that the damage can be seen after the initial 1000 cycles of stress have been applied. This was demonstrated both by the research that was done on the damage indicator as well as by the numerical findings

Keywords: fatigue behavior, dynamic load, prosthesis foot, numerical analysis, life prediction

Received date 02.12.2022
Accepted date 15.02.2023
Published date 28.02.2023

***How to Cite:** Shomran, A. T., Faisal, B. M., Hussein, E. K., Santos, T., Fatima, K. (2023). Identifying some regularities of the fatigue behavior of the reinforced carbon-fiber with Al_2O_3 nanoparticles composite structure of the prosthesis foot. Eastern-European Journal of Enterprise Technologies, 1 (7 (121)), 32–39. doi: https://doi.org/10.15587/1729-4061.2023.274573*

1. Introduction

Amputations of the lower limbs have a devastating impact on quality of life because they limit basic bodily functions including movement. Amputees can regain not only their mobility but also their sense of well-being with the help of prosthetic lower limbs. The use of prosthetics is one of the most important aspects of rehabilitation for amputees missing lower limbs foot. Since the SACH (Solid-Ankle Cushion-Heel) foot was invented in 1957 [1]. There have been various different forms of prosthetic feet introduced that are intended for this function. Patients with disabilities have been given SACH as a prescription because it has the potential to reduce the impact loading experienced during heel striking [2]. Nevertheless, this prosthetic foot is capable of storing and then releasing a negligible quantity of elastic energy [3]. Other previous versions of prosthetic feet, made of materials such as wood, metal, and vulcanized rubber, confronted amputees with a number of challenges, including a lack of longevity. and a sense of unease. Previously, difficulties with prosthetic foot designs such as the Shape and Roll foot, the Niagara Foot, and the Jaipur foot were explored by a number of studies [4]. These studies all stated that the same problems of decreased durability and increased weight existed with these designs. According to the findings of prior research [5] carbon-fiber composites were deemed to be an appropriate alternative to the materials that were originally utilized for prosthetic feet, which caused a number of issues. [6] advocated for the utilization of composite materials in the development of prosthetic feet due to their potential for energy storage. This capacity offers a rehabilitative advantage to amputees who are required to maintain a high level of activity.

In a similar [7] advocated for the use of carbon fibre and glass fibre in prosthetic applications due to the low density, lightweight quality, and tremendous strength that these materials possess. The carbon-fiber laminated prosthetic foot has been shown to retain elastic energy in recent studies [8]. This not only aids in forward motion, but also reduces the impact felt by the remaining limbs [9]. The prosthetic foot's mobility is improved by this design element, making it more like a real foot in terms of its performance.

Since the beginning of the industrial revolution, carbon fiber has been a material of essential importance. Because of their exceptional strength-to-weight ratios as well as their stiffness-to-weight ratios, these components find several applications in the automotive, aerospace, and prosthetics sectors. According to [10], historically, prosthetic devices were built primarily from wood and metal. While this is true, other materials have seen significant development in the past. Nevertheless, [11] pointed out the drawbacks of using such materials as prosthetics, including a lack of durability and an inability to withstand things like humidity and rust. Another study reached the same conclusion, saying that durable and stable materials, including synthetic fibres, are necessary for prosthetic applications to provide comfort and control to amputees [12].

Therefore, studies that are devoted investigate the fatigue behavior of a reinforced carbon fibre composite structure of a prosthesis foot that also contains nanoparticles of AL_2O_3 are scientific relevance.

2. Literature review and problem statement

A number of investigations, a lot of work, both theoretical and experimental, has been put in to improving carbon-fiber composites' mechanical characteristics. To improve performance outcomes for unidirectional fibres, authors [13] have studied two alternative fiber-type composite materials. Supported the enhanced mechanical qualities of carbon-fiber composites by showing that, across the board, increasing the number of layers in carbon-fiber laminates led to better mechanical performance. [14]. A recent investigation that was carried out by [15] has demonstrated that the utilization of 15 % carbon-fiber reinforcements results in a rise of 17 % in flexural strength.

In a similar [16] offered proof that enhancing the interlaminar features and reinforcing the resin matrix can boost the mechanical strength of composites. It has been found by Scholz and coworkers that the biocompatibility and excellent strength-to-weight ratios of these composites are what set them apart from competing materials.

In addition, [17] It has been argued that the enhanced qualities of fibre composite materials make them suitable for application in the prosthetics business, among other fields including sports, aeronautics, and aerospace. Research in this area has also led to the development of nanocomposites based on polypropylene (PP) that incorporate nanoclay, basalt fibres, and graphene for use in aerospace applications [18]. An additional type of composites referred to as fiber laminated metals (FML) has also been investigated for the purpose of determining the effect that they have on the mechanical strength of aviation components. The findings demonstrated an increase in the tensile strength of the material as a whole when fiber laminated metals were used [19]. The mechanical properties of fiber composites can be improved using a variety of approaches, making them more applicable to a wide range of manufacturing sectors. According to [20] the use of prosthetics has become significantly dependent on carbon fibers due to the potential of carbon fibers to store energy and the adaptability of carbon fibers. Epoxy resins and woven carbon fibers can be utilized in the production of carbon-reinforced composites, which allows for the modification of the physical characteristics of carbon fibers. According to [21], the lamination technique has the potential to combine certain tensile qualities and rigidity by managing the specific angles and modifying the matrix. An experimental protocol that was designed by [22] illustrates that blended polymer frameworks may be constructed through the use of a variety of different lamination processes. These frameworks can then be used in the production of prosthetic limbs. Laminations of metal, plastic, or other materials are used in today's fast prototyping systems to produce orthotic and prosthetic devices [23].

It has been found by certain researchers that the orientation of the polymer laminates is less important than the reinforcement material for achieving the desired increased tensile strength. a correlation between the reinforcement material's weight and the material's tensile strength; this correlation allows for the optimization of qualities including elasticity, yield strength, and ultimate strength by adjusting the fibre composites' weight percentage. These properties include ultimate strength, yield strength, and tensile strength. In the course of the past decades, a number of different methods that were both cost-effective and efficient for the manufacture of carbon-fiber composites to enhance their mechanical properties were introduced [24]. Processes including hand layup, compression moulding, vacuum bagging, and vacuum-assisted resin transfer moulding can all be used to produce epoxy-based composites. The appropriateness and effectiveness of the technique that is chosen is a critical factor in determining whether or not the created composites will have their qualities improved. For instance, Earlier carbon-fiber laminates were built using the hand layup method, followed by vacuum bagging, which greatly enhanced the mechanical performance of the carbon-fiber composites. The material's tensile and flexural strengths were significantly improved by the vacuum bagging method compared to those achieved with hand layup [25].

Others [26] presented an alternative viewpoint on the limits of the wet hand layup approach in comparison to fiber 3D printing (F3DP). According to the findings of the study, the hand layup process resulted in prostheses having more flexure than tensile strength when they were constructed. In this research, the effects of a range of laminated composite materials on the lifetime and angle of dorsiflexion of the foot were analyzed. The inquiry combined a theoretical strategy for vetting purposes with an experimental method for creating the foot samples. By testing, we were able to ascertain both the durability and the dorsiflexion angle of the samples. Below-knee sockets are made from composite materials, the fatigue and creep behavior of which has been studied extensively.

The vibration behavior of the ankle and foot was modeled using both experimental and numerical methodologies in their work. In 2013, a large number of researchers examined a variety of materials and their behavior for use in prosthetics and orthotics. Eventually, the best composite materials can be used to create prostheses and orthotics, they concluded. In 2017, [27] studied stress analysis and materials characterization for prostheses. Prosthesis was analyzed and characterized, and the effects of different sized holes on the stress it experienced were also studied as part of the experiment. During this time period [28] also investigated the effects of UV light (with and without a heat effect) on the fatigue behavior of materials used in below-knee prostheses. . An experimental method was utilized during the course of the investigation in order to determine the fatigue life strength of the composite materials that were in use. In addition, [29studied the properties of composite materials in 2017 for use in knee prosthetic sockets. Using a computational method, they also investigated the stress analysis of artificial knees. Both an experimental and a numerical approach were used during the course of the analysis, with the former used to investigate the mechanical characterizations of composite materials and the latter used to calculate the stress experienced by knee prosthesis. investigated the mechanical properties of a SYMES-type prosthetic socket. The SYMES' mechanical behavior was then computed using a numerical method, and the mechanical properties of the materials used in its construction were determined using an experimental approach. Researchers [30] studied the effects of different composite laminated materials on the fatigue life and strength of composite material used to make half foot. The experimental method used to calculate the mechanical characteristics and the fatigue characterizations of the various types of composite materials used in the manufacture of [31] looked at how the mechanical functioning of the leg would be impacted by a newly constructed prosthetic foot. In addition, the effect of temperature on the mechanical behavior of the novel prosthetic foot was calculated as part of the investigation. An analysis of stress and mechanical properties of the composite material employed in this study was published by the authors [32, 33]. This effort was put in as part of this inquiry. Using the experimental method and a calculation of the prosthetic's mechanical behavior, they utilized the finite element technique [34, 35]. The work focused on developing an intelligent transfemoral prosthetic by making use of a variety of composite materials. In addition to the production and design of transfemoral prosthetics, the investigation involved analyzing various composite materials and using a variety of different composite materials for transfemoral prosthetics [36–38]. There are a number of gaps that have been indicated in the current study, and some of these gaps are as follows: only a small number of studies have numerically described the behavior of fatigue. In addition to that, the utilization of the nanoparticles in the manufacturing process of the nanoparticles. Therefore, fatigue behavior of the reinforced carbon-fiber with Al_2O_3 nanoparticles composite structure of the prosthesis foot has been investigated and analyzed numerically.

3. The aim and objectives of the study

The aim of the study is to is identifying regularities of the fatigue behavior of improved carbon-fiber composite structures for the application of prosthesis feet including AL_2O_3 nanoparticles. The findings of the experiment method that used the composite sample will be validated as a result of this investigation.

To achieve this aim, the following objectives are required:

– to investigate manufacturing life based on the fatigue behavior;

– to explain biaxiality indication;

– to predict damage indicator;

– to calculate the equivalent alternative stress depending on Von-Mises criteria.

4. Materials and methods

4. 1. Object and hypothesis of the study

Object of the study is to fatigue process of the reinforced carbon fiber with AL_2O_3 nanoparticles composite structure of the prosthesis foot. The reinforced carbon fiber with AL_2O_3 nanoparticles composite structure of the prosthesis foot. In the computations that have been performed, consideration of the GoodMan theory has been included. The ANSYS software has been used to carry out the simulation procedure, which is dependent on the static structural modelling.

4. 2. Mechanical properties

The mechanical parameters of the model have to be specified in advance in order for the simulation technique to be utilized. The reinforced carbon fiber with AL_2O_3 nanoparticles composite structure of the prosthesis foot has been designed with the following features in mind: Differences in the Ultimate Tensile Strength, Measured in Percentage of Pascals Maximum Stress, Measured in Megapascals Variations in the Ultimate Tensile Strength (MPa). 1.5 % of the nanoparticles in this investigation were found to be composed of AL_2O_3. In Table 1, the mechanical characteristics of the materials that are currently available are presented.

Table 1

Mechanical properties of the reinforced carbon fiber with AL_2O_3 nanoparticles composite structure of the prosthesis foot

Modulus of elasticity, GPa	Ultimate tensile stress, MPa	Density, g/cm^3	Volume fraction of Nano, wt
37	150	1.9	1.5 %

In order to carry out the simulation process by making use of the static structural tool of AL_2O_3 nanoparticles composite structure of the prosthesis foot, there were four primary parameters that were taken into consideration. The volume fraction of Nano. Volume fraction was calculated to be 1.5 % for the purposes of this study.

4. 3. Meshing and modeling

ANSYS The meshing procedure was executed with the assistance of meshing, which was employed in order to execute the meshing procedure for the issue at hand. A model that initially comprised a limitless number of particles must go through the process of meshing in order to have that number of particles cut down to a more manageable level. Fine mesh was crafted with the use of a structured mesh grid so that accurate responses could be obtained. Because of this, it was possible to manufacture the mesh. The desired result of a fine mesh was accomplished with the assistance of managing the sizing by employing the curvature size with a coarse mesh and the element size with face meshing. This allowed for the achievement of the desired outcome of a fine mesh. It has been determined that a total of 44536 binary nodes have been formed as a consequence of the development of binary nodes for the wedge across all of its zones. Fig. 1 provides a picture of the type of mesh in a space that is just two dimensions deep. Because the 3D wedge is symmetric, the only feature of the model that has been developed and modeled so far is the aspect that is symmetric. This is because the symmetry of the 3D wedge was discovered by accident. In this particular piece of study, the authors made use of three different forms of boundary conditions: wedge, symmetry, and far field.

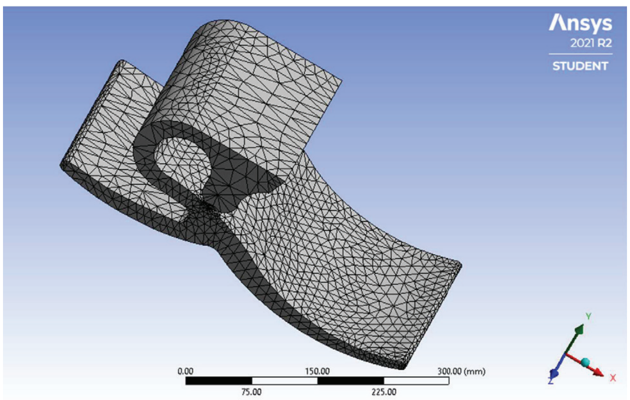

Fig. 1. Meshed model of the prosthesis foot

The model was processed for edges to use in the selection process, which finally led to the production of this list of requirements as shown in Fig. 1.

4. 4. Boundary conditions

A uniaxial fatigue test was performed as part of the overall scope of this investigation. 1000 Newton-meters was the force that was utilized to apply pressure. This investigation utilized a method for the fatigue tests that was based on a real prosthetic foot. Also, the specimens were loaded while being subjected to tension-compression stress while the test was being carried out. Failure due to fatigue can occur in a material after it has been subjected to a number of load cycles with amplitudes that are less than the material's ultimate static strength [14]. In the course of this inquiry, fatigue tests were performed in a laboratory on a sample constructed of reinforced carbon fiber with AL_2O_3 nanoparticles composite structure of the prosthesis foot.

4. 5. Convergence analysis

A convergence test is the method that has been chosen to be used in the empirical studies that have been conducted on the connection. This method is used to carry out the results of the numerical analysis. The purpose of this test is to evaluate and contrast two different sets of findings that have been computed numerically. It has been decided that the life forecast that is offered in the fatigue tool would be the primary indicator for convergence as shown in Fig. 2. This was reached through consensus. By taking into consideration two different answers, the procedure for obtaining convergence has been finished and is now complete. The number of cycles counted at the beginning for the first solution was 3.7e-3 mm, whereas the number of cycles counted at the beginning for the second solution was 3.47e-3.

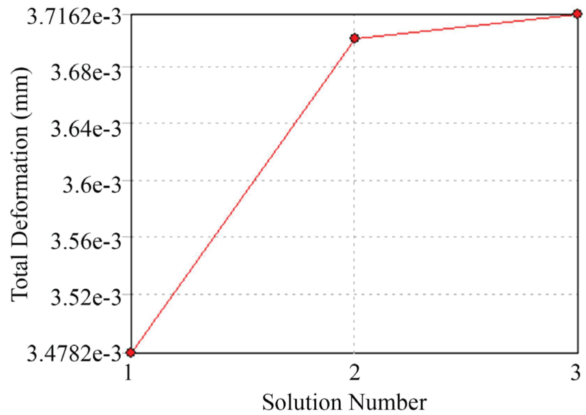

Fig. 2. Convergence analysis of the composite of the prosthesis foot

The mesh that is used in the present model has been improved so that it shows the second solution more correctly in order to reflect the changes that have been made. The addition of new data helped make this advancement work out in a way that was before impossible.

5. Results of research of the fatigue behavior of the reinforced carbon-fiber with AL_2O_3 nanoparticles composite structure of the prosthesis foot

5. 1. Life indexing

For the purposes of this investigation, a prediction was made regarding the amount of time that fatigue spacemen made from carbon-fibre reinforced with nano particles would be functional when subjected to an alternative load. As a result of the 1000 N fatigue load that was applied, a research into the life expectancy prediction was carried out. The results of this investigation are depicted in Fig. 3.

Throughout the entirety of the simulation process, the tool within the ANSYS software referred to as the Static structural tool was utilized. According to the results of the computational analysis, the PLA composite structure specimen that is reinforced with kenaf particles has a maximum number of cycles that may be applied to it that is quite near to one 10^6. As a result, it is recommended that the current analysis be invalidated somewhere in the vicinity of the 10^6 cycle.

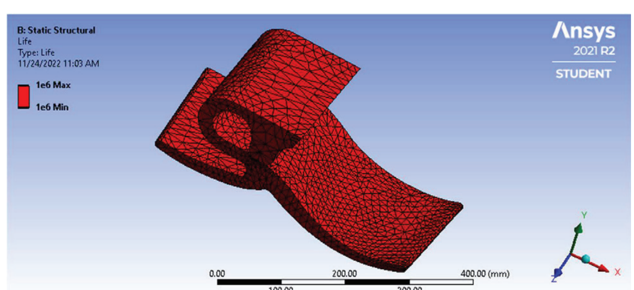

Fig. 3. Life prediction of the current geometry

The current configuration of the composite prosthetic foot has undergone evaluation for its safety factor, which has been completed. According to the conclusions of the numerical analysis, the typical safety factor produced by the load that was applied has reached 15 as shown in the Fig. 4.

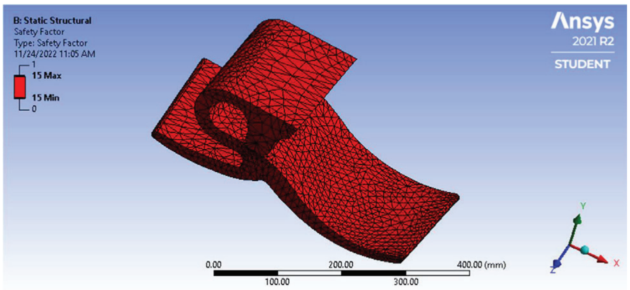

Fig. 4. Safety factor of the current prothesis foot

The configuration of the composite prosthetic foot has been evaluated for its risk factor, and the results of those tests have been summed up and presented.

5. 2. Biaxiliray indexation

In the current investigation, the biaxiality indication provides information on the stress condition that was experienced over the model as well as how the results should be interpreted. This information is included in both the results and the biaxiality indication, so look in both of those places for it.

In this particular scenario, the biaxiality indication is calculated by dividing the principal stress that has a smaller magnitude by the principal stress that has a larger magnitude, while ignoring the principal stress that has a magnitude that is closest to zero. In other words, the calculation ignores the principal stress that has the smallest magnitude. The purpose of this particular calculation is to determine whether or not the material possesses biaxiality. A stress that only acts in one direction, known as uniaxial stress, is the same as a stress that has no biaxiality at all. The application of the alternative load of 1000 N caused the biaxiality indicator to reach a minimum of – 0.9995 before it reached that value. As a result, the biaxiality indicator is now 0.9808. The results of the simulation, which were shown in Fig. 5, revealed that the tips were the locations where the maximum case biaxiality indication occurred. This information was presented in the simulation.

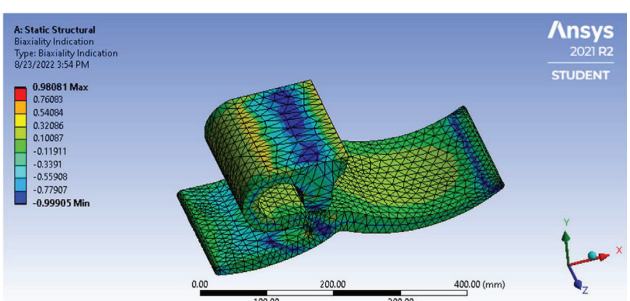

Fig. 5. Biaxiliray indexation due to the applied load

According to the findings of the simulation, the tips were the places where the largest case biaxiality indication took place. This was discovered by looking at the results. Within the framework of the simulation, this information was discussed.

5. 3. Damage calculation

The likelihood that loading will cause the structure to sustain damage is depicted in Fig. 6, which shows how likely it is. It was shown that this prospect has become a reality. In order to complete the computational modeling of the 3D fatigue spacemen, specimens have been loaded with an alternative force that is equivalent to 1000 N. They have been entrusted with the duty of bearing this burden in their shoulders.

The minimum number of cycles that need to be finished before the potential for maximum damage can be reached is 1000, while the number of cycles that need to be finished before reaching the potential for maximum damage is also 1000. According to the findings of the simulation, the damage will most likely start to become noticeable somewhere in the middle of the fatigue specimen.

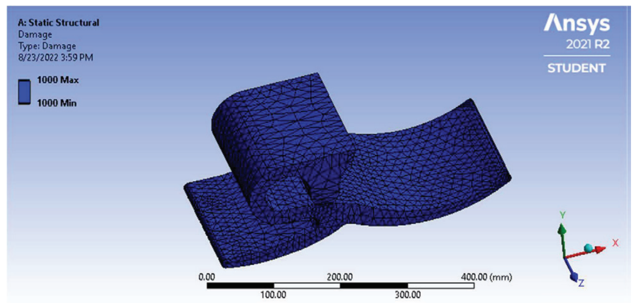

Fig. 6. Damage explanation due to the applied load

The fatigue indicator was used in the ANSYS software to make a prediction of the damage indication. The simulation of the dynamic applied load was carried out using the structural model that was static.

5. 4. Equivalent alternative stress

The results of the simulation have made it possible to identify the regions of the composite specimen that were affected by the alternative load of 1000 N that was applied. This has been made possible as a result of the findings of the simulation, which have made it possible to pinpoint these regions. The strain is delivered along a uniaxial axis all the way through the body of the specimen that is being tested. This ensures that the strain is distributed evenly. The body of the fillet that was used for the composite fatigue sample was subjected to alternating stresses that were concentrated there. There was a concentration of these pressures there. According to the findings of the investigation, the fillet parts of the specimen are subjected to a maximum alternative stress of 52.8 MPa. This value was determined based on the results of the investigation. As shown in Fig. 7, the alternative stress must be at least 5.2 MPa in order to be considered acceptable.

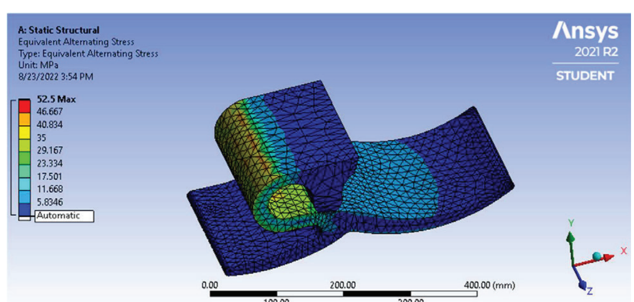

Fig. 7. Numerical results of Equivalent alternative stress

The stress is applied along a uniaxial axis all the way through the body of the specimen that is being examined. This ensures that the stress is distributed evenly. This ensures that there is no uneven distribution of the strain. Alternating loads that were focused there were applied to the body of the fillet that was utilized for the composite fatigue sample. These stresses were applied repeatedly.

6. Discussion of the fatigue behavior of the reinforced carbon-fiber with AL_2O_3 nanoparticles composite structure of the prosthesis foot

In order to investigate the fatigue behavior of reinforced carbon-fiber with AL_2O_3 nanoparticles, the finite element method was utilized. the finite element method was evaluated alongside previous research and the results were discussed accordingly.

In order to evaluate the fatigue behavior of the reinforced carbon fibre with AL_2O_3 nanoparticles composite structure of the prosthesis foot, the current has been obtained. The behavior was examined in the context of the life forecast, which revealed that it had advanced to the 1e6th cycle at the time it was observed. indication of biaxiality, in addition to analysis of damage and equivalent alternative stress.

In order to analyze the fatigue behaviour of the reinforced carbon fibre with AL_2O_3 nanoparticles composite structure of the prosthetic foot, as illustrated in Fig. 3, the current has been described using fatigue life as the key indicator it has reached 10^6 Cycles.

Fig. 5 provides an explanation of the biaxiality indication, which demonstrates that the alternative load of 1000 N led the biaxiality indicator to reach a minimum of 0.9995, but the maximum biaxiality indicator is now 0.9808. In addition to an analysis of the damage in Fig. 6. The equivalent alternative stress has been shown in Fig. 7, it reaches 52 MPa.

In order to undertake an examination of fatigue brought on by dynamic load, the finite element methodology was utilized. The investigation revealed how the prosthetic foot responded to the load that was delivered in the appropriate manner.

The use of composite material in the application of the prosthetic foot is an advantage that the current study possesses. The incorporation of nanoparticles into a material results in an improvement in that material's characteristics. When compared to the results of earlier investigations, these results have demonstrated a significant leap in quality [39].

This research has the constraint that it can only investigate fatigue behavior using four parameters: life prediction, biaxiality indication, analysis of damage indicator, and equivalent alternative stress. These limits prevent the research from being more comprehensive. prosthesis foot consisting of a reinforced carbon-fiber and AL_2O_3 nanoparticles composite structure.

When utilizing this method, there are a few challenges that can be noted, one of which is the usage of expensive materials in the fabrication of the specimen test. This is one of the challenges that can be observed.

Another one of the challenges is to look for a point of interest and base an actual test on it.

There is a possibility of encountering a number of difficulties, one of which is the meshing model of the tired spacemen. Among the other potential difficulties are: Convergence analysis of the mesh and the model can be challenging to properly set. In the event that the mathematical model used by the Ansys program is not accurately defined, the results will not be reliable.

7. Conclusions

1. Fatigue life of the composite reinforced carbon-fiber with AL_2O_3 nanoparticles has been predicted using the computational method. The numerical results have proven the maximum predicted life of the composite prosthetic foot is reached 10^6 cycles.

2. Biaxiality indication has been investigated and analyzed accordingly. The application of the alternative load caused the biaxiality indicator to reach a minimum of –0.9995 before it reached that value. As a result, the biaxiality indicator is now 0.9808.

3. The damage indicator has been calculated. The number of cycles that must be completed before the potential for maximum damage whereas the number of cycles that must be completed before reaching the potential. According to the findings of the simulation, the damage will most likely start to become noticeable at 1000 Cycles at the middle of the fatigue specimen.

4. The equivalent alternative stress has been investigated. According to the findings of the investigation, the fillet parts of the specimen are subjected to a maximum alternative stress of 52.8 MPa. This value was determined based on the results of the investigation. the alternative stress must be at least 5.2 MPa in order to be considered acceptable.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

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