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MEASUREMENT OF THE FATIGUE LIFE OF MINI DENTAL IMPLANTS: A PILOT STUDY

Dennis Flanagan, DDS; Horea Ilies, PhD; Paul McCullough; Scott McQuoid

The fatigue life of mini or small-diameter dental implants is of particular interest because these implants are used to retain and support fixed and removable dental prostheses. The fatigue life of an implant depends on both the implant itself as well as on the physical properties of the bone. However, the capability to predict the fatigue life of a newly placed implant is currently inexistent. This pilot study represents the first step in developing such a methodology and focuses on the design of a cost-effective device to measure the fatigue life of a dental implant. In our measurements, the implant has been mounted in an essentially rigid support, but test specimens can also be bone mounted in vitro. Furthermore, we developed a finite element-based computer model capable of predicting the corresponding fatigue life. The finite element analysis was performed in ABAQUS, and the results predicted by the model correlated fairly well with our initial experimental results. Most of the 2-mm diameter implants fractured after more than a million cycles.

Key Words: cyclic loading, very small diameter implants, dental prosthetics

INTRODUCTION

Very small diameter or mini dental implants have been used to support fixed and removable prostheses. The fatigue life expectancy of these implants is of particular interest because of their popular use by dentists to retain and/or support fixed and removable dental prostheses.¹⁻⁵ Most dental implant sites have a paucity of presenting bone volume. An atrophic edentulous ridge may be too narrow to place a standard-diameter (3.75–4.1 mm) implant. Some clinicians have reported successful treatment with 2.0-mm diameter implants supporting fixed prostheses in atrophic or compromised osseous sites. Proprietary data of implant manufacturers suggest that there may be sufficient durability and resistance to cyclic loading forces at 200 N for these very small diameter implants to be used to support fixed dental prostheses (Figure 1) (MDL, Intra-Lock,

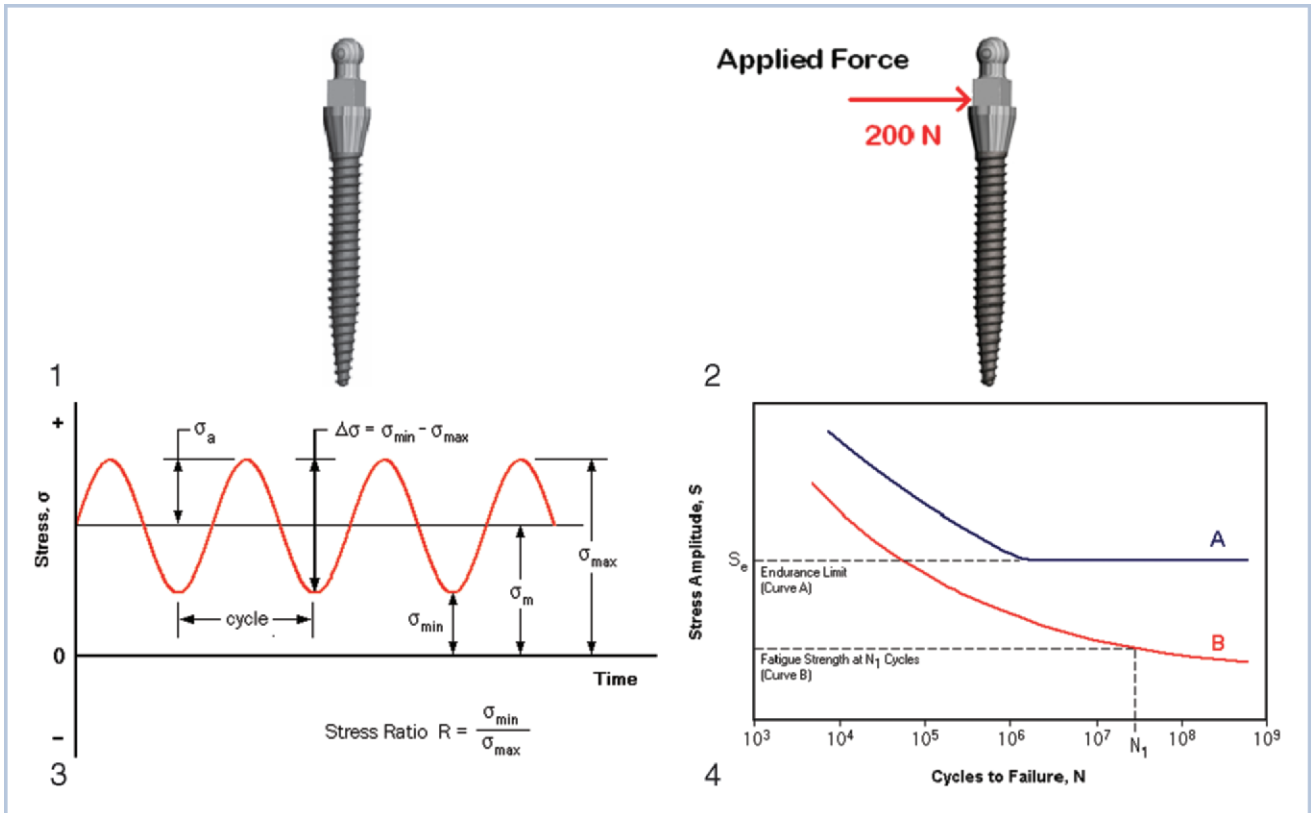
Boca Raton, Fla). Proprietary research has used bidirectional cyclic loads to test for metal fatigue of the implants embedded in acrylic resin (GC Pattern Resin, GC America, Alsip, Ill); however, there has been no extramural cyclic load testing of these implants (data from Intra-Lock).

Knowledge of the fatigue life of an implant may prove to be an important therapeutic parameter. To accurately and confidently predict how long one of these very small diameter implants will function properly, fatigue tests are needed to find the fatigue life of the implant. With the information on how many cycles the implant functions until failure, the life expectancy of the implant can be predicted more accurately, which is important for prosthetic longevity.

The fatigue life of an implant depends on both the implant itself as well as on the physical properties of the bone. However, the capability to predict the fatigue life of a newly placed implant does not currently exist. In this study, we take the first steps toward developing such a capability by creating a cost-effective device that can accurately measure the fatigue life of a dental implant and a computer model whose predictions correlate well with our measurements. The purpose of this study was to test 2.0-mm

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FIGURES 1-4. FIGURE 1. A 2-mm (Mini-Drive Lock, Intra-Lock, Ardmore, Okla) dental implant. FIGURE 2. The cyclic loading force was applied in a perpendicular direction to the axis of the implant where the crown ferrule would be located. FIGURE 3. The graph depicts the cyclic loading that was applied. FIGURE 4. The graph depicts the endurance and fatigue of the implant.

diameter, 1-piece dental implants for 200 N unidirectional cyclic loads while embedded in a rigid base and to find an appropriate mode of testing for future research. We have also developed a finite element-based computer model capable of predicting the corresponding fatigue life. The finite element analysis was performed in ABAQUS (SIMULIA, Warwick, RI) and the results, as predicted by the model, correlated fairly well with experimental results. Consequently, such a computer model can be used to predict the fatigue life of other implants without requiring additional physical testing.

MATERIALS AND METHODS

The implant analyzed in this project is a 2.0-mm diameter Mini-Drive Lock (MDL) implant (Intra-Lock) (Figure 1). Determining the fatigue life of this implant was the focus of this experiment.

Testing consisted of 9 cyclic fatigue tests on 9 titanium alloy implants (Ti-6Al-4V) (Table 1). Even though such a small test sample is not statistically significant, the results can be used to understand and

to plan more efficient and more significant further testing.

To test these implants, a loading device and a data acquisition system were designed. The loading device imparted a cyclic load onto the titanium implant until the titanium implant failed (Figures 2 through 5). The device was designed to generate a force in the range of 200 to 300 N on the implant, the average force in the anterior section of the human jaw. The load cycle was delivered at a rate of 6 cycles per second. The stress cycle is not a reversed cycle, so the force applied was only in one direction. LabVIEW (National Instruments, Austin, Tex) was used to acquire all the necessary data. A load cell was used to record the force data and the cycle data.

RESULTS

The fatigue testing machine was built and calibrated. Six titanium implants were tested until failure (Figure 6). The implant on the far right is discolored, perhaps because of thermal damage from autoclaving. Thermal metallic changes may have caused the implant to fail

TABLE 1

Material property values that were used for the TI-6AL-4V dental implants

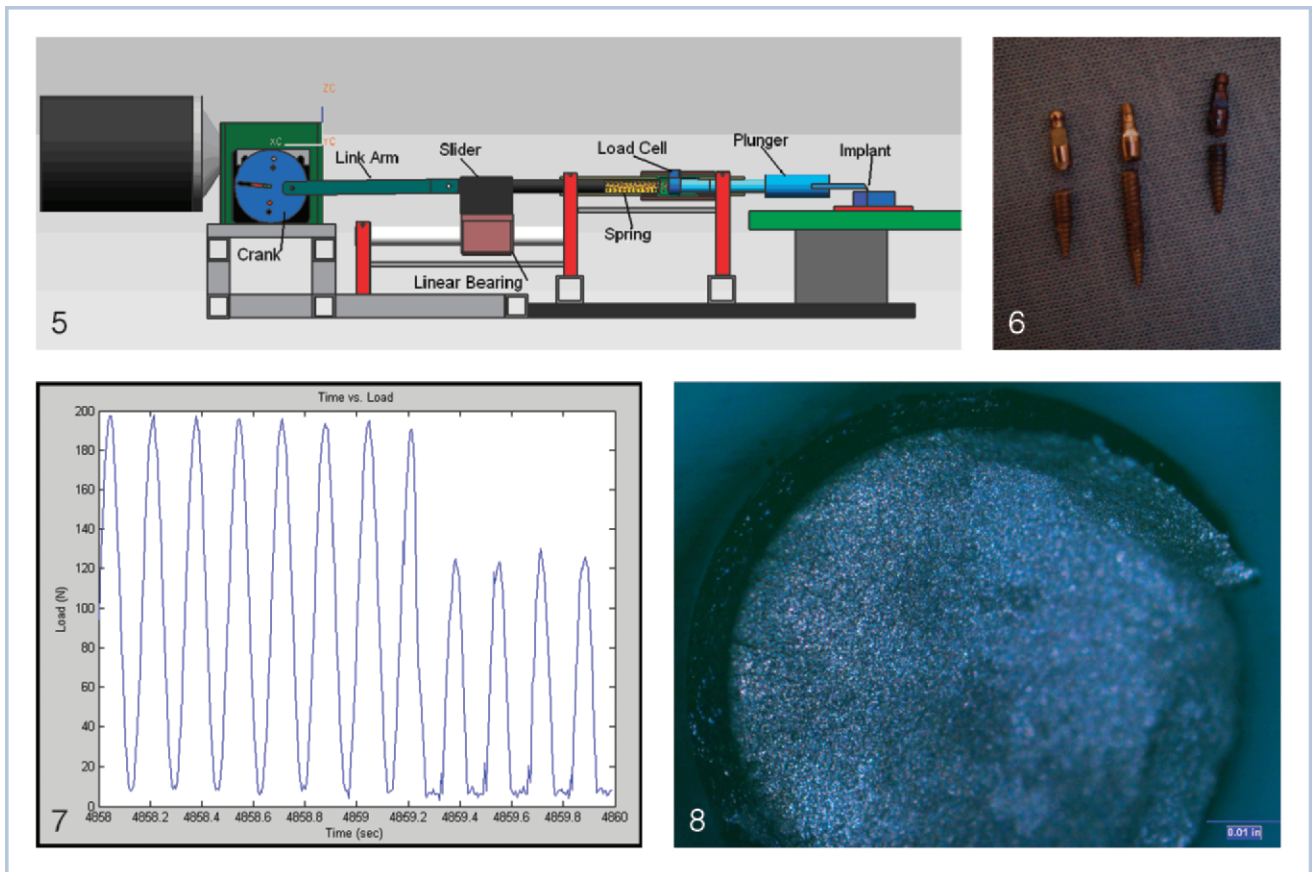
σ_o	= 8.05e8 Pa
σ_u	= 8.45e8 Pa
σ_f'	= 1.293e9 Pa
b	= -.088
ϵ_f'	= .841
c	= -.749
E	= 117e9 PA

far sooner than implants that were not autoclaved. Note that all failures occurred at the junction of the implant collar and screw threads as predicted by the computer simulation. This correlates well with the prediction of the finite element model.

A graph of the data collected from the load cell was made (Figure 7). The load average remains constant until the implant failed catastrophically. Once this happens the load range decreases significantly. At

this point the computer outputs a signal to the relay network to shut off the motor. The number of cycles until failure is tabulated in Table 2.

As evident from the data, the implants failed at a wide variety of cycles. The 2 implants that failed the earliest, implants 3 and 4, were visibly changed from autoclaving. These implants were a purplish color, indicating that heat and pressure may have weakened them, which probably caused earlier failures. All implants failed at the junction of the implant collar and at the beginning of the threads where the collet was holding the implant. The rigid retention may have contributed to the failure site and lowered the number of cycles to fail. Intra-Lock company data results gave a higher number of cycles to failure, but the testing conditions were different than ours. First, their implant specimens were retained in an acrylic base that may have allowed some movement of the implant or absorption or dissipation of some of the applied force



FIGURES 5-8. FIGURE 5. A schematic graphic of the design of the testing apparatus. FIGURE 6. All failures occurred at the junction of the implant collar and screw threads as predicted by the computer simulation. FIGURE 7. A graph of the data collected from the load cell was made showing the catastrophic failure. FIGURE 8. A macroscopic view of the implant 3 failure region. Note the flat surface and the absence of undulations indicating a catastrophic failure.

TABLE 2

Number of cycles until failure	
Implant	Cycles
1	240 264
2	1 855 000
3	11 250
4	16 000
5	1 389 462
6	127 920
7	954 438
8	83 574
9	121 650

into the acrylic base. Second, their testing setup applied a bidirectional cyclic force on the implant.

A macroscopic view of the failed region of the implant is shown (Figure 8). The entire surface of the failed cross section is typically referred to as a rapid fracture area.⁶ In fatigue testing, the fractured surface may exhibit a pattern of rings or undulations called beach marks, which indicate an advancement of a failing crack front. However, the implants tested do not exhibit this phenomenon, indicating a catastrophic, rapid failure due to the cyclic stress.

DISCUSSION

One study has shown that full-dentition adults can apply a maximum force on their teeth ranging from 244 to 1243 N, with an average of 720 N.⁷ This force vector applied to the tooth is in both the axial direction and the lateral direction. The force vector important to the current study is the predominant force in the fatiguing of the dental implant, that is, the lateral force. Lateral, off-axial forces, applied in a cyclic fashion from masticatory patterns and parafunction, may fatigue the implant, causing it to fracture. Studies have also shown that a young adult man applies a level-3 force (a force that is three fourths the magnitude of the subject’s maximum biting force), an average of 314 times. A young adult man will apply this level-3 force on his teeth an average of 325 times a day, including during sleep. This means that a young adult man will chew with a moderate amount of force an average of 325 times a day, mostly during meal times. These numbers for an adult woman were found to be 439 times during meal times and 453 times a day.⁸ Men apply greater maximum biting forces than women, meaning an implant should have a better chance of failing in a male patient.⁹ With knowledge of the magnitude of the applied forces and the numbers of chewing cycles a human applies each day, the

fatigue test may allow a prediction for the life of an implant or the number of years until failure.

Before testing, however, an understanding of fatigue and fracture mechanics is needed. Most engineering materials will fail sooner when the applied stresses are cyclic rather than static. This failure also tends to occur at a much lower stress level than the tensile strength of the material. This failure is attributable to fatiguing, a phenomena caused by cyclic loading.¹⁰ Cyclic loading is defined as a load that varies between a maximum stress, σ_{max} , and a minimum stress, σ_{min} . The amplitude of the stress, σ_a , is defined as half the difference between the maximum stress and minimum stress.

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{1}$$

Another property of the cyclic load that is important to the fatigue life of the sample is the mean stress, σ_m , where

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{2}$$

The cycling between constant maximum and minimum stress is called constant amplitude stressing. This stressing cycle will be applied to the implant to test the fatigue life of the sample. Figure 4 shows the cyclic stresses as a function of time. Here, the amplitude, minimum stress, maximum stress, and mean stresses are shown. In a fatigue analysis, the effect of cyclic loading is approached from several different directions. When the stress levels are significantly below the yield stress of the material, one uses the stress-based approach to fatigue. Using the definition given in Equations 1 and 2, an equivalent static stress can be approximated as follows:

$$\sigma_E = \sigma_a + K_f \sigma_r \frac{S_y}{S_e} \tag{3}$$

where K_f is the fatigue stress concentration factor, S_y is the yield strength of the material, and S_e is the modified value of the endurance limit. The value of K_f and S_e depend heavily on geometry, surface condition, and material variation.¹¹ The corrected endurance limit must account for these imperfections through the use of correction factors. For types of steels, the endurance limit is approximately half the ultimate strength of the material. The value of the equivalent stress allows for a static analysis of a cyclic problem.

The failure attributable to fatigue is attributable to the propagation of microscopic cracks in the material. The field of fracture mechanics analyzes the rate and

manner of crack propagation. When a material is initially subjected to fatigue loading, small cracks begin to form. As the fatiguing continues these cracks begin to get larger or propagate. The rate at which these cracks propagate has a direct influence on the fatigue life of the material. The faster the crack propagates, the sooner the part will fail. Unlike static loading failure, where small scratches or tool marks have little effect, cyclic loading failure is influenced greatly by these small imperfections.

Cracks initiate because of the imperfections and nonuniform characteristics of real materials. When these imperfect materials are stressed in the elastic range, small, irreversible changes and dislocation movement occur. These changes are too small to be detected. However, when many cycles of this stress occur, these changes become noticeable and harmful to the material.¹³ These irreversible changes eventually lead to the initiation of a small crack. Once a crack is formed, it initially propagates very slowly along crystallographic planes of high stress and subsequently fails.^{6,13,14}

CONCLUSIONS

The fatigue-testing machine was designed and built to apply a cyclic horizontal force to measure the number of cycles to failure of dental implants. It can apply a cyclic load from 0 to 200 N at a rate of 6 Hz and can be used to measure the fatigue life of a variety of dental implants. A finite element analysis analysis was performed on the implant geometry to numerically predict the fatigue life. The Goodman method of S-N curves closely approximated the average life expectancy of the experimental data.

Although we did not test a statistically significant number of samples, the 9 failed implants show the typical range of fatigue life values that can be obtained even for implants having identical nominal geometry. The fatigue life of the tested implants varied significantly, as expected. The maximum fatigue life exceeded 1.6 million cycles, and the minimum fatigue life (of possibly heat-damaged implants) just passed 10 000 cycles. Thermal damage and pre-stressed implants can account for some, but not all, of the low fatigue life of some of the tested implants. Broadly speaking, a number of other factors can contribute to such a variation, including material defects and internal stresses induced by the implant manufacturing process. Our results agree with the other fatigue life testing for mechanical systems in that this study indicated clearly indicated that more

implants should be tested to provide a statistically significant sample. Furthermore, additional testing and simulation of implants secured in natural or artificial bone, as well as rigid mounting, should be considered.

The predictions of our finite element-based model correlated fairly well to the experimental results obtained for the implants that had not been heat damaged, and they consistently predicted the location of the failure for the implants. This suggests that finite element models can be used as reasonable predictors of fatigue life for implants. This implies that finite element models can enhance our understanding of how different design variables of these implants influence their fatigue life.

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