

Design of Prosthetic Foot from Polymer Materials Reinforced by Carbon Fibers

Dr. Jawad Kadhim Olewi 

Materials Engineering Department, University of Technology / Baghdad

Email: jawadkad@yahoo.com

Ahmed Namah Hadi

College of engineering, University of Misan / Misan

Email: ahmednamah4@gmail.com

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ABSTRACT

Loss of the lower limb can cause loss of mobility. At all places and at all times, efforts have always been made to make up for such a loss. In this work polymer composite materials had been used to manufacture prosthetic foot. Polymer composite materials PMMA:SR/PUR reinforced by carbon fibers (CF) were prepared as suitable material for prosthetic foot then, tensile characteristics were measured and determined. Numerical work included Finite element method (ANSYS-15) was used to analyze and evaluate deformation, stress and strain characteristics of a new designed prosthetic foot, which was treated as three-dimensional structure composite polymer material. The experimental and theoretical results were improved that polymer composite material can be used for this application.

Keywords: Poly methyl methacrylate (PMMA) , Silicon Rubber (SR) , Polyurethane Rubber (PUR) , Carbon Fibers (CF).

INTRODUCTION

Prosthetic limbs are fabricated devices that provide amputees with a replacement for their missing lower limbs, restoring some function such as walking, running and skiing. New design of prosthetic feet does not replicate the features of normal foot and wide range activity between the normal and prosthetic foot. Today engineering of prosthetic feet looking for number acceptance activity prosthetic foot for amputees to be able functions [1].

Primary prosthetic foot was made from wooden with metallic bars have many restricted for amputees peoples by heavy weight, lower durability , hard process and high cost and this limitation of primary or originally prosthetic foot caused more restricted for amputees functions. Novel material such as polymer, polymer blends and polymer composite reinforced by different fibers (Glass, Carbon or Kevlar) were suggested as suitable materials for this application for their good performance, low weight, easy process and low cost and many researchers had been see this new material is more popular and suitable for prosthetic foot application [2,3,4].

The properties of polymer material can be developed by many ways such as blending with other polymer or reinforcement with different fibers to enhancement the mechanical properties such as tensile, flexural, fatigue and impact energy which is very important for this application. Fiber as reinforcement material of composite

material can be design by many ways chopped or woven for this application and carbon fiber is the most reinforcement material suitable for prosthetic foot for good mechanical properties. Matrix of polymer can be selected according to easy to molded or easy processed such as resin polymer self-cold cure [2,5,6].

Prosthetic foots suffer from unsolved problems, (failures) due to many factors related to the essential characteristics of the materials and the stressed within the prosthetic foot. Mostly failures occur when a prosthetic foot is used in walking on a rigid surface or by fatigue failure, as the prosthetic foot deforms continually by surface forces. The maxillary prosthetic foot is subjected to bending deformation, tensile stress and stresses concentration, which lead to increase the prosthetic deformation as shown in Figure (1). This shows the most failures that happen in a prosthetic foot.

The materials used for manufacturing a prosthetic foot have many problems such as poor durability, hard to mold to shape, with high cost. Many developments for these reasons were carried out by many researchers for development of this application. The silicon and polyurethane rubber (SR/PUR) as toughing for the PMMA to provide flexibility that is very necessary for this application with good binder for bonding for reinforcement material (CF) to the matrix to enhance mechanical properties. In addition the material use in this work good mechanical properties, easy to mold (Self Cure) with lower cost for this application can be safe money for replacement lower limbs.



Figure (1) Failure prosthetic foot including tore foot region.

Experimental Part

Material and Method

PMMA polymer was supplied from Italian BMS Co., as polymer and hardener self-curing while SR and PUR elastomers supplied from Shenzhen Hong Ye Jie Technology Co., LTD. The reinforcement material, carbon fiber with length 3-5mm supplied from Shenzhen Technology Co. ; The Table (1) can be illustrating the mixture ratio for polymer samples for experimental work.

Firstly, added PMMA resin polymer to SR or PUR which is in a liquid state, mixed well by used mechanical mixer to form a binary polymer blend than reinforced by carbon fiber (CF) according to the mixture ratios in (Table 1). Secondly, pouring the blend into the mould and casting sheet was left inside the mould at room temperature about (15-20 min.) under constant vacuum. Finally, solidification the testing samples were obtained by cutting the cast sheets according to ASTM D638 than tensile properties was measured at room temperature using universal testing machine (Lloyds, capacity 1-20 kN). Testing speed was set at 5 mm/min .

Table (1) The mixture ratio (wt. %) of polymer composite samples.

PMMA	SR	PUR	CF
70	30	—	0
70	30	—	5
70	30	—	10
70	30	—	15
70	—	30	0
70	—	30	5
70	—	30	10
70	—	30	15

Numerical Part

The finite element method (FEM) technique was applied for modeling governed by 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 [7,8]. Analysis Procedures for numerical work can be referring the following steps:

A. Modeling

The FEM was analyzed the load applied on the new design of prosthetic foot, a model of three dimensions finite element built according to the true geometrical dimensions of the human foot this model designed by Auto CAD program that export to ANSYS 15. The new design of prosthetic foot can be shown in Figure (2).

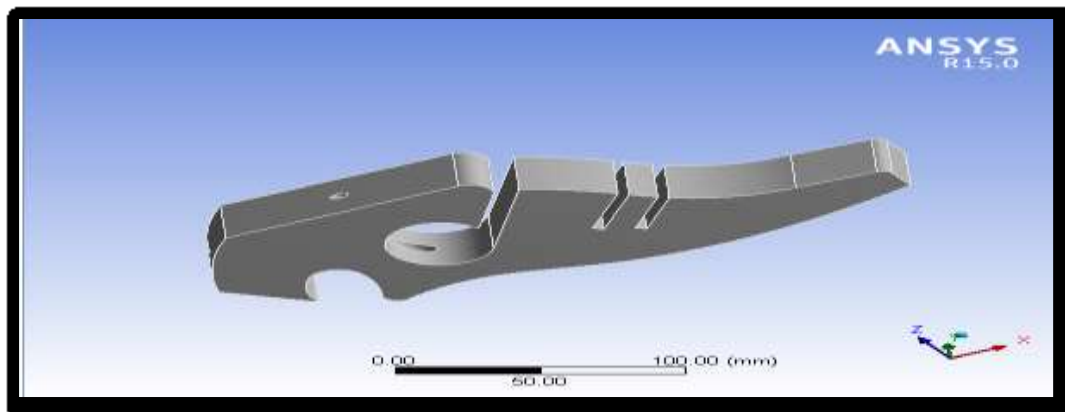


Figure (2) A new model of prosthetic foot designed.

B. Element Type Selection

The element type chosen in this study is (Solid -185) as shown in Figure (3) is used for 3-dimension modeling of solid structures. It is defined (provided) by 8 nodes having 6 points of freedom at each node include (U_x , U_y , U_z) translation in three direction [9].

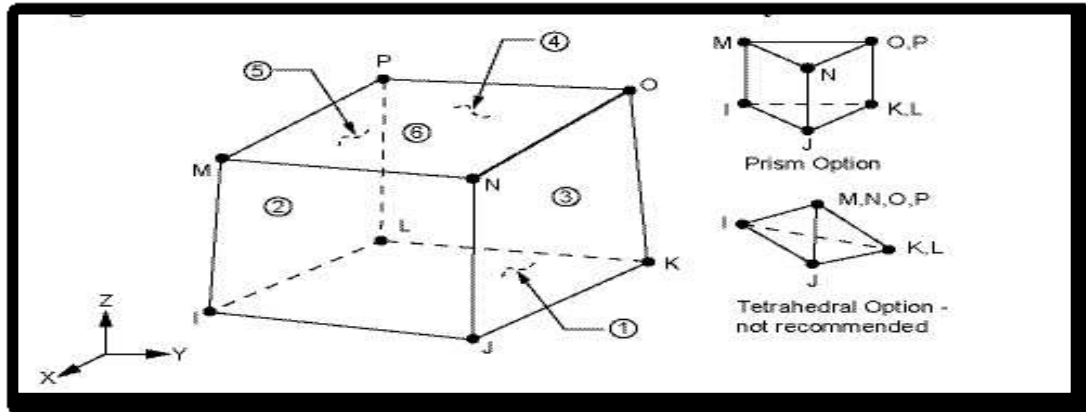


Figure (3) The solid -185 [8].

C. Properties of Material

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

D. Mesh Generation

The first step of the finite element analysis is to discretize the structure into finite elements connected at nodes. For a structure, as a prosthetic foot , as showed from the

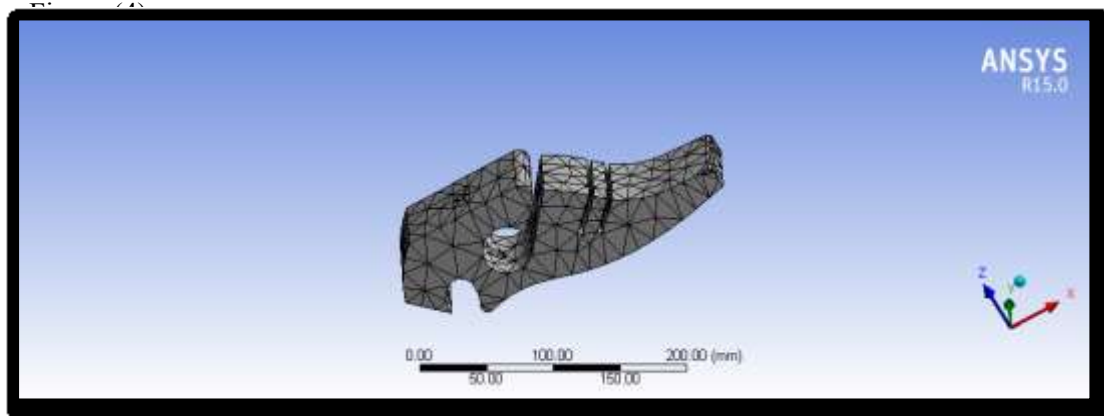


Figure (4) Mesh prosthetic foot designed.

E. Boundary Condition

Figure (5) illustrate 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 .

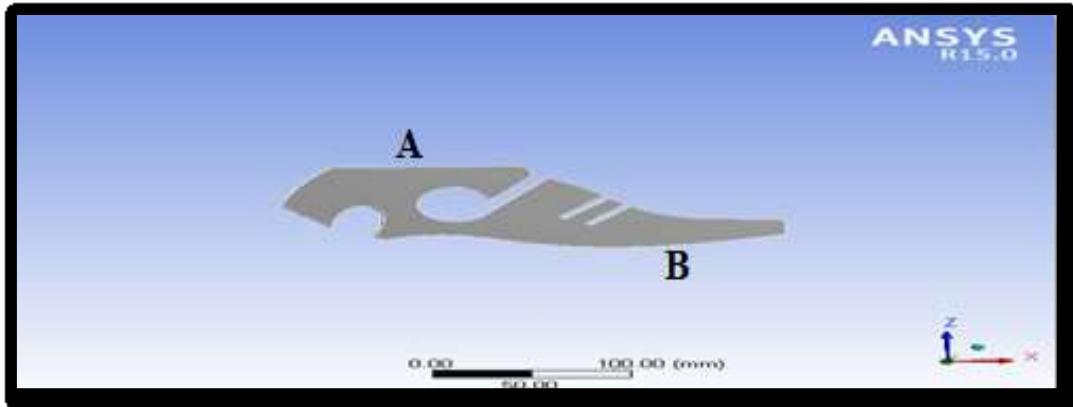


Figure (5) A fixed point, B loads applied point on the prosthetic foot designed .

F. Solving

The steps used to calculate the deformation, stress and strain properties of prosthetic foot than the dorsiflexion angle was determined 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

A. Tensile Test Results and discussion

As showed from the Figures (6 and 7) the tensile strength, modulus of elasticity results for PMMA/SR and PMMA/PUR with ratio of carbon fibers (CF), tensile strength , modulus of elasticity increased with increasing the ratio of carbon fibers that due to the fibers will carry and distribute most the load applied on the specimens of composite material all that will lead to raise the strength of composite material while the effect of rubber content when added to PMMA decrease the tensile strength and modulus of elasticity for all polymer composites .

Tensile strength for pure PMMA polymer was 78 MPa but improved by blending it with SR or PUR and then reinforced by carbon fibers, as showed from the previous figures the tensile strength for PMMA:SR and PMMA:PUR groups were improved by 39% and 42% respectively at 15% CF, this slightly different for improvement depends on the nature of each rubber used as blends with PMMA.

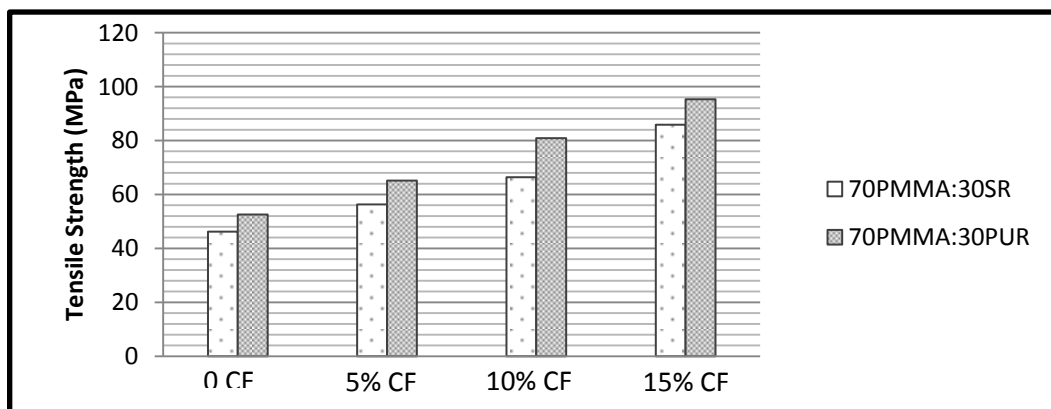


Figure (6) Effect of CF on the tensile strength of polymer composite samples.

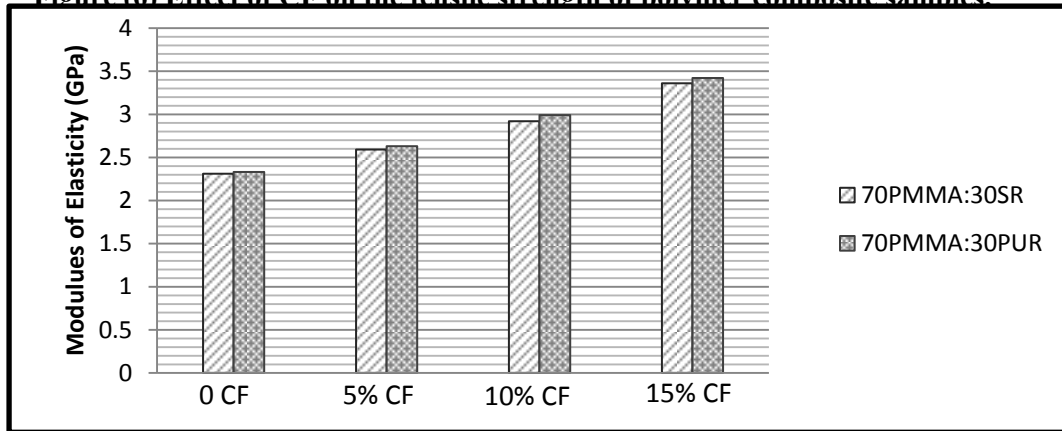


Figure (7) Effect of CF on the modulus of elasticity for polymer composite samples.

B. Numerical Results and discussion

According to the tensile results, total deformation analyzed on the designed Prosthetic foot can be seen in Figures (8,9,10 and 11) for polymer composite material from PMMA:SR .

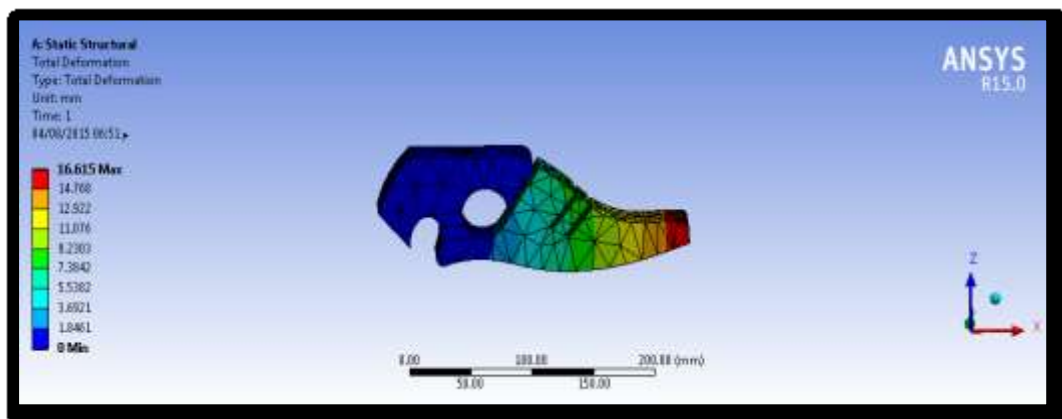


Figure (8) Total deformation results of 70PMMA:30SR before the reinforcement.

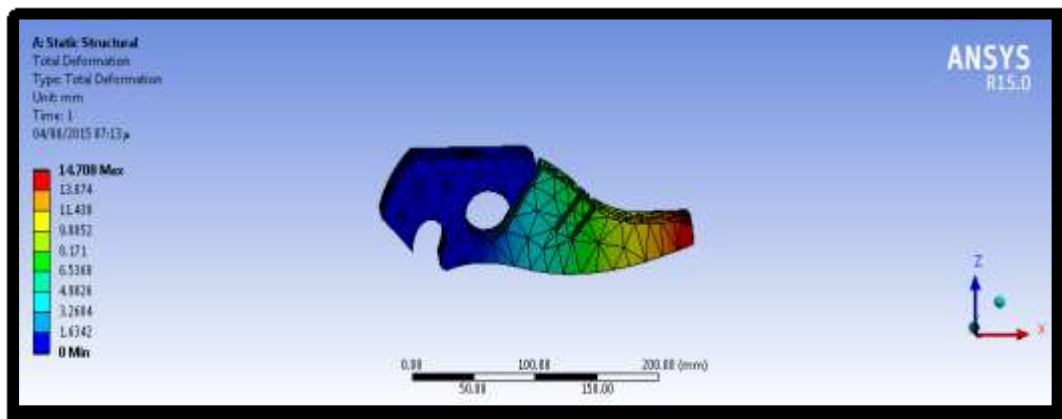


Figure (9) Total deformation results of 70PMMA:30SR reinforced with 5% CF.

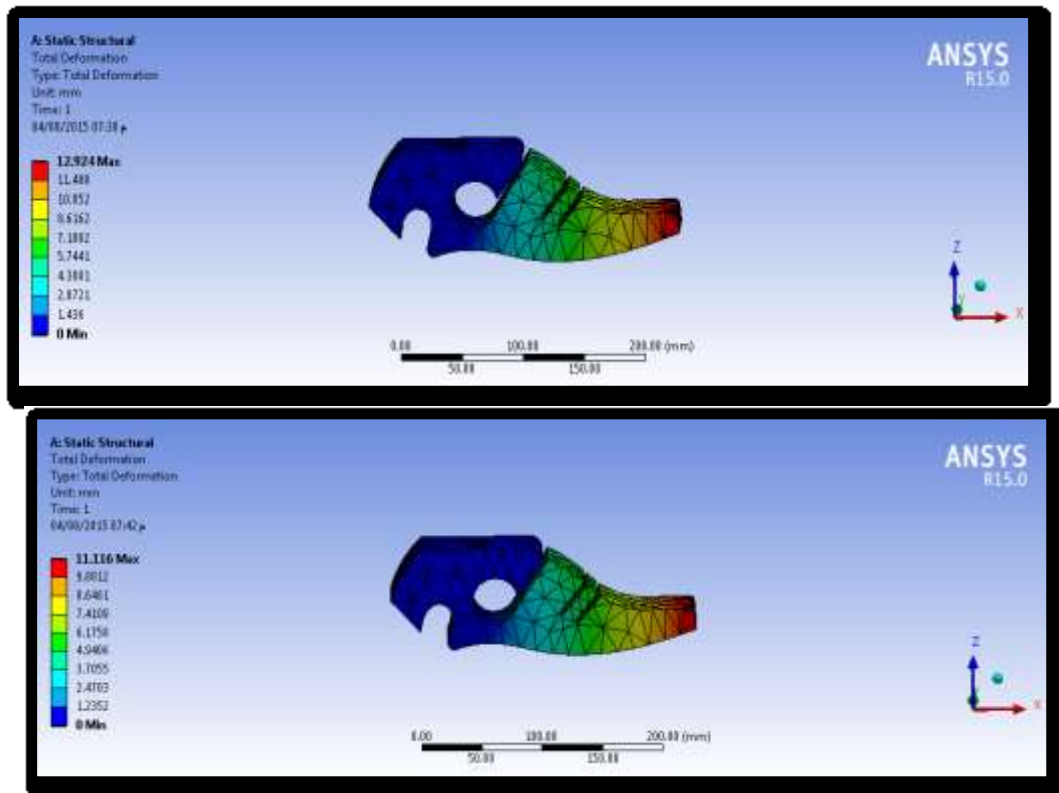


Figure (11) Total deformation results of 70PMMA:30SR reinforced with 15%CF.

In addition total deformation analyzed results on prosthetic foot designed can be seen in figures (12,13,14 and 15) for polymer composite material from PMMA: PUR.

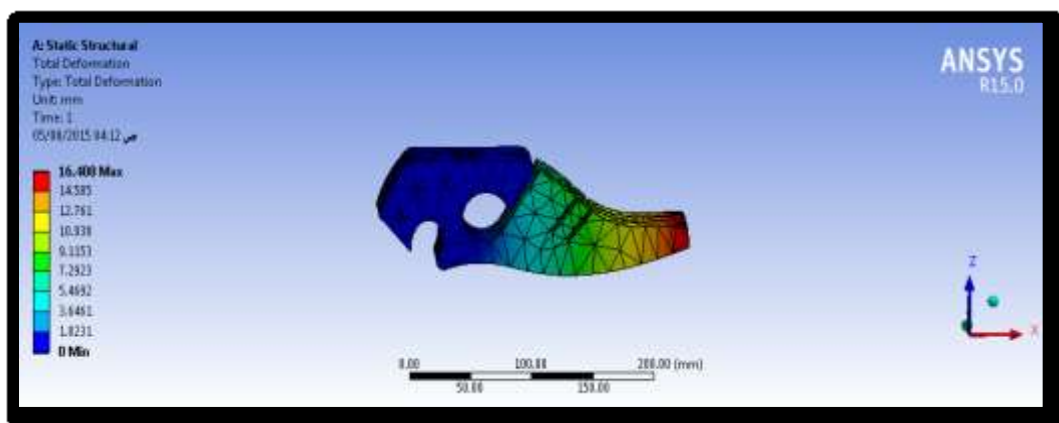


Figure (12) Total deformation results of 70PMMA:30PUR before the reinforcement.

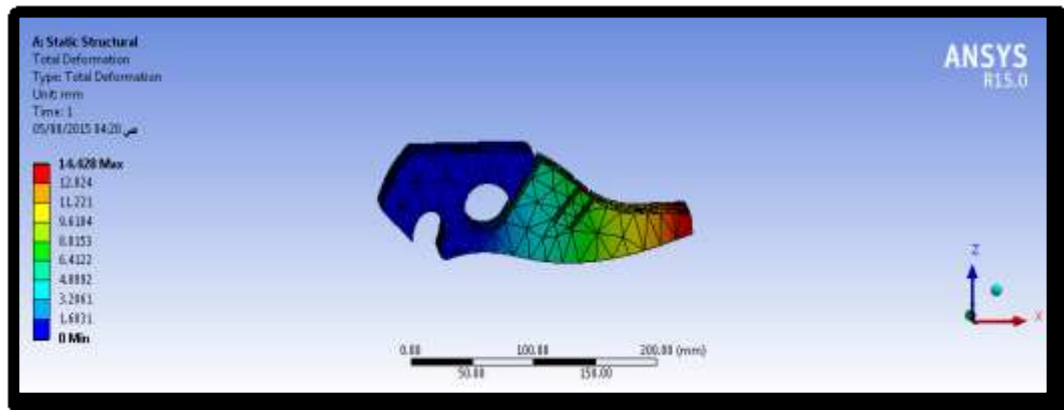


Figure (13) Total deformation results of 70PMMA:30PUR reinforced with 5% CF.

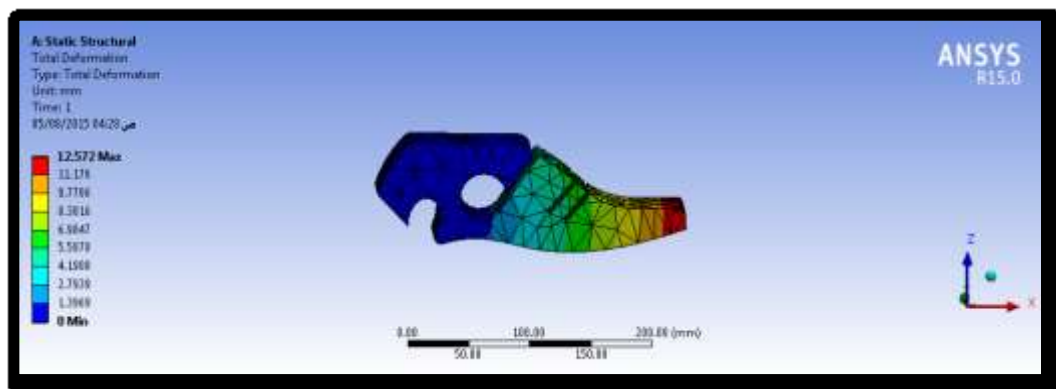


Figure (14) Total deformation results of 70PMMA:30PUR reinforced with 10% CF.

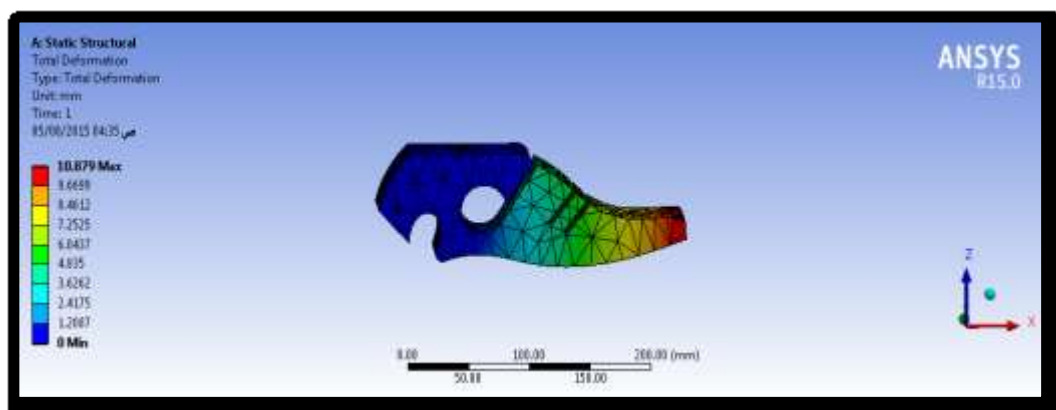


Figure (15) Total deformation results of 70PMMA:30PUR reinforced with 15% CF.

As showed from the previous figures, generally total dorsiflexion decrease with increasing ratio of carbon fibers for polymer composite samples, for PUR polymer blend group the total dorsiflexion was lower than SR polymer blend group and this was corresponding with experimental results due to nature glue for PUR which provide high bonding between the matrix and fibers.

In addition the dorsiflexion angle can be calculated for all eight samples depends on the dorsiflexion value by determined $\tan \theta$ which represent to the angle between the line from forepart prosthetic foot design to fixed point and the length of dorsiflexion caused by force applied, as showed from the table (2) below and figures (16 and 17) 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 prove this acceptable and can be recommended for this application [10].

Table (2) Dorsiflexion and Dorsiflexion angle for prosthetic foot designed.

PMMA	SR	PUR	Dorsiflexion mm	Dorsiflexion Angle $^\circ$
70	30	—	16.61	4.74
70	30	—	14.70	4.20
70	30	—	12.92	3.69
70	30	—	11.11	3.17
70	—	30	16.40	4.68
70	—	30	14.42	4.12
70	—	30	12.57	3.59
70	—	30	10.87	3.11

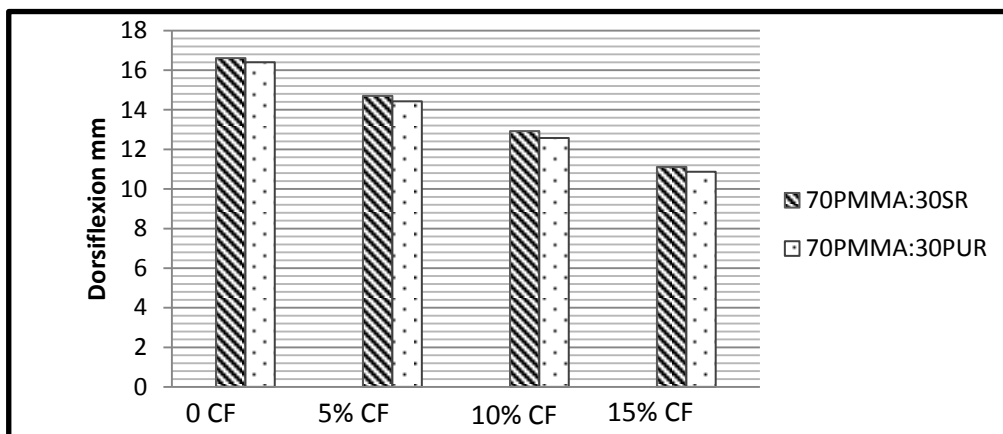


Figure (16) Effect of CF on the dorsiflexion of polymer composite samples.

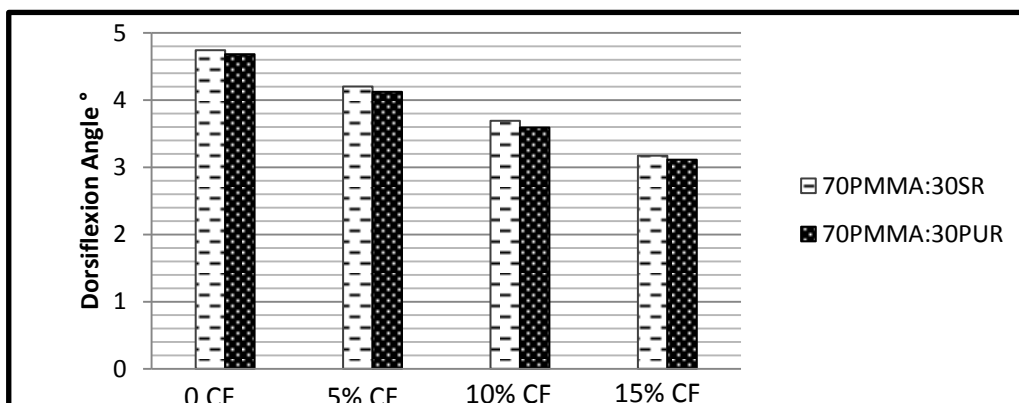


Figure (17) Effect of CF on the dorsiflexion angle of polymer composite samples.

The figures (18,19) illustrate equivalent stress and strain results, the result of equivalent stress was lower than the yield strength of composite material.

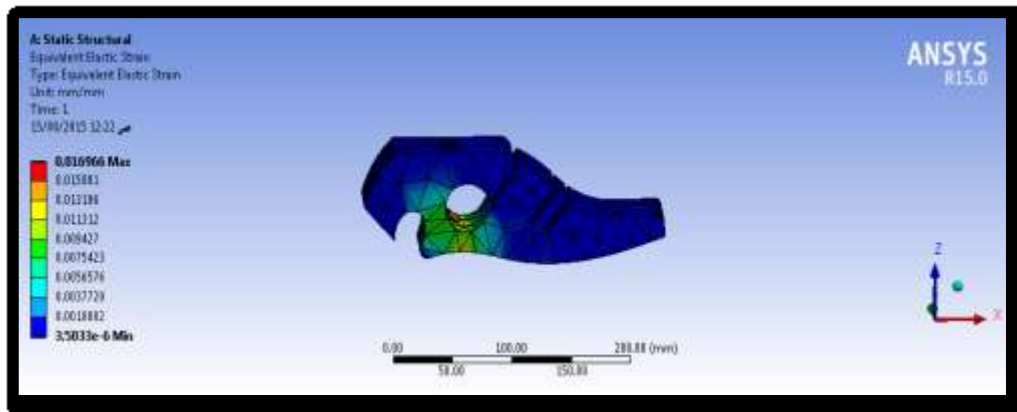


Figure (18) Equivalent Elastic Strain results .

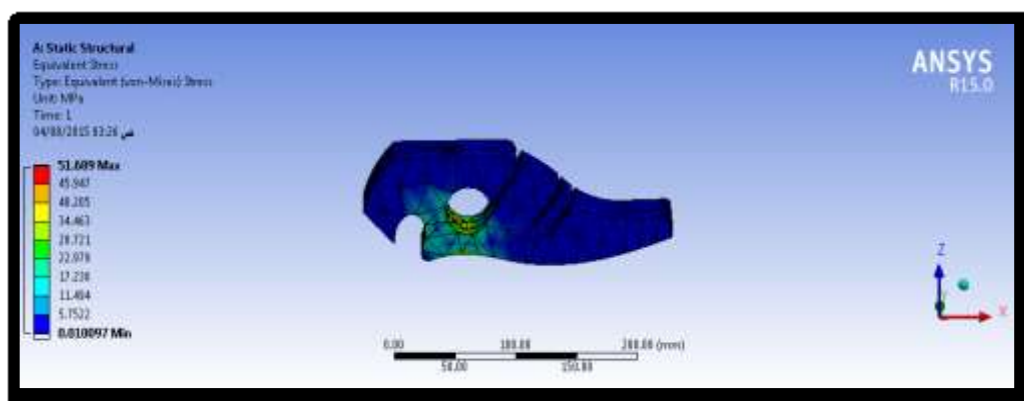


Figure (19) Equivalent Stress results .

CONCLUSIONS

- Generally, tensile strength and modulus of elasticity for polymer composite samples contain PUR are higher than, that contains SR due to glue nature for PUR which improved slightly mechanical properties. In addition PMMA:SR/PUR with reinforcement by CF as suitable material, offer many advantages such as easy to mold to any shape and lowering the cost for lower limbs prosthetic foot spatially for lower economic countries.
- Tensile strength was improved by 37-39% with reinforced by CF for PMMA:SR groups and 40-42% for PMMA:PUR groups.
- Rubbers were used as blend for brittle polymer material as PMMA led to improve the interface (fiber-matrix) which enhanced the mechanical properties.
- It is obtained a new design of prosthetic foot with more acceptable deformation under loads at good dorsiflexion angle.

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