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Design and Modeling the Prosthetic Foot from Suitable Composite Mateials

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Abstract: This research concerns developing a composite material which can be used in manufacturing prosthetic feet with a reasonable cost and satisfying mechanical properties. The characteristics were investigated by mechanical tests of tensile properties and Charpy impact strength. The study of date palm wood and its effects on the mechanical properties of polyethylene have received little attention. It was found that Young's modulus of 40% High Density Polyethylene (HDPE) filled with sixty percent of Date Palm Wood (DPW), significantly increased to 80% compared with pure HDPE. Moreover, the yield and ultimate stresses were improved which was approximately two times higher than that observed for pure HDPE; the elongation at break and impact energy were decreased significantly. The characteristics exhibited by prosthetics compared to those of a human foot were investigated further. The analytical section presents the results of the static analysis by numerical methods (Finite Element Method FEM), ANSYS Workbench 14 and experimental methods. Thus, the new foot was designed and the dorsiflexion was measured. Overall, the non-articulation of this type of foot is compared against the SACH foot by cost and weight, so that, the cost of the non-articulated foot is lower than that of the other by about 60%. We also found the new weight is lighter than that of by about two percent. The new model of prosthetic foot has better characteristics which includes foot life cycle (7.5° and 1,049, 135), respectively when compared with the other (6.4 and 896213), respectively.

INTRODUCTION

Recently, there have been several researchers that have studied prosthetic feet designed and manufactured from polyethylene. It has good characteristics when compared with the SACH foot such as good dorsiflexion (4.2 and 1.9°), stored energy return (58.9 and 13.14°), the force transmitted at impact heel (154 N and 205 N), the effective length ratio (0.76 and 0.64) and life (1233417 and 896213) cycles presented by Rasan[1]. The foot is one of the most complicated structures of the human body; it offers an extremely high degree of stability and activity and it not only bears the weight of the whole body but has multi-functions such as extension, compression, tortuosity bouncing, shock absorption and friction described by Zhang *et al*.[2]. Current prosthetic designs provide a wide range of choices for below-knee amputees. The appropriate choice of prosthesis can significantly improve the comfort and performance of the patient. Most of the currently available prosthetic ankles, however, do not provide enough energy to propel the body forward studied by Zeng[3] ; High-Density Polyethylene (HDPE) made by low-pressure methods. In this method, pure ethylene polymerized at a pressure of about 50 atmospheres and temperature between 60-200°C the presence of the Zeigler Natta catalyst system and supported oxide catalyst[4]. Such polymers are over 90% crystalline, more linear compared with low density type and had a density above 0.95 g b^{-1}[5]. Several researchers have studied composites by preparing polymeric matrices from date palm fibers. The fibers prepared from the date palm are important to making these prosthetics affordable, especially in countries in which date palm tree production is high. The mechanical and thermal properties of HDPE and PS matrices were tested rein forced with powder from date palm pits[6]. The mechanical properties of composites were based on their Linear Low-Density Polyethylene (LLDPE) lended with Date Palm Wood powder (DPW); High-Density Polyethylene (HDPE) mixed with LLDPE blends with DPW. The mechanical properties were determined in the tensile and impact energy to utilize and apply the best properties on the new design of prosthetic foot. This study used new blends of (HDPE and DPW). In addition, the new prosthetic foot has been tested for stress and strain by ANSYS Workbench. The fatigue and dorsiflexion tests have been thorough.

MATERIALS AND METHODS

Experimental works: A sensitive electronic read-out weighing machine, Italy 1700 Model was used to measure a 100 of each blend portion of the LLDPE and HDPE pellets, respectively. The blend ratios obtained by mixing LLDPE and HDPE resins. Where w is a weight of a mass of blends in grams. Each of the blends was pulverized using a mechanical blender to ensure through mixing. The blended composition was charged into an injection machine. The following operating conditions: die-head temperature of 183+10°C and 120 bars. The blend composition was then passed through the die head orifice of the injector which determines the thickness of the blown films.

Preparation specimen: In order to prepare the prosthetic, there should be a mold made of iron with the dimensions of 20 cm 17.5 cm×5 mm. It was made by using ASTMbD638 and Surf-cam program and CNC milling machine Model XK7124 with feed rate 1000 and speed relative to the blend ratio. DPW requires higher speed than HDPE to avoid to Peels or bulge.

RESULTS AND DISCUSSION

Mechanical properties of HDPE and DPW blends: In this part, we characterize the mechanical properties of the composites tested in the tensile mode at room temperature (25°) in a bent position. Table 1, shows the effect of the additive of DPW on the mechanical properties of HDPE blend, tensile strength at yield ultimate stress, modulus of elasticity and impact energy.

However, this study focus is on the study of properties to design a prosthetic foot from new available and low cost material. Therefore, the purpose of the use of HDPE reinforced with DPW is to get the best mechanical efficiency that when mixing HDPE (40 g) with DPW (60 g) increases the yield of stress from 18 MPa to 45 MP and ultimate stress from 26-50 MPa an increase of Young's modulus from 1.1-1.8 GPa. According to the values taken from the impact test, we can observe decreases in the energy impact. To reduce the cost of the materials used Recycled Linear Low-Density Polyethylene (RLLDPE) was blended with Date Palm Wood powder (DPW)[7]. Thus, tie-molecules are important for all strength properties of polyethylene. Hence, the increasing concentrations of LLDPE introduced tie molecules into the polymer blend.

The stages of preparing the new prosthetic foot:

- Drawing the shape in Auto CAD program, then send to ANSYS Workbench to analyze the models of prosthetic foot
- Sculpting the general shape
- Casting a negative mold from metal
- Modifying the negative mold
- Arrangement of the mold inside the injection machine

Preparing the granule of polyethylene in machine cone and adjusting temperature (200°C), pressure and time of injection. The injection machine contains four heat zones, first heater is (80°C) and fourth heater is (300°C) for the blend of HDPE and DPW. The composite materials have been taken 300°C. This temperature increases gradually. Injecting the hot mixture of composite materials granule inside the mold. The injected foot is visible in Fig. 1.

Numerical analysis results

Static analysis: The fatigue and static properties of two models of non-articulated foot investigated using finite element method (ANSYSb14).

Table 1: Mechanical properties of blends at 25. The x/y notation represents the DPW/HDPE w/w ratio

Parameters	Blends ratio of DPW/HDPE	Yield stress (MPa)	Ultimate stress (MPa)	Modulius of elasticity (GPa)	Density (kg m^{-3})	Energy (J)	Cross section exact area (mm^2)	Impact energy (KJ m^{-2})
	60/40	45	50	1.8	961.6	3.895	9.95*4.66	84

Table 2: Material properties and element types of the anatomical parts of the finite element model[8]

Component	Young's modulusb (MPa)	Poisson's ratio	Element type	Cross sectional (mm^2)
Bones	7300	0.3	3D-tetrahedral	
Soft tissue	Hyperbelastic		3D-tetrahedral	
Cartilage	10	0.4	3D-tetrahedral	
Ligaments	260	0.4	Tension-only truss	18.4
Plantar fascia	350	0.4	Tension-only truss	58.6

Fig. 1: The injection foot blended of (DPW+HDPE)

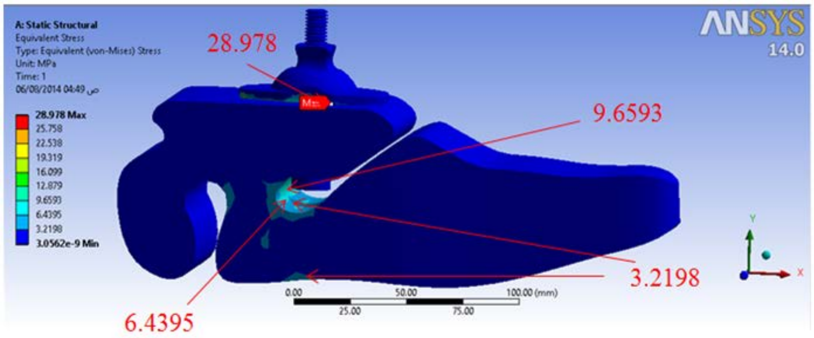

Fig. 2: Von-Misses stresses along the non-articulated foot of (HDPE+LLDPE)

The aim of this analysis is to investigate the stresses and deformations of a clamped non-articulated foot with force after assuming that this value is the average of applied load (86kg or 846N) (Fig. 2).

Figure 2 and show the Von-Misses stresses distribution along the non-articulated foot at the deformation of the above mentioned foot and Von-Misses where the stress contour at the toe off phase with force of (846 N), respectively.

Figure 2 shows the Von-Misses stresses for presented foot is from observing the maximum Von-Misses stress as 28.978 MPa at the adapter and the minimum value was 3.0562*MPa at n non-articulated foot of HDPE and DPW.

The results in Fig. 3 were observed as the maximum value of strain and the maximum region of failure. The maximum values of strain in the foot of HDPE and DPW were 0.0073236. Comparing the results of stress on the non-articulated prosthetic foot from ANSYS with the results of a human foot from ABAQUS Young's modulus and Poisson's ratio of the cartilage ligaments and the plantar fascia were selected from the literature as shown in Table 2[8].

The predicted Von-Misses stress distributions of bony structures for both models are given in Fig. 4. Regarding joint stress distributions fo an average prosthetic foot, web predict a peak Von-Misses stress of about 6.766 MPa[8] while for

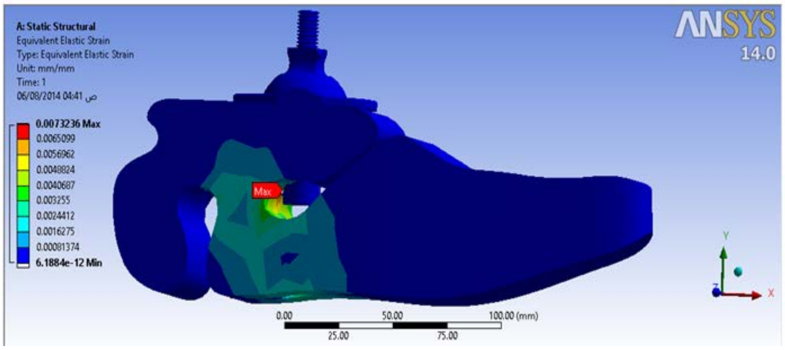

Fig. 3: Von-Misses strain along the non-articulated foot of (HDPE+LLDPE)

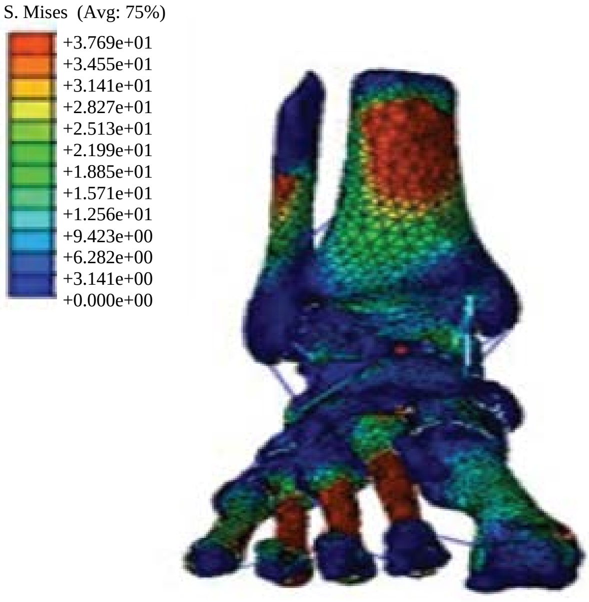

Fig. 4: Von-Misses stress distribution of normal foot[8]

prosthetic foot of HDPE and DPW the peak value was 9.6593. This study was to generate models of normal foot, soft tissues by using CT images and MIMICS (Materialize) software and SOLID WORKS software then export this model into ABAQUS codes[8].

Fatigue foot tester results: The durability and fatigue characteristics of the prosthetic foot are very important when deciding which type of prosthetic foot to prescribe for a particular patient. The fatigue tester was suitable for this investigation as it applied forces approximating ground reaction forces for the normal walking cycle[9]. In order to have a realistic assurance of the prosthesi's durability and long-term performance, cyclic loading tests must be performed on the foot. A previous senior design team built an experimental fatigue tester. The machine consists of a frame, two pneumatic pistons and a control box that commands solenoid valves to allow air pressure into the cylinders. In order to determine the validity of the non-articulated foot fatigue tester in comparison to other testers currently being used the industry standard SACH foot was tested in one of the test stations in order to determine its time failure (Fig. 5).

The SACH foot removed from the tester at 896.213 cycles was placed on the tester within a few months of manufacturing. This may indicate the material degradation is a factor in the life expectancy of SACH feet; however, further testing would have to be undertaken. The new design of non-articulated foot failure occurred in one specimen at 1,049, 135

Fig. 5: Failure region in non-articulated foot (HDPE+LLDPE)

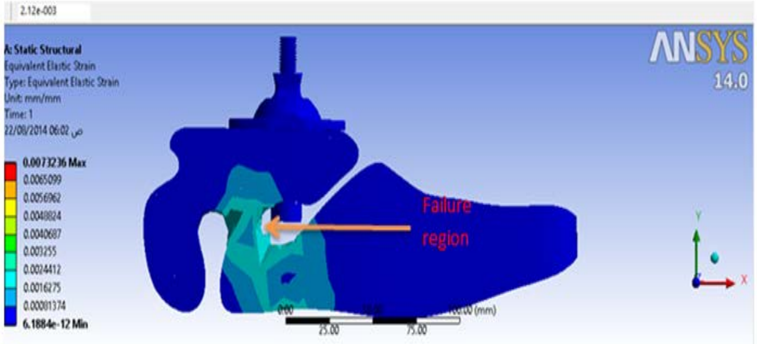

Fig. 6: Failure region in non-articulated foot (HDPE+LLDPE) by ANSYS program

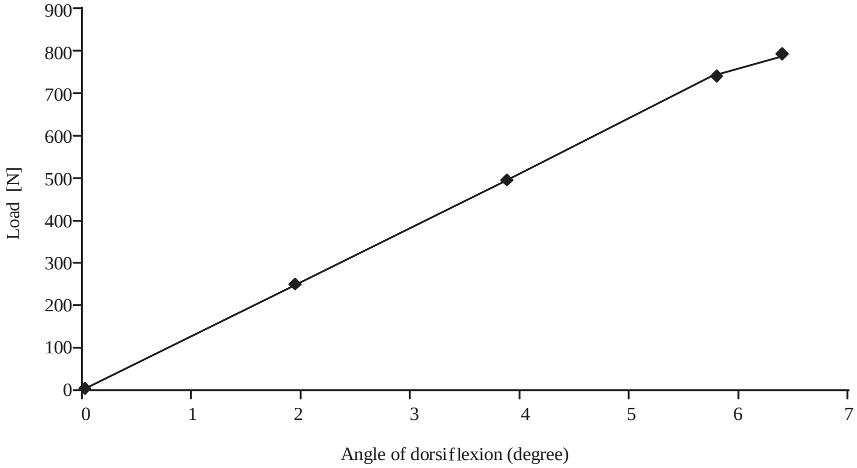

Fig. 7: Experimental load with dorsiflexion angle for SACH

cycles for the foot that manufactured from the blended of 60% of LLDPE and 40% of HDPE (Fig. 5).

This study was investigated by ANSYS Workbench where bit's noted that the failure region in the experimental work was the same failure region in this program as shown in Fig. 6. Figure 5 refers to the real region of failure.

Dorsiflexion: Figure 7 and 8 show the result of the dorsiflexion angle respectively for SACH foot, non-articulated foot of HDPE and DPW. The dorsiflexion angles were obtained using a digital camera. The maximum dorsiflexion angles for normal human foot, SACH foot and non-articulated foot are recorded.

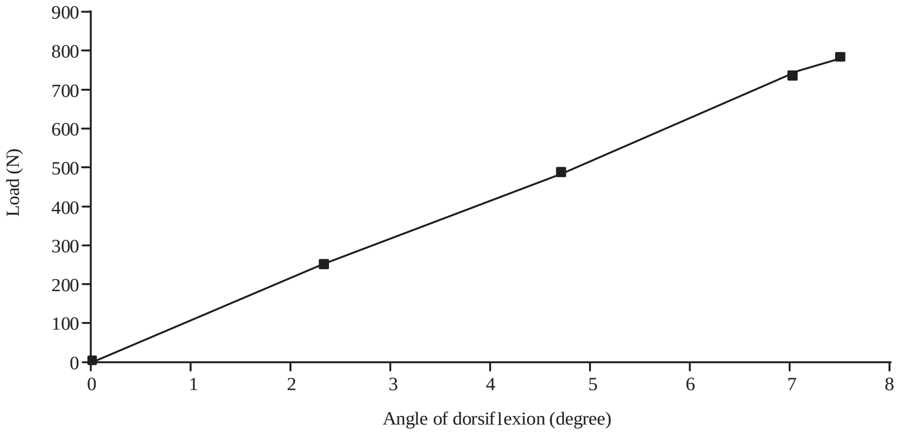

Fig. 8: Experimental load with dosiflexion for non-articulated design foot of (HDPE+DPW)

CONCLUSION

In this study, two different composite materials HDPE and LLDE composites have been developed. The preparation has been done via. mold injection. The mechanical properties including impact energy and tensile strength which yield stress ultimate stress and modulus of elasticity. The specific conclusions of the study are that it showed the yield and ultimate stresses significantly increased by 60 and 44% frequently with mixed blends o 40 g HDPE with 60 g DPW. Overall, it was observed that the modulus increased by 80% compared w ith pure HDPE and slightly decreased in impact energy by 1%. Further, increases in the content caused negligile influences on the stress at break of the materials which indicated a low interfacial interaction between the polymer and the filler. Generally, the results obtained in this research recommend using these materials for the prosthetics.

From the results obtained both theoretically and experimentally the following conclusion can be drawn:
Using the properties of composite materials of HDPE and DPW for manufacturing the flexible non-articulated foot gives high dorsiflexion angle and long fatigue life.

The dorsiflexion angle for the non-articulated foot is greater than that of the SACH foot, so, it may give a end up to an acceptable limit. Lengthening the supporting keel along the whole lengthbofbthebnon-articulated foot gives the best stability to gait profile and long fatigue life. The special design with a slotted region on the upper side ofbthebnon-articulated foot makes an increment in dorsiflexion angle so it leads to more flexibility in gait profile. The non-articulated HDPE and DPW foot is compared with the SACH foot in cost and weight, the cost of non-articulated foot is than that of the other by >80% and the new weight is lighter by about 51.33%. That would be more comfortable for the patient.

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