

# Fatigue Testing of Laser Treated Endosseous Implants With an Internal Trilobe Connection

Robert W. Berg\*, Kenneth S. Kurtz†, Jason A. Griggs‡, Ikuya Watanabe§ and Paulo G. Coelho§

**Abstract** - This study investigated the effect of laser treatment on the fatigue resistance of a 3.5-mm diameter implant with an internal trilobe connection. Twenty two implants were embedded into acrylic resin blocks. Half the specimens were used as control group, and the other half were laser treated circumferentially around the 1.5-mm polished collar with argon shielding. Implants were fatigue tested using a step-stress accelerated lifetime test in a servo-hydraulic test machine. Despite the trend pointing towards higher fatigue resistance of laser treated specimens versus controls, step-stress analysis did not determine significant differences in the fatigue lifetimes.

KEY WORDS: Dental implant, mechanical testing, fatigue, internal connection

## INTRODUCTION

Minimal independent *in vitro* information is currently available with regard to fatigue failure of internal connection type endosseous implants and their associated prosthetic components. Most of the long-term clinical data on implant/abutment interfaces reported in the literature involve the external hexagon connection<sup>1-6</sup>. Biomechanical problems can be categorized into prosthetic component failure (screw failure) or implant failure (fatigue fracture or loss of integration) for either type of implant connection. Eckert and Wollan described late implant failure in the partially edentulous arch as a consequence of implant fracture more often than loss of integration<sup>7</sup>.

In an attempt to overcome some of the biomechanical limitations of the externally hexed implant/abutment connection, internal connections between implants and abutments were developed. Internal connections offer a reduced vertical height platform for restorative components, distribution of lateral forces within the implant body, and protection to the abutment screw<sup>3,8</sup>. The major disadvantage of internally connected systems is the decreased dimension of the lateral fixture wall. These thin lateral walls may become compromised with large lateral forces. It has been shown<sup>9</sup> that the internally hexed implant showed a larger absolute value of strain because of the thinner wall of the abutment connection area. Differences in implant size and implant material, screw material, and type of connection cause differences in stress distribution<sup>9,10</sup>. Thus, while different implant-abutment connection designs may render higher mechanical strength under single load to fracture, cyclic loading due to mastication may result in clinical failure due to connection loosening or part fracture<sup>11-13</sup>.

As the implant/abutment interface is subjected to *in vivo* masticatory loading<sup>14-18</sup>, fatigue testing may supply clinicians with information regarding relationships between fracture surfaces and loading conditions for a selected implant type, which would aid in the analysis of clinically failed implants. It also provides comparative information regarding the biomechanical performance and reliability of different implant-abutment systems. From a structural perspective, endosseous implants manufactured from commercially pure titanium (CP-Ti) have less favorable mechanical properties than implants manufactured from titanium alloys (mainly Ti-6Al-4V)<sup>19-21</sup>. Strengthening mechanisms for CP-Ti are of interest to clinicians as improvements in physical properties, including fatigue resistance, may be obtainable.

Laser peening is an innovative surface enhancement process used to increase the resistance of aircraft gas turbine engine compressor and fan blades to damage from foreign objects and to improve high cycle fatigue life<sup>22-25</sup>. This process creates residual compressive stresses deep into part surfaces, typically five to ten times deeper than conventional metal shot peening. These compressive surface stresses inhibit the initiation and propagation of fatigue cracks. Such laser treatment drives a high-amplitude shock wave into a material surface using a high energy pulsed laser<sup>26</sup>. The effect on the material being processed is achieved through the mechanical "cold working" effect produced by the shockwave, not a thermal effect from heating the surface by the laser beam. When laser peening is applied to titanium, it is expected that the titanium will have higher mechanical strength to withstand mastication loads<sup>27</sup>.

The purpose of this study was to evaluate the effect of laser peening a commercially pure titanium endosseous implant with an internal connection on the fatigue resistance of the implant/abutment system.

\* DMD

† DDS

‡ PhD

§ DDS, PhD

## MATERIALS AND METHODS

### Specimen Preparation

Twenty two 3.5 mm (D) X 13 mm(L) narrow platform, tapered, screw type, CP-Ti Type 4, machined, endosseous implants, with a TiUnite® surface, (Replace Select, Nobel Biocare, Yorba Linda, CA) were measured and placed into a lubricated, plastic ring and cap assembly (Acrylic pouring molds, Allied High Tech Products Inc., Rancho Dominguez, CA). Autopolymerizing acrylic resin (Palapress Vario, Heraeus Kulzer, Germany) was mixed according to the manufacturer's instructions and poured into the ring/cap assembly so that 3.0 mm of the implant was exposed above the acrylic resin to simulate the worst case clinical scenario for crestal bone loss in accordance with ISO:14801<sup>28</sup>. The specimens final position allowed the loads in fast fracture and step stress to be applied directly towards the centre of one of the connection's lobe (direction rationalized since as per the manufacturer's recommendation that one of the lobes should be directed towards the buccal flange).

Half the specimens (C group, n=11) were taken directly from the manufacturer's sterile packaging and embedded into the acrylic resin block (Figure 1a). Prior to embedding in acrylic resin, the other half of the specimens were laser treated in contact mode (LTI group, n=11) circumferentially around the 1.5 mm polished collar with argon shielding using a dental Nd:YAG laser welding machine (Neolaser L, Girrbach, Germany) with a 0.8-mm spot diameter, a 3.0-ms pulse duration, and an excitation voltage of 150 V. The collars were laser treated 32 times circumferentially and four times in height with an average 50% overlap of the previously treated area (Figure 1b and 1c).

Single tooth abutments, 10 mm in height (29476, Nobel Biocare, Yorba Linda, CA) were then inserted and torqued to 35 Ncm as per the manufacturer's specifications. All specimens were secured in a mounting jig designed to prevent deformation of the specimen. The specimens were clamped into the jig so that its axis made a 30° angle with the loading direction of the testing machine as per ISO:14801<sup>28</sup>. A hemispherical loading member (standard stainless steel round end screw) was placed into the free end of the implant abutment to maintain the desired loading centre on the axis of the implant. This screw was modified to prevent contact with the implant abutment screw.

### Single Load to Fracture

Single load to fracture testing was accomplished prior to fatigue testing to determine the step stress profiles load limit for fatigue testing. Two specimens from each group were utilized and the fracture load range recorded.

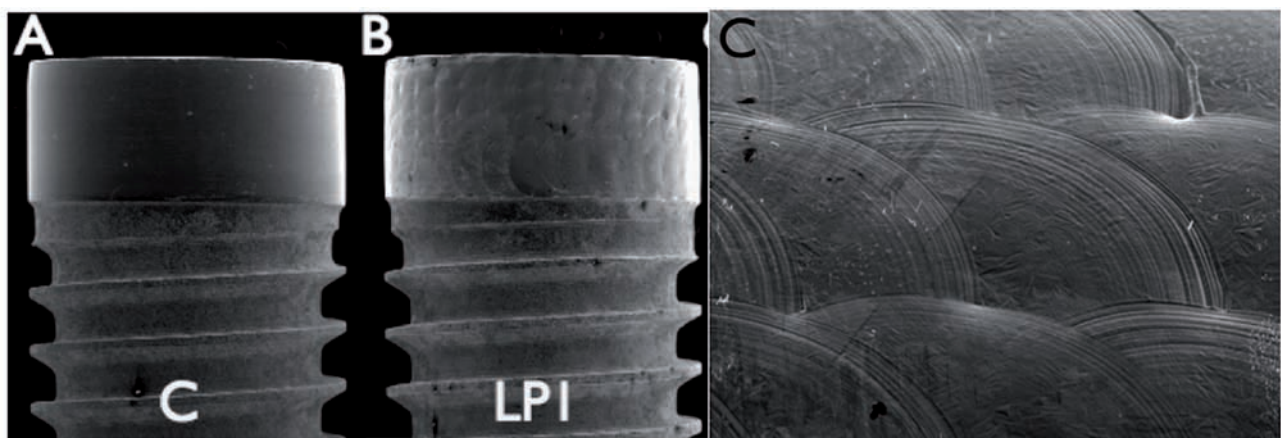
### Fatigue Testing

The implants were fatigue tested in 37°C deionized water using a servo-hydraulic test machine (Minibionix II, MTS Systems Corporation, Eden Prairie, MN) with a 2 Hz sine wave and 0.1 min/max load ratio. Two load-time profiles were used for specimens in the C and LTI groups<sup>29</sup>. The load amplitude started at 1.8 N and increased by 1.8 N every 30 or 60 cycles until fracture (n=5 and n=4, respectively, for each experimental group). This fatigue testing approach consists of testing the samples at stress levels higher than use stress in order to facilitate failures in a timely manner. The results of these tests were then analyzed so that a profile of the failure behaviour of the specimens at a use stresses can be determined based on the behaviour of the samples at the accelerated stresses<sup>29</sup>. Step-stress statistical analysis<sup>29</sup> (ALTA Pro 6, Reliasoft, Tucson AZ) with a use level probability Weibull (probability of failure vs. cycles) with an inverse power law load-life relation was used to estimate the lifetime under constant load amplitudes of 200N and 400N for C and LTI specimens. In addition, Kaplan-Meier analysis<sup>20</sup> (SigmaPlot 10, Systat Software, Richmond, CA) was used to construct cumulative failure probability models for C, and LTI specimens, and a log-rank test ( $\alpha=0.05$ ) was used to detect for significant differences between these models.

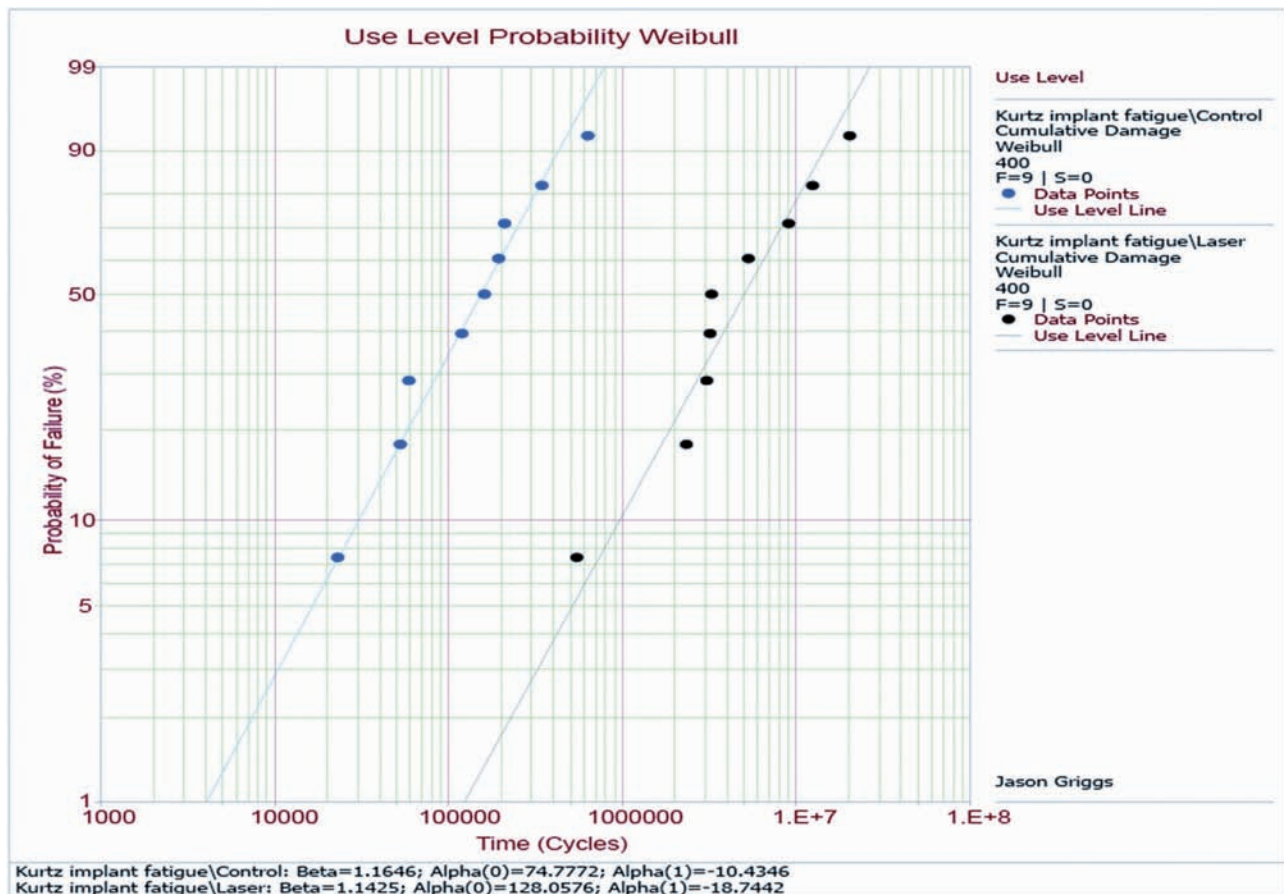
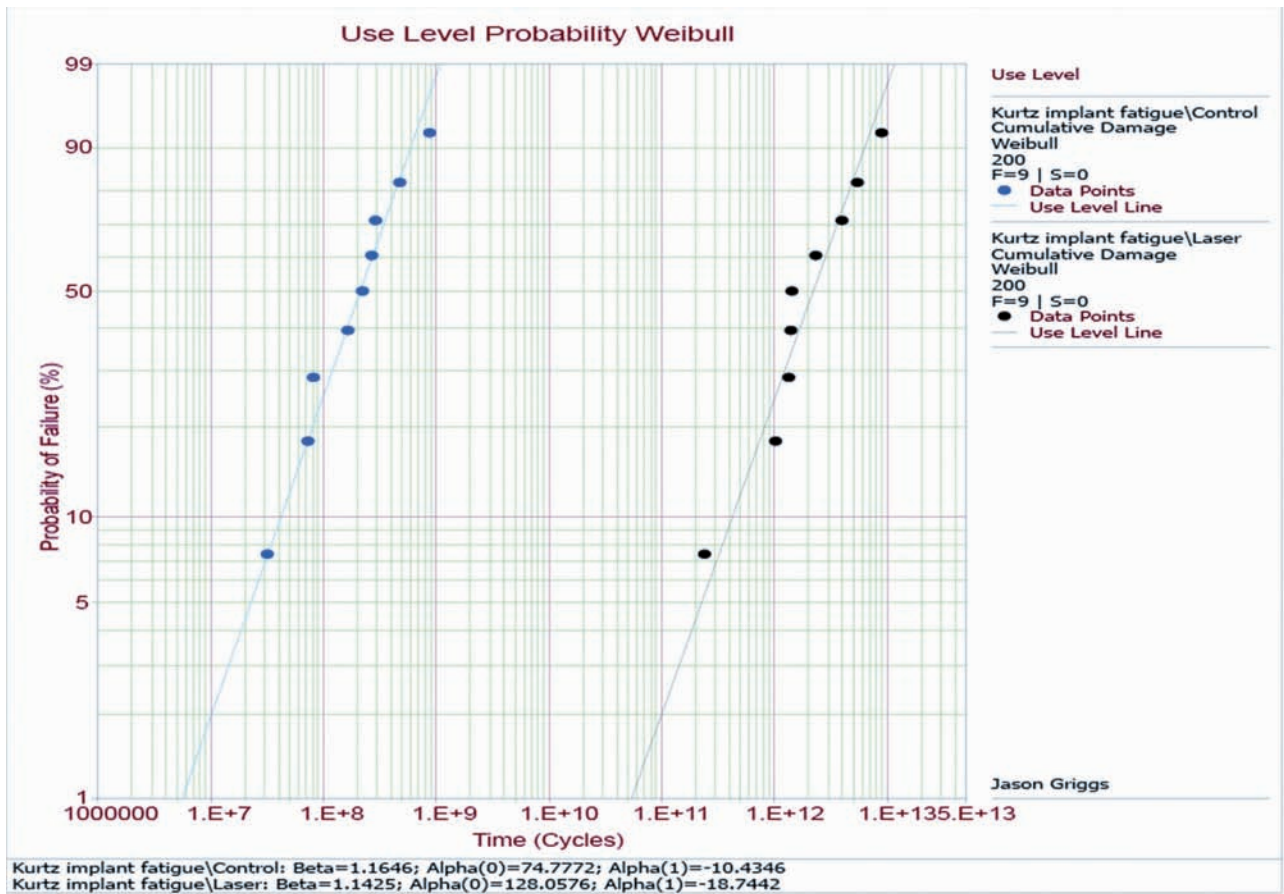
The fracture surfaces were observed using scanning electron microscopy (JSM-6300, JEOL, Tokyo, Japan).

**Table 1.** Single load to fracture values were acquired to determine the fatigue step-stress profiles.

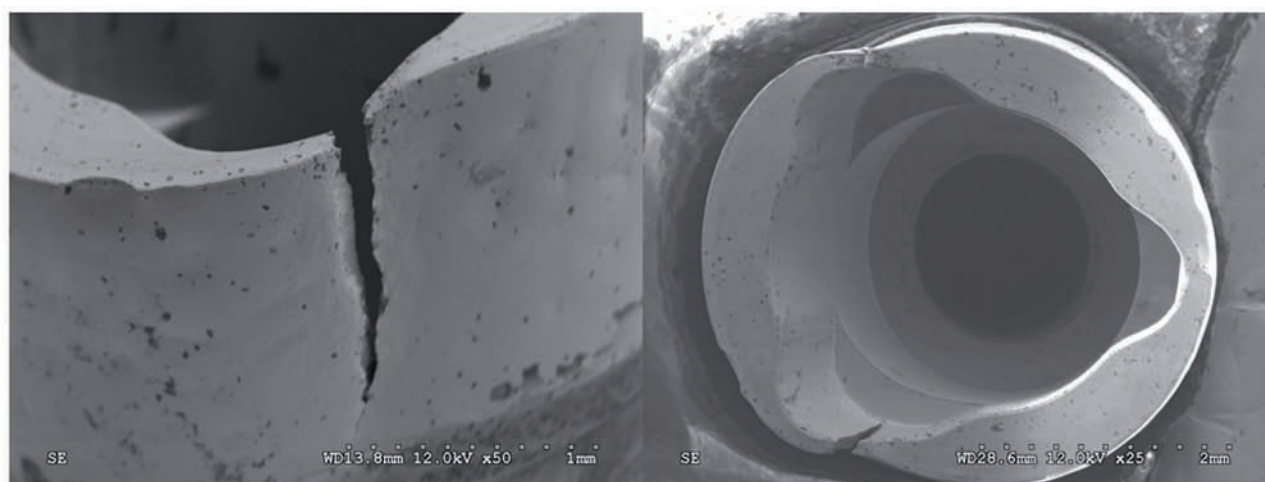
Specimen	Compressive Load at Break
C1	621.74
LT1	599.19
C2	586.44
LT2	577.61



**Figure 1.** Low magnification scanning electron micrographs of (a) Control (C) and (b) Laser Treated (LTI) implants (original mag 20X). A high magnification scanning electron micrograph (c) of the laser treated group (original mag 170X).



**Figure 2.** Step-stress analysis estimating the lifetimes under constant load amplitudes of (a) 200N and (b) 400N for C and LTI specimens. No significant differences were observed between groups at 200N and 400N ( $p > 0.05$ )



**Figure 3.** Irrespective of group tested, all fatigues specimens presented fractures at the trilobe connection region.

## RESULTS

Fast fracture results showed that failures occurred over a ~ 577N to 621N load range (Table 1).

The results of step-stress analysis estimating the lifetimes under constant load amplitudes of 200N and 400N for C and LTI specimens are presented in Figure 2. No significant differences were observed between groups at 200N and 400N ( $p > 0.05$ ) Beta values for the analysis for the C and LTI groups were 1.16 and 1.14, respectively, showing that damage accumulation influenced failures over cyclic loading. Note that the beta value (called the Weibull shape factor) describes failure rate changes over time (beta < 1: failure rate is decreasing over time, commonly associated with “early failures” or failures that occur due to egregious flaws; beta ~1: failure rate that does not vary over time, associated with failures of a random nature; beta > 1: failure rate is increasing over time, associated with failures related to damage accumulation). Laser treated specimens had longer estimated lifetime under both 200N and 400N loads, but this difference was not statistically significant ( $p > 0.05$ ). The Kaplan-Meier analysis showed that C and LTI specimens had similar cumulative failure probability. The log-rank test showed that these differences were not significant ( $p = 0.398$ ).

Failures obtained by step-stress fatigue originated from the thinnest portion of the internal connection in all specimens (Figure 3).

## DISCUSSION

In an attempt to overcome some of the biomechanical limitations of the externally hexed implant/abutment connection, internal connections between implants and abutments were developed. Internal connections offer potential advantages such as a reduced vertical height platform for restorative components, distribution of lateral forces within the implant body, protection to the abutment screw, long internal walls that resist joint opening, the potential for a microbial seal, extensive flexibility restoratively, and the ability to lower the restorative interface to the implant level aesthetically<sup>3</sup>.

In order to determine the step-stress profiles<sup>29</sup> utilized in the present study, the fast fracture value range was obtained by loading the implants towards one of the internal connection lobes. The manufacturer recommends aligning one of the connection’s lobes to the direct facial for prosthetic ease. Fast fracture testing showed that such alignment resulted in failures along the thinnest portion of the implant platform at load values mainly below 600N. When the fast fracture failure values are compared to normal function load values observed at anterior and bicuspid regions<sup>16</sup> where implants of the tested diameter are most commonly utilized, the results obtained are indicative that single load catastrophic failures of such connection are unlikely in clinical scenarios<sup>16</sup>.

The step-stress is a method utilized for accelerated fatigue testing. This method has been widely utilized in military and in the aircraft industry for determining reliability of materials, components and assemblies and it has been applied recently to the testing of implant materials<sup>31</sup>. The fatigue testing was conducted following two step-stress (load) profiles until failure was observed<sup>29</sup>. The method allows the prediction with confidence intervals (based on calculation of a master Weibull distribution) of the life expectancy of a given material as a function of a specified load.

The rationale for utilizing different load-time profiles is based on the need to accelerate and distribute failures across a wider time interval allowing more precise estimation, narrowing the confidence bounds. The mathematical approach has been previously covered in textbooks<sup>11</sup>, and computer programs are available for life expectancy calculations (Alta Pro, Reliasoft, Tuscan, AZ). One of the attractive features of step-stress accelerated fatigue testing is the decreased number of specimens necessary before fatigue endurance trends can be observed compared to conventional fatigue testing<sup>11</sup>.

The calculated fatigue endurance under loads of 200N and 400N generally showed that laser peening (LTI) the implant surface resulted in a positive trend in fatigue resistance compared to control implants, even though no significant differences were observed. This result indicates that the surface treatment applied likely resulted in higher ability to withstand crack propagation compared to the untreated

surface condition, as previously reported in other structural applications<sup>11</sup>.

While a positive trend in fatigue resistance was observed for the LTI specimens compared to the control group, all samples failed in a similar manner. Samples from all groups failed in the thinnest wall of the connection where stress concentration was likely highest given the internal connection geometry and loading condition.

## CONCLUSIONS

The findings obtained in this preliminary investigation suggest that surface treatments should be considered as an alternative or adjunct strategy for strengthening thin-walled areas subject to cyclic loading, along with proper materials selection and improvement of implant-abutment connection geometry. Despite the trend pointing towards higher fatigue resistance of laser treated specimens versus control, step-stress analysis did not determine significant differences in the fatigue lifetimes of dental implants.

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## ADDRESS FOR CORRESPONDENCE

Dr. Kenneth S. Kurtz, Director-Prosthodontic Research, Graduate Prosthodontics, Department of Dentistry, Montefiore Medical Center/Albert Einstein College of Medicine Bronx NY USA. E-mail: ksk4@nyu.edu

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