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Research Paper

Mechanical assessment of grit blasting surface treatments of dental implants

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ABSTRACT

This paper investigates the influence of surface preparation treatments of dental implants on their potential (mechanical) fatigue failure, with emphasis on grit-blasting. The investigation includes limited fatigue testing of implants, showing the relationship between fatigue life and surface damage condition. Those observations are corroborated by a detailed failure analysis of retrieved fracture dental implants. In both cases, the negative effect of embedded alumina particles related to the grit-blasting process is identified. The study also comprises a numerical simulation part of the grit blasting process that reveals, for a given implant material and particle size, the existence of a velocity threshold, below which the rough surface is obtained without damage, and beyond which the creation of significant surface damage will severely reduce the fatigue life, thus increasing fracture probability.

The main outcome of this work is that the overall performance of dental implants comprises, in addition to the biological considerations, mechanical reliability aspects. Fatigue fracture is a central issue, and this study shows that uncontrolled surface roughening grit-blasting treatments can induce significant surface damage which accelerate fatigue fracture under certain conditions, even if those treatments are beneficial to the osseointegration process.

1. Introduction

Dental implants offer a highly successful solution for missing teeth, contingent upon the well-known osseointegration process. Albrektsson et al. (1981) stated that the implant's surface properties affect the successful course of osseointegration. Those properties can be addressed from three different directions: Mechanical, topographic, and physicochemical (Albrektsson and Wennerberg, 2004).

The effect of surface topography on the biological reaction and on bone-implant contact has been studied extensively in the dental implant research field, for over a decade. Average height deviation parameters (R_a and S_a) between 1 and 2 μm, which define a "moderately rough surface", were found to be optimal for a successful osseointegration process (Albrektsson and Wennerberg, 2004; Elias and Meirelles, 2010; Wennerberg and Albrektsson, 2009, 2010).

A great variety of surface treatments exist today, in order to achieve a desired degree of surface roughness. Those include machining, plasma spray and laser peening (LST), acid etching, grit blasting followed by acid etching, anodizing and biomimetic coating. Among those, grit blasting is one of

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the most common dental implant surface treatments (Elias and Meirelles, 2010; Wennerberg and Albrektsson, 2010). Blasted surface roughness with S_a values ranging from 0.6 and 2.1 μm is deemed ideal for the implant's osseointegration (Wennerberg and Albrektsson, 2009). During this process, implants made of pure titanium (CP–Ti) and titanium alloy (Ti–6Al–4V) – which are the most widely used biomaterials for fabrication of dental implants (Elias et al., 2008) – are blasted with air – propelled hard ceramic particles (Al_2O_3, TiO_2 or $Ca_2P_2O_7$) (Guéhennec et al., 2007). Depending on the size and shape of the ceramic particle, which is polyhedral with sharp corners (Barriuso et al., 2014), and on its velocity, erosion and material tearing of the titanium surface, is inflicted. The result is different surface roughness levels that can be produced on the implant's surface.

While the biological benefit of such surface treatment has become a paradigm in the field of dentistry, the *mechanical properties* of the implant surfaces have not been thoroughly studied yet, and researches dealing with the effect of the surface treatment on the implant's mechanical behavior are still scarce.

Late treatment complications in implant dentistry include mechanical failures. Those consist of abutment screw loosening, abutment screw fracture, implant's abutment fracture and *implant fracture*. Implant and implant components fracture are considered severe in dentistry, because they often necessitate extra surgery, and lead to the loss of implants and loss of the prosthesis supported by the implants. Pjetursson et al. (2012) reported an incidence of implants (and parts) fracture of the order of only 0.5%, after a follow up time of at least 5 years. Pommer et al. (2014) recently published a meta-analysis on the incidence of implants' fracture, reviewing clinical studies that reported such fractures. Their study concluded that the incidence of implant fracture jumps to 2.8% after a follow up time of 8.3 years. Most fractured implant included in this study, occurred just after 4.1 ± 3.5 years. These incidences clearly highlight the *importance of follow up time* on the occurrence of implant fracture. Here, the concept of "bathtub curve" which is quite central in reliability engineering should apply to dental implants as well. This concept shows that failure occurs largely over the first short period of life of a component (e.g. infant mortality), settles down to a low level (service time), then finally rises dramatically towards the end of the product's life (Henley and Kumamoto 1981). One could therefore surmise that the studied period of less than 10 years, for the specific fracture of implants, *is most likely located in the bottom of the bathtub curve* (See Pjetursson et al., 2012; Pommer et al., 2014). Thus, in order to prevent future implant fracture, it is important to identify the relevant physical and mechanical causes. This point should be clearly understood, since the current paradigm, which states that implant fracture is a rare exception, is mostly based on an extrapolation of results valid over 5 years to much longer periods, with the inherent error related to the very concept of data extrapolation. All the more so, when *fatigue fracture* (the main identified fracture mechanism) amounts to damage accumulation over time, as discussed in the sequel.

Detailed failure analyses of retrieved fractured dental implants are quite rare in the dental and in the biomechanical literature alike. 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. A few published articles (Choe et al., 2004; Morgan et al., 1993; Sbordone et al., 2010; Shemtov-Yona and Rittel, 2014; Yokoyama et al., 2002), that examined the fracture surface of retrieved fractured dental implants, identified the probable causes leading to mechanical failure. Most studies (Choe et al., 2004; Morgan et al., 1993; Sbordone et al., 2010) identified *metal fatigue* (Suresh 1994) as the main failure mechanism. As opposed to the crack growth mechanism, the cause(s) for fatigue crack initiation and the crack nucleation site(s) *could not be clearly identified*.

With that, *implant design* that includes significant stress concentrators (Morgan et al., 1993) can be incriminated. In addition, large dents and scratches, with foreign particles, introduced during the *manufacturing process*, have also been considered as another cause for fatigue crack initiation (Choe et al., 2004; Yokoyama et al., 2002). All those are surface defects.

Fatigue properties of metals are largely affected by surface condition/topography, since fatigue cracks generally initiate from free surfaces. The presence of notch-like surface irregularities *related to machining and surface treatments*, may have a deleterious effect on fatigue crack initiation and on the total fatigue life. In addition, embedded particles and/or particles adhered to the surface, combined with high surface roughness, might induce stress concentrations and significantly degrade the metal fatigue performance (Novovic 2004). Examination of treated CP–Ti or titanium alloy by scanning electron microscopy reveals the aggressive effect of the blasting treatment. The treated metal surface is rough, as expected, but it may also comprise multiple notch-like superficial defects. These defects are the evidence of erosion and material tearing caused by the sharp edges of the ceramic particles. Moreover, firmly embedded ceramic particles can also be found attached to a crater-like morphology which they have created (Leinenbach and Eifler, 2006; Multigner et al., 2009; Pazos et al., 2010). These particles sometimes cause very fine cracks in their immediate vicinity (Barriuso et al., 2011; Conforto et al., 2004). All those evidences are certainly detrimental to the long-term mechanical performance of the implants.

The effect of grit blasting treatments on the fatigue performance of *titanium and titanium alloys* was studied in several instances. Baleani et al. (2000) showed that grit blasting of Ti6Al4V can reduce the fatigue endurance limit by 35–40%. The authors incriminated the surface roughness and the sharp defects created by the treatment. Conversely, Pazos et al. (2010) reported that the fatigue behavior of blast-treated and machined CP–Ti surface is similar, in spite of the inherent stress raisers related to the alumina particles. The authors invoked the beneficial effect of blasting induced compressive residual stresses that balanced the negative effect of the stress raisers. Leinenbach and Eifler (2006) compared the fatigue performance of grit blasted and polished Ti–6Al–4V cylindrical specimens. The results showed that the endurance limit of the grit blasted material