Mechanical Properties of Hybrid and Polymer Matrix Composites That Used To Manufacture Partial Foot Prosthetic

Hassanein Salih Hussain
Mechanical Eng. Dep.
Al-Nahrain University
hassaneinseruk91@gmail.com

Ayad Murad Takhakh
Mechanical Eng. Dep.
Al-Nahrain University
ayadmurad@nahrainuniv.edu.iq

Abstract

In this study, an experimental comparison has been made between the traditional plastic materials (Polypropylene and Polyethylene) and selected composite materials (Perlon-Carbon-Perlon and Hybrid Carbon fiber-Glass fiber) to manufacture a long life Partial Foot Prosthesis. To improve the mechanical properties, increase the lifetime of the prosthesis, and reduce the cost to the patient, two types of composite materials were used and compared with plastic materials. Samples were manufactured and tested with different test methods (Tensile, flexural, and fatigue test). All tests were performed at room temperature.

The results showed that the composite materials achieve a large increment in mechanical properties such as (σ_y, σ_{ult}, E, σ_b, and E_f) which were increased to a percentage of (200% - 261%), (330% - 243%), (295% - 203%), (276% - 270%), and (413% - 301%) in Perlon-Carbon-Perlon lamination as compared with Polypropylene and Polyethylene respectively. However the increasing percentage in Hybrid Carbon fiber-Glass fiber was (353% - 270%), (470% - 347%), (388% - 267%), (203% - 199%), and (244% - 178%) as compared with Polypropylene and Polyethylene. At the same time, the fatigue life was sharply increased in both of the Perlon-Carbon-Perlon and Hybrid Carbon fiber-Glass fiber.

Keywords: Partial Foot Amputation; Prosthetics; Composite Materials; Perlon-Carbon-Perlon; Hybrid carbon fiber-glass fiber.

1. Introduction

Composite materials are usually composed of a reinforcement such as a fiber and a matrix such as a resin. Nylon, fiberglass and carbon fibers and polyester, acrylic, and epoxy resins are the commonly used composite materials in prosthetics and orthotics. Several factors can greatly affect the strength and performance of composite materials. The adhesion at the interface between the resin and fiber, and the mechanical properties of the resin and fiber, greatly affect the composite performance. The fiber length, orientation and ratio of fiber to the resin, and processing techniques used to fabricate the composite also affect the composite properties [1].

Nowadays, the composite engineers are focusing on the development of new stronger, tougher, lightweight structural materials supporting latest technologies and design concepts for the complex shaped structures [2].

The development of composite materials improves their performance based on the reinforcement of two or more fibers in a single polymeric matrix, which leads to the advanced material system called hybrid composites with a great diversity of material properties. This is a major challenge that can only be met through an understanding of the relationships between materials architecture and mechanical response [3].

In the ever-changing field of orthotics and prosthetics, recent advancements have been achieved with the use of new materials and resins. In the spring of 1981, a study project was initiated in an attempt to learn the proper use of these high-tech materials. Data was accumulated from various chemistry and physics texts on the characteristics of composite materials, specifically carbon, Kevlar, and fiberglass [4].Prostheses and Orthoses prescribed for partial foot amputations vary in design and principle [5]. The main goals of orthotic and prosthetic devices in partial foot amputations are to restore stability, maintain support, and protect the function of the residual limb. The materials and techniques used today have had significant positive effects on function and comfort of partial foot amputees [6].

Many of literature were worked on orthosis and prosthesis's design and manufacturing: Muhsin J.Jweeg, et.al, used (perlon 6, 9 and 12 layers) [7]. Muhsin J.Jweeg and Jana S. Jaffar used perlon-carbon-perlon (424) [8]. S.S.Hasan**,** et.al, used different types of laminations [9]. Ayad M. Takhakh, et.al, used polypropylene [10].

In this work, different types of materials (plastic and composite) were used to get the best results that can be used to manufacture a partial foot prosthetics to achieve a good design of PFP and acceptable mechanical properties with long life.

2. Experimental Work

The development of new materials for fabrication of orthoses & prostheses is a great effect of the new technology, as these materials can increase comfort for the patient, reduce weight and increase strength and durability of the prosthesis or orthosis. [11]

Two groups of materials were selected to fabricate the specimens and make a comparison between the groups. By doing the mechanical tests, the material that has the best results will be selected to manufacture the Partial Foot Prosthetic.

Group A (thermoplastic materials):

- Polypropylene
- Polyethylene

These two materials will be the reference for the second group because they are usually used in the manufacturing of prosthesis and orthosis. **Table 1** shows the physical and mechanical properties of plastic materials.

Table 1: Physical & mechanical properties of the plastics. [9]

Material	Thickness (mm)	ρ_c (g/cm^3)	σ_{ult} (MPa)	E (GPa)	Strain to failure %
Polypropylene	5	0.905	28-41	1.3	>5
Polyethylene	5	0.910-0.940	7-41	0.13-1.3	>5

Group B (composite materials)

Most of the used materials are from Ottobock HealthCare [12].

- Perlon stockinet white (ottobock health care 623T3).
- Carbon stockinet black (ottobock health care).
- Hybrid Carbon fiber – Glass fiber meshed at (42-74) º (ottobock health care).
- Lamination resin 80:20 polyurethane (proter hand icap technology).
- Hardening powder (ottobock healthcare 617P37).
- Polyvinyalcohol PVA bag (ottobock health care 99B71).
- Materials for gypsum mold.

The equipment includes gypsum mold (positive mold rectangular cuboids in shape with size) 15*30*5)cm^3 as shown in **Fig.1**.

Figure 1: Gypsum mold.

Vacuum forming system includes a vacuum pump and some types of stands, pipes and tubes as shown in **Fig.2**.

Figure 2: Positive mold with a vacuum system.

The mechanical workshop includes different types of cutting tools, forming and measuring machines. Testometric machine for tensile and 3-point bending test (flexural test).

For tensile test, samples for each lamination and plastics were machined according to ASTM D638 [13] with 50mm original length and 13mm width while thickness varies with the type of layup. For 3-point bending, samples machined according to ASTM D790 [14] with 125 mm in length and 13mm in width while thickness varies. Alternative bending fatigue machine (HI-TECH) for fatigue test. Samples for each lamination were machined according to Standard of Fatigue Devise - HSM20 with 100 in length and 10 mm width while thickness varies [15]. Sensitive weighting device (four digits) for measuring the weight of specimen as achieving the requirement of good socket design for acceptable mechanical properties.

The procedure for the fabrication of the composite samples involves several steps. Laminations were performed under vacuum; the following procedures will show the fabrication steps of composite samples:

- Mount the positive mold at the laminating stand and complete the connection with the vacuum forming system through the pressure tubes and pull the (PVA) bag in the positive mold, then open the pressure valve to the value of approx. (40-80 KPa) at room temperature.
- For the Perlon-Carbon-Perlon lamination: put the perlon stockinet (4 layers) then the carbon fiber stockinet (2 layers) and then perlon stockinet (4 layers).For Hybrid Carbon fiber-Glass fiber lamination: put (8 layers) one above the other, then pull the outer (PVA) keeping the smaller end positioned over the

value area (use cotton string to tie off the (PVA) bag).

- Mix the lamination resin 80:20 polyurethane with the hardener according to the standard ratio for each 100 part of acrylic resin mixed (2- 3)part of hardener [12]. Then put the resulting matrix mixture inside the outside (PVA)bag and distributing the matrix homogeneously over all area of lamination stockinet.
- Maintain constant vacuum until the composite materials becomes cold and then left the resulting lamination as shown in **Fig.3** and **4**.

Figure 3: Positive mold before and after

Figure 4: Positive mold (Hybrid Cf-Gf).

The tensile, 3-point bending and fatigue specimens were machined.

a) For tensile test, five samples for each lamination and plastics were machined.
b) For 3-point bending, five samples machined.
c) At the same time, 12 samples for each lamination were machined for fatigue test.

So the total of tensile and flexural specimens is 64 samples. **Fig.5** shows the shape of each tensile and flexural sample.

(a): Tensile Samples.

(b): Flexural Samples.

(c): Fatigue Samples.

Figure 5: Samples of the used materials.

All the above 64 samples tested using Testometric machine test for tensile and 3point bending test, and Alternative bending fatigue machine (HI-TECH) for fatigue test at Applied Mechanics Laboratory / Al Nahrain University.

3. Result and Discussion

In samples physical features, the average thickness and weight for the Sample set were measured using digital Vernier and digital sensitive weighting device while sample density and volume fraction were calculated according to [16].The physical properties of a (65*13) mm sample are shown in **Table 2**.

Table 2: Physical properties of each sample.

Material	Lay up	Thickness(mm)	W (g)	ρ_c (g/cm^3)	v_f%
Polypropylene	1	5	3.925	0.929	--
Polyethylene	1	5	4.63	1.09	--
P-C-P	424	5	5.319	1.259	**0.6**
Hybrid Cf-Gf	8	3.5	4.652	1.572	**0.44**

3.1 Tensile Test Results

For tensile test, all 24 specimens of the tensile test were tested using the Testometric instrument for tensile testing. Five specimens of each material were tested to get stress-strain curves for each sample. **Fig.6** shows the tensile specimens under tensile test, and **Fig.7, 8, 9,** and **10** shows a stress- strain curve for each type of the materials.

Figure 6: Specimens under tensile test.

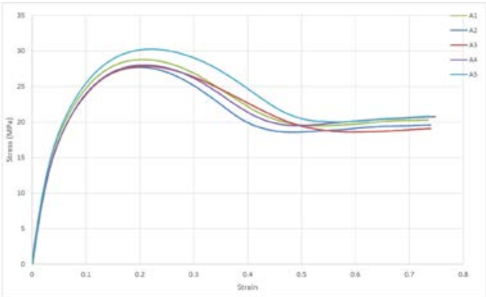

Figure 7: Stress-Strain curves for PP.

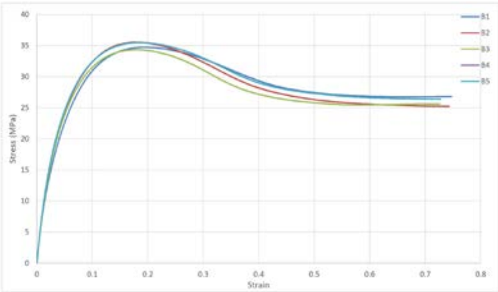

Figure 8: Stress-Strain curves for PA.

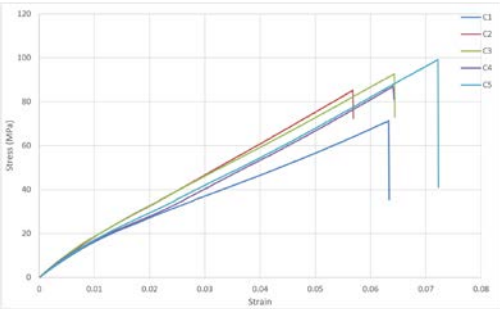

Figure 9: Stress-Strain curves for PCP (424).

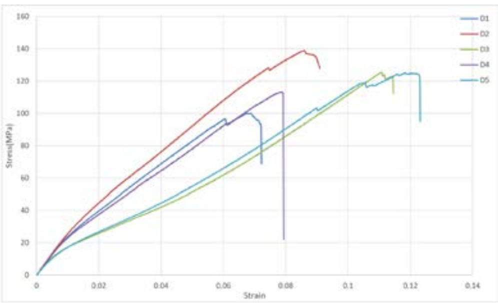

Figure 10: Stress-Strain curves for Hybrid Cf-Gf.

After plotting the stress-strain curve, mechanical properties of all samples will be calculated and by taking the average value of the mechanical properties (σ_y, σ_{ult} and E). The mechanical properties of all materials can be found as shown in **Table 3**.

Table 3 and figures Fig.7, 8, 9, 10 shows that there is a large difference in the mechanical properties (σy, σ_{ult} and E) between composite materials and plastic materials. The increase in those mechanical properties is attributed to the inclusion of the samples fibers such as carbon fibers and perlon in PCP (424) samples, glass fibers and carbon fibers in Hybrid Cf-Gf samples. These fibers were arranged in layers, therefore; it will cause an increase in that property.

Table 3: Mechanical properties calculated from stress-strain curves.

Material	Lay Up	σ_y (MPa)	σ_{ult} (MPa)	E (GPa)
Polypropylene	1	16	24	0.602
Polyethylene	1	21	32.5	0.875
P-C-P	424	41.8	79	1.778
Hybrid Cf-Gf	8	56.6	112.8	2.341

3.2 Flexural Test Results

In 3-point bending test, the Testometric device is used for 12 specimens for all groups of each material. The load-deflection curves show different results of each type of materials. **Fig.11** shows the 3-point bending specimens under flexural test and **Fig.12, 13, 14,** and **15** shows load-deflection curve. After plotting the load-deflection curve, mechanical properties of all sample will be calculated and by taking the average value of the mechanical properties ($\sigma_{b(max)}$, and $E_{flexural}$) using the following equations: [14]

$$\sigma_f = (3PL/2bd^2)[1 + 6(D/L)^2 - 4(d/L)(D/L)] \quad ...(1)$$

$$\varepsilon_f = 6Dd/L^2 \quad ......(2)$$

$$E_f = (\sigma_{f2} - \sigma_{f1})/(\varepsilon_{f2} - \varepsilon_{f1}) \quad ......(3)$$

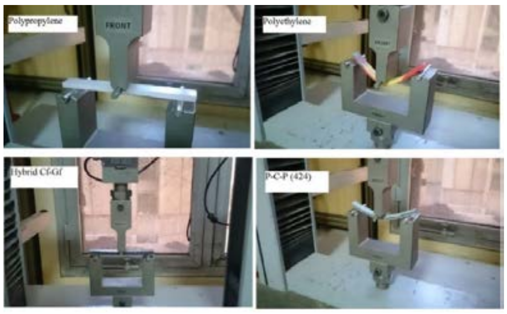

Figure 11: Specimens under flexural test.

The mechanical properties of all materials can be found as shown in **Table 4**.

Table 4 and Fig.12, 13, 14, 15 shows the results of the flexural test in which a large magnitude of increasing in maximum bending stress (σ_b max) in composite materials as compared with plastics. This increase is attributed to inclusion of the laminations fibers as layers which caused a reduction in the magnitude of deflection with increasing the applied load.

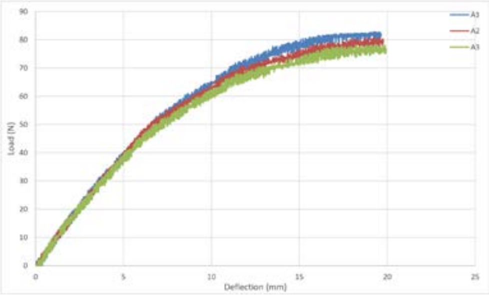

Figure 12: Load-Deflection curves for PP.

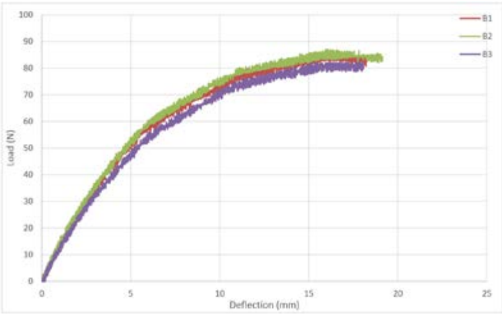

Figure 13: Load-Deflection curves for PA.

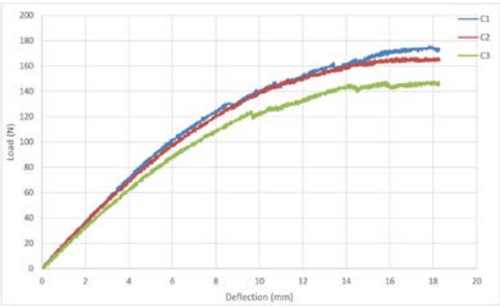

Figure 14: Load-Deflection curves for PCP (424).

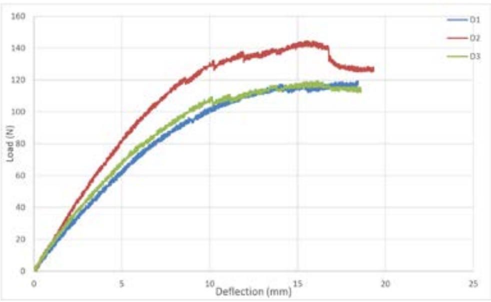

Figure 15: Load-Deflection curves for Hybrid Cf-Gf.

Table 4: Mechanical properties from flexural testing.

Material	Lay Up	$\sigma_{b(max)}$ (MPa)	$E_{flexural}$ (GPa)
Polypropylene	1	50.65	1.7
Polyethylene	1	51.8	2.33
Hybrid Cf-Gf	8	103.1	4.15
P-C-P	424	140.2	7.03

3.3 Fatigue Test Results

For fatigue test, the type of fatigue testing machine is alternating bending fatigue with constant amplitude. The specimens were subjected to deflection perpendicular to the axis of specimens on one side of the specimens, and the other side was fixed to develop the bending stresses. The fatigue specimens have the geometry as described. A dial gauge was used to measure the deflection; their values were used to determine the maximum alternating bending stress The S-N curves was obtained with and without temperature effect.

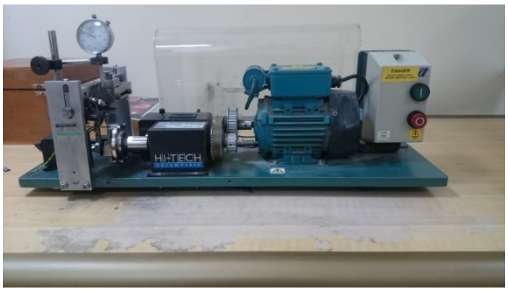

Figure 16: Alternative bending fatigue machine.

Fig.17 shows the fatigue test devise. **Fig.18** S-N curve for each type of composite materials and due to the difficulty of obtaining the result of (S-N) curve for PP and PE by fatigue test, therefore it was adopted from [17-18]. **Fig.18** and **19** shows the S-N curve for the plastic materials (PP and PE).

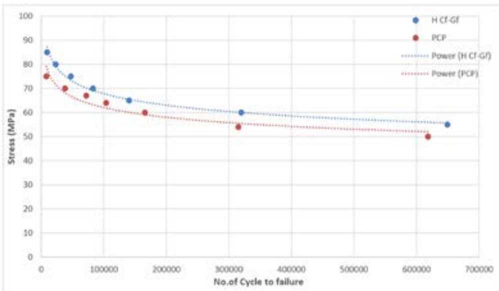

Figure 17: S-N curves for both composite materials.

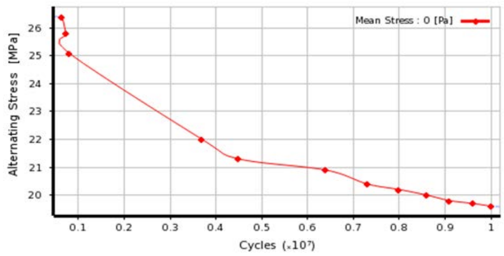

Figure 18: S-N curve for PP [17].

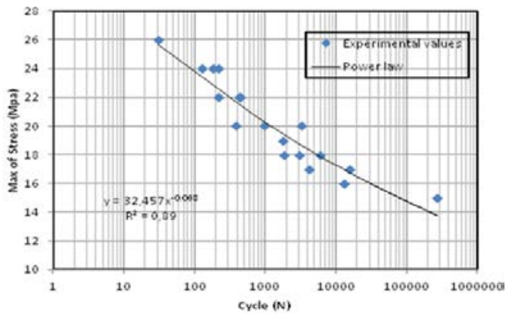

Figure 19: S-N curve for PE [18].

Fig.20 shows the S-Log N curves for composite materials and **Table 5** shows the readings and results of each lamination.

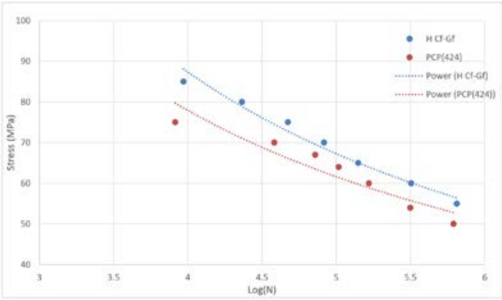

Figure 20: S-Log N curves for composite materials.

Table 5: Fatigue readings and results for composite materials.

Sample NO.	Hybrid Cf-Gf			PCP (424)		
	Stress MPa	No. of cycle	Log N	Stress MPa	No. of cycle	Log N
1	85	9342	3.97044	75	8220	3.914872
2	80	23161	4.364757	70	38254	4.582677
3	75	47294	4.674806	67	72175	4.858387
4	70	82674	4.917369	64	103845	5.016386
5	65	140532	5.147775	60	165797	5.219577
6	60	319874	5.504979	54	315436	5.498911
7	55	649497	5.812577	50	618522	5.791355

Table 5 and Fig.17, 18, 19, 20 show the results of fatigue tests. The fatigue life of samples was highly increased in the composite materials as the applied load was increased when compared with plastic materials that immediately fail when applying a high load. **Table 6** shows the fatigue life equation for each lamination.

Table 6: Fatigue life equation and Endurance for each lamination.

Material	Fatigue life equation	R^2	Endurance Limit at $6*10^5$ cycle
PCP (424)	$\sigma = 190.14N^{-0.097}$	0.9252	52
H Cf-Gf	$\sigma = 228.75N^{-0.106}$	0.9898	56

4. Conclusions

1. For tensile properties, In PCP lamination, σ_y increased about (261% - 200%) compared with (PP and PE) respectively and in Hybrid Cf-Gf lamination, σ_y increased about (353% - 270%) compared with (PP and PE) respectively. For σ_{ult}, the increase was (330% - 243%) on PCP compared with PP and PE, also in Hybrid Cf-Gf the increase was (470% - 347%). For the modulus of elasticity, PCP increased (295% - 203%) compared with PP and PE, where it was (388% - 267%) in Hybrid Cf-Gf. The strain is reduced as much as possible in the composite materials which make the possibility of failure in the prosthesis a minimum state. So, this is what we will notice in the fatigue test. The increase in the mechanical properties will make the prosthetic much stronger compared to the traditional one which is used in the market. The composite prosthetic will resist high loads and hard mechanical conditions compared with the plastic socket.
2. For the flexural test, In PCP lamination, the increase of maximum bending stress was (276% - 270%) as compared with PP and PE respectively, and in Hybrid Cf-Gf lamination, the increase was (203% - 199%) as compared with PP and PE. In all cases, we see that the deflection was constant, but the applied force is sharply increased where the percentage of increase reach to (215 % - 200%) in PCP lamination and (150 % - 141%) in Hybrid Cf-Gf lamination compared with PP and PE. The chord modulus, (*Ef*) is also increased in both laminations according to an increase of bending stress. In PCP lamination, the increase was (413% - 301%) compared with PP and PE respectively and in Hybrid Cf-Gf lamination the increase was (244% - 178%) compared with PP and PE. The difference in the mechanical properties of composite materials will make the probability of prosthesis failure when subjected to a high bending load much smaller as compared with a plastic prosthesis.
3. For fatigue test, the lifetime of any prosthesis depends on the applied load and the material type. The lifetime of composite materials (PCP and Hybrid Cf-Gf) is much longer than the plastic materials (PP and PE). This increase in lifetime will reduce the cost for the patient who wears the prosthesis for a very long time without the need of periodic maintenance or the purchase of a new one from time to time.

References

[1] Douglas A. Taylor, C.P., Jeremy C. Gilbert, and Eugene P. Lautenschlager, “Testing of Composite Materials Used in Orthotics and Prosthetics” Newsletters and Journals, JACPOC Vol 27, Num 2, pp. 62,1992.

[2] Gururaja M N and Hari Rao A N, “A Review on Recent Applications and Future Prospectus of Hybrid Composites”, International Journal of Soft Computing and Engineering (IJSCE), Vol. 1, No. 6, pp. 352-355, 2012.

[3] Prabhakaran R T D, Madsen B, Toftegaard H and Markussen C M , “Flexural Properties of Hybrid Natural Composite-Micromechanics and Experimental Assessment”, Proceedings of 3rd Asian Conference on Mechanics of Functional Materials and Structures (ACMFMS), Vol. 1, pp. 469-472, Indian Institute of Technology, New Delhi,2012.

[4] Dale A. Berry, C.P. “Composite Materials for Orthotics and Prosthetics” Orthotics and Prosthetics vol.40, No.4, pp.35-43, 1987.

[5] Melvin L. Stills, C O., “Partial Foot Prostheses/Orthoses” clinical Orthotics and Prosthetic vol.12, No.1, pp.14-18, 1988.

[6] Terrence M. Philbin, DO, Manuel Leyes, MD, James J. Sferra, MD, and Brian G. Donley, MD, “Orthotic and Prosthetic Devices in Partial Foot Amputations”,2001.

[7] Muhsin J.Jweeg, Kadhim K. Resan and Muhanad N. Mohammed,” Design and Manufacturing of a New Prosthetic Low Cost Pylon for Amputee”. Journal of Engineering and Development, Vol. 14, No. 4, 2010.

[8] Muhsin J.Jweeg and Jana S. Jaffar,” Vibration Analysis of Prosthesis for the through Knee Amputation”. Al-Nahrain University, College of Engineering Journal (NUCEJ) Vol.91 No.1, 2016 pp.46 – 55,2013.

[9] M.J.jweeg, S.S.Hasan, and J.S.Chiad,” Effects of Lamination Layers on the Mechanical Properties for above Knee Prosthetic Socket”. Eng. &Tech.Journal, Vol.27, No.4, 2009.

[10] Ayad M. Takhak, Jumaa Salman Chiad and Fahad Mohanad Kadhim,” Vibration Measurement and Analysis of Knee-Ankle-FootOrthosis (Kafo) Plastic-Metal Type”. Journal of Engineering and Development, Vol. 17, No.6, 2013.

[11] Justin B: Orthoses& Prostheses Technology .http://www.Myspace.com. March 2008.

[12] Ottobock quality for life “orthotic-prosthetic materials catalog", 2007.

[13] American Society for Testing and materials information, Handing series "Standard Test Method for Tensile Properties ", 2000.

[14] American Society for Testing and Materials Information, Handing series "Standard Test Method for Flexural Properties ", 2000.

[15] N.P.Roberts Fatigue Manual_HSM20 “instruction manual for alternative bending fatigue machine”, 2001.

[16] K. Smith" Laminated Socket Properties” Monash Rehabilitation Technology Research, Monash Australian international university, 1998.

[17] Maier C, & Calafut T., “Polypropylene – the Definitive user’s Guide and Databook”, In Woishnis, Plastics Design Library a Division of William Andrew Inc. New York; 1998.

[18] A. Djebli, M. Bendouba and A. Talha “Uniaxial Fatigue of HDPE-100 Pipe” Engineering, Technology & Applied Science Research Vol. 4, No. 2, pp. 600-604, 2014.

الخواص الميكانيكية للمركبات الهجينة و ذات أساس بوليمر المستخدمة لتصنيع طرف لبتر جزئي للقدم

حسنين صالح حسين
قسم الهندسة الميكانيكية
جامعة النهرين

أياد مراد طخاخ
قسم الهندسة الميكانيكية
جامعة النهرين

الخلاصة

في هذه الدراسة, تم عمل مقارنة عملية بين المواد البلاستيكية التقليدية (البولي بروبلين و البولي اثيلين) و مواد مركبة مختارة (برلون-كاربون-برلون و الياف الكاربون –الياف الزجاج الهجين) لتصنيع طرف لبتر جزئي ذو عمر طويل. لتحسين الخواص الميكانيكية, زيادة العمر الافتراضي, و تقليل الكلفة على المريض, تم استخدام نوعان من المواد المركبة وتمت مقارنتهما مع المواد البلاستيكية. العينات تم تصنيعها واختبارها بعدة اختبارات (الشد, الثني, والكلال). جميع الاختبارات اجريت بدرجة حرارة الغرفة.

أظهرت النتائج بأن المواد المركبة حققت زيادة كبيرة في الخواص الميكانيكية مثل (اجهاد الخضوع, أقصى اجهاد, معامل المرونة, اجهاد الثني, معامل الثني) بنسب (261% - 200%), (330% - 243%), (295% - 203%), (276% - 270%), (413% - 301%) في مادة برلون-كاربون-برلون اذا ما قورنت بالبولي بروبلين والبولي اثيلين على التوالي. بينما نسبة الزيادة في مادة الياف الكاربون –الياف الزجاج الهجينة كانت (353%- 279%), (470% - 347%), (388% - 267%), (203% - 199%), (244% - 178%) مقارنة بالبولي اثيلين والبولي بروبلين على التوالي.

في نفس الوقت, العمر الافتراضي زاد بحدة في كلتا المادتين المركبتين اذا ما قورنت بالمواد البلاستيكية.