COMPARATIVE STUDY OF THE FATIGUE STRENGTH OF DENTAL IMPLANT SYSTEMS WITH PRE-ANGLED AND STRAIGHT CONNECTING PARTS

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RESUMEN

Los implantes dentales deben pasar una certificación donde se determina su resistencia a fatiga según la norma internacional ISO 14801. En esta norma se puede distinguir entre implantes angulados y rectos. En algunos países se exige obtener esta curva de fatiga para el implante angulado aunque ya se haya obtenido para el mismo implante pero recto. En este trabajo se muestra tanto experimental como analíticamente que el angulado es más resistente que el recto. Además, también se muestra que solamente sería necesario ensayar de un tipo, o angulado o recto, y a partir de ahí obtener la curva correspondiente para el otro. Para ello se han ensayado implantes rectos y angulados para dos modelos de implantes, mostrándose las vidas obtenidas en función de una tensión equivalente. También se analiza el posible efecto sobre la vida a fatiga de la variación de distintos parámetros de la geometría del implante.

PALABRAS CLAVE: Fatiga, Implantes dentales, Ensayos, Titanio, Pre-angulados

ABSTRACT

Dental implants need to pass a certification where their fatigue strength is determined following the international standard ISO 14801. This standard distinguishes between straight and pre-angled connecting parts. In some countries, it is obligatory to obtain the fatigue curve for the pre-angled implant although it may have already been obtained for the straight one. This paper shows experimentally and analytically that the implant with pre-angled connecting part is more resistant that the straight implant. Furthermore, it is shown that only one type of implant, either straight or pre-angled, needs to be tested and from this result the fatigue curve of the other one can be inferred. For this purpose, various sets of implants, straight and pre-angled for two different designs, have been tested, showing the fatigue lives against an equivalent stress. Finally, the effect over fatigue life of different geometric parameters has been analysed.

KEYWORDS: Fatigue, Dental Implants, Tests, Titanium, Pre-angled

1. INTRODUCTION

Dental implants are traditionally designed as mechanical components subjected to a cyclic loading scenario such as mastication. The designs of these components must be properly tested in order to know if the design has fatigue problems. The estimation of a component's fatigue life is a complex process that requires a lot of resources and time. The serious consequences of the fracture of these components from a clinical standpoint become a solid reason for an exhaustive testing phase. Many of these tests are done in accordance with ISO 14801 [1]; which specifies a method for fatigue testing of single post endosseous dental implants of the transmucosal type and their premanufactured prosthetic components. It is most useful for comparing endosseous dental implants of different designs or sizes than for determining specifically the fatigue strength of these implants under real masticatory loads. The kind of implant under study has been analysed before by the authors modelling the fatigue response in this type of test [2,3] and the fixing conditions [4].

This standard considers that the connecting parts of dental implant systems (also called pillars or abutments) can be divided between pre-angled or not pre-angled (also called straight). For each of these types of dental implants systems, the standard specifies different schemes for test installation. Straight dental implants are the most common ones and there is not much information in the literature about the pre-angled abutments. Usually, in the literature pre-angled or angulated implants are actually straight implants but collocated in the mandible at an inclined angle [5,6]. Some study the behaviour and interaction with the bone [5] concluding, among other things, that the stresses in the pre-angled abutment are higher. In [6] the authors measure the stress in the implant through strain gages and also find them higher for angulated abutments. As said earlier, these are not pre-angled implants as defined in the standard. In other cases [7] the authors use pre-angled connecting parts but they are loaded vertically, measuring the strain with digital image correlation and also concluding that the stresses are higher in the pre-angled one. Others simulate the bone support and measure the stresses using photoelasticity [8]. They find higher stresses in the material when using implants with pre-angled abutments, but the comparison is made against a straight implant loaded axially. All of these results seem to imply that the implants with a pre-angled connecting part are weaker, but, as will be shown, from the point of view of the ISO standard they are stronger. The reason is that the geometrical disposition is different.

The aim of this paper is to show that, if certain conditions are met and if ISO 14801 is used to validate and certify an implant, the fatigue strength of dental implant systems with pre-angled connecting parts is significantly higher than that of implant systems with the same body but with straight connecting parts. In other terms, this paper pretends to show that, under certain conditions, a dental implant system with straight connecting parts represents the worst case scenario. Thus, this configuration must be the one used to properly estimate fatigue strength and fatigue life, as the standard clearly states that testing shall be carried out for the worst-case conditions within the recommended use. Another direct consequence of this affirmation is that, for certain conditions, fatigue test for dental implant systems with pre-angled connecting part does not provide trustworthy information about fatigue behaviour as this configuration does not fulfil worst-case condition.

The analysis is carried out both theoretically as well as experimentally. First, based on tests requirement, an analysis of the nominal stresses produced in the failure zone for straight and pre-angled pillars is shown. Also, a comparison of experimental fatigue lives obtained with specific types of pre-angled and straight pillar is presented. Finally, some conclusions are obtained from the previous analysis.

2. TESTING METHOD DESCRIPTION

This section explains, in general terms, the methodology followed for sample preparation and fatigue testing according to ISO Standard 14801:2007. The testing method consists in cyclic loads applied on the implant that vary sinusoidally with $R = Pmin/Pmax = 0.1$.

The standard differentiates the test set up of both implant systems. Testing systems with straight connecting parts requires a test set-up such as the one schematically shown in the standard ISO 14801. According to this diagram, the test samples have to be clamped so that, during the test, its axis is inclined 30º ± 2º with the loading direction of the testing machine.

On the other side, for testing systems that includes pre-angled connecting parts, the standard states that the test samples shall be clamped such that the angle with the loading direction of the testing machine is 10º greater than the angle between the implant axis and the axis of the angled portion of the connecting part, designated as α in this document.

3. THEORETICAL VALIDATIONS

This aim of this section is to theoretically validate that when a dental implant system is tested following the ISO 14801:2007 guidelines and under certain circumstances, it can be shown analytically that the damage parameter (stresses and strain combination producing fatigue) is significantly lower when the dental implant has pre-angled connecting parts that when those connecting parts are straight.

Fatigue failure of a dental implant system, is a phenomenon that depends on many different factors. These factors may be local factors (specific zones), such as the local geometry in the crack initiation area, or global factors, such as the value of the stress in the area crack of development.

This study assumes that the fracture of the system will occur frequently in the implant's body, far away from the connecting parts, in the border of the clamping zone. If the implant's body is identical in both systems, the stress concentration is the same and it seems perfectly reasonable to compare the behaviour using the nominal stresses, and thus eliminating from the study the influence of local factors in the initiation and crack propagation.

Therefore, to compare the fatigue strength of systems with pre-angled and straight connecting parts, it will be necessary to analyse the value of the maximum stress in the area of crack initiation in both systems.

In figure 1, it can be seen the different forces and torque generated by the application of the loading force F. This force can be decomposed in two different forces, one parallel to the axis of the implant, Fv, and the other orthogonal to it, F_H. The torque, Mv, will be the result of turning effect of the force F_H.

From figure 1 it is easy to see that the zone of maximum nominal stresses in the implant is the clamping plane, which is located 3 mm below the nominal level of the bone. As the implant body lacks of rotational symmetry and in order to provide the worst case scenario during the tests, the specimens were placed so that the maximum tensile stresses appear at the point of highest stress concentration. Thus, the maximum stress concentration will combine with the maximum nominal stress (initiation zone).

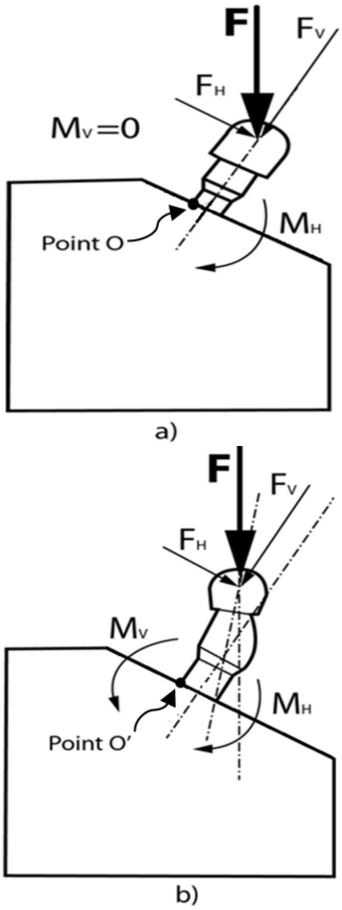

Figure 1. Simplified model of dental implant test with straight (a) and pre-angled (b) connecting parts.

The maximum nominal stress $\sigma_{nom,max}$, at the crack initiation zone can be obtained by combining the effects of bending and compression, both induced by force *F*. Thus:

$$\sigma_{nom,max} = \sigma_{felx,max} + \sigma_{comp} \quad (1)$$

The maximum nominal stress caused by bending of the implant body can be estimated by the following expression, which is valid for a cylindrical bar subjected to bending:

$$\sigma_{felx,max} = \frac{M}{\frac{\pi}{32}D^3} \quad (2)$$

Where *D* is the diameter of the implant and *M* is the bending moment induced by the applied force *F*. The value of *M* can be calculated by:

$$M = F \cdot y \quad (3)$$

The moment arm, *y*, according to the ISO 14801 Standard, represents the minimum distance between the axis of the force and the point where the moment is evaluated and, as it may be verified later, it depends only on the geometry of the test. Moreover, the compressive stress can be calculated by projecting the force *F* in the direction of the axis of the implant from the expression:

$$\sigma_{comp} = -\frac{F_{comp}}{\frac{\pi}{4}D^2} \quad (4)$$

In equation (4), F_{comp} is the compression component of the force *F*. The compressive stresses have the opposite effect to those caused by bending, which are traction stresses in the area of crack initiation. The tensile stresses tend to open the crack, unfavourable in terms of fatigue, while compression tends to close, so they are considered favourable.

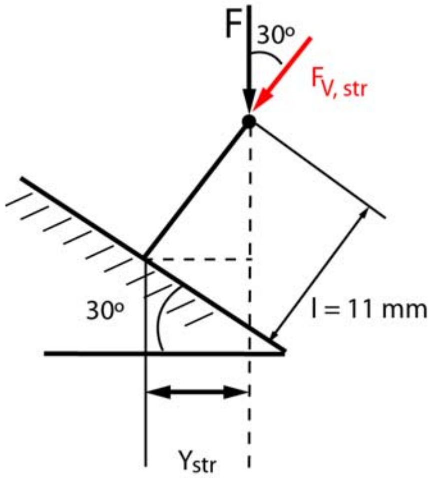

Figure 2. Test configuration scheme implant systems with straight connecting parts.

In the case of an implant system with straight connecting parts, the value of the maximum nominal stress can be obtained through the following expressions, for this particular case (see figure 2):

$$\sigma_{nom,max}^{str} = \sigma_{flex,max}^{str} + \sigma_{comp}^{str} \quad (5)$$

$$\sigma_{nom,max}^{str} = \frac{F \cdot y_{str}}{\frac{\pi}{32}D^3} - \frac{F_{comp}^{str}}{\frac{\pi}{4}D^2} \quad (6)$$

$$\sigma_{nom,max}^{str} = \frac{F \cdot 11\sin(30°)}{\frac{\pi}{32}D^3} - \frac{F \cdot \cos(30°)}{\frac{\pi}{4}D^2} \quad (7)$$

$$\sigma_{nom,max}^{str} = \frac{4F}{\pi D^3}\left(88 \cdot \sin(30°) - D\cos(30°)\right) \quad (8)$$

In the case of an implant system with pre-angled connecting parts, schematized in figure 3, the maximum nominal stress can be obtained through the following expressions:

$$\sigma_{nom,max}^{ang} = \sigma_{flex,max}^{ang} + \sigma_{comp}^{ang} \quad (9)$$

$$\sigma_{nom,max}^{ang} = \frac{F \cdot y_{ang}}{\frac{\pi}{32}D^3} - \frac{F_{comp}^{ang}}{\frac{\pi}{4}D^2} \quad (10)$$

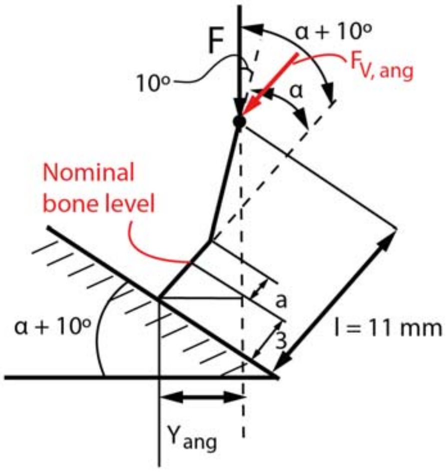

Figure 3. Test configuration scheme implant systems with pre-angled connecting parts.

In this case, y_{ang} can be calculated by trigonometry and is given by the expression:

$$y_{ang} = (3 + a)\sin(\alpha + 10) + (8 - a)\sin(10)\sqrt{1 + tg^2\alpha} \quad (11)$$

Where α is the relative angle between the axis of the implant and the angled portion of the connecting part and a is a parameter that takes into account that in many connecting parts the angled portion does not start at the nominal level of the bone but slightly above. In commercial implants, this parameter a usually varies between 0 and 2 mm.

To properly compare the maximum nominal stresses in implant systems with the same body but with straight and angled connecting parts, a function, h, is defined as:

$$h = h(D, \alpha, a) = \frac{\sigma_{nom,max}^{str}}{\sigma_{nom,max}^{ang}} \quad (12)$$

$$h = \frac{88 \cdot \sin(30°) - D\cos(30°)}{8(y_{ang}) - D\cos(\alpha + 10)} \quad (13)$$

The function h represents, as stated above, the ratio of the value of maximum nominal stresses in dental implant systems between straight and angled connecting parts for the same applied load. As shown in the expression above, the value of the function h only depends on the geometry of the implant, the geometry of the connecting part and the test setup. According to this definition, a value of h greater than 1 indicates that the value of the maximum nominal stress is higher in the case of straight connecting part.

Figure 4 schematizes the evolution of h for different values of the angle of the connecting part, α, and for different values of the diameter of the implant body, D.

It has been considered a value of a = 2 mm, in other words, the angled part of the connecting part begins 2 mm above the nominal level of the bone, the worst-case condition, as it will be shown below. In this figure, it can be seen that the value of the maximum nominal stress in the case of straight connecting parts is greater than that for angled connecting parts, for values of α lower than approximately 42°. The graphic also shows that for values of α equal or lower than 25°, the maximum nominal stress for straight connecting parts is above 40% higher than the corresponding value in a dental implant system with angled connecting parts.

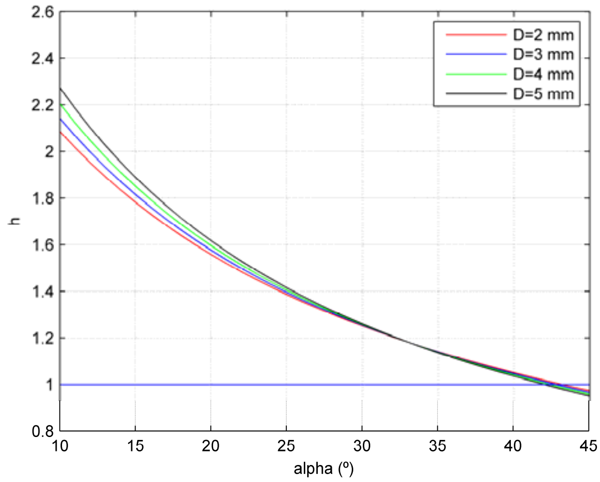

Figure 4. Evolution of h depending on abutment angle for a = 2 mm and several values of D.

To properly analyse the influence of the parameter a, figure 5 shows the evolution of h depending on the angle of connecting parts for different values of a. The value of D has been set at 3.5 mm. This figure shows that, as the value of a increases, the value of h decreases, and therefore so does the difference between the maximum nominal stresses associated with implant systems with straight and angled connecting parts, although the value of h is still greater than 1.

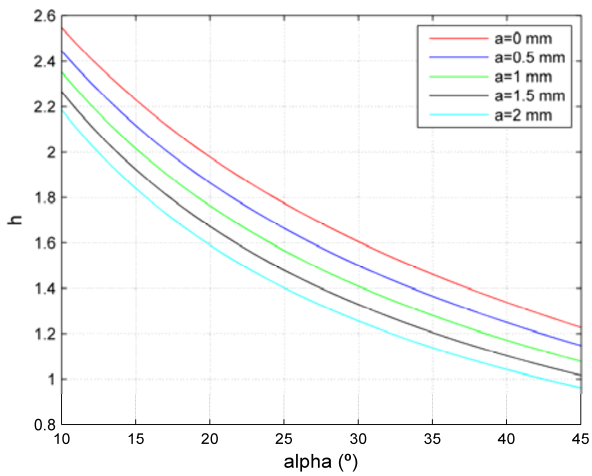

Figure 5. Evolution of h depending on abutment angle for several values of a (D = 3.5 mm, a = 2 mm).

In conclusion, it must be stated that when testing the fatigue strength of a dental implant system according to the ISO 14801 standard, and according to criteria established by this standard that says that the test shall be conducted under the worst-case scenario of all potential configurations of such system, the test shall be conducted using dental implants systems with straight connecting parts. This conclusion is only valid if fracture is located at point O' in figure 1 and the angle α is less than 42°.

4 EXPERIMENTAL VALIDATIONS

This section describes some experimental results to corroborate the analytical demonstration shown in the previous section. It has been analysed experimentally, following the guidelines of ISO 14801, the fatigue behaviour of a straight implant system and another one with pre-angled connecting part.

4.1 Description and specifications of dental implant system

The body of implant tested is a cylindrical threaded implant type, connected to its connecting part by an internal type connection. This implant system body is self-threading type, with three cutting grooves in the apical zone. It is made of grade 4 titanium in accordance with ISO-5832-2 [9]. A 25º angled column has been chosen to act as the connecting part. This element has been designed to hold the prosthesis performed by the prosthodontist. This connecting part has a through hole to accommodate a retention screw.

4.2 Testing methodology

According to ISO 14801 Standard, the dental implant system with straight connecting part shall be tested at an angle of 30° relative to the direction of loading and the dental implant system with pre-angled connecting part shall be tested with an undercorrection of 10°. The force is applied through the design of the hemispheric loading member ensures the geometric test conditions imposed by ISO 14801 Standard. The hemispheric loading member can be seen in figure 6.

The clamping system employed to place the sample in the correct test position is composed of a copper tube, with a longitudinal cut and the same inner diameter as the external diameter of the implant, and a jaw grip, figure 7. The implant is inserted into the copper tube which, when compressed by the jaws, is plastically deformed exerting a uniform tightening of the implant. With the exception of the tube, all components of the system are made of steel. The copper tube has an elastic modulus close to 110 GPa, above the minimum established by ISO 14801. The design of the loading device ensures no lateral constraints in the directions transverse to the load.

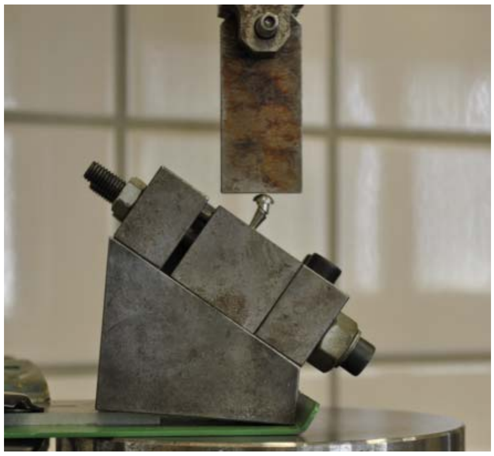

Figure 6 Hemispheric loading member configurations for pre-angled abutment test.

Figure 7 Clamping system with copper tube.

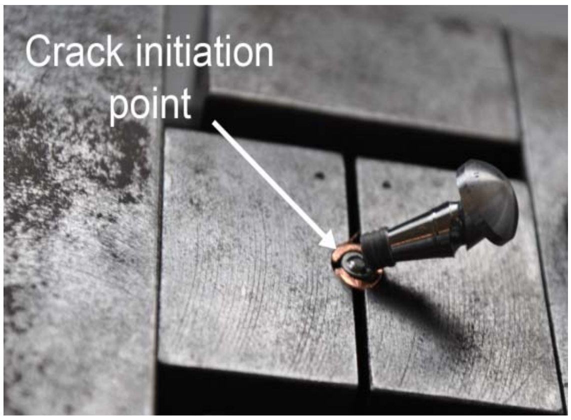

Figure 8 Failure Point.

The press system has lateral guides to ensure parallelism between the fixed and moving parts thereof. The torque applied to the screws is enough to produce small plastic deformation inside the copper tube. Screws are handily tightened ensuring that the clamping system is centred on the press system fixed and moving parts and, also, the final torque should be the same on both screws.

4.3 Test results

The initiation point of the crack is located at the surface of the implant system´s body, coincident with the specimen potting level, in the zone where, for this implant system, the tensile stresses are maximum. Later the crack propagates perpendicular to the implant axis. This occurs for both implants, with the straight and pre-angled connecting parts, figure 8.

In section 3 it was determined that for the same load and a certain range of angle *α*, the nominal stresses in the straight implant were higher than in the pre-angled one. Therefore, the fatigue strength of the implant with pre-angled abutment should be higher. Figure 9 shows the fatigue results for both set of implants showing the higher resistance of the ones with pre-angled abutment. The two groups of data come together if the same set of results are drawn but representing the nominal stress vs. number of cycles, as calculated in section 3, instead of the force, figure 10. This shows experimentally that the nominal stress calculated at the critical point determines fatigue life, for the same cross section of the implant.

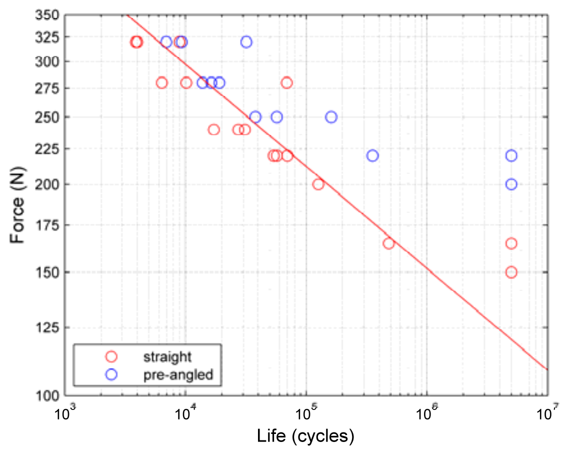

Figure 9. Fatigue test results (force vs. cycles).

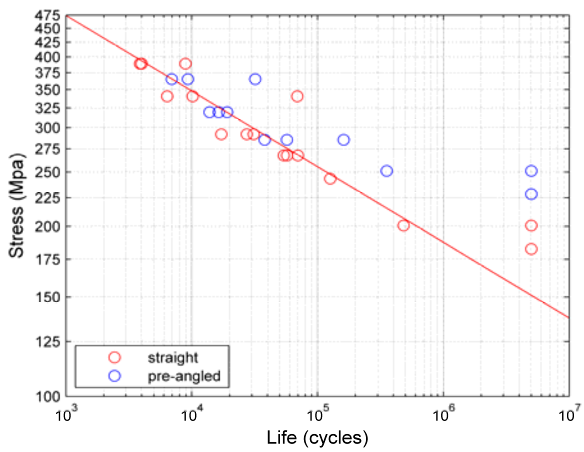

Figure 10. Fatigue test results (nominal stress vs. cycles).

5. CONCLUSIONS.

It has been shown theoretically and experimentally that the implants with pre-angled connecting parts have a higher fatigue strength if the ISO 14801 is used to validate them. Although this does not mean that they will last longer when they are collocated in the jaw because the loads applied in this case may have very different directions. This is a contradiction that the authors think should be pointed out and maybe lead to a modification in the standard. Nevertheless, more implants with different parameters needs to be tested to confirm these hypothesis.

ACKNOWLEDGMENTS

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