Fatigue Life of Polymer Dental Crown

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Abstract

In this article fatigue life of polymer dental crown will be analyzed. Chewing forces occurring in repetitive cycles can lead to fatigue destruction of material. To predict a number of cycles to failure finite element method can be applied and results may be used to improve the design of acrylic dental crowns. Also, the modal analysis will be performed in order to find natural frequencies of the system and prevent destruction from vibrations.

Keywords: fatigue, modal, vibrations, dental crown, polymers, acrylic, finite element method

1. Introduction

Out of all human prosthetic devices, teeth are the most commonly replaced parts of the organism. Formerly common dentures and skeletal prosthesis are now being forced out of the market by crowns and bridges fixed to properly prepared teeth remainings. Crowns are the most effective dental prosthesis because of their esthetical features and reduced area of contact with soft tissue which results in higher patient comfort.

Stomatology is currently being revolutionized by CAD/CAM methods. These methods allow dental technicians to design prosthesis in a virtual environment and reach a higher level of customization. However, CAE methods are still not popular in stomatology applications. Their use in this field could allow prediction of dental prosthesis durability.

Polymer dental crowns are temporary acrylic replacements but they are often used for multiple years because of their low price. The purpose of this study was to predict how long polymer dental crowns can be used before fatigue destruction will occur. Finite element method can be used for such an estimation.

Most works focus on fatigue testing for ceramic crowns. Usually, experiments on universal materials testing machines are carried out. For example, Zahran et al. [1] in their work manufactured several ceramic crowns and applied a compressive load to simulate occlusal forces.

One of a very few papers about polymer dental crown fatigue testing was written by Keilig et al. [2]. Their work focused on the fatigue durability of the new high-performance polymer. They also used fatigue testing machine. They observed that modern polymer may have higher fatigue limit than human teeth.

Fatigue destruction of materials occurs when the load is repetitive. Load cycle can be determined or random. The first type includes constant changes such as sinusoidal load and the second one involves randomness and unpredictability of changes. Another classification divides cycles to periodic (repeated or fully reversed) and undetermined (fluctuating) [3]. Chewing force cycles are undetermined but for the purpose of numerical analysis, it can be assumed that they are repeated.

Fatigue endurance can be defined as maximum stress at which object will not be destroyed after reaching a number of cycles threshold.

There is two types of fatigue – low and high cycle. High cycle approach assumes that stress is low enough to neglect plastic deformation. Usual diagram of high cycle fatigue is Wohler's stress-life curve. It shows the relation between stress amplitude and a number of cycles to failure. Low cycle fatigue can be defined when a number of cycles are lower than 10^3. It is represented on a strain-life curve and may be calculated using Manson-Coffin equation [4]:

$$N_t = \frac{1}{2}\left(\frac{\sigma_f^{'}}{\varepsilon_f^{'}E}\right)^{\frac{1}{c-b}} \tag{1}$$

where: N_t is transition fatigue life, $\sigma_f^{'}$ - fatigue strength coefficient, $\varepsilon_f^{'}$ - fatigue ductility coefficient, E – Young's modulus. c and b are fatigue ductility and strength exponents.

Additionally, the modal analysis was carried out to find natural frequencies of the dental crown model. If forced vibrations reach any of these frequencies, then resonance occurs. It means that oscillating system gains maximum amplitude and vibrations can cause it to fall apart. In case of dental crowns forced vibrations may originate from oscillating dental tools, such as drills.

The simplest equation describing natural frequencies of the mechanical system is as follows [5]:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

where: f_n is natural frequency, k – stiffness, m – mass.

2. Numerical results

Fatigue life prediction was calculated in SolidWorks Simulation software using finite element method. The dental crown was scanned with an optical 3D scanner. For the purpose of FEA analyses CAD model was created in Autodesk Inventor basing on scan result (Figure 1). Approximate model dimensions are shown in the next picture (Figure 2). Model's height is 5,5 mm and hole's depth is 4 mm. The model was imported to SolidWorks where fatigue simulations are available.

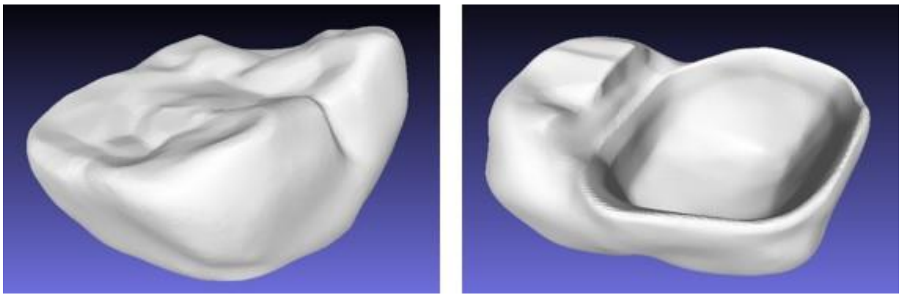

Figure 1. Scanned dental crown model

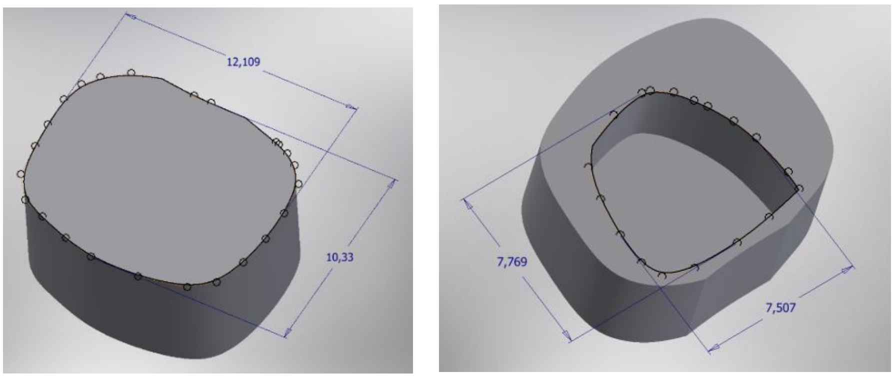

Figure 2. CAD model dimensions

Fatigue simulation uses results from the static analysis. Load magnitude was defined as 400 N of compression chewing force applied perpendicularly to the upper surface of the dental crown model [6]. The fixed constraint was applied to the hole's inner walls and ceil to simulate the supporting function of prepared tooth underneath the crown. In case of this crown hole's ceil is also leaning because of stump's cylinder-like shape. Applied load and boundary condition (fixed constraint) are shown along with mesh distribution in the picture below (Figure 3).

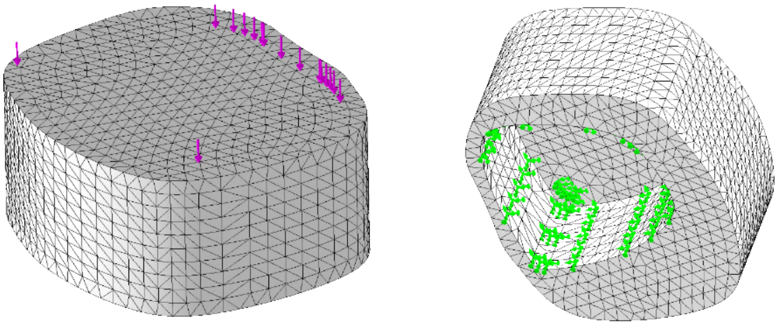

Figure 3. Applied load and fixed constraint with mesh view

The acrylic material was applied and material data defined as follows: Young's modulus: 2.5 GPa, Poisson's ratio: 0.4 and density: 1180 kg/m^3.

All finite element calculations in this work were done with mesh type set with the manual slider as close to dense. A number of elements for created mesh reached 15118 (23474 nodes).The maximum element size was 0.572867 mm.

Results from the static analysis (Figure 4-5) can be compared with material's yield strength. In this case, it's value is $7\cdot10^7$ Pa (70 MPa). The maximum von Mises stress was calculated as $1.323\cdot10^7$ Pa (13.23 MPa). It means that there is no risk of destruction caused by the static load.

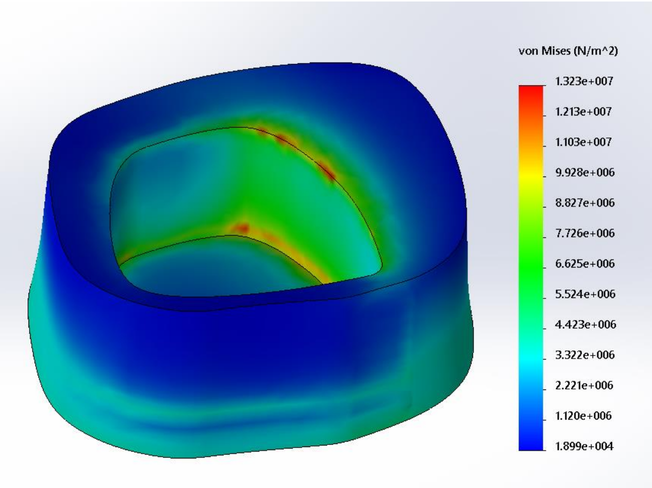

Figure 4. Von Mises stress for static load

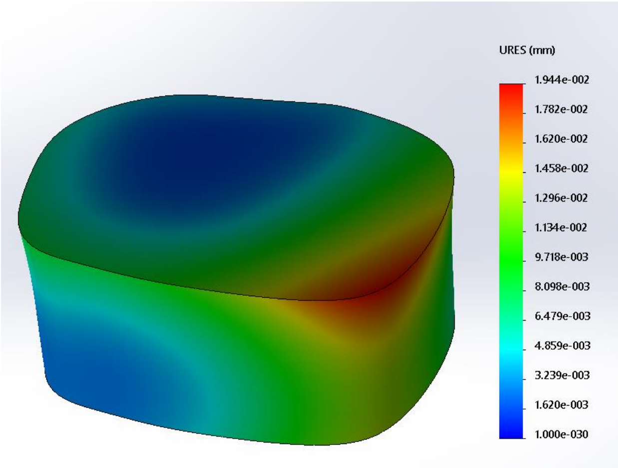

Figure 5. Displacement for static load

This static load case was defined for the purpose of the later fatigue simulation involving repeated cycle (from 0 to maximum value). In SolidWorks Simulation it is called zero-based.

Cycle cutoff value was set to 2 mln as this is the estimated value achieved after 4 years of usage [7].

Fatigue S-N curve was derived in SolidWorks Simulation from material's elastic modulus.

The most important result of fatigue analysis is always a plot showing the distribution of the number of cycles to failure for different parts of the model (Figure 6).

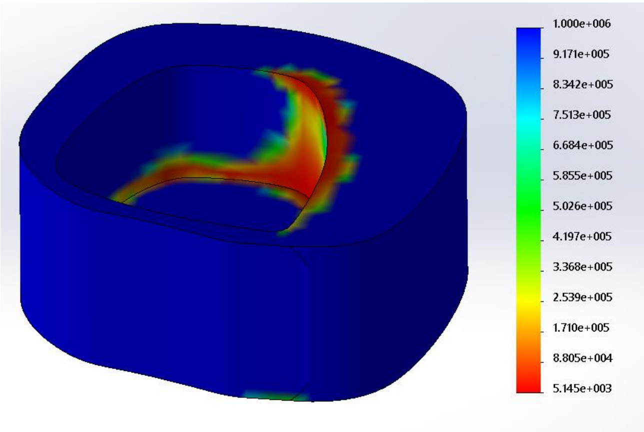

Figure 6. Cycles to failure plot

Acquired results suggest that the part the most susceptible to fatigue damage is the inner edge of the hole. Also, part of the outer edge can be damaged after a short amount of time. First signs of fatigue damage may occur after only 5150 cycles which is equal to a few days of intense usage. Most parts of the crown, however, should not be damaged even after a large number of cycles.

Results from the modal analysis are in form of 5 natural frequencies found for the system and their corresponding mode shapes. Constraint (fixture) was applied on the same surfaces as in previous simulations. Values of these frequencies are as follows: 41068 Hz, 48224 Hz, 55486 Hz, 73370 Hz and 78352 Hz.

They can lead to the destruction of the polymer crown caused by resonance phenomenon.

Mode shapes for these frequencies are shown in the following plots (Figure 7-11).

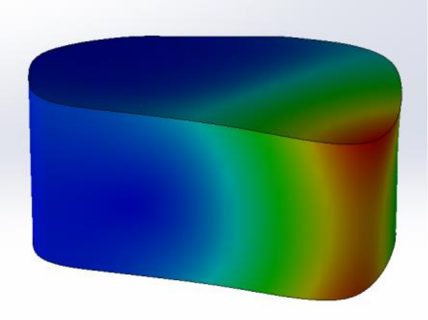

Figure 7. Mode shape for 41068 Hz

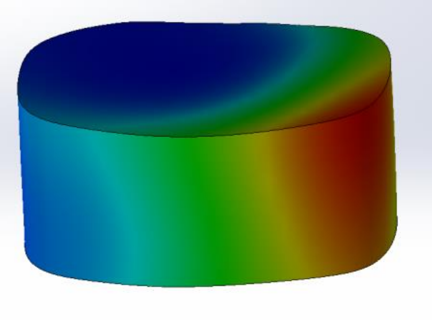

Figure 8. Mode shape for 48224 Hz

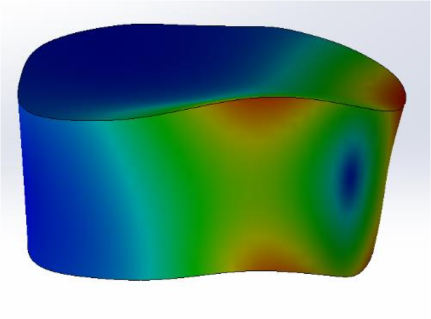

Figure 9. Mode shape for 55486 Hz

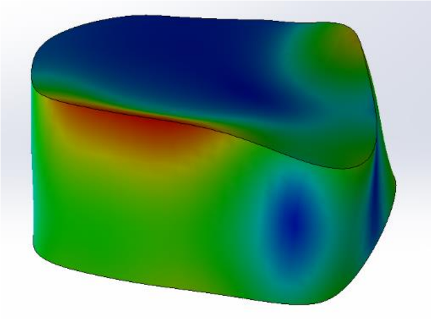

Figure 10. Mode shape for 73370 Hz

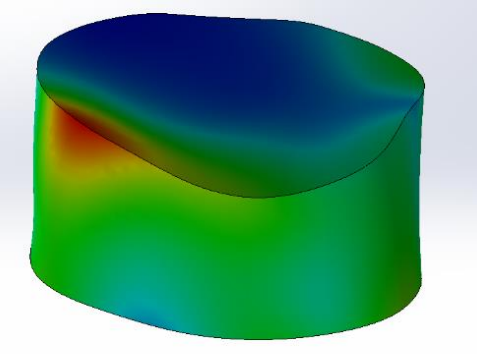

Figure 11. Mode shape for 78352 Hz

3. Conclusions

Results obtained from the simulation show that some specific parts of polymer dental crowns may be particularly vulnerable to fatigue when subjected to load cycle involving chewing forces. The predicted durability of such crowns under constant chewing is about few days.

These results confirm that acrylic dental crowns should be used only as temporary replacements. The risk of failure is too high to adapt this prosthesis for longer time periods.

Modal analysis showed which vibration frequencies can be dangerous for polymer crown and thus should be avoided when using dental tools. Frequency response analysis for the range of these frequencies and applied load could give an idea of how such a tool will affect the crown.

However, it has to be borne in mind that these results are only an approximation and there are multiple factors not included in the simulation. First of all, the 3D model used for analyses had to be prepared in CAD software instead of using scanning result directly.

This is caused by problems with surface subdivision when importing scanned models to CAD software using STL file type. SolidWorks has special add-on ScanTo3D available but in this case, resulting in surface models were not appropriate for the purpose of analysis. For these reasons, occlusal surfaces of the dental crown were omitted.

Another source of errors is the fact that contact with tissues was not included. Such contact generates differences in stress distribution but is very hard to model.

Lastly, finite element method provides only approximate results for solved problems and mesh density affects the precision of calculations.

Results obtained in this article are the basic information for estimation of dental crown endurance. They are very important for patients who need to have temporary teeth replacements. The use of computer-aided methods in the design of dental prosthesis process can significantly improve their quality. In the near future, numerical simulations may join modern design methods used already used in stomatology.

Acknowledgments

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