Effect of Dental Implant Diameter on Fatigue Performance. Part II: Failure Analysis

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ABSTRACT

Purpose: The purpose of this study was to perform fracture mode analysis for in vitro failed implants in order to evaluate the relation between the fracture mode obtained and the implants' fatigue behavior.

Materials and Methods: Eighty fractured dental implants were analyzed after being tested for fatigue performance. A macroscopic failure analysis was performed, which evaluated and located the fracture modes obtained, followed by a microscopic failure analysis comprising a detailed scanning electron microscopy (SEM) fractographic analysis.

Results: Four distinctive fracture loci were identified and macrofracture mode analysis was performed, showing that all 5-mm implants that fractured were fractured at the abutment neck and screw. In the 3.75-mm group, 44.4% were fractured at the implant neck and 55.5% at the implants second thread. Fifty-two percent of the 3.3-mm fractured implants had it at the implants second tread and 48% at the implants third thread. The implant's metallographic sections revealed that the different fracture loci were located where thin metal cross sections and sharp notches coexist. Using SEM, we were able to characterize the failure micromechanisms and fatigue characterization as transgranular fracture and arrays of secondary parallel microcracks at relatively low magnifications and classic fatigue striations at much higher magnifications.

Conclusions: The results of this study indicate that proper implant design is crucial to ensure long-term fatigue performance for dental implants. The combination of sharp notches (thread) and narrow metal cross section is quite deleterious for fatigue resistance.

KEY WORDS: implant design, scanning electron microscopy, stress concentration, striation

INTRODUCTION

Fracture of dental implants, abutment, and screws is potential mechanical complication that poses an important and difficult challenge.

In a systematic review on survival and complications of rehabilitation of dental implants after a follow-up time of at least 5 years, it was concluded that fracture of abutments and screws occurred in 1.5% of abutments after a follow-up time of 5 years and in 2.5% after 10 years. Fracture of implants showed a cumulative incidence of 0.4% after a follow-up time of 5 years and 1.8% after 10 years.[1]

In a retrospective follow-up study of one hundred sixteen dental implants placed in the maxilla of periodontal patients, 3.4% implant fractures were observed after 3 to 6.5 years of functional load, and the authors concluded that overloading and bruxism seem more hazardous for implant treatment, as compared with the history of periodontitis.[2]

In a recent review, describing the probable causes of implant fracture, it was concluded that the pathogenesis of implant fracture is metal fatigue, influenced by the implant diameter, prosthetic structure design, occlusal force magnitude, and bone resorption, which creates large mechanical forces on the implant structure.[3]

Several studies examined the fracture surfaces of dental implants fractured in vivo using a scanning electron microscopy (SEM). These studies showed the classic fatigue marking (striation) on the implants' fracture surfaces, which indicates metal fatigue as a probable cause of the implants fractured intraorally.[4–6]

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The influence of implant diameter on the stress distribution was studied in numerical (finite element) models in several studies.[7,8] These reports showed a large effect of the load angle on the stress distribution in the implant. Nagasawa and colleagues[8] showed that the use of narrow (<3.3 mm) implants increased the magnitude of the stress applied to the abutment head. The latter was found to be concentrated around the implant neck. However, the finite element model did not include the various threads present in a typical implant and instead assumed perfectly bounded surfaces. Therefore, any potential stress concentration related to threads was overlooked, thereby limiting the generality of the results and conclusions to a certain class of implant design where threads are nonexistent.

The fatigue performance of three different diameter implant structures (5, 3.75, and 3.3 mm) was recently evaluated in a mechanical research that showed that the 5- and 3.75-mm implants exhibit a classic comparable fatigue behavior, while the 3.3-mm implant did not exhibit a typical fatigue behavior at all. The research emphasized the significant effect of implant diameter on fatigue performance.[9]

From the above literature, it appears that implant fracture by fatigue is a probable cause for dental implant mechanical failure. Most studies failed to show the clear relation between the mechanical reasons for failure and the resulting fracture mode arise from it. The goal of the present study was to perform a detailed macrofailure analysis of dental implants that were fractured in vitro by cyclic loading. Additionally, a detailed microfailure analysis with a fractographic characterization was performed using SEM.

MATERIALS AND METHODS

To perform this experiment, conical 13-mm dental implants made of titanium alloy (Ti6Al4V) were connected to a standard straight 8-mm abutment using 7-mm-long screw. Three implants diameters were tested for their fatigue performance: 3.3, 3.75, and 5 mm at implant neck. The fatigue testing was performed under load control as previously described.[9] Selected loads were applied as a sinusoidal load to the implant abutment at an angle of 30° off-axis inducing a bending moment. The test machine stopped operating when the implant structure collapsed (fracture) or when it reached 5×10^6 cycles without apparent failure. The experimental setup includes rigid clamping of the specimen to its base. This boundary condition is more severe than the more flexible condition experienced by an implant in vivo. Yet, the rigid clamping condition used in the experiments does not affect the results and conclusions drawn in the sequel, while it allows for application of larger load levels.

A total number of one hundred twelve specimens were tested. Eighty implants were fractured and collected.

A macrofracture mode analysis was performed for the 80 implants in order to identify the distribution of the different fracture modes obtained for the three different implant diameters during the fatigue test. For the 5-mm implant diameter group, 16 fractured implants were examined. For the 3.75-mm implant diameter group, 18 fractured implants were examined. While for the 3.3-mm implant diameter group, 46 fractured implants were examined.

For microfracture analysis, the fracture surfaces of failed dental implants were examined using SEM (Phillips XL 30, Eindhoven, the Netherlands). Prior to insertion to the SEM, the fracture surfaces were coated with a thin gold foil using sputtering in order to increase the specimen electrical conductivity when using the SEM.

RESULTS

Four distinct fracture modes were identified, as shown in Figure 1:

1. Abutment neck and screw;
2. Implant body–neck. The specimen was broken at the implant neck;
3. Implant body–thread 2. The specimen was broken at the implant second tread;
4. Implant body–thread 3. The specimen was broken at the implant third tread.

The total distribution of the four fracture modes to the three different implant diameters is summarized in Table 1. For the 5-mm implant, 100% of the fractured implants were fractured at the abutment neck and screw. For the 3.75-mm implant, 55.5% were fractured at the implants second thread, which is the dominant fracture mode, and 44.4% of the fractured implants were fractured at the neck of the implant. For the 3.3-mm implant, 52% of the fractured implants were fractured at the implants second tread and 48% were fracture at the implants third thread.

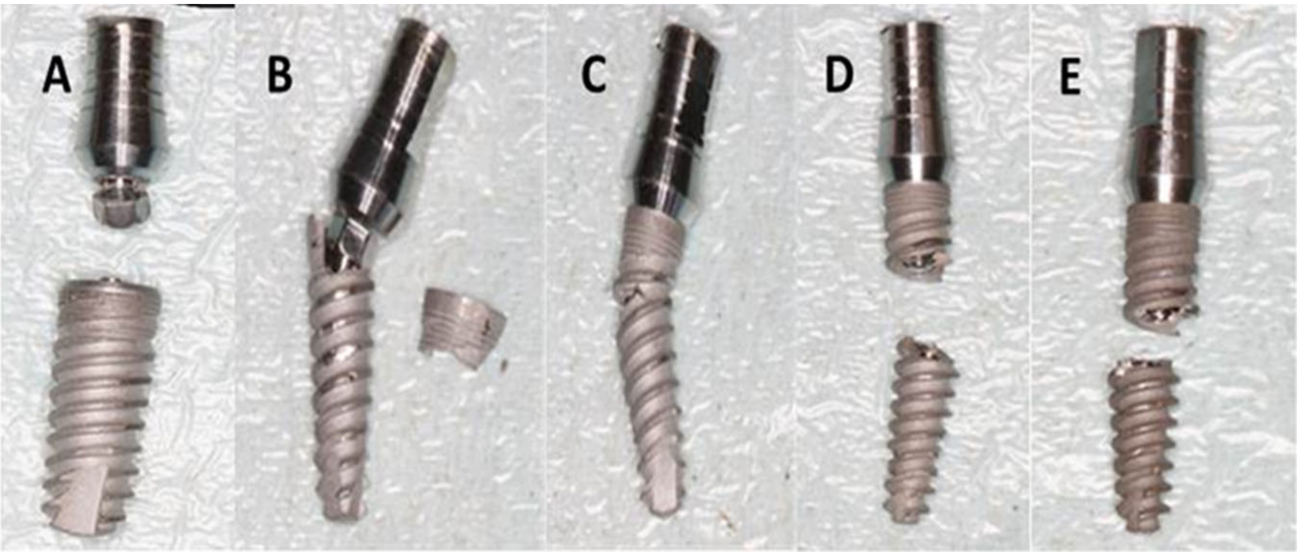

Figure 1 The four modes of fracture. A: 5-mm specimen broken on the screw and abutment neck. B: 3.75-mm specimen broken on the implant neck. C: 3.75-mm specimen broken on the implant second thread. D: 3.3-mm specimen broken on the implant second tread. E: 3.3-mm specimen broken on the implant third tread.

The next step was to examine the percentage of each individual fracture mode per implant diameter, in relation to the probability of fracture obtained from the fatigue test. The probability of fracture indicates the percentage of implant that fractured relative to the total number of implants tested at the same load magnitude. That is, probability of fracture (20%) means that from all implants tested at the same load magnitude, 20% fractured and 80% reached 5×10^6 cycles on the machine without apparent failure.

Figure 2 describes each implants' group behavior. For the 5-mm implants, a single fracture mode, abutment neck and screw, was observed throughout the whole range of probability of fracture. For the 3.75-mm implants, when the probability of fracture is 100%, the dominant failure mode is the implant body–thread 2 identified in 70% of the implants that belong to the same probability of fracture. As the probability of fracture decreases, the implant body–thread 2 tends to decrease, being gradually replaced by failure in the implant body–neck, being 100% when the probability of fracture is 16.7%.

For the 3.3-mm implant group behavior, it can be seen that irrespective of the probability of fracture from 40 to 100%, the two fracture modes, implant body–thread 2 and implant body–thread 3, are equally distributed around 50%.

TABLE 1 The Distribution of Fracture Modes per Implant Diameter

	Implant Diameter		
Fracture Mode	3.3 mm	3.75 mm	5 mm
Abutment neck and screw	–	–	100%
Implant body–neck	–	44.5%	–
Implant body–thread 2	52%	55.5%	–
Implant body–thread 3	48%	–	–

Metallographic Sections

Longitudinal metallographic sections from an unbroken sample were prepared in order to identify the different fracture loci along the implant design longitudinal axis (Figure 3). The 5-mm implant metallographic section (see Figure 3A) reveals the location of the fracture mode "abutment neck and screw," which was the only one identified in this test group. The width of metal cross section in this area is approximately 0.5 mm, which is quite narrow; therefore, the combination of thin metal cross section and sharp notch is probably responsible to this failure mode.

The 3.75-mm implant metallographic section (see Figure 3B) reveals the location of the two fracture modes. The "implant body–neck" fracture mode is located on the implant neck where the width of metal in this area is approximately 0.6 mm. The fracture mode "implant body–thread 2" is located opposite the place where the inner thread creates a sharp notch that

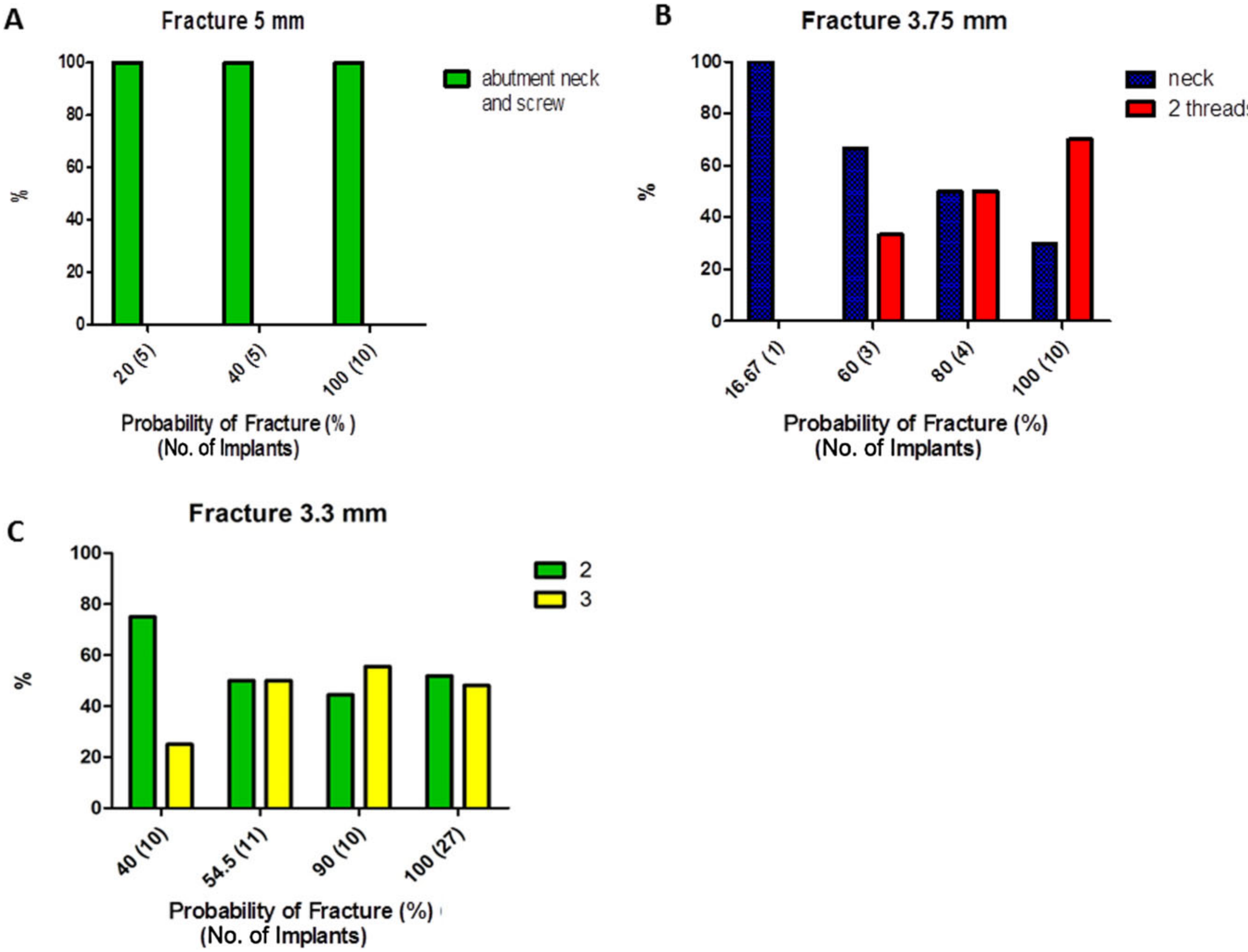

Figure 2 Fracture mode analysis. A: Fracture mode analysis for 5 mm–diameter implant specimen. One failure mode is operative, namely, abutment neck and screw. B: Fracture mode analysis for 3.75-mm specimen. Notice the distribution of the two different modes of fracture found in the 3.75-mm specimens as a function of the probability of fracture. C: Fracture mode analysis for 3.3-mm specimen. This graph shows the distribution of the two different modes of fracture found in the 3.3-mm specimens as a function of the probability of fracture.

increases the local stress level. The width of metal in this area is approximately 0.7 mm. It can be seen that for this implant diameter, the combination of thin metal cross section and sharp notch is probably responsible to the failure mode as well.

The 3.3-mm implant metallographic section reveals the location of the two fracture modes adjacent to the location of the implant internal threads, designed as sharp notches. The width of metal in this area is approximately between 0.5 and 0.7 mm. It can be seen that the internal thread (connecting the abutment) increases the local stress level, thereby leading to the two observed fracture modes.

SEM

Representative macro- and microfractographs are shown in Figures 4–7. The macroscopic appearance of failed specimens shows two different regions. Upon magnification between 1 and 5k, arrays of parallel secondary cracks are visible, which are parallel to the macroscopic propagation direction of the crack front. It is only at relatively high magnifications, between 10 and 20k, which one can discern faint striations, whose observation is not straightforward.

DISCUSSION

In our previous study, we have reported that 5- and 3.75-mm implants showed a classic comparable fatigue behavior, while the 3.3-mm implant did not exhibit a typical fatigue behavior. It was proposed that the nontypical fatigue behavior observed for the 3.3-mm implant diameter is probably the result of stress concentrations generated along the structure's surface.[9]

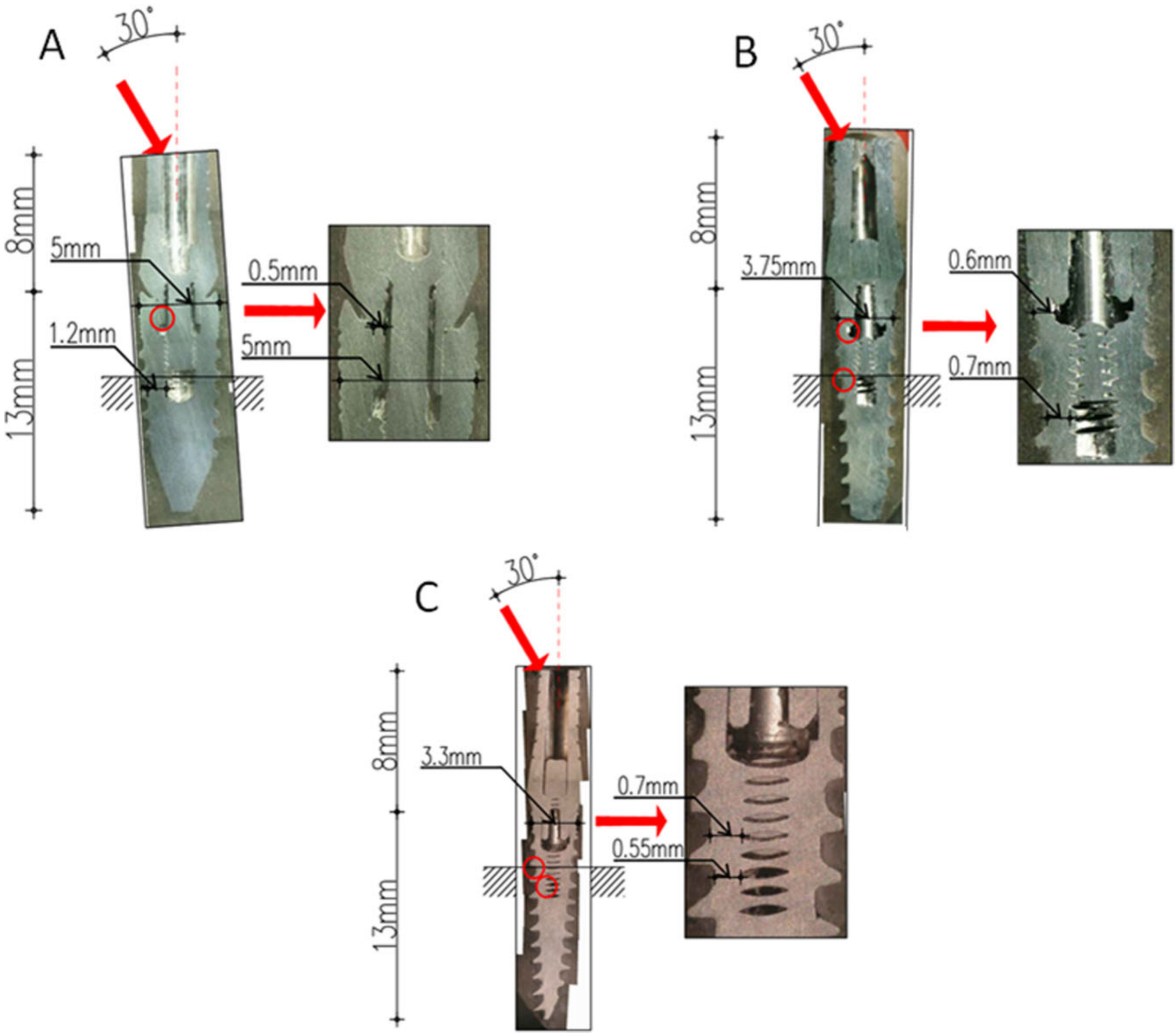

Figure 3 Metallographic section of the three-implant diameter testing group. A: 5-mm implant. B: 3.75-mm implant. C: 3.3-mm implant. The length and width of the implant and abutment are indicated. The upper red arrow indicates testing force applied to the implant abutment and the force direction at an angle of 30° off-axis. The red circles indicate the different fracture modes found at each implant diameter. The magnified picture shows the fracture location and the corresponding metal width at the fracture location.

The various failure loci observed in this work all relate, as expected in fatigue failures, to some sort of *stress concentration*. The latter is caused by geometrical (design) effects. Here, stress concentration stems from the combined influence of the inner thread roots that are rather sharp, and the fact that the metal cross section that is supposed to sustain the loads in this region is of limited thickness, a point that becomes particularly evident in the narrow implants (3.3 mm). This effect was evidenced in those implants in which two failure loci (modes) were clearly identified, both with a similar frequency of occurrence. The fact that the two failure modes appeared with a similar frequency might point to the fact that they are related to equally potent stress concentrations in the implant, while the exact determination of the one to fail first is statistical.

The present test shows the negative effect of the internal hex connection design on narrow diameter implants, as the inner thread creates deep notches into the thin metal cross section (see Figure 3C) and thus creates undesired high stress concentration that might lead to early fracture.

The effect of the difference in implant-abutment connection design on mechanical stability was evaluated

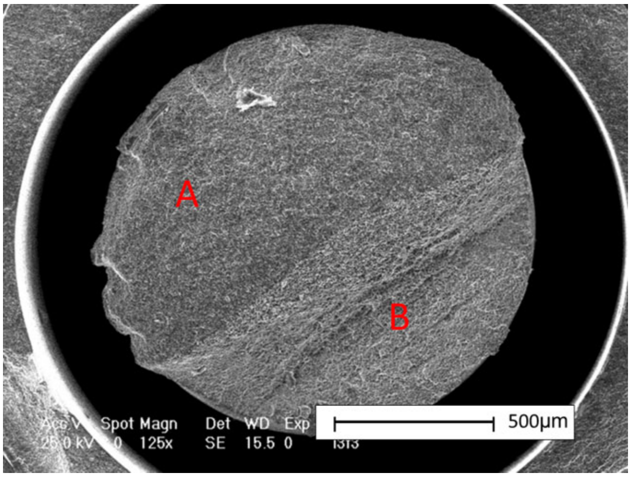

Figure 4 Fracture surface of 5-mm implant specimen in 500-µm magnification. The maximum load was 852 N and the specimen failed after 162,458 cycles. Using the scanning electron microscopy, we can identify the different fracture modes. A: Fatigue. B: Final fracture (monotonic overload). Fatigue failure does not originate on well-defined flaws and seems to have multiple sources.

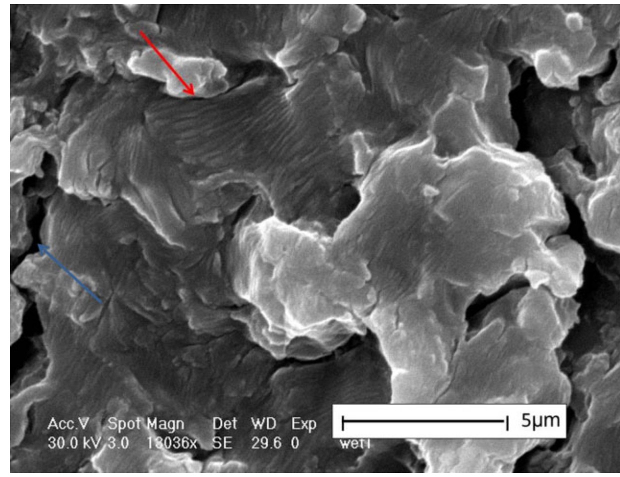

Figure 6 Fatigue striation (red arrow) between transgranular fractures (blue arrow) indicating fatigue fracture. Taken from a 3.75-mm implant, with maximum load of 810 N and 73,983 cycles to failure. Note that fatigue striations are only discernable at relatively large magnifications, on the order of ×10k.

in various in vitro studies.[10–13] Those tests showed superior mechanical stability to the internal hex connection design. Most studies evaluated implant-abutment connection strength on static loading only[12] and fatigue tests were partial without a uniform basic fatigue plot.[10,11,13]

The fractographic analysis revealed that the identification of a fatigue failure mechanism, mostly for the purpose of a failure analysis of in vivo failures, is quite delicate. In fact, the "classical" fatigue striations were only observed at relatively large magnifications (on the order of ×10k) and require some expertise for detection. On the other hand, the numerous secondary parallel microcracks (see Figure 5) are clear indicators of fatigue failure process. It appears that when analyzing field failures, the very fine and faint striations might go undetected, while the coarser secondary microcracks will be sufficient to clearly indicate the fatigue process. Yet, additional work is needed to systematically compare "in vivo failures" with the guidelines outlined in this work.

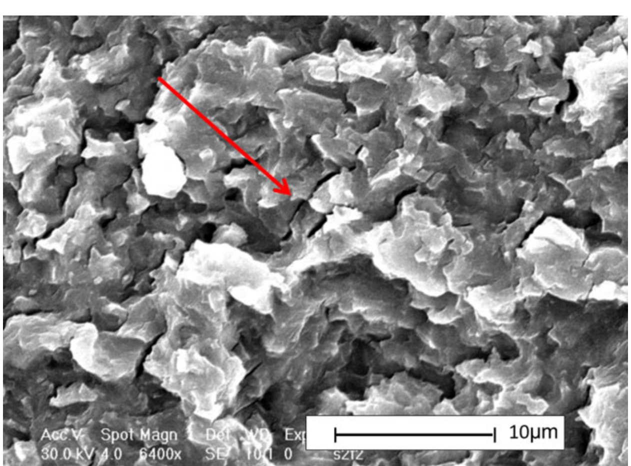

Figure 5 A view of a fatigue fracture mode found in the fracture surface of a 3.3-mm implant. The maximum load was 438 N and the specimen failed after 1,420,000 cycles. Fatigue failure is characterized by transgranular fracture with many secondary parallel cracks (arrow) perpendicular to the local crack-front propagation.

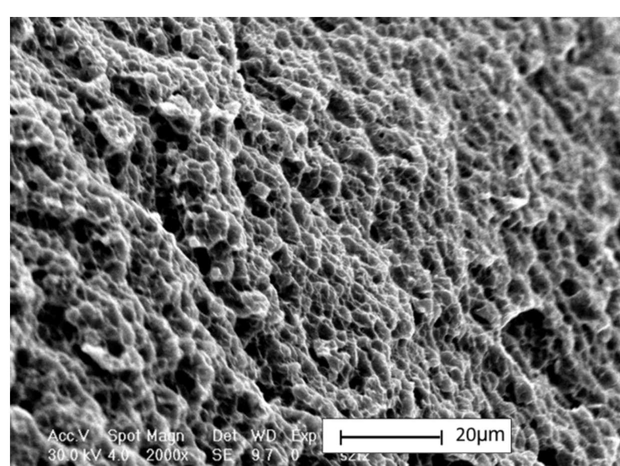

Figure 7 A view of final fracture (monotonic overload). Found on the fracture surface of the implant described at Figure 14. Final fracture failure is characterized by equiaxed dimples.

CONCLUSIONS

This study demonstrated that proper implant design is crucial to ensure long-term fatigue performance for dental implants. The combination of sharp notches (thread) and narrow metal cross section (less than 0.7 mm) might be deleterious for fatigue resistance especially in Ø 3.3-mm implants. Fracture mode analysis enables to identify the different failure loci, in relation to the various stress concentrations leading to fatigue failure.

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