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Identification of failure mechanisms in retrieved fractured dental implants

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ABSTRACT

Dental implants treatment complications include mechanical failures. These complications were considered minor until now but several clinical trials showed that mechanical complications are common in implantology and in implant rehabilitation. The aim of the study was to perform a detailed systematic failure analysis on Ti–6Al–4V and CP-Ti retrieved dental implants.

A total number of 10 CP-Ti and 8 Ti–6Al–4V retrieved fractured dental implants and implant parts were collected and there metal composition was identified using SEM–EDX (energy dispersive X-ray spectroscopy).

The identification of the implants failure mechanisms was done by comparing the fracture surfaces of retrieved fractured dental implants to fracture surfaces of implants fractured in lab conditions in room air, and also in an environment mimicking the intraoral environment, which includes artificial saliva and fluoride (exemplar testing). The analysis was done by using Scanning Electron Microscopy (SEM).

The overall fracture mechanisms that were identified on the retrieved Ti–6Al–4V and of CP-Ti dental implants were identical to those found on fatigue fracture surfaces of the specimens' fractured in lab conditions. No evidence was found for corrosion products on the metal surface, which might suggest the operation of a corrosion processes participating in the crack formation.

This study clearly shows that fatigue is the main failure mechanism for Ti–6Al–4V and CP-Ti retrieved dental implants. The fractographic analysis showed that implants and their parts might be broken at relatively low cyclic load levels, of the kind that matches the load levels generated during mastication.

1. Introduction

The use of dental implants as a treatment option for the rehabilitation of missing teeth is met with a very high success rate. Despite this, complications associated with this treatment do exist, which may eventually lead to the loss of both the implant and the prosthesis. Late treatment failures can be caused by mechanical complications which may involve screw loosening and/or fracture, abutment fracture and implant fracture.

A systematic review, on survival and complications of dental implants, after a follow up time of at least 5 years, showed that mechanical complications are common, including fracture of abutments and screws with the incidence of 2.5%, after a

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follow up time of 10 years. Fracture of implants, a relatively rare event, showed a cumulative incidence of 1.8% after a follow up time of 10 years [1].

A long term retrospective cohort study, which evaluated the outcome of implants therapy over a period of 10–16 years, showed that mechanical complications, which include implant fracture, abutment fracture, fracture of the implant's screw and prosthesis porcelain fracture all had an incidence of 31%, as compared to 16.9% for biological complications [2].

Today, dental implants are made of either pure (CP) titanium or titanium alloys. Among the latter, Ti–6Al–4V has been a main biomedical titanium alloy used for the fabrication of dental implants [3]. The high physico-mechanical properties of those materials, i.e. relatively low Young's modulus (important when the implant is to be matched to bone structure for instance), high fatigue and corrosion resistance, and excellent biocompatibility are all important properties of the titanium alloys that makes them a suitable choice for implant material [4,5].

Detailed fracture analyses of retrieved fractured dental implants are quite rare in the dental and in the biomechanical literature alike. That is because the incidence of fractures of dental implants and implant parts is rather low. Most fractured implants are left in the alveolar bone after fracture because of the difficulty to retrieve them. In most cases, the fracture surface of the implants, which is essential for fracture analysis, is destroyed or heavily damaged to a point that renders fractographic analysis impossible. In parallel, there are no clear and conclusive professional directives for the handling and preservation of fractured implants and implants' parts.

Yokoyama et al. [6] compared retrieved fractured dental abutment screw, made of CP-Ti, to an as-received abutment screw, by using SEM (Scanning Electron Microscope) and microstructural examination. The fracture surface of the retrieved fractured screw showed mixed ductile fracture and fatigue striations. The authors postulated that the fracture was caused by trans-granular stress corrosion cracking, without performing a detailed comparison with the fracture surface of the as-received screw, fractured by fatigue, in vitro conditions (exemplar testing).

Scanning electron (SEM) fracture surface analysis of six fractured CP-Ti dental implants, which had fractured intra orally after an average duration of 30 months, was carried out by Choe et al. [7]. The analysis claimed to have identified fatigue striations in all six specimens. Yet, the SEM fractographic pictures did not reveal a conclusive identification of fatigue or of the final fracture mode, because of the rather low magnification (X0.5 K) used in the article. Moreover, the authors concluded that the development of corrosion is the main reason for the failure of the collected fractured dental implants. Yet, no evidence of corrosion (corrosion products or pitting) could be identified in any of the presented SEM pictures.

Manda et al. [8] made a detailed fracture analysis of a single fractured CP-Ti implant and abutment screw. The broken parts were stored in 10% buffered formalin solution before being examined by SEM. The results showed that the fracture surface was covered by calcium, phosphorous and oxides. Even though, fatigue striations could be identified on the fracture surface. The authors concluded that the organic Ca/P depositions were an integral part of the mechanism which had led to the observed failure. While the organic deposits were carefully identified by those authors in order to assess the composition of the environment the implant was placed in, they covered large parts on the fracture surface, thereby hampering the progress of the fracture analysis. The authors did not show how or when the deposits were formed on the fracture surface, nor did they identify any effect on the material's microstructure. Nevertheless they concluded that these organic deposits played a role in the fracture process.

SEM fractographic analysis of seven fractured CP-Ti hollow dental implants, which had fractured intra orally after an average of 36 month, was reported by Sbordone et al. [9]. The SEM pictures published on the results showed clear fatigue striations; nevertheless, the authors identified cleavage type fracture as the failure mechanism. In addition, those authors did not show a comparison to hollow implants, fractured under lab conditions (exemplar testing), which could have shed additional light on the operating fracture mechanisms.

The above-mentioned studies illustrate the partial nature of the failure analyses carried out on CP-Ti implants so far. Yet, one can expect an increased incidence of mechanical complications as time passes. Therefore, a systematic analysis of fractured surfaces, which includes proper specimen handling and cleaning techniques, a large sample size, exemplar testing if necessary is highly desirable both for dental practitioners, implants' manufacturers and designers alike.

2. Materials and methods

2.1. Specimen collection

Twenty-four, in vivo fractured implants or implant parts, were collected for failure analysis. Unfortunately, no medical record of the retrieved fractured dental implants was made available. No information about the implant: intra-oral location, service years, carried prosthesis, proximity to additional implants or eventual bone loss. Likewise, no information was available about the patient, such as gender, age, oral status and habits. Consequently, the broken parts were investigated on purely technical grounds without addressing the related medical issues.

The first step was a macroscopic examination of the fracture surfaces in order to identify the fracture surface conditions and if a fracture mode analysis could be done using a binocular. Six implants were in poor condition (destruction during the extraction procedure) which hampered any practical observation from of the fracture surface at the macroscopic level, and were consequently set aside.

2.2. Specimen identification

In order to identify the metal composition of the specimen an EDX (energy dispersive X-ray spectroscopy) analysis was made. The identification is semi-quantitative, but it nevertheless provides a clear distinction between pure Ti and its alloys. A total number of ten CP-Ti and eight Ti–6Al–4V retrieved dental implants were thus identified using SEM–EDX.

While identifying the metal composition of the retrieved fractured dental implants, one could notice that parts of the fracture surfaces where covered with different types of layers which were first identified using the EDX and subsequently removed in order to completely reveal the fracture surface. The composition of the layers was as follows:

1. Titanium – pure or alloy – the fracture surface itself.
2. Organic layer – consists mainly of carbon.
3. Inorganic layer – consist mainly of Ca/P – probably bone/calculus material.

Fig. 1 shows a typical EDX spectrum.

2.3. Fracture surface cleaning

Table 1 is a proposed cleaning protocol which was devised and implemented on all the retrieved implants/implant parts.

The specimen was inserted into a 100 ml glass beaker. The beaker was filled with the selected chemical solution until the specimen was completely covered by the solution. During the time in the solution, the beaker was kept in a hot water ultrasonic bath. Between solutions, the specimen was thoroughly rinsed with water or ethyl alcohol.

2.4. Exemplar testing

Previous studies of a similar character have established fatigue as the most likely failure mechanism [10]. Specimen identification revealed two different metal compositions, CP-Ti and Ti–6Al–4V. Our previous work presented a thorough fractographic characterization of fatigued Ti–6Al–4V implants in both room air and artificial saliva (artificial saliva substitute containing 250 ppm of fluoride) environments [11]. Consequently, in order to complete the overall picture, similar tests were carried out on home-made CP-Ti implant-like specimens in both kinds of atmospheres. The Exemplar testing set-up is detailed in Appendix A. Fatigue testing was performed under load control, according to ISO 14801 recommendations. The load magnitude was selected according to the static bending strength of the implant specimens and of home-made CP-Ti implant-like (cylindrical) specimens. A vertical load was applied at a displacement rate of 0.4 mm/min until the sample fractured or exhibited a significant amount of (permanent) plastic deformation accompanied by a load drop. Two to five specimens were quasi-statically tested and the maximum applied load was recorded. The average load was found to be of 930 N ± 77 N for Ti–6Al–4V implant specimens, and 1400 N ± 102 for home-made CP-Ti implant-like specimens. The

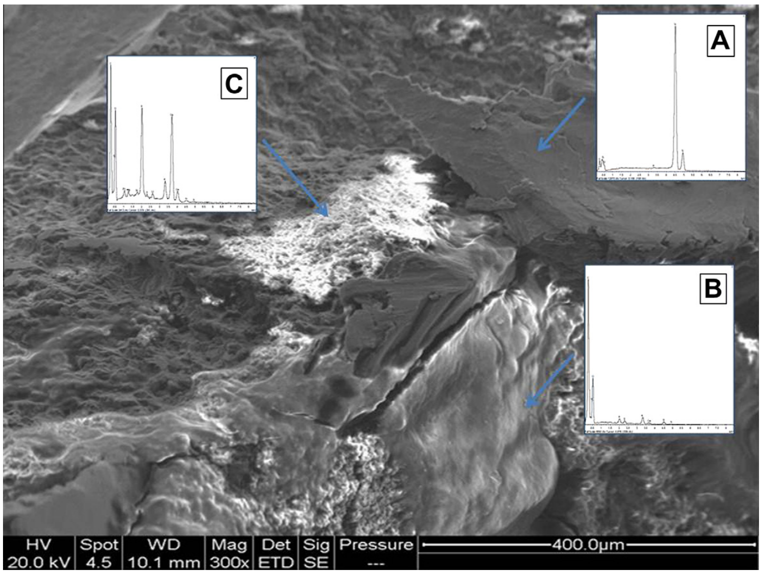

Fig. 1. EDX analysis of example fracture surface of retrieved fractured CP-Ti dental implant. (A) The metal composition CP-Ti – The spectra shows high energy peak corresponds to CP-Ti. (B) Organic layer – The spectra show high energy peak corresponding to carbon. (C) Inorganic layer consisting mainly of Ca/P. The spectra show high energy peaks corresponding to calcium, phosphorous and oxygen.

Table 1
Proposed cleaning protocol for retrieved dental implants.

Layer to be removed	Chemical solution	Time in solution
Blood/soft tissue	Sodium hypochlorite 3%	<10 min
Organic layer	Acetone (commercially pure)[a]	30 min
Inorganic layer	EDTA 17%[b]	As needed

[a] *Acetone*, organic solvent.
[b] *Ethylenediaminetetraacetic acid*, chelating agent, sequester metal ions such as Ca^{2+} and Fe^{3+}.

fatigue loads chosen for the test were 85% of the specimens bending strength, namely 1190 N for the CP-Ti implant-like specimens and 714 N for the Ti–6Al–4V implants.

The loads was directly applied to the implant abutment head as a sinusoidal force, with minimum to maximum loading ratio of $R = 0.1$. The test frequencies were in the range of 15–20 Hz. The machine stopped working automatically when the specimen fractured and the total number of cycles was recorded.

2.5. Fractographic analysis

The fracture surfaces of retrieved fracture dental implants and of implants fractured in laboratory conditions were examined using SEM (Phillips XL 30, Eindhoven, Netherlands).

3. Results

3.1. Exemplar testing results

Table 2 presents fatigue test results for implants that were cyclically loaded to failure, tested both in room air and in artificial saliva in lab conditions.

The results presented in Table 2 for fatigued Ti–6Al–4V implants were collected from our previous work that presented a thorough fractographic characterization of fatigued Ti–6Al–4V implants in both room air and artificial saliva [11].

3.2. Fractographic analysis of retrieved dental implants made of CP-Ti and Ti–6Al–4V-macrographs

Fig. 2 shows representative macroscopic images of retrieved dental implants and implant's parts made of both CP-Ti and Ti–6Al–4V. The fracture surfaces clearly show, at low magnification, a generally uniform and flat fracture surface. This observation suggests the operation of a single failure mechanism until final failure of the implant.

3.3. Fractographic analysis of retrieved CP-Ti and Ti–6Al–4V dental implant

Figs. 3–8 shows representative fracture surface topographies of retrieved dental implanted made of both CP-Ti and Ti–6Al–4V. Examination of the fracture surfaces clearly reveals fatigue as the dominant failure mechanism of the retrieved dental implants.

For all the examined specimens, more than 90% of the fracture surface of the retrieved CP-Ti and Ti–6Al–4V dental implants contained typical metal fatigue markings. The clear dominance of metal fatigue, spanning most of the fracture surface suggests that the fatigue crack propagated under relatively low cyclic loads, corresponding to a low stress intensity range (ΔK).

3.3.1. CP-Ti implants

Figs. 3–5 show typical fracture surface topographies of CP-Ti dental implants. Those figures also show typical fractographs of exemplar tests of similar implants, to allow for a detailed comparison and identification of the failure mechanisms.

The fatigue fracture surfaces of retrieved CP-Ti dental implants show an overall trans-granular fracture with faceted crystallographic appearance or cleavage-like facets at magnification of 2–4 K with clear fatigue striations (Fig. 3A1 and A2). The

Table 2
Examplar test results.

Metal composition	Load magnitude	Environment	No. of cycles to failure
CP-Ti	1190 N	Artificial saliva	10,078
CP-Ti	1190 N	Room air	32,500
Ti–6Al–4V	714 N	Artificial saliva	28,351
Ti–6Al–4V	714 N	Room air	157,790

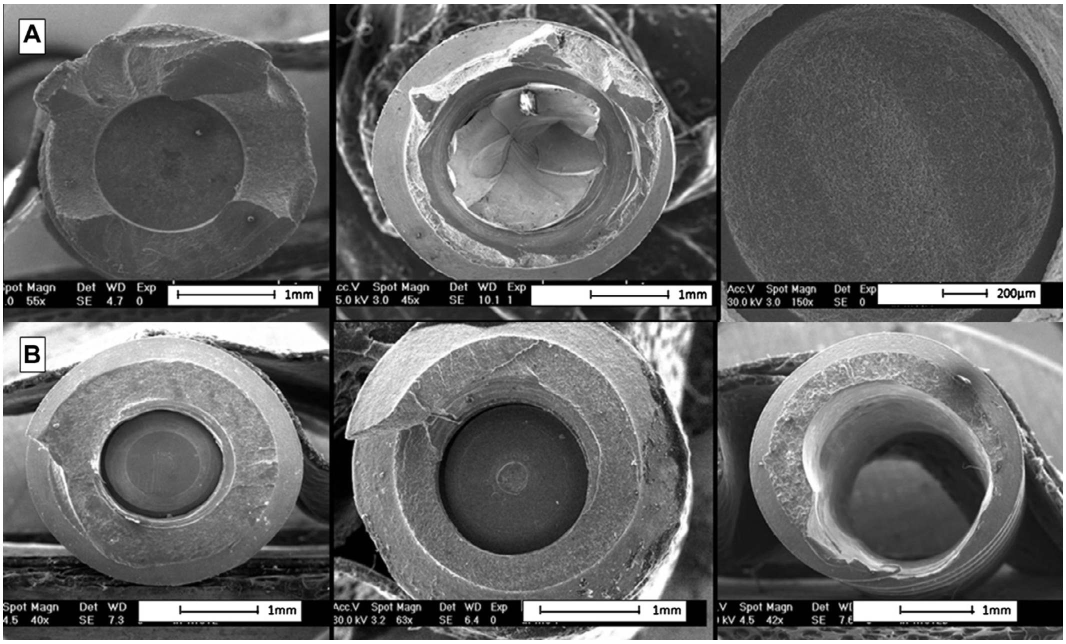

Fig. 2. Macrographic images of retrieved dental implants made of CP-Ti and Ti–6Al–4V. (A) Implants and implant's parts made of CP-Ti. (B) Implants and implant's parts made of Ti–6Al–4V.

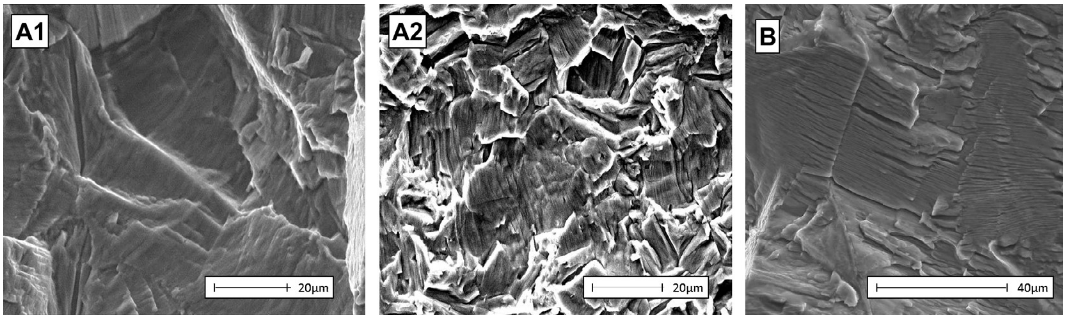

Fig. 3. Fractographs of CP-Ti dental implants. (A1) Retrieved dental implant. (A2) Retrieved dental implant. (B) Exemplar testing. A CP-Ti implant-like specimen was fractured in lab conditions in artificial saliva. The load magnitude was 1190 N the number of cycles to failure was 10,078. Note the high resemblance of the in vivo and in vitro fracture surface topographies.

fatigue fracture surfaces of CP-Ti implant-like specimens fractured in laboratory conditions, both in room air and in artificial saliva, show very similar fractographic features of a trans-granular fracture with faceted crystallographic appearance or cleavage-like facets with clear fatigue striations at the same magnification. Fig. 3B shows a typical fatigue fracture surface of a specimen tested in artificial saliva.

The typical fatigue striations can be identified easily at magnifications of (6 K), on the flat facets (Fig. 4), both on retrieved CP-Ti dental implants fractured intra-orally (Fig. 4A1 and A2) and on CP-Ti implant-like specimens fractured in lab conditions, air and artificial saliva (Fig. 4B).

Final fracture marking, dimples, that are typical of ductile overload failure, can be identified on retrieved specimens on magnification of 1 K (Fig. 5A1 and A2). The area of overload fracture with dimpled structure is also shown at a magnification of 1 K, in a specimen tested in laboratory conditions, both in air and artificial saliva (Fig. 5B). One can again note the similarity of features between the in vivo and in vitro specimens.

3.3.2. Ti–6Al–4V implants

The procedure followed for these implants was identical to that reported for the CP-Ti implants, as illustrated in Figs. 6–8.

The fatigue fracture surfaces of retrieved Ti–6Al–4V dental implants show an overall trans-granular fracture with secondary cracking at magnification of 3–6 K (Fig. 6A1 and A2). The fatigue fracture surfaces of Ti–6Al–4V implants specimens fractured in lab conditions, both in room air and in artificial saliva show an overall similar fractographic appearance of a

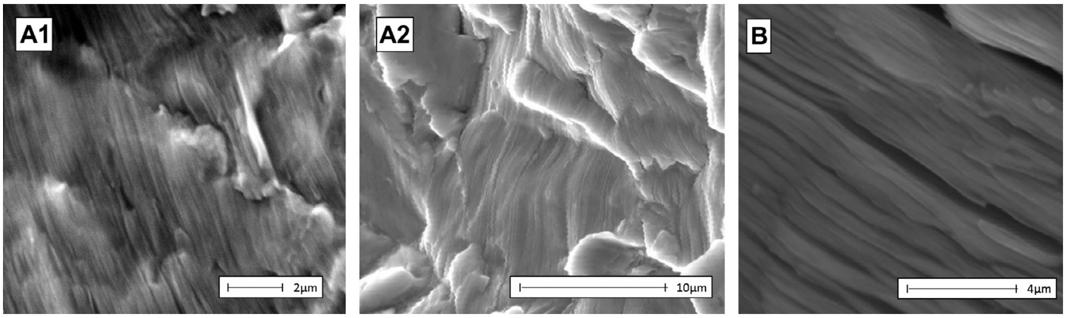

Fig. 4. Fatigue striations in CP-Ti dental implants. (A1) Fatigue striations from retrieved implant. (A2) Fatigue striations from retrieved implant. (B) Fatigue striations from home-made CP-Ti implant-like specimen fractured in lab conditions and tested in artificial saliva. The load magnitude was 1190 N the number of cycles to failure was 10,078. Note the high resemblance of the in vivo and in vitro fracture surface topographies.

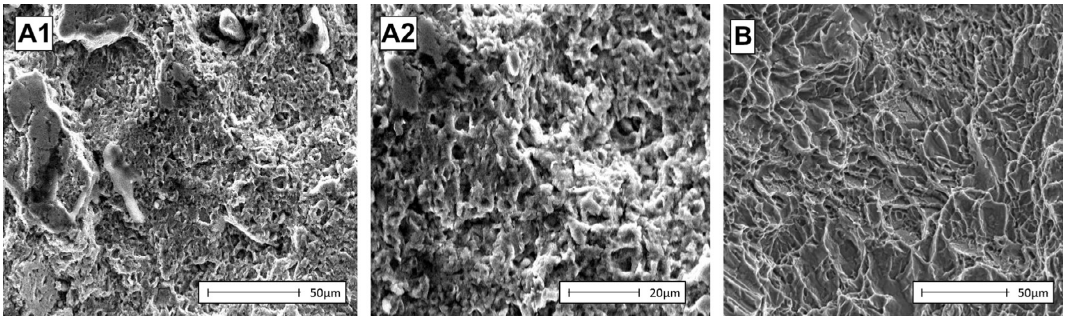

Fig. 5. Final fracture in CP-Ti dental implants. (A1) Dimples from retrieved implant. (A2) Dimples from retrieved implant. (B) Dimples from CP-Ti implant-like specimen fractured in lab conditions tested in artificial saliva. The load magnitude was 1190 N. Note the high resemblance of the in vivo and in vitro fracture surface topographies.

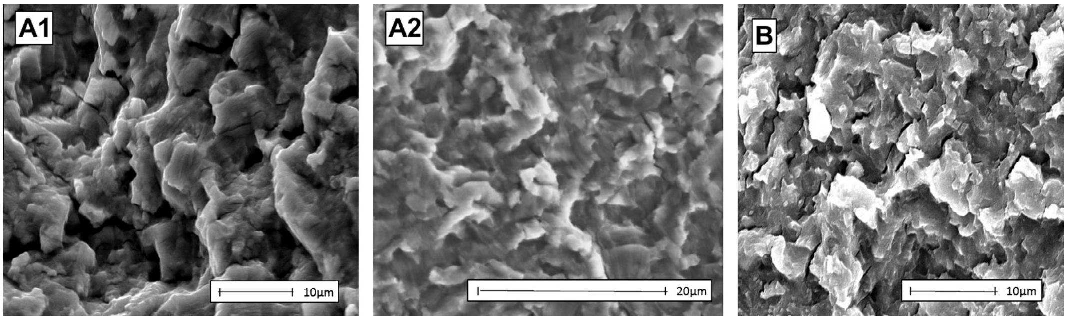

Fig. 6. Fracture surface topography of Ti–6Al–4V dental implants. (A1) Fractograph taken from retrieved implants. (A2) Fractographs taken from retrieved implant. (B) Fractograph of Ti–6Al–4V dental implants fractured in lab conditions, tested in room air. The load magnitude was 714 N and the number of cycles to failure was 157,790. Note the high resemblance of the in vivo and in vitro fracture surface topographies.

trans-granular fracture with secondary cracking (Fig. 6B). Fatigue striation cannot be clearly identified (ill-defined). Fig. 7 shows faint classic fatigue striations that were identified on retrieved Ti–6Al–4V dental implants using magnifications as high as 15 K (Fig. 7A1 and A2). For specimens tested in lab conditions, the typical fatigue striations can only be identified in specimens fractured in room air environment at the same high magnifications (13 K, Fig. 7B).

Final fracture marking, dimples, that are typical of ductile overload failure, can be identified on retrieved specimens on magnification of 1 K (Fig. 8A1 and A2). The area of overload fracture with dimpled structure is also shown at a magnification of 1 K, in a specimen tested in laboratory conditions, both in air and artificial saliva (Fig. 8B). One can again note the similarity of features between the in vivo and in vitro specimens.

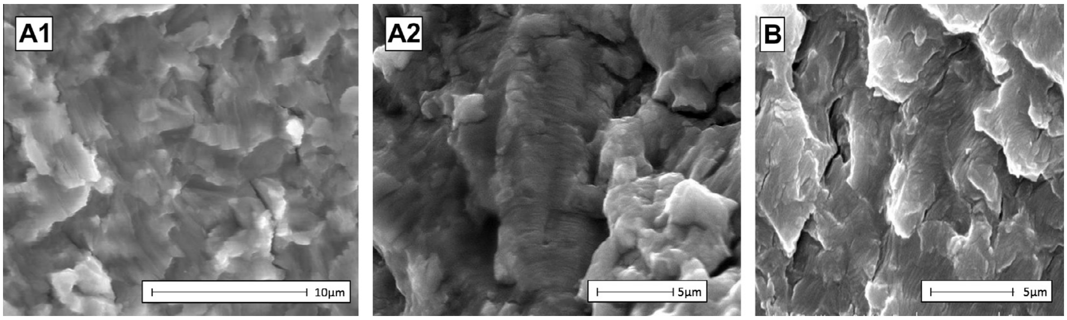

Fig. 7. Fatigue striations in Ti–6Al–4V dental implants. (A1) Fatigue striations from retrieved implant. (A2) Fatigue striations from retrieved implant. (B) Fatigue striations from Ti–6Al–4V dental implants fractured in lab conditions, tested in room air. The load magnitude was 714 N the number of cycles to failure was 157,790. Note the high resemblance of the in vivo and in vitro fracture surface topographies.

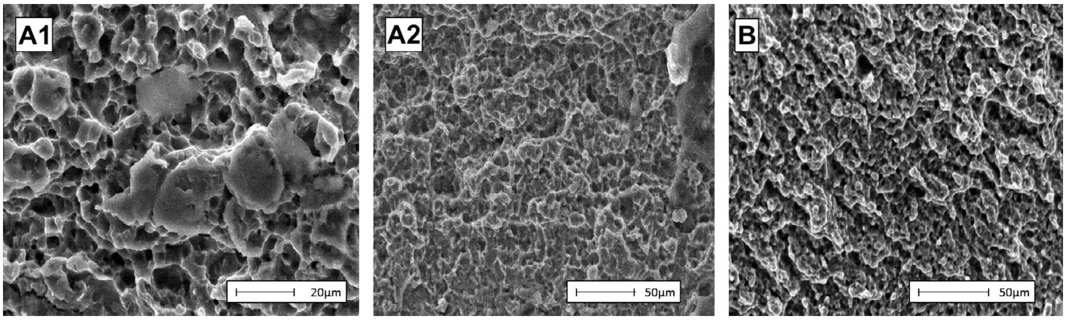

Fig. 8. Final fracture in Ti–6Al–4V dental implants. (A1) Dimples from retrieved implant. (A2) Dimples from retrieved implant. (B) Dimples from Ti–6Al–4V dental implants fractured in lab conditions tested in room air the load magnitude was 714 N. Note the high resemblance of the in vivo and in vitro fracture surface topographies.

4. Discussion

The aim of this study was to perform a detailed systematic failure analysis on dental implants which failed intra-orally.

The importance of a detailed systematic failure analysis to the medical/dental field is profound as a means to prevent the failure reoccurrence and to improve the implants' mechanical and biological performance.

The present research is one of the first large scale studies that establish unambiguously metal fatigue as the main failure mechanism in retrieved dental implants. The analysis was done on 18 fractured implants and implant's parts made on both CP-Ti and Ti–6Al–4V. Classical fatigue markings as fatigue striations were shown on all of the specimens collected.

Our study also comprised a systematic exemplar testing in order to complete the failure analysis. The aim of the exemplar testing was to clearly identify the fatigue fracture mechanism in dental implants made of CP-Ti and Ti–6Al–4V. The results of the exemplar testing have also shown that the intra-oral environment might cause a significant reduction in implant's fatigue performance [11]. As emphasized in our previous work, while the failure mechanism is definitely fatigue, the oral environment plays most likely a significant role in reducing the overall fatigue life of the implants.

The fractographic analysis presented on implants tested in lab conditions, showed no difference in the overall fractographic appearance for implants tested either in room air or in artificial saliva. Studies that examine the effect of different environments on the fractographic appearance for CP-Ti and Ti–6Al–4V all showed that the overall fractographic appearance does not change as a result of the environment. Even so, it has been clearly shown the environment definitely has an effect on the metal's crack propagation rates [12,13].

Our study did not identify any evidence of the operation of corrosion or stress corrosion mechanism, as the cause for fatigue failure. Such mechanisms were invoked in previous studies with little if no supporting evidence. Our results provided no evidence of the operation of such failure mechanisms.

One important point remains to be elucidated, namely what is the factor that causes the development of fatigue cracks in dental implants? This important point was not elucidated in the present study and it should be at the center of future studies if one wants to have a better control over the fatigue life and survivability of dental implants.

5. Conclusions

- An organized protocol for analyzing fractured implants and implant's parts was developed. This protocol offers an alternative to ill-defined cleaning procedures that have been reported in the literature.

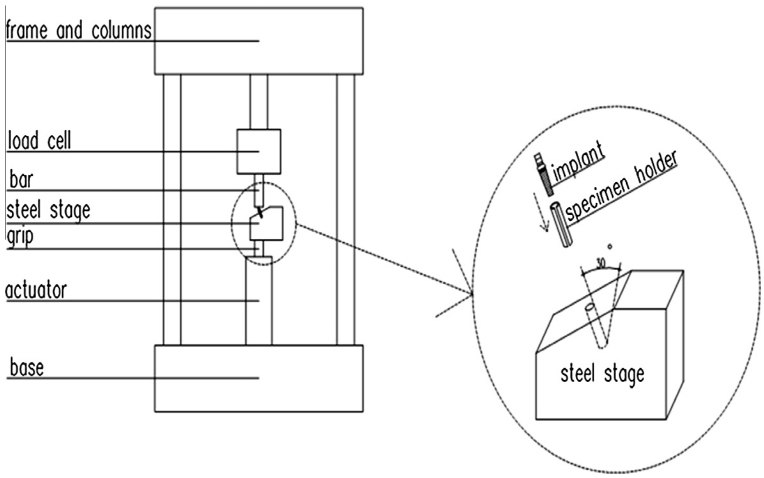

Fig. A1. Schematic diagram of test set-up. To fix the specimen, a steel base was machined with a hole on its upper face so that the specimen, once inserted, would form an angle of 30° [15].

- Until now failure mechanisms were identified for implants made of CP-Ti. Our study is the first to show and identify failure mechanisms in implants made of Ti–6Al–4V.
- The study showed that implants and implant's parts might be broken at relatively low cyclic load levels, of the kind that matches the load levels generated during mastication.
- Additional work needs to focus on the identification of the causes for fatigue crack development in dental implants.

Appendix A

Exemplar testing (static and cyclic) was performed using an MTS servo-hydraulic load frame (MTS system, Minneapolis, MN) with 250 kN load capacity, driven under load-control. To apply loads to the tested implants and fix specimens to the testing machine, a custom-designed holding stage made of high-strength steel was machined. To fix the test implants rigidly, a specimen holder was machined, which consists of a longitudinal slotted steel cylinder. The implant was inserted into the hole of the specimen holder up to the second thread from the head of the implant. The specimen holder was then inserted to the holding stage at an angle of 30° off-axis, and fixed to the testing machine (Fig. A1). This way the testing force which was applied to the implant abutment induced a bending moment, as recommended by the ISO standard for dynamic fatigue testing for dental implants [14].

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