EXPERIMENTAL AND NUMERICAL INVESTIGATION OF LOWER LIMB PROSTHETIC FOOT MADE FROM COMPOSITE POLYMER BLENDS

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ABSTRACT

In this work, two composite polymer blends, PMMA/SR and PMMA/PUR, reinforced with carbon fibers (CF) were prepared as a suitable material for lower limb prosthetic foot. The tensile properties were measured experimentally. The theoretical part of this work deals with calculations of the deformation and dorsiflexion angle. The finite element technique (ANSYS-15) was used to analyze and evaluate the tensile characteristics, represented by total deformation distribution, equivalent stress and equivalent elastic strain. Results showed that the reinforcement has an influence on the measured properties. Composite polymer blends gave optimum experimental, numerical and theoretical results, which indicates that the composite polymer blends are the best option for the lower limb prosthetic foot.

KEYWORDS: Poly Methyl Methacrylate, Silicon Rubber, Polyurethane Rubber (PUR) & Carbon Fibers

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INTRODUCTION

The option of the artificial foot is vital because it tries to restore the normal gait pattern and the motion Ankle. The foot choices are selected based on their day to day activities, related to requests and individual parameters, for example, age and weight of available prosthetic feet, including dynamic reaction feet, like Flex-Foot, which as of now takes into consideration the most characteristics that have 6-degrees of motion at the lower leg joint. However, artificial foot designs lack the adaptability fundamental for amputees to perform exercises, for example, bowing and putting on shoes. The proposed configuration more likely than not expanded adaptability to encourage stooping, while at the same time, keeping up or improving the ordinary step designs that are made by the present, top-notch prosthetic. The foot should likewise give steadiness and adjust to the amputee's comfort [1-2].

Primary material made of metals and wood for manufactured lower limbs had real difficulties, since they were constrained by the weight and had poor resistance to erosion and dampness instigated swelling. These confinements restrained the client to moderate and non-strenuous activities because of the poor versatile reaction amid position, which is caused by impediments. Polymer matrix composites were presented as an alternative material for appendage frameworks, as a result of their "lightweight, resistance to corrosion, resistance to fatigue, and simplicity of fabrication [3].

Since the past decade, carbon fibers have been used as the significant reinforcing fibers for prosthetic utilization. These composites are selected due to their adaptability and ability to store energy. The reinforcing

fibers can be created in various ways, for example, being interlaced, woven or laminated. The lamination would enable them to have a certain degree of rigidity and specific tensile properties by changing the matrix and controlling the angles of succeeding plies [4-5].

This application is improved in such differing regions as conducting and storage of elasticity, heat, and light. To be sure polymers have played and will keep on playing an inexorably vital part in all parts of life. As of late blended frameworks or mixes of various polymers have been produced which are of increasing significance in the orthopedic business including prosthetic lower limbs [6].

M.J.Jweeg et al. studied the interaction between fatigue and creep for composite materials to be used in manufacturing the prosthetic composites. They concentrated on finding the fatigue failure at room temperature till 50 °C, which are compatible with summer environment in Iraq and other Gulf area countries [7].

M.J.Jweeg et al. achieved an experimental and theoretical study on the characterization of the reinforcement fiber types of composite materials such as long, short, woven, powder and particles reinforcement with a different volume fraction of fibers. Good results of the modulus of elasticity were obtained for the unidirectional fiber types ,while the woven type has shown the best results in the transverse direction [8].

A number of studies have investigated the characteristics of polymer blends reinforced with carbon fibers as suitable material for prosthetic foot, in 2015, Hadi A.N. and Olewi J.K., improved tensile strength of polymer blends consist of 90PMMA:10SR reinforced by CF as prosthetic foot material and the results showed effect reinforcement material on tensile properties of polymer composites which considered as one improvement for this application, and in same year Hadi A.N. and Olewi J. K. improved flexural properties of blend PMMA:SR by reinforced with CF as artificial foot and the results showed effect carbon fiber on flexural strength of the blend were measured as good improvement for this application [9-10].

The objective of this study was to develop characteristics of polymer blend material that can be used as lower limb prosthetic foot and new design prosthetic foot can be good acceptance for human amputees in order to overcome the prosthetic foot failure. We selected for this work acrylic cold cure blend with silicone and polyurethane rubber, then reinforced with carbon fibers for more development prosthetic foot characteristics, The new foot was checked with the ANSYS and the development in the material was continued until the fair property was reached. The new foot was examined to find out such characteristics as equivalent stress and strain with dorsiflexion angle. Figure (1) shows the failure of the prosthetic foot.

Figure 1: Failure Prosthetic Foot Including Fore Foot Region

MATERIALS AND METHODS

The polymer PMMA was supplied from BMS Italian Co, and SR and PUR elastomers supply from Shenzhen Ye Jie Tech. Company, LTD. white color, and self-curing at room temperature, reinforcement material chopped carbon fiber

with length 3-5mm, Table 1, illustrates the mixture ratio for polymer samples.

Table 1: Mixture Ratio of Polymer Composite Samples

PMMA	SR	PUR	CF
60	40	-	0
60	40	-	5
60	40	-	10
60	40	-	15
60	-	40	0
60	-	40	5
60	-	40	10
60	-	40	15

The first step added PMMA resin polymer to SR firstly and to PUR and secondly mixed by using a mechanical mixer to work a blend after that chopped carbon fibers add as a reinforcement according to the mixture ratio in (Table 1). The second step is the pouring the mixture into the mold and the ply was left in the mold for time (15 - 20 minute) at room temperature under constant vacuum. After that , using the cutter to form the tensile samples according to the standard ASTM D638 and by using universal tensile test machine with load (1-20 KN) and strain rate (5 mm/min).

The numerical part of this work finite element technique is applied for modeling governed by a differential equation or an energy formulation. In order to obtain a solution to the stresses in the body under an applied load, the body is divided into an assembly of subdivisions by using finite elements [11-12]. Analysis Procedures for numerical work includes the following steps:

1. Modeling

The most important point of the FEM in order to analyze the load applied on the prosthetic foot, a model of three dimensions finite element built according to the true geometrical dimensions of the human foot this model designed by the Auto CAD program that export to ANSYS 15 as showed from the figure (2).

Figure 2: Model Prosthetic Foot Designed

2. Element Type Selection

The element type chosen in this study is (SOLID -185) as shown in Figure (3) is used to the modeling of structures in three dimensions. It is defined (provided) by 8-nodes having six degrees of freedom at each node include (U_x , U_y , U_z) translation and three rotation motion [13].

Figure 3: SOLID -185 [8]

3. Material Properties

Most element types require material properties depending on the application of these materials. Here the materials were assumed quasi-isotropic homogeneous and linear elastic, tensile characteristics for composite materials were used.

4. Mesh Generation

The first step of the analysis is to divide the structure into small finite elements. Figure (4) shows the structure of the prosthetic foot.

Figure 4: Mesh Prosthetic Foot Designed

5. Boundary Condition

Figure (5) illustrates the applied load, the prosthetic foot design for 80Kg assuming weight for people amputees, for that the force applied was 1019 N according to $(1.4 \times 80 \times 9.8 = 1019 \text{ N})$, the fixed point from the top of the foot designed at **A** than the applied force at **B** was 1019 N.

Figure 5: A Fixed Point, B Load Applied Point on the Prosthetic Foot. Designed

6. Solving

The steps used to calculate the deformation, stress and strain properties of prosthetic foot than the dorsiflexion angle was determined to depend on the $\tan \theta$ for slop prosthetic foot during deformation prosthetic foot designed and prove if this design was good for this application from the results.

RESULTS AND DISCUSSIONS

1. Tensile Test Results and Discussion

As shown from figures (6-9) the tensile strength and modulus of elasticity results for PMMA/SR and PMMA/PUR with a ratio of carbon fibers. The tensile strength and modulus of elasticity increased with increased ratio of carbon fibers that due to the resin blends considered as brittle materials where it is shows low tensile strength and after making reinforcement by fibers the property will be improved that due to the fibers will carry the major load and so as will increase the tensile strength of the composite, while the effect rubber content, when added with PMMA, decrees the tensile strength and modulus of elasticity for all polymer composite.

As showed from there figures that tensile strength after reinforcement by CF were improved by 30-35% for PMMA/SR groups while improved by 25-30% for PMMA/PUR groups and for this slightly different for improvement depends on the nature of rubber used as blends with PMMA, In addition blended the PMMA with rubbers provided flexible situation in all structure less the energy for the walking for prosthetic foot application.

Figure 6: Relationship between Tensile Strength and CF % for PMMA/SR Blends

Figure 7: Relationship between Tensile Strength and CF % for PMMA/PUR Blends

Figure 8: Relationship between Modulus of Elasticity and CF % for PMMA/SR Blends

Figure 9: Relationship between Modulus of Elasticity and CF % for PMMA/PUR Blends

2. Numerical Results and Discussion

According to the tensile results, total deformation analyzed on the designed prosthetic foot can be seen from the figures (10-17) for polymer composite material of PMMA/SR and PMMA/PUR polymer blends.

Figure 10: Total Deformation Results of 60PMMA:40SR:0CF

Figure 11: Total Deformation Results of 60PMMA:40SR:5%CF

Figure 12: Total Deformation Results of 60PMMA:40SR:10%CF

Figure 13: Total Deformation Results of 60PMMA:40SR:15%CF

Figure 14: Total Deformation Results of 60PMMA:40PUR:0CF

Figure 15: Total Deformation Results of 60PMMA:40PUR:5%CF

Figure 16: Total Deformation Results of 60PMMA:40PUR:10%CF

Figure 17: Total Deformation Results of 60PMMA:40PUR:15%CF

As shown from the figures (10-17), the total dorsiflexion decreases with increasing ratio of carbon fibers for polymer composite samples, this decreasing in total deformation change and vary for each polymer composite, Silicon Rubber (SR) and Polyurethane Rubber (PUR) when blended with PMMA provided high bonding between the matrix and fibers and provided flexible situation which is important for this application represented by dorsiflexion angle.

In addition the dorsiflexion angle can be calculated for all eight samples depends on the dorsiflexion value by $\tan \theta$ which refer to the angle between dimension of the length between the fixed point and the start of the designed prosthetic foot which applied to the load caused deformation, as shown from figure (18) and the table (2) and figures (19 - 22) refer to the effect CF on the dorsiflexion and dorsiflexion angle on the polymer composite samples respectively, Dorsiflexion angle of prosthetic foot designed was below 5° that proves this acceptable and can be recommended, According to that 90PMMA:40SR: 10/15% CF and 90PMMA:40PUR: 5-10-15% CF can be recommended for this application because the dorsiflexion angle lower than 5° [14].

Figure 18: Illustrated Dorsiflexion Angle for Designed Prosthetic Foot

Dorsiflexion Angle = $\tan^{-1} \frac{D}{200}$, where is D is dorsiflexion in mm

Table 2: Dorsiflexion and Dorsiflexion Angle for Prosthetic Foot Designed

PMMA	SR	PUR	Dorsiflexion mm	Dorsiflexion Angle °
60	40	-	20.19	5.76
60	40	-	17.60	5.02
60	40	-	15.47	4.42
60	40	-	14.56	4.16
60	-	40	18.91	5.40
60	-	40	17.06	4.87
60	-	40	15.22	4.35
60	-	40	14.45	4.13

Figure 19: Effect CF on the Dorsiflexion of Polymer Composite Samples

Figure 20: Effect CF on the Dorsiflexion of Polymer Composite Samples

Figure 21: Effect CF on the Dorsiflexion Angle of Polymer Composite Samples

Figure 22: Effect CF on the Dorsiflexion Angle of Polymer Composite Samples

The stress and strain contour results can be shown from the figures (23-26) was equal for all samples which indicate that the results were lower than the yield strength of the composite material for stress analyzed as showed from a table (15).

Figure 23: Equivalent Elastic Strain Results of PMMA/SR Polymer Blends

Figure 24: Equivalent Elastic Strain Results of PMMA/PUR Polymer Blends

Figure 25: Equivalent Stress Results of PMMA/SR Polymer Blends

Figure 26: Equivalent Stress Results of PMMA/PUR Polymer Blends

CONCLUSIONS

The main conclusions were:

- Tensile strength and modulus of elasticity are for polymer composite samples contain SR and PUR bonding the fiber to the matrix lead to improved mechanical properties slightly, Although this improved slightly because high rubber content through polymer composite but remain to provide middle state between flexibility which very important for dorsiflexion angle and mechanical properties represented by tensile strength.
- Tensile strength after reinforcement by CF was improved by 30-35 % for PMMA:SR groups while improved by 25-30% for PMMA:PUR groups.

- Silicone rubber, when blended with a brittle polymer material such as PMMA lead to make as a binder for bonding the fibers to the matrix for more improvement, mechanical properties including tensile strength and provide a flexible situation in structure, leads to less energy of the walking for amputees peoples.
- Designed prosthetic foot showed an acceptable deformation level under loading with good dorsiflexion angle for this application.
- PMMA:SR and PUR with reinforcement by CF are considered as a suitable material, offer many things such as easy to mold to any shape and lowering the cost of lower limb prosthetic foot spatially for lower economic countries.

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