INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT
ISSUE ON APPLIED MECHANICS RESEARCH
Volume 8, Issue 6, 2017 pp.491-500
Journal homepage: www.IJEE.IEEFoundation.org

The effect of ultraviolet radiation on the modulus of stress relaxation of polypropylene prosthetic sockets

Kadhim K. Resan

Materials Engineering Department, Faculty of Engineering, Al-Mustansiriyah University, Baghdad, Iraq.

Received 15 Nov. 2016; Received in revised form 29 Nov. 2016; Accepted 30 Nov. 2016; Available online 1 Nov. 2017

Abstract
In some countries such as Iraq, the high temperature and high exposure to ultraviolet (UV) rays in summer, result in changes to the mechanical and physical properties of polypropylene sockets. In this study four groups of sockets were exposed to ultraviolet rays for different periods of time: zero, 20 hours, 40 hours and 60 hours. Also, the stress relaxation modulus was measured for these groups at 50 ^{o}C. Also, the effect of ultraviolet on the stress relaxation modulus, tensile strength, hardness and morphology of polypropylene is determined. The interface pressure is measured between the prosthetic below the knee socket and stump by f-socket sensors and then this socket is modeled by ANSYS 15 Workbench, from results the stress relaxation modulus decreases with increasing UV exposure time and temperature.
As a result of high temperature and high exposure of ultraviolet (UV) ray in summer in some countries such as (Iraq), the mechanical and physical properties of polypropylene socket are changed. In this study there a four groups of polypropylene were exposure by ultraviolet ray at different time, zero, 20 hours, 40 hours and 60 hours .Also, the stress relaxation modulus was measured for these groups at 50 ^{OC}. So the main aim of this study is to find the effect of ultraviolet on the stress relaxation modulus, tensile strength, hardness and morphology of polypropylene .The interface pressure is measured between the prosthetic below the knee socket and stump by f-socket sensors then modeling this socket by workbench ANSYS 15. The ultimate stresses are decreasing with time and the hardness are alternative value, it is decreasing at 20 hours exposure UV and then increasing at 40 hours and 60 hours . The modulus of stress relaxation at not exposure specimen down a lot compared with the other groups this behavior led to deflection of socket is increasing.

Keywords: Amputee; Ultraviolet; Polypropylene; F-socket; Relaxation modulus.

1. Introduction
Polypropylene is a widely applicable polymer material because it has distinct advantages such as excellent processing qualities and low production cost [1]. There are different types of socket materials for prosthetic sockets. However, prosthetic sockets for the below the knee (transtibial amputees) to support the residual limb (or stump) are manufactured from polymer or polymer-based composite materials (polypropylene sheets or laminate sockets), [2].
In Iraq, due to the ongoing conflict, there are increasing numbers of amputees (as shown in Figure 1), and a corresponding increase in the production of below the knee sockets has been required. The socket would be exposed to natural weathering such as heat, humidity and ultraviolet radiation. The main source

of ultra-violet radiation is the sun. The radiation in the ultra-violet spectrum is categorized by three main wavelength ranges; UVA (310-410) nm, UVB (285-315) nm and UVC (90-285) nm [3]. As a result of the long summers (in Iraq) ultra violet exposure is an increasing cause of change in the mechanical properties of polypropylene.

Polypropylene is one of viscoelastic materials; the most properties of viscoelastic materials are that they exhibit a time dependent variable stress to a constant strain and a time dependent variable strain to a constant stress. The stress relaxation modulus of polypropylene has a high rate of decrease with time [4]. This research as studied the effect of ultraviolet exposure over time, on the stress relaxation modulus of polypropylene socket materials and its effect on the deformation of the socket.

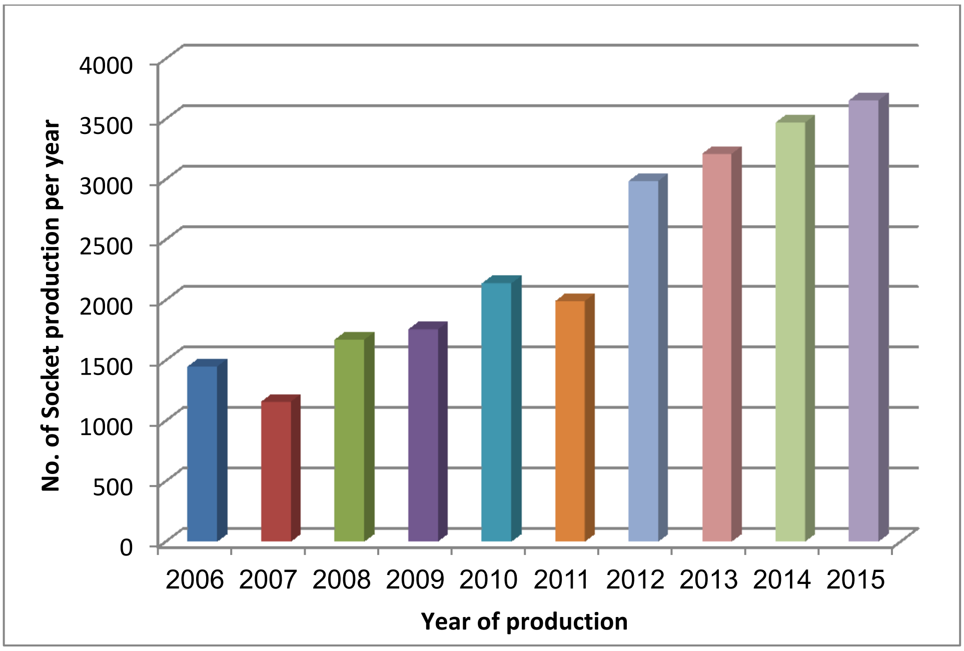

Figure 1. Production of below knee socket in Iraq during recent years [5].

2. Stress relaxation modulus

All models of viscoelasticity are made up of dashpot and spring. There are many types of viscoelastic models such as those of Kelvin (Voigt), Maxwell, Standard Linear Solid models and Burger's Four Elements, in this paper Burger's model was used [4].

Burger's model is shown in Figure 2 where the Kelvin and Maxwell models were connected in series.

The creep behavior of Burgers four element is [4]:

$$\sigma(t) = \frac{\varepsilon_o}{A}\left((q_1 - q_2\, r_1)e^{-r_1 t} - (q_1 - q_2\, r_2)e^{-r_2 t}\right) \tag{1}$$

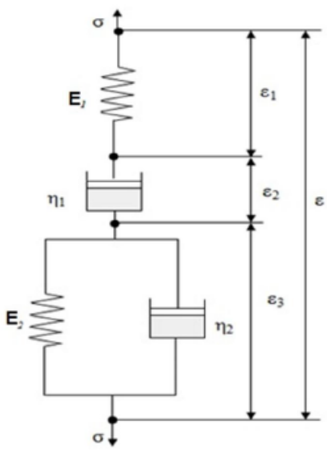

Figure 2. Burger model [4].

3. Methods

The effects of UV degradation on polypropylene socket distributed by the International Committee of the Red Cross (ICRC), was an exposure necessitating a long service life. Therefore, this exposure was measured by conducting accelerated exposure tests, and stress relaxation tests. Elastocon equipment was used to measure the effect of weather temperature and UV exposure, then in manufacturing the socket and in measuring the interface pressure. F-socket sensors were attached to the residual transtibial amputation limb.

3.1 Ethical statement

All human test protocols were approved by the materials engineering department, Al-Mustansiriyah University under reference number 63 and written, informed consent was obtained from the subject before data collection. The approval process involved a presentation, guidelines and limitation.

3.2 Subject

The participant is a 23 years old, male, weight 56 kg, height 168 cm, and has a transtibial amputation of the right leg as result of a bomb blast that occurred in Baghdad about 6 years ago. He subsequently underwent consecutive adaptation periods with repeatedly different prosthetic setups. The subject now has a SACH foot type, polypropylene socket. All prostheses were properly aligned by a certified prosthetic technician.

4. Experiments

4.1 Materials

The base polymer used in this study is a ICRC polypropylene, and it was implemented by referring to guidelines from the International Committee of the Red Cross. The process of polypropylene making involves casting, alignment and rectification methods which adhere to international prosthetic standards of practice and therefore not described in the ICRC manufacturing guidelines [6].

4.2 Specimen preparation

Four different groups of specimens were prepared in this investigation. The first group was not exposed to UV, the remaining three groups were exposed for different lengths of time: 20, 40 and 60 hours respectively. The tensile and creep specimens were cut using CNC tools according to the recommendations of ASTM D-638[7] and ASTM-D2990 [8] for the tensile and stress relaxation tests respectively.

4.3 Exposure procedure

The specimens were exposed to Ultraviolet radiation for different periods: 0, 20, 40 and 60 hours, by using fluorescent Ultra violet accelerated by a weathering device. This is a laboratory weather simulation for the purpose of predicting the relative durability of materials exposed to environments, a test which accords with the ASTM G151 [9] standard. This standard provides general procedures to be used when exposing non-metallic materials in accelerated test devices, under laboratory light sources.

4.4 Testing procedure

4.4.1 Tensile testing

Mechanical properties such as ultimate stress, and young's modulus were measured using a Tinius Olsen machine, at a speed of 5 mm/min on the polypropylene test specimens, which were subjected to UV at different exposure lengths, and were prepared following the ASTMD-638 [7] standard.

4.4.2 Creep and relaxation testing

Specimens for creep tests are used to predict the properties of viscoelastic materials using Elastocon equipment. The dimensions of creep test specimens are cutting according to the ASTM-D2990 standard [8]. The relaxation test equipment has three stations as shown in Figure 3. For creep or relaxation tests, the stations can be set for either state tension or compression. The stress used in this test is (1MPa) at a temperature of 50 ^oC and the applied stress is below the allowable stress for each material.

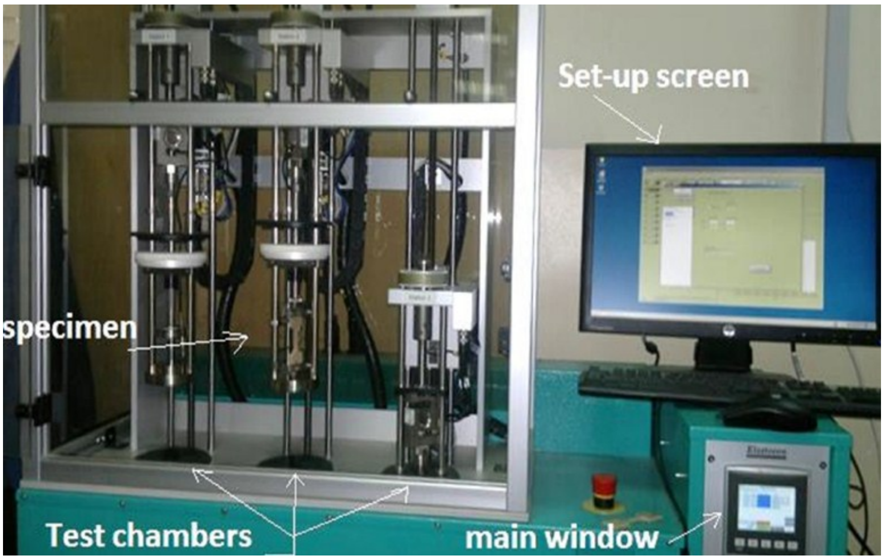

Figure 3. Stress relaxation/creep equipment.

4.4.3 Scanning electron microscope procedure

In tests of specimens by electron microscope, scanning required the samples to be firstly coated with a metal possessing a high conduction-rate. This is so that it is able to absorb the electrons generated by a scanning Electron Microscope; therefore gold was used due to its high conductivity. A scanning electron microscope beam was used throughout this project to obtain microstructural observations of propylene specimens that were exposed for different periods to ultra violet radiation to thus determine the effect of the UV radiation on the microstructure of the samples. This test was conducted by Te-scan SEM device as shown in Figure 4, and conducted in a vacuum, at a magnification of around 7 kx.

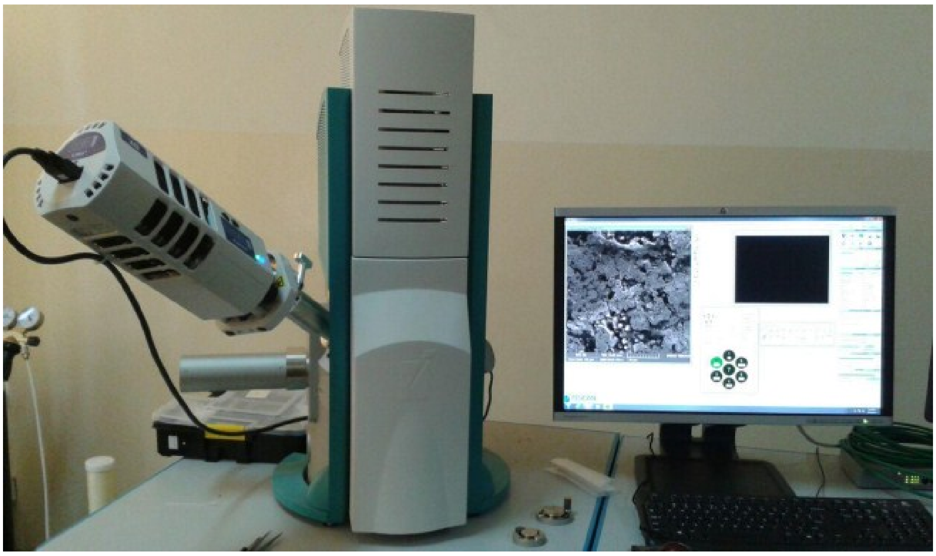

Figure 4. Scanning Electron Microscope device.

4.4.4 Interface pressure using F-socket

The steps for measuring of the interface pressure between socket and stump start by applying the sensors of the F-socket device as shown Figure 5 at the anterior of the stump of limb. Then the socket was put on, the patient begins to move and the software commences to record the movement and draw a curve between the pressure and gait cycle.

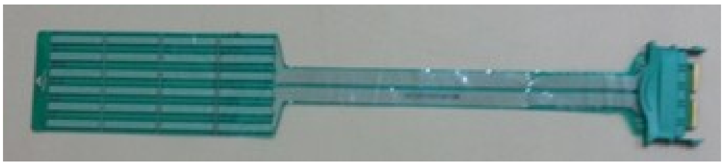

Figure 5. Interface pressure f-socket sensor.

5. Modeling a prosthetic socket

For this work, the patient's socket was drawn by an AutoCAD 2014 program, then the drawing was exported to an ANSYS program. Finite element is with the aid of ANSYS software used as a numerical analysis to illustrate the effect of stress relaxation modulus decrease in a structural to determine its behavior under maximum stress and maximum deformation. The element (solid, brick 8node 45, the total number of elements are (15433), as shown in Figure 6) were used in this work.

The boundary condition which is used in the ANSYS Workbench software will be a fixed support at the adapter of the socket, while pressures were distributed according to the F-socket sensor test, where maximum stresses in this case were found in the interior of socket while the patient was walking.

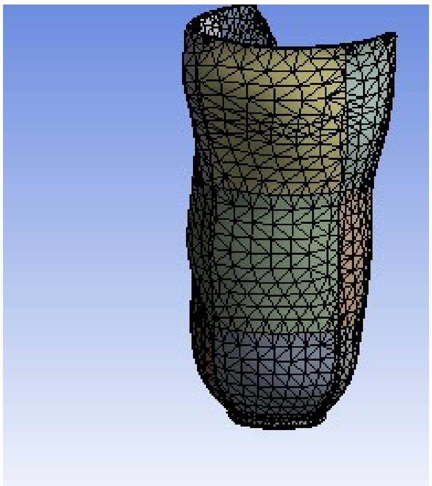

Figure 6. Mesh of socket.

6. Results and discussion

6.1 Tensile test results

The results of the tensile test of the polypropylene are shown in Table 1.

Table 1. Different exposure time groups with ultimate stress.

Groups	Exposure Time (hrs)	Ultimate Stress (MPa)	Modulus of Elasticity (MPa)
A	0	26.3	1620
B	20	25.7	1184
C	40	21.4	1376
D	60	20.4	1101

From Table 1 it shows that the material in group A has a higher ultimate tensile strength than other groups and the material in group B has higher mechanical properties than group C and D. The differences in the mechanical properties of these materials is related to different lengths of ultraviolet exposure time [10]. Under a tensile load, the amorphous structure easily becomes volatile, with polymer molecules unwinding and sliding by each other due possessing weak intermolecular bonds. The crystalline structure of the amorphous molecular has a much stronger bond. It is vulnerable to puffing up and re-orientation, as well as slight expansion. The ultimate stress of the polypropylene depends on the duration of exposure, temperature, and loading. It seems that a longer exposure time results in a low ultimate tensile strength as given in group D. The ultimate stress decreases for all samples over different

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

periods of time due to the effects of polypropylene degradation which could be attributed to the photo-oxidation of the polypropylene, resulting in the molecular chain under ultraviolet exposure [10].

6.2 Creep and stress relaxation results

The polypropylene groups were tested in a stress relaxation machine with a yields stress of (1 MPa) at a temperature of (50°C). The results from the creep test of the specimens at different exposure times to the UV. The test results are shown as in Figure 7.
The stress is required to maintain the strain at a constant value for the duration of time required.
The modulus of stress relaxation in Group A (zero time) decreased significantly compared with the rest of the other groups B, C and D, the decrease of modulus in Group A was due to a change of value in the molecular structure of the PP sample. The modulus of elasticity (before exposure) is much higher than that of other samples.
From eqution (1), the stress relaxtion modulus for group A is:

$$E(t) = 1540.6\, e^{-0.019\,t} + 79.5\, e^{-15.18\,t} \quad (2)$$

Figure 7 shows the curve of this equation. Also the modulus of relaxation for the other specimens have been estimated according to the previous procedure.
Group B:

$$E(t) = 1120.2\, e^{-0.023\,t} + 64.3\, e^{-14.18\,t} \quad (3)$$

Group C:

$$E(t) = 1376.7\, e^{-0.027\,t} + 56.1\, e^{-13.18\,t} \quad (4)$$

Group D:

$$E(t) = 1040.6\, e^{-0.025\,t} + 61.3\, e^{-16.25\,t} \quad (5)$$

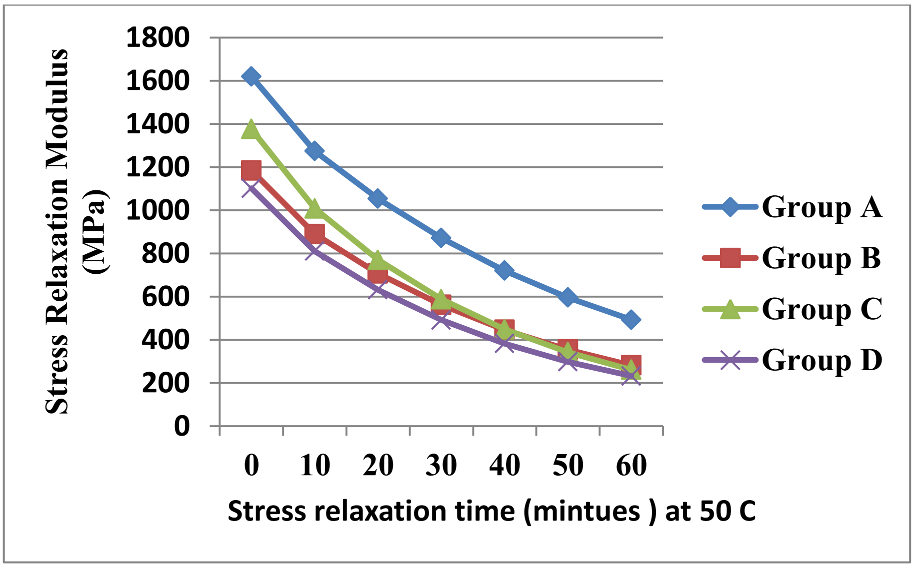

Figure 7. Stress relaxation modulus for different groups.

6.3 Scanning electron microscope results

Figure (8-a) to figure (8-d) show surfaces before and after exposure. The surface of specimens before exposure looks relatively smooth as shown in Figures (3-8). After 20 hrs of exposure, the surfaces became not smooth as in Figure (8-b).
From Figure (8-a) which shows polypropylene and its component after 40 hrs of exposure, it is clear that there are cracks and micro-fissures which could be seen on the surface of degraded specimens and which

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

increased significantly at 60 hrs of exposure, and some particles can be observed, as in Figure (8-d). All of these surfaces changed form arbitrarily during ultraviolet exposure as a result of the change of surface, resulting in shrinkage.

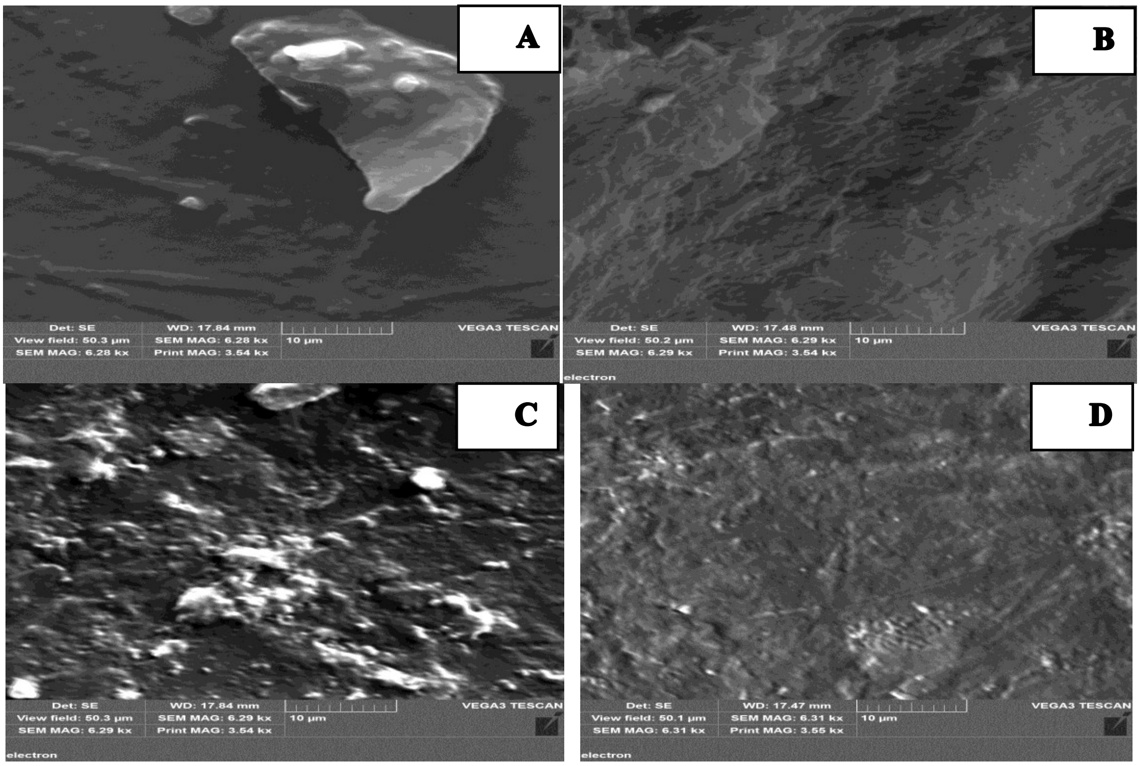

Figure 8. Surface aspects for different groups of exposure.

6.4 Interface pressure result

The result of interface pressure between the socket and stump of the amputee by F-socket device is shown in Figure 8. Pressure measurements are repeating during the gait cycle, the pressure reaching its maximum point at 215 kPa in the interior region of the socket. The distribution of stress at the socket was determined as shown in Figure 9 by using the ANSYS program, and by applying the recording pressures as (215, 182, 146, and 83) kPa on several points on socket according to the positions of maximum and minimum stress recorded by the F-socket.

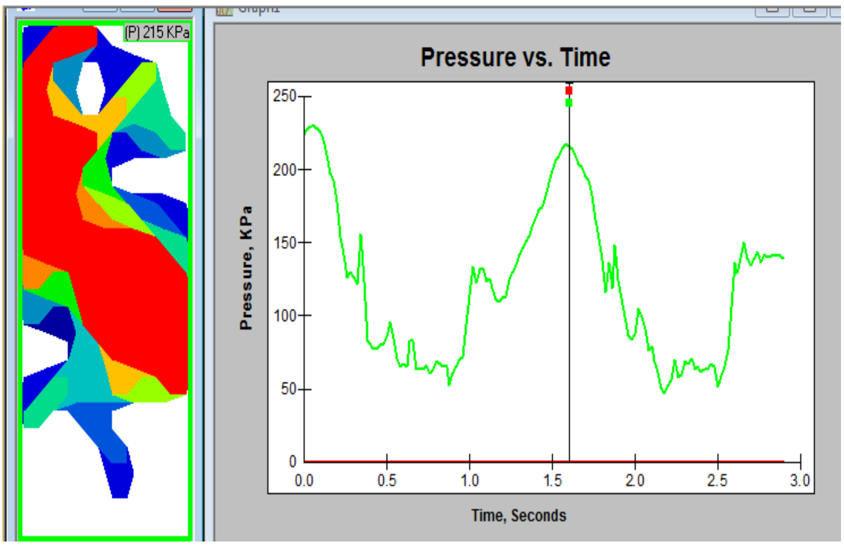

Figure 9. The interface pressure results from the f-socket sensor.

6.5 The deformation on the different sockets

The value of polypropylene deformation is dependent on its resistance to the temperature effect. Due to the socket being made from polypropylene which is affected by interface pressure lead to Von Mises stress not exceeding the allowable stresses. The ability of a polypropylene to deform is determined by the movement of its molecules that are accelerated by UV without temperature; this effect is clear in Figure 10. In the findings in this paper, it was also determined that when the applied pressure is entered into the ANSYS program with the modulus of relaxation of different groups and at a temperature 50oC for 60 minutes, deformation of the material was found. In Figure (11-a) to Figure (11-d) the moduli relaxation stress with time according to equation (2) to equation (5), were (492.7, 281.8, 261.3 and 232.1) MPa at (0, 20, 40 and 60) minutes respectively at a temperature of 50oC. The results of deformation are due to the applied pressure and due to a decrease in stress relaxation modulus with time and temperature. This decrease in stress relaxation modulus causes an increase of deformation with time. The direction of the deformation is from inside of the socket wall to the outside of the socket and causes the socket to sag with time. If the deformation increases more than allowable socket deformation range (2-6) mm, [11] then the socket will sag resulting in an uncomfortable fitting between stump and socket. This means that in order to produce a perfect socket with good properties, the materials chosen must be of the type that resists all kinds of deformation resulting from creep, stress relaxation, temperature and/or pressure.

Figure 11 shows the maximum deformation from the effect of temperature for all four groups, indicating that those in group A and group B are comfortable sockets (5.7 mm and 6.1mm) respectively, but groups C and D are sagging sockets (6.4 mm and 7.8 mm) respectively. Therefore, in the case where a polypropylene prosthetic socket is at 50 oC with an exposure to UV of more than 40 minutes, this type of material is not recommended for use.

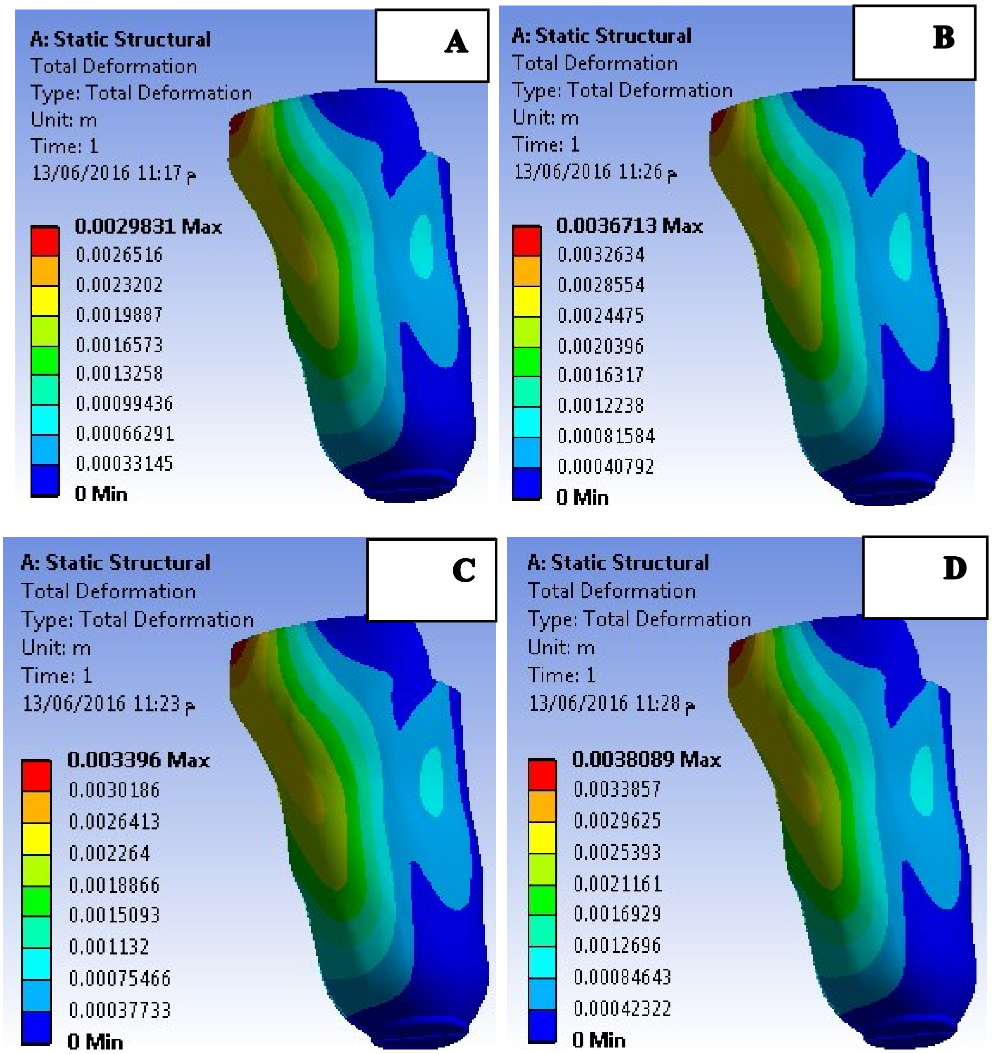

Figure 10. maximum deformation in socket for all groups without temperature effect.

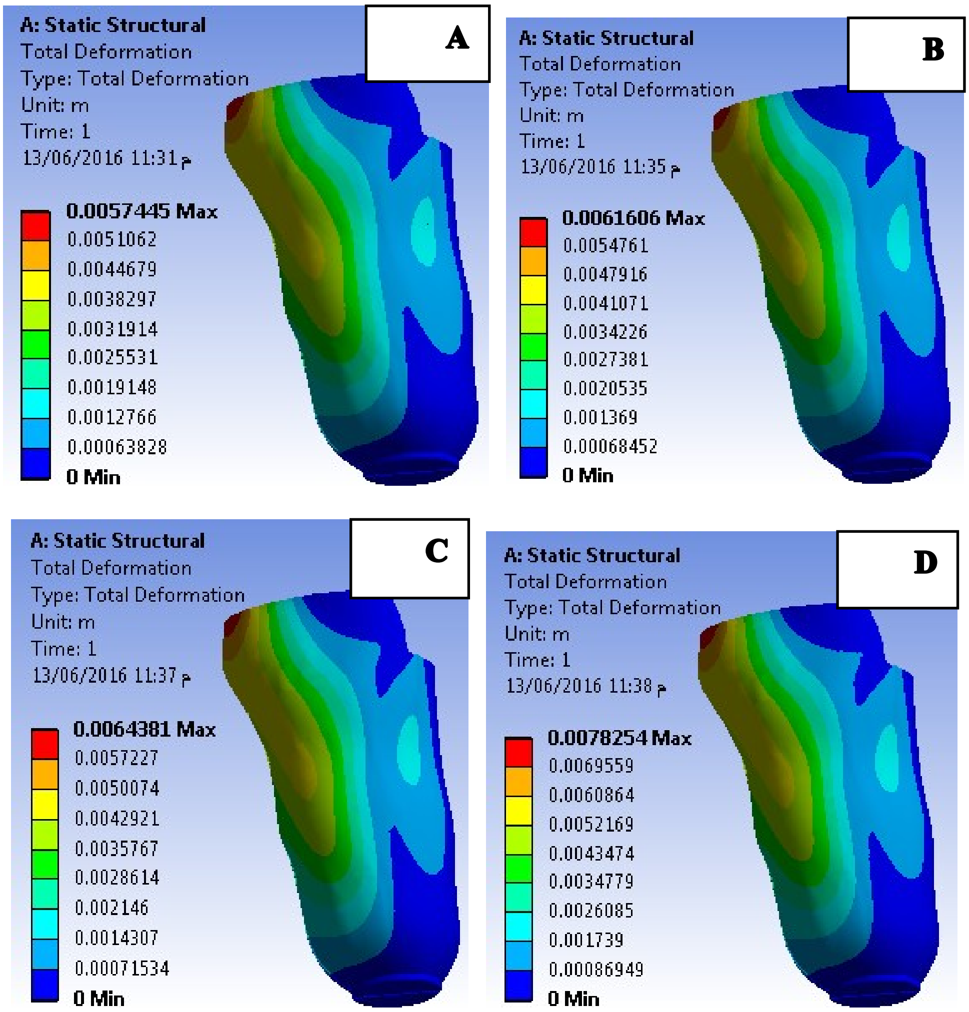

Figure 11. Maximum deformation in socket for all groups at 50 °C.

7. Conclusions

1. Decreasing mechanical properties such as ultimate stress and modulus of elasticity correlating with increasing exposures to UV over time.
2. Burger model of viscoelastic is a good prediction of the modulus of elasticity.
3. The stress relaxation modulus decreases with increasing UV exposure time and temperature.

Acknowledgement
All staff of prosthetic and orthoses lab. at college of engineering - Al-Nahrain University

Nomenclatures

Symbol	
σ	Stress N/mm^2
t	Time Minute
ε_o	Strain mm/mm
A	Cross section area mm^2
q1,q2,r1 , r2	Burger model constant
E_1,E_2	Spring stuffiness N/mm
η_1 , η_2	Dashpot coefficient

References

[1] Mashael Al-Shabanat (2011) "Study of the Effect of Weathering in Natural Environment on Polypropylene and Its Composites: Morphological and Mechanical Properties", International Journal of Chemistry, Vol. 3, No. 1.

[2] Kadhim K. Resan, Yasir K. Ibrahim Shireen H. Challoob (2015), "Stress Relaxation on Prosthetic Laminated Socket Materials, Journal of Engineering and Development", Vol.20, No. 3.
[3] Haigh, Joanna D. (2007). "The Sun and the Earth's Climate: Absorption of solar spectral radiation by the atmosphere". Living Reviews in Solar Physics 4.
[4] Shireen Challoob, Kadhim Resan and Yasir Ibrahim, "Stress Relaxation and Creep Effect on Polypropylene below Knee Prosthetic Socket", Journal of JSEM, Vol.15, Special Issue, 2015.
[5] Statistical of socket production, ministry of health in Iraq, 2016.
[6] Manufacturing Guidelines, "Trans-Tibial Prosthesis Physical Rehabilitation Programmer", International Committee of the Red Cross, 2006.
[7] American Society of American Testing for Standard "Test Method for Tensile Properties of Plastics", 2014.
[8] American Society of American Testing for Standard "Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics", 2001.
[9] American Society of American Testing for Standard "Practice for Exposing Nonmetallic Materials in Accelerated Test Devices that Use Laboratory Light Sources", 2010.
[10] Andrej Demšar1, Dragan Žnidarčič2 and Diana Gregor Svetec , "Impact of UV radiation on the physical properties of polypropylene floating row covers", African Journal of Biotechnology Vol. 10(41), pp. 7998-8006, 3 August, 2011.
[11] Muhsin J. Jweeg, Kadhim K. Resan and Mustafa T. Ismail, "Study of Creep – Fatigue Interaction in a Prosthetic Socket below Knee", ASME 2012 International Mechanical Engineering, Houston, Texas, USA, November 9-15, 2012.

