Improving Mechanical and Fatigue Characteristic of Trans-Tibial Prosthetic Socket

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***Abstract*-In this work, Five laminated composite materials used for manufacturing trans-tibial prosthetic sockets by using vacuum molding technique. The matrix materials of these composites is Blend of (50 wt. % Epoxy and 50 wt. % PMMA), reinforced with perlon layers, fiber glass layers, carbon fiber layers, hybrid (carbon and glass) fiber layers, and hybrid (carbon and glass) layers with micro Silica particles.**

The tensile properties, max. shear stress, fracture toughness and alternating bending fatigue properties were measured experimentally. The theoretical part of this work deals with calculations of the fatigue ratio, theoretical factor of safety and failure index. The finite element technique (ANSYS-11) is used to analyze and evaluate alternating bending fatigue characteristics by observing the contours distribution of fatigue life, safety factor, equivalent Von Mises stress, total deformation and maximum shear stress.

The results show that changing the type of reinforcement and matrix has a great influence on the measured properties: ultimate tensile strength of (Blend with Glass reinforcement) is the highest. The highest maximum shear stress, fracture toughness, fatigue limit, strain energy limit and safety factor is obtained in Blend with Glass composite with (59.42) MPa, (8.45) MPa.m$^{1/2}$, (62) MPa, (96.66) Joul/mm^3 and (9.3), respectively. Reinforcement with perlon gave the lowest values in all measured properties used in this study.

(Blend with Glass reinforcement) composite gave optimum experimental, numerical and theoretical results which make it the best candidate to improve the fatigue characteristics of trans-tibial prosthetic socket.

Keywords— transtabial socket; prosthetic; composites

I. INTRODUCTION

Prosthesis an artificial device used to replace a missing body part, such as a limb, tooth, eye, or heart valve. For optimal prosthetic performances, the socket must be facilitate motion. Forces, generated by the residual limb through gait motion, must be efficiently transmitted from the limb to the prosthesis; thus, any relative motion exhibited between the residual limb and the socket will challenge successful ambulation, thereby increasing fatigue and discomfort. Patients except to receive prosthesis with proper fit, ultimate comfort and functionality. Additionally, the prosthesis must be light weight and cosmetically appealing. Majority of the failure of prosthetic components are fatigue related under cyclic walking loads. Materials and mechanical properties of the prosthetic socket were studied by many investigators. T.A. Current et.al. quantified the structural strength of various trans-tibial composite sockets. Five different reinforcement materials and two resin type were used to construct the sockets [1]. A. A. Ibrahim investigate the structural strength of the syme prosthesis by proposing two laminate with different reinforcement materials [2]. Sam L. Philips and William Crelius initiates a data base on material properties of typical laminations used in prosthetic limb sockets, the authors subjected samples of common prosthetic laminations to tensile and bending tests. Eight varieties of lay-up materials (fibers) were each laminated separately with one of three common resins (matrix), resulting in 24 combinations of fiber/resin laminates [3]. H. F. Neama, presents analyses for below knee prosthetic socket. Socket stress distribution is performed on three types of sockets, polypropylene (5mm), polypropylene (3mm) and standard laminate (8 layers of nylglass) (3mm) sockets to determine the stress path through the prosthetic socket during gait cycle [4]. S. H. Mohammed investigated the ankle-foot orthoses numerically and experimentally using perlon-carbon-fibers-acrylic materials instead of typical used polypropylene materials [5].

This article reports the effect of materials type on the tensile properties (Young's modulus, tensile strength and elongation at break) and fatigue properties (S-N curve, strain energy-N and fatigue limit) of trans-tibial prosthetic socket, by quantifying socket's structural strength (Experimentally, Numerically and Theoretically) of five different reinforcement [perlon fibers, carbon fibers, glass fibers, (carbon+glass) fibers and (carbon+glass) fibers+SiO$_2$ particles] with Blend of (50 wt. % Epoxy and 50 wt. % PMMA) as a matrix.

II. THEORETICAL PART

Theoretical part of this article is based on the following Theories and Criteria:

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A. Goodman relationship

An empirical relationships have been devised to describe the relationship between fatigue limit and mean stress [6]

B. Strain Energy criterion

The strain energy may be used as a fatigue failure criterion for fiber-reinforced materials. Since this parameter does not rely on the different failure modes obtained in composites, it gives equally good results independent of the failure mechanism [7]. The area under the stress-strain graph is the strain energy per unit volume [8]

C. Von Mises Equivelent stress

The Von Mises stresses "allow the most complicated stress situation to be represented by a single quantity" [6] [9]

D. Maximum Shear Stress [6]

Factor of Safety

The maximum equivalent stress failure theory states that a particular combination of principal stresses causes failure if the maximum equivalent stress (σ_e) in a structure equals or exceeds a specific stress limit (σ_{ts}). Therefor the equation of safety factor can be written according to Goodman [10]

Fatigue Ratio (R_f)

The fatigue ratio (R_f) is the ratio of the endurance limit to the tensile stress [11].

III. EXPERIMRNTAL PART

Materials needed in the lamination of the below knee socket for this study are: Epoxy resin, PMMA resin, Carbon fiber stockinet, Fiber glass stockinet, Hybrid (Fiber glass + carbon) stockinet, Perlon stockinet and micro precipitated Silica particles with median particle size of (15µm). Other materials needed for the manufacturing of prosthetic socket were: Hardening powder, polyvinyl alcohol PVA bag and Materials for Japson mold.

The following tests were performed:-

Tensile Test is performed according to (ASTM D638) at room temperature with (5 KN) applied load and strain rate of (1 mm/min). Figure (1) shows a tension standard specimen [12].

Maximum Shear Stress is measured from “Three- Point Test”. This test is performed according to (ASTM D790) at room temperature by three- point bending test machine (Lybold Harris No.36110). Figure (2) shows standard specimen for this test [13].

Impact Test is performed according to (ISO- 179) at room temperature. Figure (3) shows standard specimen for impact test. In this test, the calculation of the fracture toughness depended on the calculation of the required energy for fracture [14].

The Fatigue testing used was by an alternating-bending fatigue testing machine with the specification of (fatigue testing machine HSM20, 1400 rpm ,spanning voltage 230 V , frequency 20Hz, Normal power 0.4 Kw), and performed at room temperature and a stress ratio of R= - 1 (tension–compression). Figure (4) shows the fatigue standard specimen test according to the machine's manual [15].

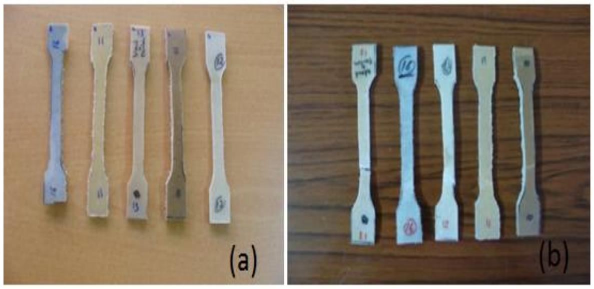

Fig. 1 Experimental Tensile Specimen (ASTM D638), (a) Before (b) After Test.

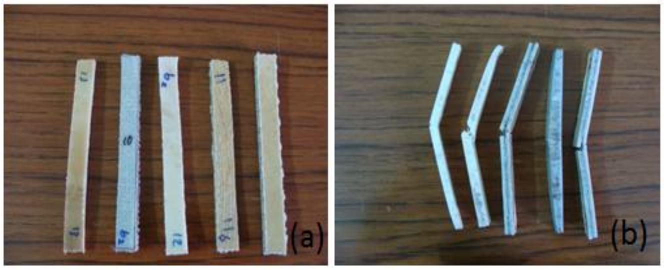

Fig. 2 Experimental Flexural Specimen, (ASTM D790)., (a)Before and (b)After Test .

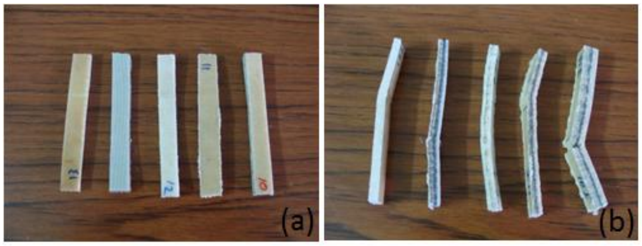

Fig. 3 Experimental Impact Specimen, (ISO- 179), (a) Before and (b) After Test.

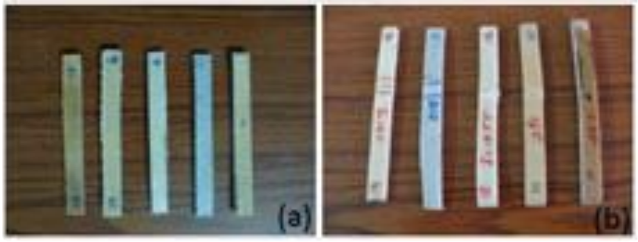

Fig. 4 Experimental Fatigue Specimen, (a) Before and (b)After Test.

IV. FINITE ELEMNT ANALYSIS

Finite Element Analysis provides (Fatigue Life, Fatigue Factor of Safety, Equivalent Alternating Stress (Von Mises Stresses), Maximum total Deformation, Maximum Shear Stress) distribution of the simulated prosthetic socket of 75.5 kg in body mass.

As shown in fig.(5). The purpose of the sliding and cutting the gypsum socket is to get accurate dimensions (x, y & z), by this step more than 400 point is gotten which used then to draw the socket by Auto CAD and then analyzing the stresses under the applied force in fatigue conditions in ANSYS is done. The socket is analyzed at the most extreme load conditions, which exist at heel strike in Gait cycle. Pressures values [16] listed in table (1) were applied on sockets plane shown in fig.(5c).

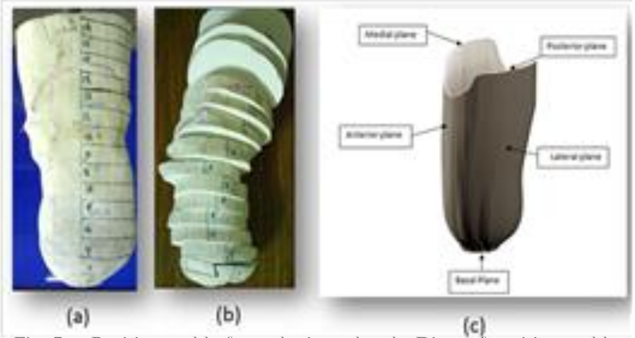

Fig. 5 a- Positive mold of prosthetic socket. b- Discs of positive mold. c- Auto CAD model of prosthetic socket.

Table (1): Location and average pressure values of Heal strike generated in socket [16].

Location	Average Pressure value (MPa)
Anterior	0.011655
Posterior	0.0444075
Medial	0.03434
Lateral	0.045765
Basal	0.288

The Ansys (11) package is used here for this type of analysis, the three-dimensional element is SOLID 185 as in Fig.(6) is used for 3-D modeling of solid structures [6]. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. Fig.(7) represents the mesh generation of the composite sockets.

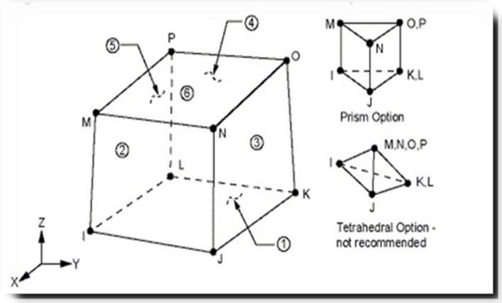

Fig. 6 3-Dim. Element solid 185 [6].

Fig.7 The meshed socket

V. RESULTS AND DISCUSSION

This study compares the tensile properties (Young's modulus (E), Ultimate tensile strength, and percentage of elongation at break) of trans-tibial composite prosthetic sockets. Changing the type of reinforcement and matrix has a great influence on tensile properties. It is clear from fig. (8) that the reinforcement with Glass and Hybrid (Glass+Carbon) gave the optimum tensile properties, where they both have a high Young's modulus (E), Elongation, and Ultimate tensile strength. This improvement in tensile behavior came from the fact that both Epoxy and PMMA are brittle in nature, and the tensile behavior of the in-situ polymerized MMA/Epoxy system is presented demonstrating a remarkable synergistic effect for the strain at break evidenced from Fig.(8) which shows that (Blend+Glass) composite gave the largest elongation at break. In addition to high tensile strength showed in Fig.(8), this lamination achieve an economy goal by reducing the cost of the socket lamination to optimum value by keeping the mechanical properties with acceptable value [17]. From Fig. (8) it is noted that reinforcement of Perlon gave the lowest tensile properties, meaning that perlon did not improve the properties of matrix material to any extent and the tensile properties of matrix are predominated in the overall behavior of the composites.

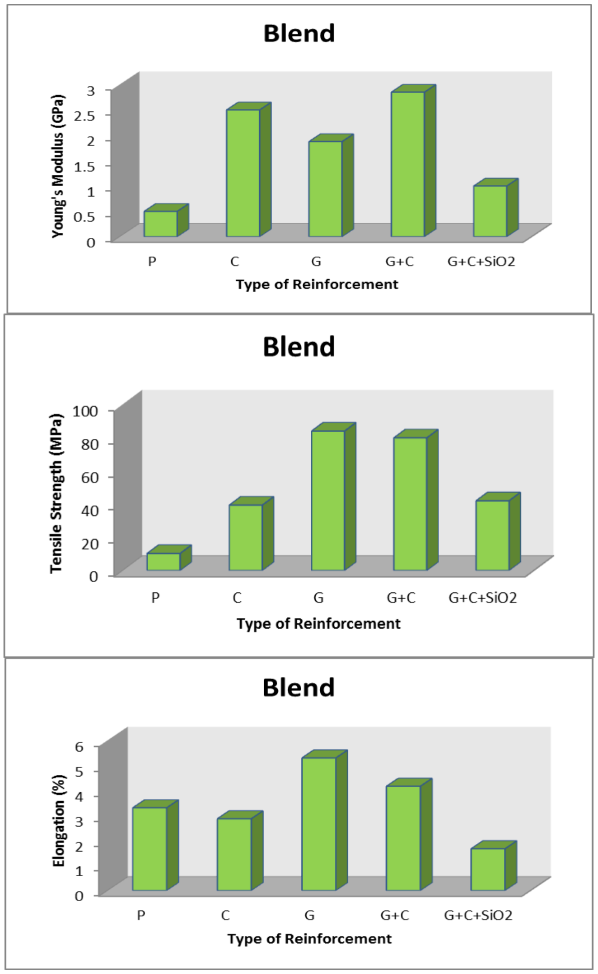

Fig. 8 Tensile Properties (Young's Modulus, Tensile Strength, Elongation (%)) of Blend Matrix Composite.

Fig.(9) shows the max. shear stress of composites used in this study. The highest maximum shear stress is obtained in Blend with Glass reinforcement with 59.42 MPa respectively. The high (fiber- matrix)bonding [18] of the composite mentioned above have a remarkable effect on increasing the max. shear stress. The effect of the presence of SiO_2 particles together with matrix of polymer blend results in inhomogeneity that produces stress concentrations [6] that can reduce bonding strength. Low amount of bonding strength contribute in low max. shear stress of perlon reinforcement with 6.987 MPa.

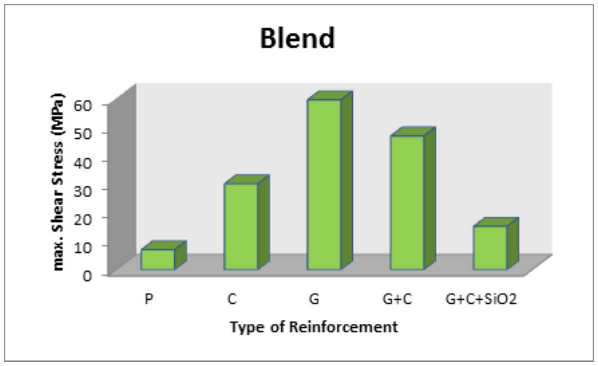

Fig. 9 Max. Shear Stress of Blend Matrix Composites.

Fig.(10) shows the Impact Fracture Toughness of composites used in this study. The maximum fracture toughness is obtained in Blend with Glass composite with 8.45 MPa.m$^{1/2}$. The high modulus of elasticity and high (fiber- matrix) bonding of the composite mentioned above have a remarkable effect on increasing the fracture toughness. Blend has a pronounced effect in increasing the fracture toughness of Blend with Glass and Blend with Hybrid (Glass+Carbon) composites by giving a large strain at break [17] combined with high modulus of elasticity and tensile strength evidenced by tension test. Low amount of Young's modulus contribute in low capacity to absorb or dissipate energies and low fracture toughness of perlon reinforcement with 1.88 MPa.m$^{1/2}$.

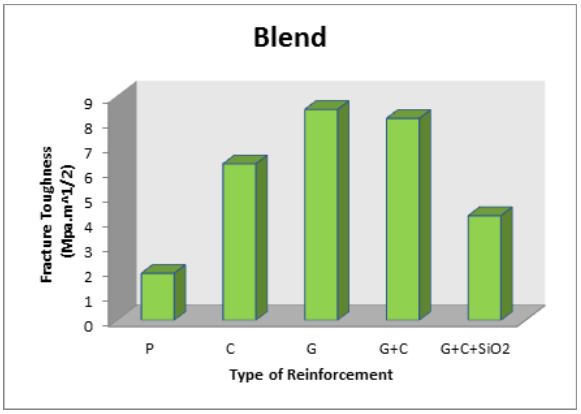

Fig. 10 Impact Fracture Toughness of Blend Matrix Composites.

The results of all fatigue tests carried out at various reinforcements are graphically displayed in the form of S-N curves shown in fig.(11). These curves are obtained by curve fitting the experimental data of fatigue test, using logarithmic formula [19]. It is noted that these equations have relatively high correlation coefficient which indicate that the experimental data are well explained by log formula. The fatigue limit (strength) of the tested materials is taken at No. of Cycle of 10^6. Since, beyond that No. of Cycles fatigue life becomes infinite [18]. In general, the fatigue limit (strength) of materials is proportional to its tensile strength [20]; hence materials with higher ultimate tensile strength possess higher fatigue limit. It is evident from fig.(11) that for all classes of laminates, reinforcement type have a pronounced influence on their fatigue resistance. As shown in fig.(11) and (12) Glass reinforcement give the highest fatigue limit. These higher fatigue limit (strength) can be attributed to the cavitation process by which the rubbery blend particles near the wake of crack tip elongate thereby absorbing much of the energy resulting in increased fracture toughness [17] combined with high Young's modulus (E) and Ultimate tensile strength and max. shear stress. Fatigue limit of Glass reinforcement increase as much as (13) times of magnitude as compared to Perlon reinforcement.

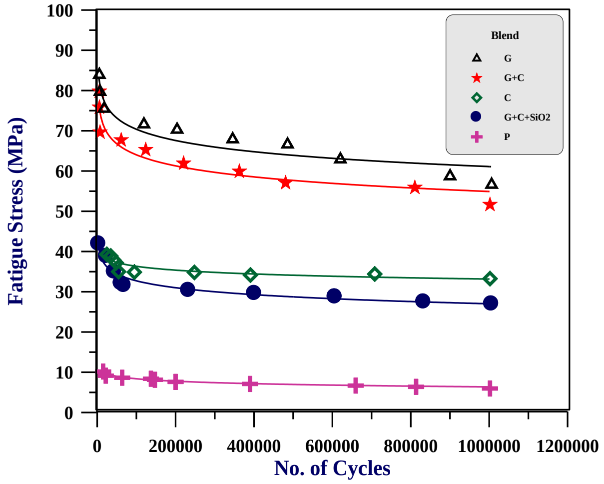

Fig. 11 S-N curves of Blend Matrix Composites with Various Reinforcement.

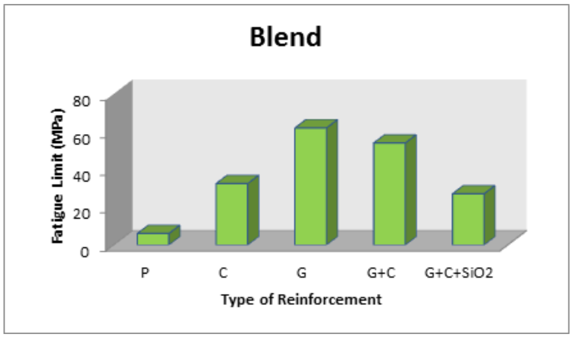

Fig.12 Fatigue limit of Blend Matrix Composite.

Both stress and strain were recorded from tension test and used to evaluate strain energy and strain energy limit for the composites and plotted in fig.(13 & 14). It can be seen that (Blend with Glass reinforcement) composite have the highest strain energy with 96.66 Joul/mm^3, that is logical since their stress and strain values are high which means that this composite material have the ability to store a large amount of energy before damage and failure take place. It can be seen that the perlon reinforcement gave the lowest values of Strain Energy and Strain Energy limits among all with 3.4 Joul/mm^3. This behavior comes from the low tension properties of this type of reinforcement. Also the logarithmic formula used in curve fitting the data of strain energy of fig. (13) as represented in Table (2).

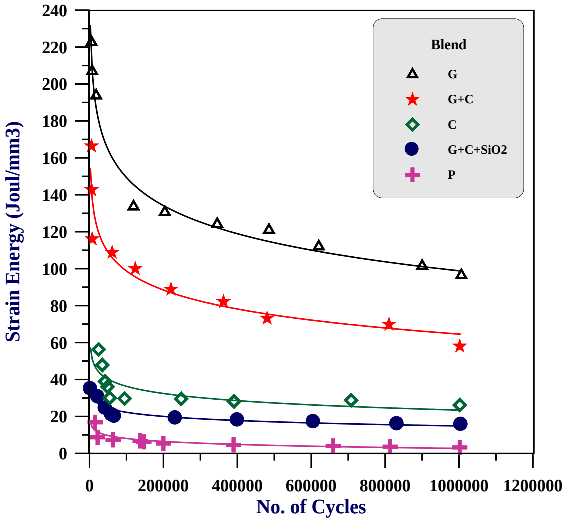

Fig.13 Strain Energy- No. of Cycles Curves of Blend Matrix Composites with Various Reinforcement.

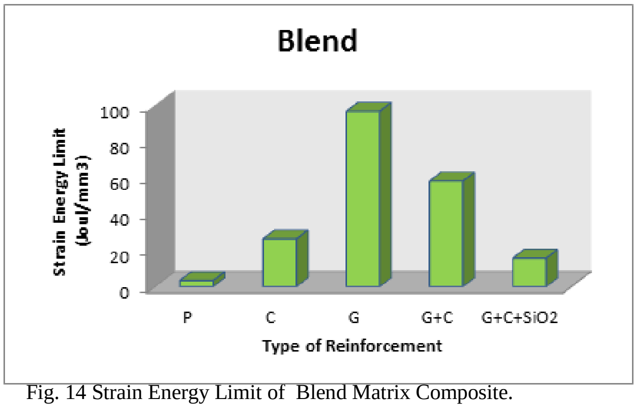

Fig. 14 Strain Energy Limit of Blend Matrix Composite.

Fatigue Life shows the available life for a given fatigue analysis. Counter plots shown in fig.(15) were used to display the overall distribution of life throughout the socket for each type of composite used in this study. In stress life analysis with constant amplitude, if the equivalent alternating stress is lower than the lowest alternating stress defined in the S-N curve, the life at that point will be used [6].

These are counter plots with respect to fatigue failure at a given design life. In Ansys, Maximum factor of safety displayed is 15, values less than one indicate failure before the design life has been reached [6]. It can be noticed in fig.(16) the distribution of safe and unsafe regions of the composites. Minimum safety factor of each composite is recorded in the mentioned figures above where it can be seen that (Blend with Glass reinforcement composite have the highest safety factors of (9.3962). It is obvious that all materials are safe [6].

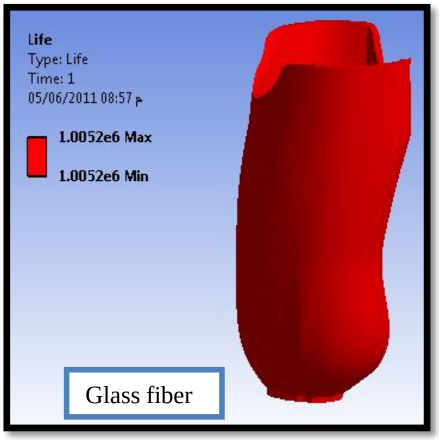

Fig. 15 Sample of contours of fatigue life distribution.

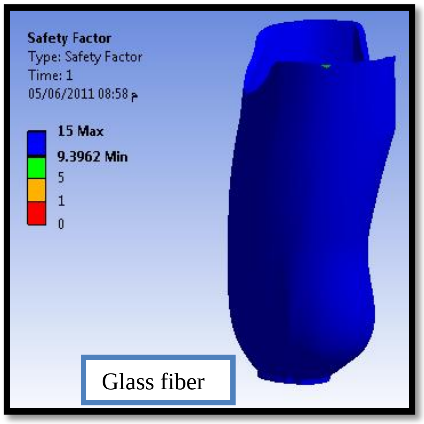

Fig.16 Sample of Contours of Fatigue Safety Factor distribution.

Equivalent alternating stress is the stress used to query the fatigue S-N curve after accounting for fatigue loading type, R-ratio effects and any other factors in fatigue analysis [6]. Equivalent alternating stress is the last calculated quantity before determining the fatigue life [6]. Fig.(17) show contour plots of the Blend composites which display the overall distribution of the Von Mises stresses throughout the material, as well as to determine the approximate location and value of the maximum Von Mises stresses. It can be seen from these figures that the highest values of Von Mises stress is concentrated in the lateral and basal planes of socket.

Figs.(18) show the total deformation for composites. The highest Total deformation values can be seen in Perlon reinforcement. It can be seen from these figure that the highest values of total deformation is concentrated in the lateral plane of socket and the smallest values of total deformation is concentrated in the basal plane of socket.

Fig.(19) show contour plots of the composites which display the overall distribution of the Maximum Shear Stress throughout the material, as well as determine the approximate location and value of the Maximum Shear Stress. It can be seen from these figures that the highest values of max. shear stress is concentrated in the lateral and basal planes of socket.

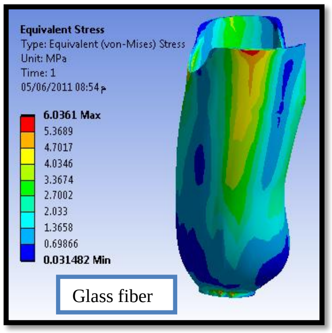

Fig. 17 Sample of Contours of Equivalent Von Mises stress distribution

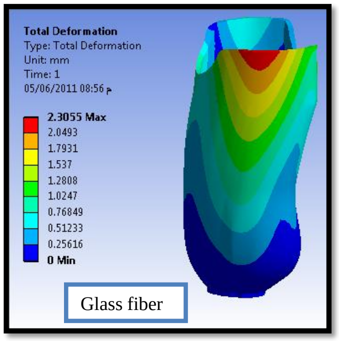

Fig. 18 Sample of total deformation.

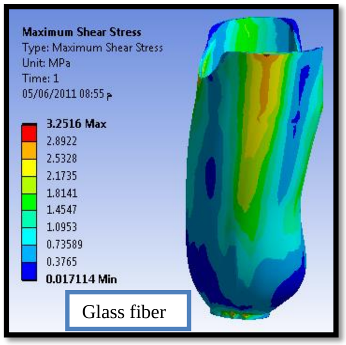

Fig.19 Sample of contours of max. shear stress

Fig.(20) shows the relationship between fatigue ratio and type of reinforcement for composites used in this study, it can be seen from this figure that fatigue ratio of (Blend with Glass reinforcement) composite is the highest with 0.738. Since, both Fatigue Limit and Tensile strength of these composites are the highest between the other composites which coincide with the experimental result.

Safety Factor of the composite materials is obtained according to Goodman Theory [21]. Fig.(21) shows the relationship between factor of safety and type of reinforcement for the three matrix used in this study, it can be seen from this figure that the factor of safety of (Blend with Glass reinforcement composite give the highest Safety Factor among all other composites with 10.27. Perlon reinforcement has the lowest amount of Safety Factor with 1.02.

Fig.(22) shows the relationship between failure index and type of reinforcement. It can be seen from this figure that the Perlon reinforcement has the highest amount of Failure Index with 0.98. (Blend with Glass reinforcement) composite give the lowest failure index among all other composites with 0.097.

Fig. 20 Fatigue Ratio of Blend Matrix Composites.

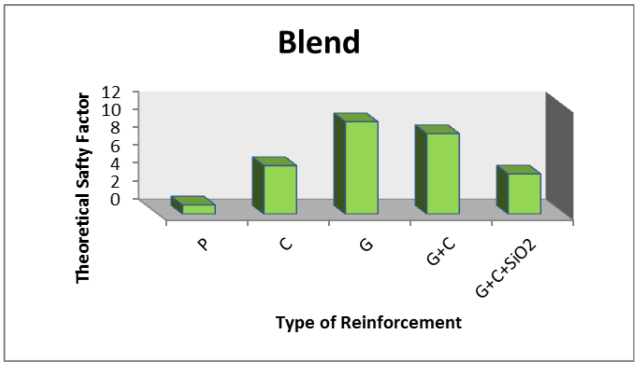

Fig. 21 Theoretical Safety Factor of Blend Matrix Composites.

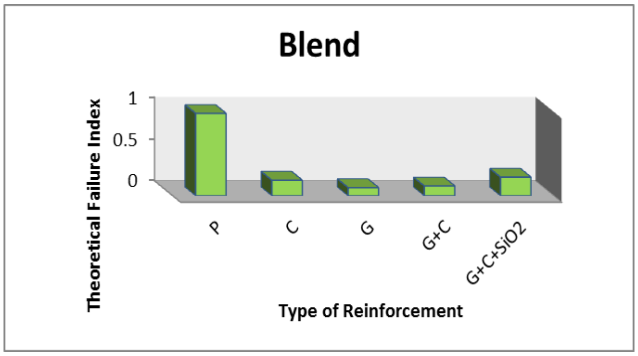

Fig. 22 Theoretical Failure Index of Blend Matrix Composites.

VI. CONCLUSION

(Blend with Glass reinforcement) composite give optimum experimental, numerical and theoretical results which make it the best candidate to improve the mechanical and fatigue characteristics of Trans-Tibial prosthetic socket.

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