Improving Fatigue Life of Bolt Adapter of Prosthetic SACH Foot

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ABSTRACT:

In this research an analysis for improving the fatigue behavior (safety factor of fatigue) of non-articular prosthetic foot (SACH) in the region (Bolt Adapter).The laser peening was carried to the fatigue specimens to improving the fatigue properties of bolt’s material. The tests of mechanical properties and fatigue behavior were carried for material that the bolt manufacture from it, a region where the failure occur and inserted of these properties to the program of engineering analysis (Ansys) to calculate the safety factor of fatigue. The results showed that the safety factor after hardening by laser is increased by 42.8%.

Keywords: SACH, bolt, foot, prosthetic, safety factor, fatigue, adapter, laser peening.

تحسين عمر الكلل للولب القدم الصناعية نوع SACH

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الخلاصة:

في هذا البحث تم تحليل و تحسين سلوك الكلال (عامل الامان للكلال) للقدم الاصطناعية غير مفصلي (SACH) في منطقة الالولب.عملية التصليد بالليزر قد اجريت لعينات الكلال لتحسين خواص الكلال لمادة الالولب.اختبارات الخواص الميكانيكيه و سلوك الكلال اجريت لمادة التي صنع منها الالولب، المنطقة التي يحصل بها الفشل و ادخال هذه الخواص لبرنامج التحليل الهندسي (SACH) لحساب عامل الامان للكلال.النتائج اظهرت ان عمر الكلال بعد التصليد بواسطة الليزر قد ازداد بنسبة ٤٢,٨%.

الكلمات الرئيسية : SACH ، لولب ، قدم ، طرف صناعي,عامل الامان ، الكلال ، adapter، التصليد بالليزر.

1.INTRODUCTION

In the development of prostheses, all prosthetic assemblies and components are subjected to structural acceptance tests which include static and fatigue tests. Static tests are required to determine the structural strength of the foot to ensure performance and safety. These are carried out on a universal testing machine. While this is important, fatigue tests to reveal the fatigue strength of the components must also be performed. Fatigue tests are designed to study performance under load for the equivalent of the expected service life during normal use (**TOH, et al., 1993**).

Fig.1 shows a schematic diagram of the mechanism by which laser peening generates residual stress. Irradiation by a strong laser pulse, exceeding the abrasion threshold, on a material submerged in water converts the material surface to plasma and generates high pressure plasma on the surface. Under water, the inertia of the water prevents the plasma from expanding, which consequently concentrates the laser energy in small area (**Sakino, 2009**). The plasma absorbs subsequent laser energy and generates a heat-sustained shock wave, which impinges on the material with an intensity of several gigapascals, far exceeding the yield strength of the material (**Standard Test Methods, 2003**).As a result, the plasma pressure becomes 10-100 times larger than in atmosphere and reaches Gpa levels. This pressure generates a shock wave that passes in the material. The shockwave causes plastic deformation of the material, and the restraint from the surrounding non-deformed spots generates compressive residual stress on the surface. The residual stress can be generated evenly and without scattering by continuously irradiating the object by moving the laser beam (**Sakino, 2009**).
Laser peening changes tensile residual stress to compressive. So it seems that laser peening will be very effective in enhancing the fatigue strength, because tensile residual stress is one of the most important factors to reduce fatigue strength. Recent studies have revealed that laser peening dramatically improved the fatigue properties of austenitic stainless steel (**Murdhi, 2013**).

2.LASER PEENING

The laser peening test was carried out at (University of Technology) by using (Q-switched neodymium –YAG laser) that has the following parameters:
1- Laser wavelength is about 1.065 μm .
2- Pulse duration 7 Nano seconds.
3- Pulse energy 300 mJ .
4- The laser spot is typically (4-7) mm in diameter.
5- The deep water to the area that treated is typically (5-10) mm.
The selection 300 mJ of plus energy of laser peening because this gave best fatigue characteristic (**Murdhi, 2013**)

Fig. 2 shows (Q-switched neodymium –YAG laser system) used in the following work.
The specimens are coated by using the dark paint as shown in **Fig.3**.

3.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.

The gait cycle is broken into two periods, the stance period and the swing period. The term stance refers to the "period of time that the foot is on the ground." The term swing refers to the "time that the foot is in air for limb advancement" .The gait cycle can also be subdivided into three main tasks: weight acceptance, single limb support, and limb advancement. These main tasks are accomplished through the eight distinct phases that occur within the gait cycle.

4. FAILURE ANALYSIS

The failure is breaking the sample into two parts.The failure occurs as a result of load that be in heel and toe of foot in intermittent periods and regular during the phases of gait and that lead to alternating moment and opposite directions about the point A

.Where at heel strike phase as shown in **Fig.4** the ground reaction force applied on the heel of the foot upward vertically and the axis of the foot is italic so that the force analyze to two components, the first parallel to the axis of the screw and its operating moment in clockwise about the point A in distance L_1 and the second perpendicular to the axis of the screw and its operating share stress and its small amount so its neglected, while at toe off phase as shown in **Fig.5** which be vertical upward to the foot and analyze to two components, the first parallel to the axis of the screw and its operating moment in anticlockwise about the point A in distance L_2 and the second operating share stress and its small amount so its neglected too. From **Figs. 4** and **5** noted that the L_2 larger than L_1 so that the moment in toe off phase larger than the moment in heel strike phase.

5. MODELING THE SACH FOOT BY AUTOCAD

In order to conduct the finite element analysis, all of the components needed to be modeled. All of the components to be tested were modeled in Pro/AutoCAD 2011, as shown if **Figs. 6-9**.

6. FINITE ELEMENT ANALYSIS

ANSYS Workbench was chosen as the FEA software package because of its ability to accept a 3D computer aided design (CAD) model and assembly of high complexity. The program also allows for the accurate placement of angled pressures and loads, in addition to the modeling of contact surfaces and large deflection.

In the modeling of SACH foot, the standard tetrahedral elements were used because the elements have plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. The automatic size control was used to mesh the model as shown in **Fig.10**, with refined meshing at the notches of the bolt.

The total number of elements was (46889 elements) with total a number of nodes of (81263 nodes.).

Applied the same boundary conditions (constraints and loads) that taken from the GRF test. The tip of the adapter was selected as fixed support for the four sides at all time. a vertical upward pressure of 310 Kpa was applied to the bottom surface of the heel from 0% to 21% of gait cycle and 310 was applied to the bottom surface of the toes from 69% to 100% of gait cycle as shown in **Fig. 11**.In this work SOLID 185 as in **Fig.12** is used. SOLID185 is used for 3-D modeling of solid structures.

7. EXPERIMENTAL

The fatigue performance of a material is determined by testing a number of similar test specimens at different levels of maximum stress. A fatigue-testing machine of type rotating bending was used to execute all fatigue tests. The fatigue test of material specimens was carried out at (AL-Kufa University) as shown in **Fig. 13** .The specimens were subjected to an applied load from the right side of the perpendicular to the axis of specimen, developing a bending moment. Therefore, the surface of the specimens is under tension and compression stresses when it rotates.

8. RESULTS AND DISCUSSION:

I. Chemical Analysis:

Chemical analysis of the alloy was carried out at the Specialized Institute using x-rays method by using the device shown in the **Fig. 14**. The results are listed in the **Table 1**, which are compared to the American Society for Testing and Materials specifications (ASTM) (A 479 316 stainless steel) (**American Society for Testing and Materials, 2007**).

II. Mechanical Properties:

Tensile specimens had been examined at room circumstances conditions and the specimens after test shown in the **Fig.15**.The results of the mechanical properties of bolt material are shown in **Table 2**, which are compared to the American Society for Testing and Materials specifications (ASTM)(**American Society for Testing and Materials, 2007**).

The tensile specimen’s geometry and dimensions knew by using standard (A370)(**Standard Test**

Methods, 2003) which was specified for metals (Stainless steel) are shown in **Fig. 16**,and the dimensions of the specimen shown in **Fig. 17** .

III. Fatigue Results (S-N Curve)

The specimens hardened by laser peening are presented in the form of table as shown in **Table 3** while the description are in curves as shown in **Fig. 18.**

In comparison the fatigue result with reference (**Jweeg, et al., 2014**) the key benefits achieved in most application with laser peening are significant increase in fatigue life and fatigue strength. **Fig. 19** shows a comparison of fatigue properties for stainless steel specimens subjected to laser peening and dry fatigue. It is clear that, the fatigue performance of 300mJ with water is the best one compared with dry fatigue. The reason is that water generates high pressure plasma, and the strength of material surface is improved owing to the impact force by the plasma (SaKino, et al., 2009).

9. THE RESULT OF THE NUMERICAL ANALYSIS AND DISCUSSION

To increasing the life of bolt adapter in reference (**Jweeg, et al., 2014**), the Laser peening (LP) is a surface enhancement technique that has been applied to improve fatigue**.** Behavior The ability to use a high energy laser pulse to generate shock waves, inducing a compressive residual stress field in metallic materials (**Singh, 2009**).

The aim of this analysis is to investigate the equivalent (Von-Mises) stress and safety factor of fatigue of prosthetic SACH foot.
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, (σ_e) is the equivalent stress, and (σ_y) is the yield stress.
The safety factor for fatigue will be safe in design if the safety factor about or more than (1.25) (Miller, 2002).
Figure (20) shows the equivalent stress-safety factor for the prosthetic SACH foot. From noted that the safety factor of fatigue after laser peening increased by 42.8% as shown in **Fig. 21** and this increment due to formed layer of compressive residual stress which inhibits both crack initiation and propagation this lead to life longer of bolt and more safety factor.

10.CONCLUSIONS:

1-An improvement in fatigue life by 42.8% due to laser peening.

2-The fatigue limet of bolt material was improved by 19.7% at 10^7 cycles under the laser treatment.

3-The results showed that good agreement was found when comparing the experimental and numerical data.

4-The minimum equivalent stress-safety factor is located in bolt at interface regain between adapter and foot at notch because the cross section is minimum at notch.

11. REFERENCES

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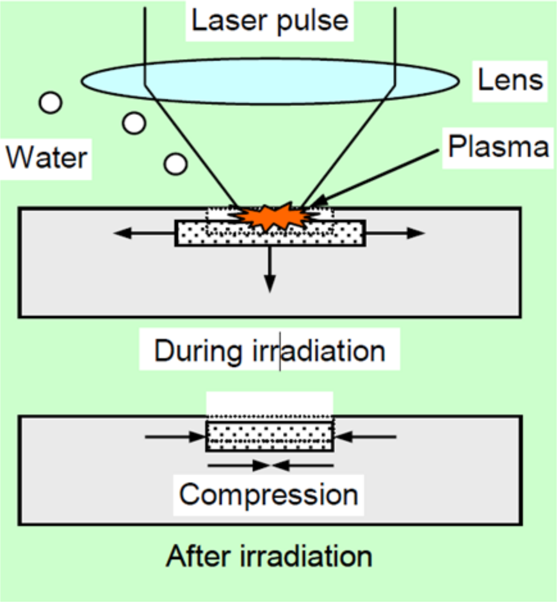


Figure 1. Basic process of laser peening (**Yoshihiro, et al., 2007**).

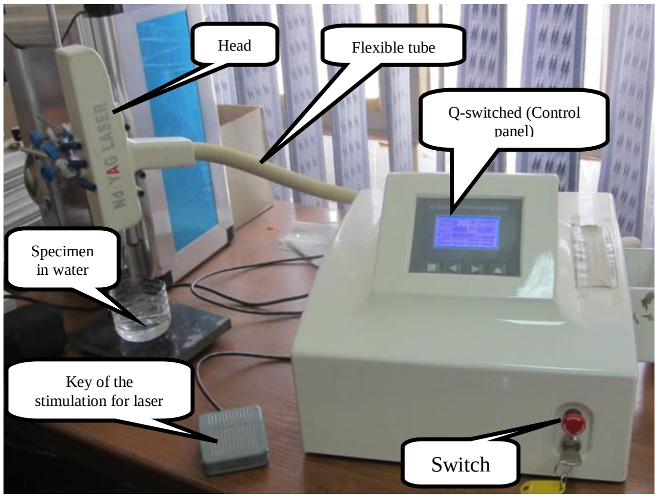


Figure 2. Details of laser peening test rig in University of Technology (Laser and Electroptical Engineering Department) (**Murdhi, 2013**).

Figue 3. The fatigue specimens test after coating.

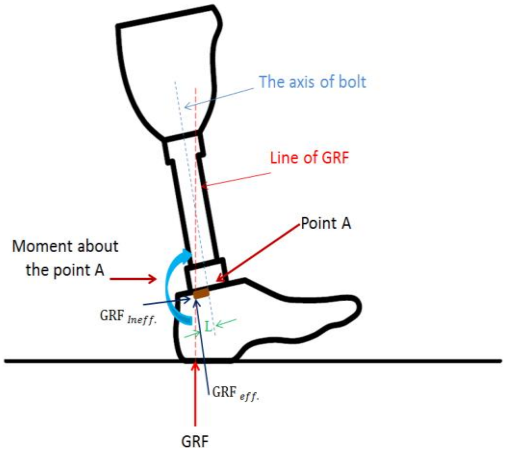


Figure 4. GRF at heel strike phase.

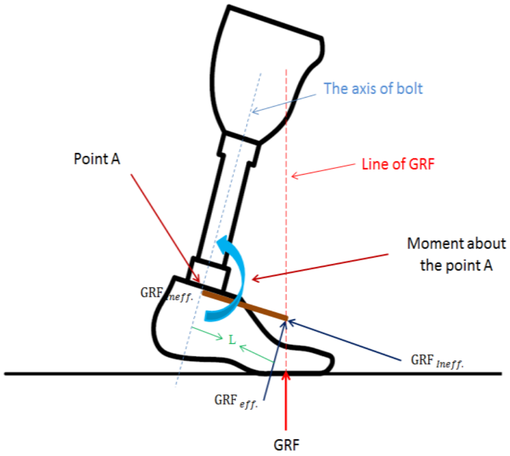


Figure 5. GRF at toe off phase.

Figure 6 . Final solid model of KEEL OF SACH foot.

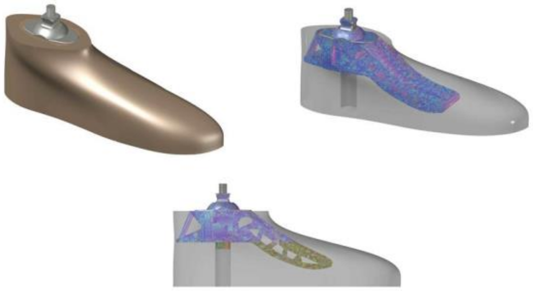


Figure 9. Multiple views of final model of SACH foot and bolt adapter.

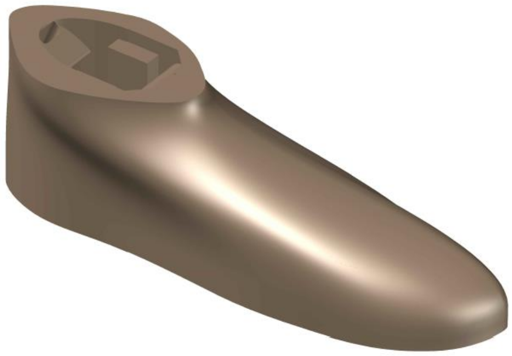


Figure 7. Simplified SACH foot.

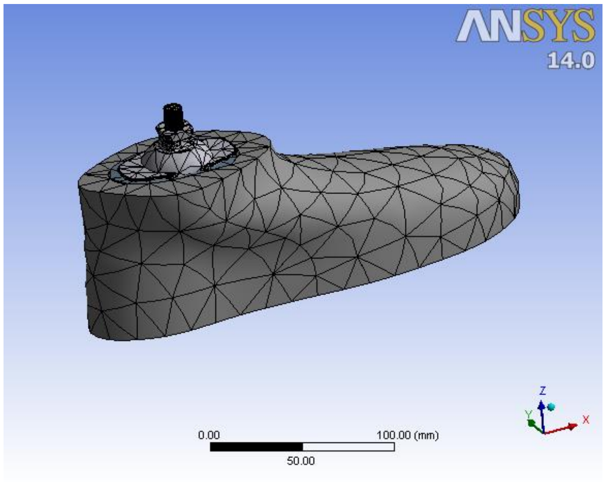


Figure 10. Meshed SACH foot models**.**

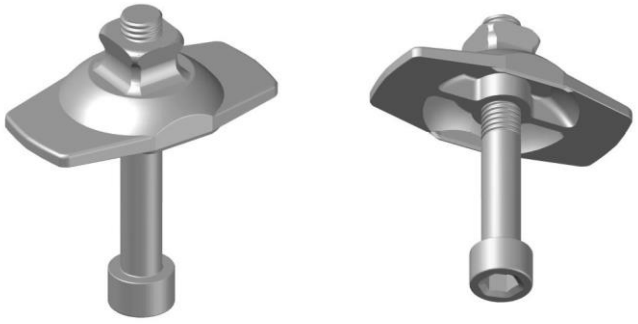


Figure 8. Final bolt adapter model.

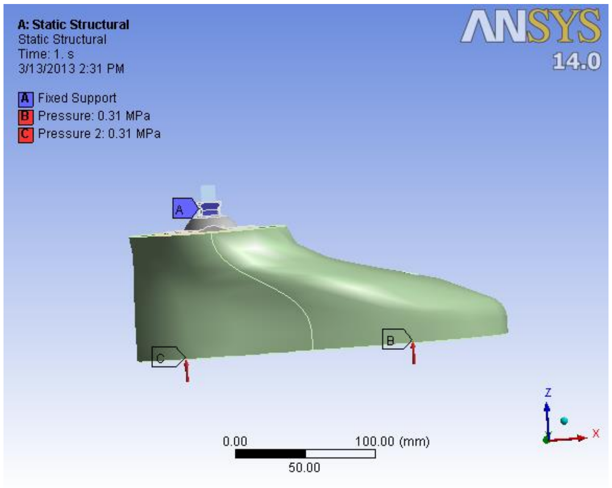


Figure 11. FEA model constraints and loads.

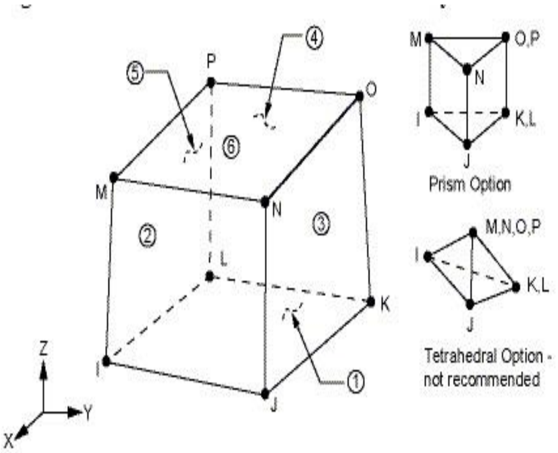


Figure 12. Solid 185.

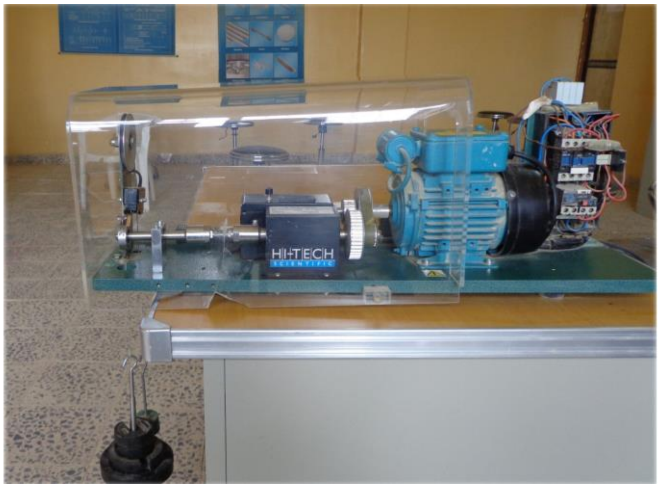


Figure 13. Fatigue Testing Machine.

Table 1. Chemical composition wt%

Material	C	Si	Mn	Cr	Ni	Other elements
bolt (experimental)	0.0089	0.867	0.475	13.48	3.6	----
Key to steel (standard)(**American Society for Testing and Materials, 2007**)	0.008	1	2	16	10	----

Figure 14. X-ray fluorescent (XRF).

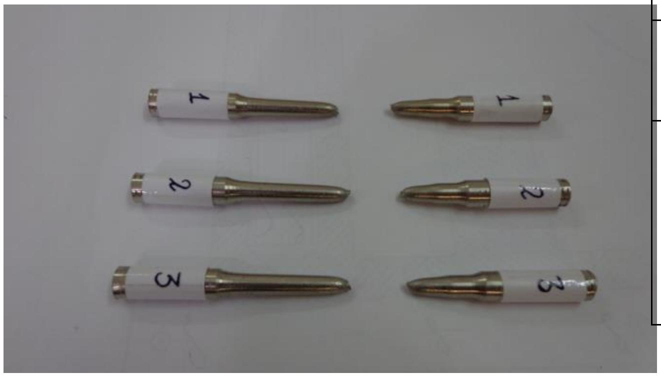


Figure 15. Tensile test specimens after test.

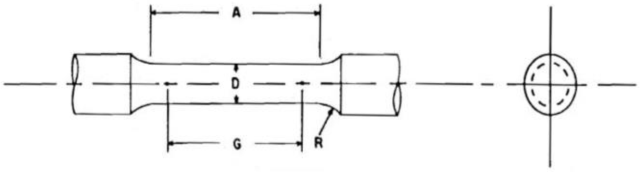


Figure 16. Circular cross section tensile test specimen according to ASTM (A370) (**Standard Test Methods, 2003**).

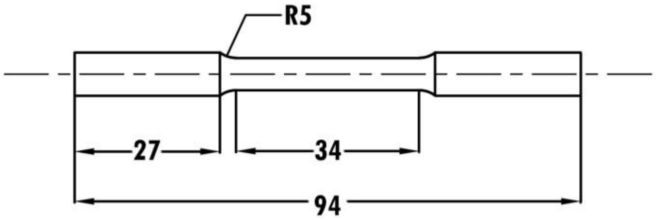


Figure 17. Tensile test specimen (all dimensions in millimeters).

Table 2. The mechanical properties of material bolt (stainless steel).

Material	Young's Modulus (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)
Experimental	185	483	570
Standard (**American Society for Testing and Materials, 2007**)	195	450	585

Table 3. S-N fatigue tests.

Test	σ_f (MPa)	No. of cycles (cycle)
1	400	10000000*
2	420	6511000
3	460	4254000
4	480	1948000
5	500	1229000
6	520	320000
7	540	102000
8	560	4000

* didn't failed specimen

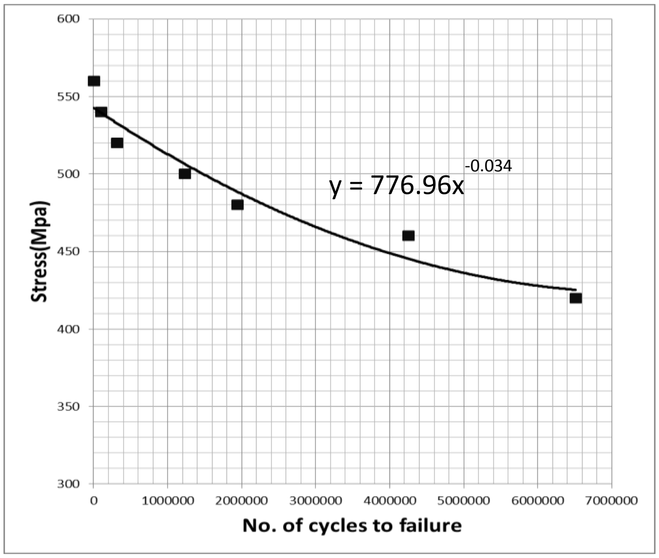


Figure 18. S-N fatigue tests curve.

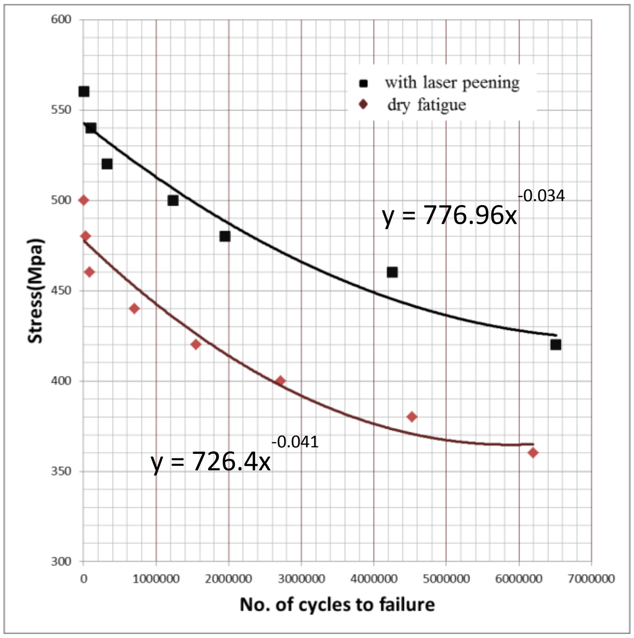
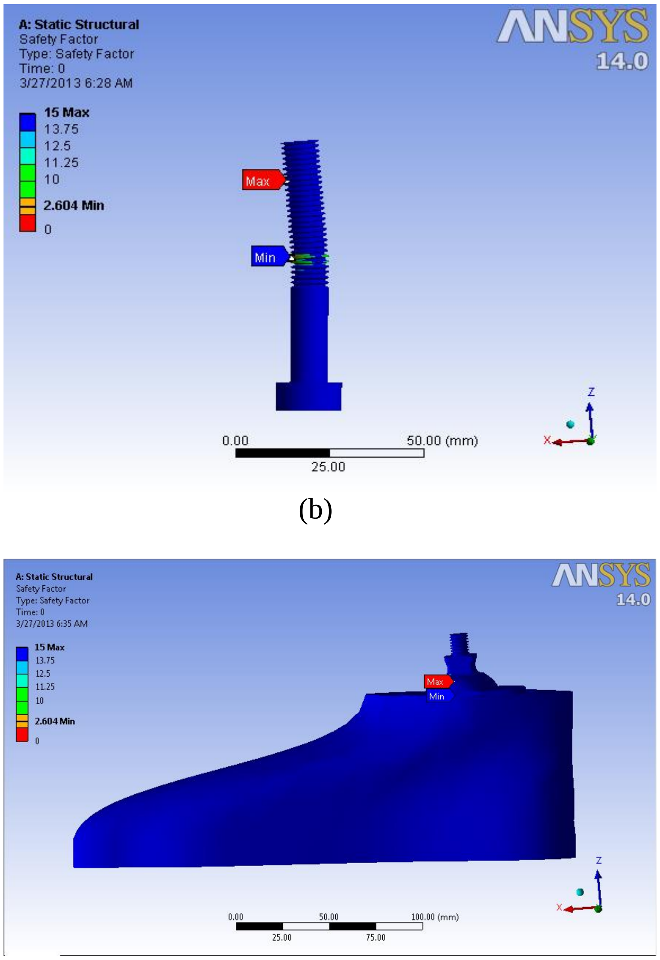


Figure 19. Comparison between the fatigue behavior with laser peening and without laser peening.



(b)

(a)

Figure 20. The equivalent stress-safety factor for fatigue of the prosthetic SACH foot.

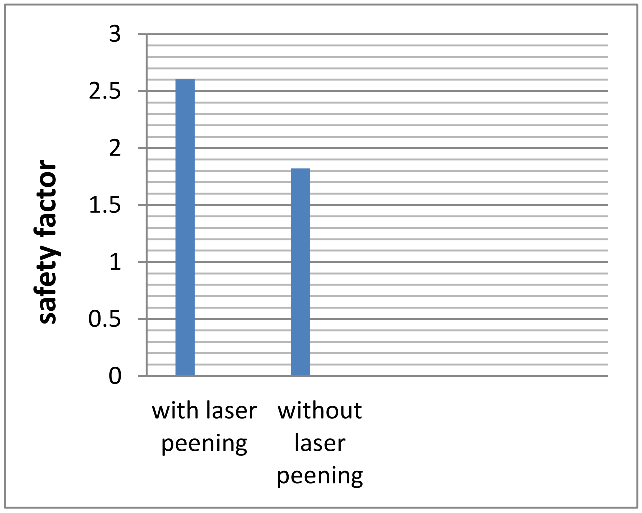


Figure 21. Comparison between the fatigue improvement factor for fatigue with laser peening and without laser peening.