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Study of Creep-Fatigue Interaction in the Prosthetic Socket below Knee

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Abstract

The increasing numbers of amputees due to insurgence actions in Iraq urges the researches to conduct this study. Two stresses of fatigue and heat are generated as a result of limbs movement during extremely hot weather. The objective of this research is to Study the effect of temperature in hot climate countries on a socket made of composite materials during the gait. Where alternating pressures on the inner surface of the socket are generated and lead to variable stresses causing fatigue failure of material. It is evident that as temperature rises, the mechanical properties decrease over time due to creep which causes socket failure due to fatigue and creep interaction. The socket failure at room temperature is determined by fatigue test to obtain S-N curve. Also, stress distribution on the socket is studied at 60 C^{o}.

Keywords: amputee, fatigue, creep, below knee, piezoelectric sensor

1. Introduction

Creep-fatigue interaction is a special phenomenon which has a detrimental effect on the performance of composite materials parts of components operating at elevated temperatures. This paper deals with the simultaneous interactions between creep and fatigue of prosthetic socket.

An amputation of a lower limb is most commonly occurred due to landmines or limb diseases. The two most often amputation procedures are truncation of the femur bone above the knee (AK) and truncation of the tibia bone below the knee (BK). The BK socket that supports the residual limb (or stump) is normally custom built to the individual's anthropometric specifications [1].

The design of a prosthetic socket largely determines the overall comfort and function for below knee (BK) prosthesis. Nicolas E. Walsh et.al [2] developed a computer aided design/computer aided manufacture (CAD/CAM) system for a lightweight, all plastic prosthesis capable of being fabricated remotely from the site of evaluation of the amputee. Virgil W. Faulkner and Nicolas E. Walsh [3] used a CT scan taken of an amputee's with below-knee residual limb, starting approximately 5cm above the knee joint space and ending at the distal end of the residual limb. This information was stored on a magnetic tape acquired from a GE 9800 scanner, and delivered to the REL. John A. Sidles and David A. Boone [4] developed a new method for describing residual limb and socket shapes using rectification maps. Rectification is subtle shape difference between below knee residual limb and prosthetic socket which fits limb. Dudley S. Childress, et al [5] studied the implementation of the finite element method to the fitting of BK sockets and dynamic rectification and alternative fabrication using (CAD/CAM) method. James Cho Hong and Peter Vee Sin Lee [6] compared the pressure distribution at residual limb and socket interface in amputees wearing a pressure cast (PCAST) socket system with amputees wearing the patellar tendon bearing (PTB) socket. In this study the fatigue and creep were investigated due to alternative pressure in socket and effect of temperature on fatigue creep interaction.

In this paper, the effect of temperature and interactive creep – fatigue on the socket is studied, where the creep should be considered when materials tend to deform as they are subjected to long-term stress, particularly when exposed to heat, fatigue occurs when a material is subjected to cyclic loading, causing damage which may progress to failure. The Creep-fatigue testing is typically performed at elevated temperatures and involves the sequential or simultaneous application of the loading conditions necessary to generate cyclic deformation/damage enhanced by creep deformation/damage.

2. Gait Analysis and Ground Reaction Forces

In order to understand the behavior of lower limb prosthetics, the act of walking must be understood. The process of walking is broken down into a series of repeated events in which a person's weight is supported by one leg while the other leg moves forward, with the weight being transferred between the two. This sequence of actions, occurring on one leg, is called the gait cycle [7]. Gait analysis provides the clinician and the researcher with useful information regarding the performance or status of a patient's walking ability. The gait cycle can most simply be described by its division into a stance phase which is defined by initial heel contact to toe-off and a swing phase from toe-off to ipsilateral heel contact. Stance phase accounts for approximately 60% of the total gait cycle and swing phase account for 40%. The stance phase is divided into a number of sub- phases which include a weight acceptance phase, mid stance phase and push-off phase [8].

3. Modeling of Prosthetic Socket Using ANSYS

The finite element method (FEM) is now widely used in a variety of fields in engineering and science. The analysis of socket models was done by FEM software to compute the equivalent (Von-Mises) stress, safety factor of stress and safety factor of fatigue.

In this work, FEM is with aid of ANSYS Workbench 12.1 software used as a numerical tool to illustrate the effect of the fatigue performance and creep in a structure element to determine the behavior of maximum stress, total deformation, fatigue life and safety factor. The meshing process has been done by choosing the volume then the shape of element was selected as tetrahedron (Automatic meshing), as shown in Figure (1). The load which used in the ANSYS Workbench software will be fixed support at the adapter of socket, while interface pressure was distributed according to particular positions. The total number of elements was (95298) with total number of nodes of (166724).

4. Experimental Analysis

4.1Tensile Test and Specimens Preparation

Mechanical properties of socket materials: The theoretical and experimental calculations depend on the mechanical properties of the material; these can be found from the tensile test of standard specimens according to the recommendation of ASTM D-638[9].

To measure the mechanical properties for composites material, the method of preparation of composite specimen is called vacuum method, it prevents cavities or defects. The fatigue of materials is a well-known situation whereby rupture can be caused by a large number of stress variations at a point even through the maximum stress is less than the proof or yield stress. The fracture is initiated by a tensile stress at macro or microscopic flaw.

4.2 Design and Manufacturing of Creep – Fatigue Device

To obtain the S-N curve for materials of socket with and without heat , the creep-fatigue device is designed and manufactured .At one end of a heavy base plate is mounted an electric motor, the motor shaft carries a pulley with a V-belt drive to a counter shaft. The counter shaft running in a substantial bearing cylinder and carry an eccentric drive mechanism. The shaft carries an aluminum pulley from one end which is driven by the motor via a V-Belt and at the other end the shaft carries an aluminum bush which is used as a link between the shaft and the reciprocating mechanism. Beside the bush an inductive proximity sensor is mounted that senses an Allen screw located on the bush and thus the sensor gives a signal to the counter at each turn (One complete revolution).

An aluminum container is used to cover the part of the machine including the reciprocating mechanism and the cantilevered specimen. The container is used with an air heater to keep a constant temperature around the specimen to study the creep phenomenon. The machine is operated by a control board which contains controlling and measuring devices that all work together to control the speed of the motor and counts the cycles of the reciprocating mechanism and also save the last readings either when the power goes off or when the specimen fails.

4.3 Fatigue – Creep Interactive Testing

This investigation addresses the interaction mechanisms of time dependent material behavior and cyclic damage during fatigue loading of fiber reinforced composite laminates.

This test method covers the determination of mechanical properties pertaining to creep-fatigue deformation or crack formation in nominally homogeneous materials, or both by the use of test specimens subjected to reverse bending under isothermal conditions.

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 at one side of the specimens, and the other side was fixed, developing bending stresses.

The test procedure is begin by deciding the material to be tested and find the published value of Young's modulus E and then selecting a stress regime and maximum stress. A nomogram is used to determine the cantilever length of the specimen and the required deflection to apply the desired stress. The test specimen is then fixed and then setting the required deflection using a dial gauge. When testing a plastic material or low melting point metals the container and heater can be used for creep testing. After all set the test begin by starting the motor and set a suitable speed depending on the time available, usually the perfect speed for fatigue testing is about 1200rpm. The fatigue of materials is a well-known situation whereby rupture can be caused by a large number of stress variations at a point even through the maximum stress is less than the proof or yield stress. The fracture is initiated by a tensile stress at macro or microscopic flaw. There are two type of testing without temperature and with temperature, the S-N curve were obtained with alternative pressure in socket without temperature effect and with 60C^{o} temperature.

4.4 Interface Pressure by Piezoelectric Sensor

The pressure distribution at the residual limb and socket interface was measured by specially built in sensor types of piezoelectric sensor as shown in figure (3) .The pressure distribution with gait cycle was obtained. This allows the amputee to walk while the pressure and force distribution data is captured. Interface pressure sensor allows closely examining the formation of pressures within the socket interface during the various phases of gait and modifying the socket/stump interface accordingly.

4.5 The Information of the Subjects and Ground Reaction Tests

The kinetics data were collected via a young subject, his age was about (23years) with height (169 cm) and weight (58 Kg). The subject was wearing composite socket below knee for his left lower extremity.

The ground reaction force is the main force acting on the body during walking. It consists of a vertical component and two horizontal components. These forces are found by having a subject walking across a force plate in the form of walkway.

5. Results and Discussion

5.1 Experimental Results

5.1.1 Mechanical Properties

The results of the mechanical properties (tensile test) of the socket material are as shown in Table (1).

5.1.2 S-N Curve With and Without Temperature

The (S-N) curves for composite layers (12) are shown in the figure (4).

The difference between curves' values is small at low number of cycles, then it increases as number of cycles increases, this is due to effect of temperature on the composite materials is increasing with time , where fatigue strength decreases as temperature increases.

5.1.3 Interface Pressure between Socket and Residual Limb

The socket interface designs can be divided into four basic categories according to their respective weight bearing characteristics (Anterior, Lateral, Medial and posterior), Upon examination of the interface pressure output, we found that the prosthetic socket interface pressure followed a wave pattern similar to that typically associated with the foot. Three points of interest were presented during the stance phase: weight acceptance, mid stance, and forward progression [11] ,as shown Figure (5) ,When identifying the force patterns expected between the residual limb and the prosthesis, Radcliffe described a pattern that was shown to be influenced by the alignment of the prosthesis, muscle action, and the angular position of the residual limb with respect to the ground reaction force [12]. Radcliffe stated that the pressure profile would experience the largest change immediately after heel strike, when the ground reaction force passes from a location anterior of the knee joint to a location posterior to the knee. This change in location changes the initial extension moment about the knee joint to a flexion moment.

5.1.4 Ground Reaction Force Results and Discussion

Figure (6) depict the contour of pressure distribution for the pathological and normal subject, respectively. The first and third segments are similar on the gait cycle scale, but the second segment (mid stance) for the pathological case approaches to be a straight line without any valley that backs to, the patient tries to keep the balance of his body through the walking, therefore, the subject’s depending was on the right leg, while the left is the defected, and the stages of the dorsiflexion of the ankle are not found in the left foot.

5.2 Numerical Results Discussion

Figure (7) shows the fatigue tool - safety factor for the internal side of the socket. It can be seen from the figure that the minimum fatigue tool - safety factor is located in the socket with temperature effect.

The model of (12) layers showed that, for fatigue safety factor was about (1.84), which is safe in design without temperature effect. While, the model of a critical result for safety factor (1.05) with temperature effect, these differences in the results were due to the change of properties of materials, where the area still constant.

According to the Von-Mises theory that considers the yield stress as criteria;

($\sigma e < \sigma y$, safe), ($\sigma e = \sigma y$, critical) and ($\sigma e > \sigma y$, failed). Where, (σe) is the equivalent stress, and (σy) is the yield stress.

The interface stress between the residual limb and the socket was found. As a result, the work presented here provides an important advancement in the structural analysis of different socket designs.

6. Conclusions

1- The effect of temperature on the fatigue strength is high in Iraq and hot state therefore it must be the introduction of that effect in the design in a future.

2- The fatigue safety factor is decreasing in the socket with temperature effect.

3- The stress at PT (patella tendon) is increasing in the second model (including temperature effect) respect with the first model.

4-There is not difference value in stresses at lateral and medial region with and without temperature effect.

Acknowledgment

Staff of Baghdad center of artificial limb

Nomenclature

A= Anterior
B.K= Below Knee
L= Lateral
M= Medial
P= posterior

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Table 1. Mechanical properties of socket materials

Materials socket	Yield stress [MPa]	Young Modulus [GPa]
12 layers including : (4 perlon , 4 fiber glass and 4 perlon) with acrylic	78.2	12.4

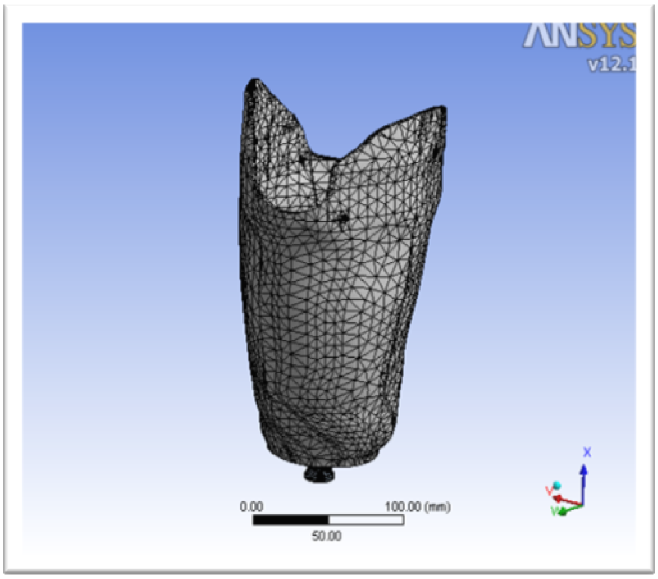


Figure 1. The Model with Mesh

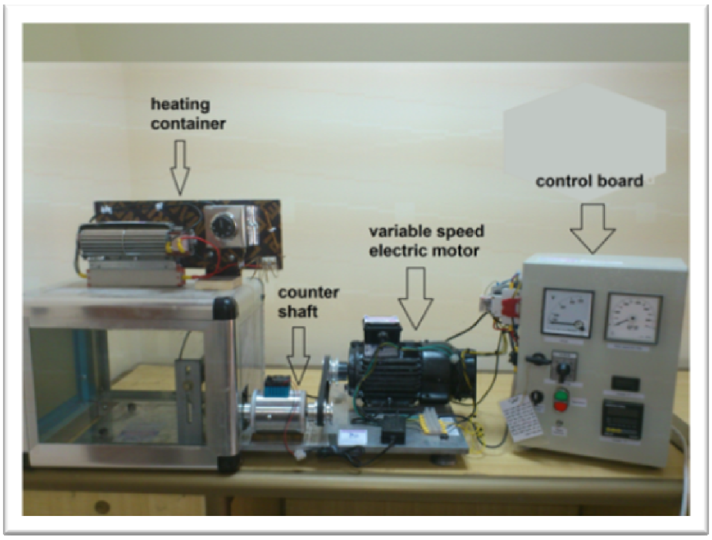


Figure 2. The Creep-Fatigue interactive Device

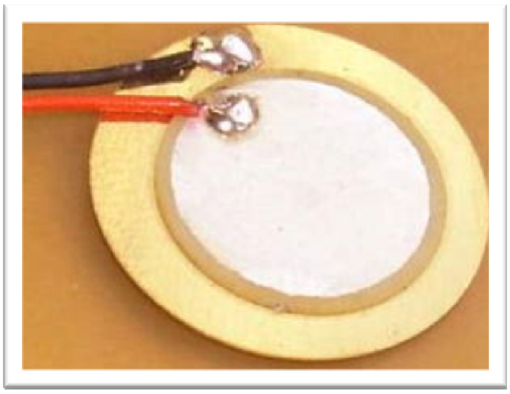


Figure 3. Interface Pressure Socket Sensor
(Diameter = 15mm)

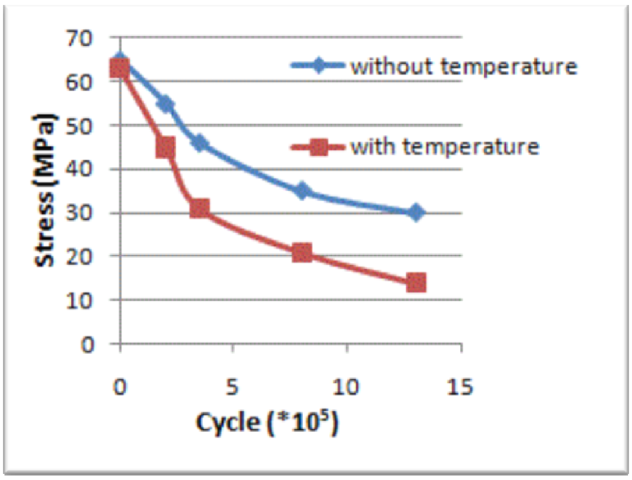


Figure 4. S-N Curves, With and Without Temperature Effect

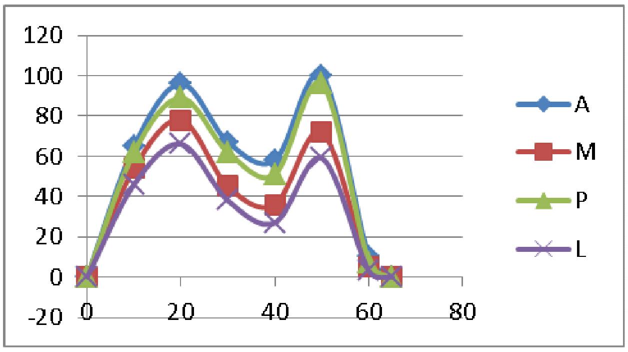
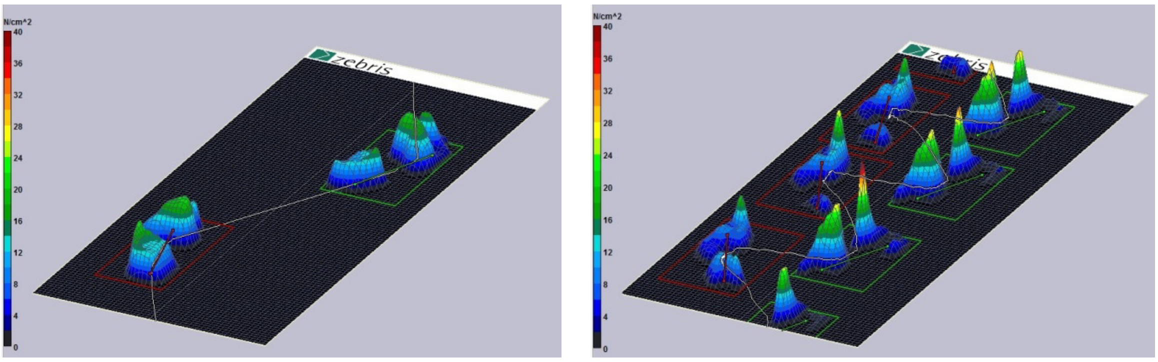


Figure 5. Pressure Distribution (kPa) at Sockets Regions



A. Normal Subject B. Pathological Subject

Figure 6. The contour of pressure distribution for Normal & Pathological subject

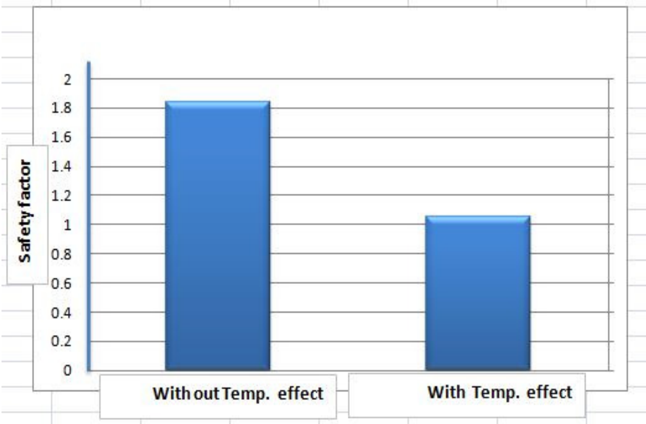
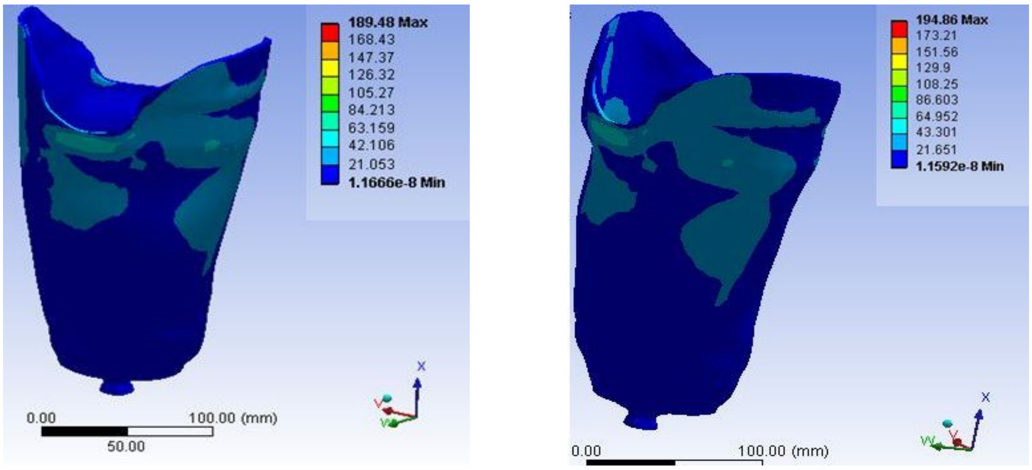


Figure 7. Safety Factor Value With and Without Temperature Effect



A. Stress Distribution without Temperature Effect B. Stress Distribution with Temperatue Effect

Figure 8. Stress Distribution in Socket