Fatigue in Dental Implants

J. M. Ayllón, C. Navarro, J. Vázquez and **J. Domínguez**

Departamento de Ingeniería Mecánica y de los Materiales, Escuela Superior de Ingenieros. Camino de los Descubrimientos s/n, 41092, Sevilla, España. cnp@us.es

ABSTRACT. *This paper studies the fatigue behaviour of dental implants made of commercially pure titanium grade 4. This work analyses the influence of different factors: stress concentration at the external thread and the surface treatment. This objective is achieved by designing a series of fatigue tests in simple geometries (smooth specimens with and without the surface treatment) and in commercial implants. On the other hand, the stresses in the implant have been modelled with ANSYS, from these stresses the stress intensity factor is calculated and the initiation and propagation phases are analysed. Finally the theoretical and experimental results are compared.*

INTRODUCTION

Dental implants are subjected many loading cycles during their life, mainly those produced during mastication. Fatigue may cause them to break, with serious consequences from a clinical standpoint. The design of implants, regarding geometry and materials, is continuously evolving. In order to evaluate the suitability of each design, standard fatigue tests must be performed in the implants. The standard used for this purpose in Spain is the UNE-EN ISO 14801 [1]. It states that a series of fatigue tests with different load levels must be performed, with increasingly lower values, to achieve three trials within the same load level with a duration over 5 million cycles. Obviously, obtaining this curve requires a great deal of time and money. Hence the interest in applying life prediction models to try to improve the design without resorting to so many tests.

There are many works that numerically model and study dental implants. Some of these studies compare the fatigue properties of various materials and the effect of surface treatment [2,3] while others estimate the fatigue life of an implant based on numerical calculations [4]. The aim of this paper is to develop a methodology to estimate the life of an implant based on material properties and on a numerical model of the implant. The paper analyses the behaviour of the implant in a standard fatigue test. A further step would be to simulate the fatigue process during the actual functioning of the implant in the jaw.

The process of fatigue failure of a component can be divided into two stages: the initiation and the propagation of a crack. These phases are modelled differently, multiaxial fatigue criteria are used for the first and fracture mechanics for the second. In theory, the two should be combined, but because of the difficulty involved in this, prediction models often disregard one of either. In practical cases where it is assumed from the beginning that there are large enough defects, the initiation phase can be disregarded [5]. In others, it will be assumed that most of the life is employed in initiation [6]. A widely used model is the critical distances one, where the stresses are evaluated in the stress raisers at a certain depth, in order to estimate the fatigue limit [7], or even to estimate life [8]. However, this sometimes leads to the evaluation of stresses from a distance that can measure up to several millimetres. In the case of implants, dimensions are so small that this would be impossible. Other prediction models combine the initiation and propagation of cracks [9,10].

The life prediction model used in this paper has previously been used successfully in several types of tests where there is a stress gradient: fretting fatigue with cylindrical contact, spherical contact, and fatigue in a holed plate [11,12]. This model combines the initiation and propagation phases without an a priori definition of where one ends and the other begins. In addition, it poses no problem when applied to components as small as implants.

MATERIAL CHARACTERIZATION

The material used in this study is commercially pure titanium Grade 4. It is an α phase with an oxygen content of 0.4% in weight and a grain size of 20 microns. This material is currently being used in the manufacture of implants in general and is replacing Ti-6Al-4V as it is free of alloying elements that may be harmful to the organism, such as vanadium. Both specimens and implants were provided by the company Galimplant ®. Tests were performed to determine the tensile strength, σ_u = 807 MPa, yield stress, σ_y = 775 MPa, and Young modulus, E = 104.5 GPa.

The crack growth properties of Ti-6Al-4V alloy will be employed [13], assuming that they are not very different, since the specific properties of the material used are currently not available. The constants used are $C = 1.8\ 10^{-13}$ and n = 5, for the velocity in metres/cycle, the stress intensity factor (SIF) in MPa $m^{0.5}$ and a load ratio R = 0.

For the fatigue properties, a series of tests were carried with zero mean stress and 10 Hz frequency on cylindrical specimens with a diametre of 3.5 mm. Two sets of tests were performed, with and without the surface treatment used in the implants. The measured surface roughness in the specimens without surface treatment was R_a = 0.2 µm. Fatigue tests were also performed with the same geometry but with the same surface treatment as applied to implants. This treatment is applied in order to produce a better osseointegration of titanium with the bone. The treatment, developed by the company Galimplant® and named Nanoblast®, consists in the generation of a surface with a high degree of purity in TiO_2 and with a roughness of about 2 µm. Figure 1 shows the fatigue curves of the titanium employed with and without surface treatment. It can be observed how this treatment reduces fatigue resistance, mainly for long lives. The reduction in the fatigue limit is approximately 12%.

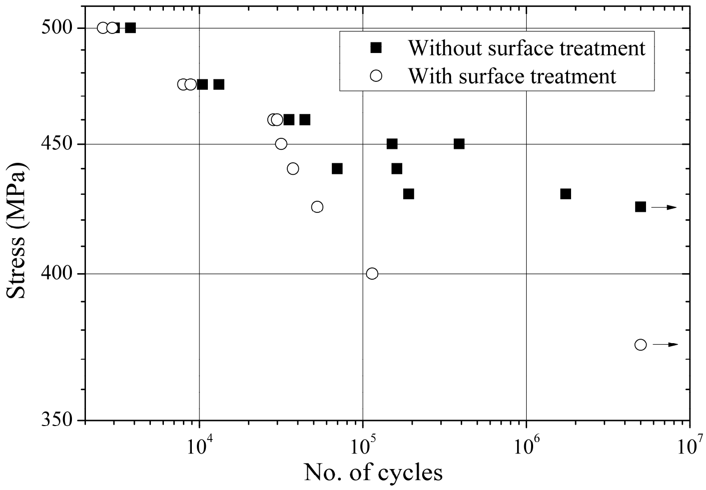

Figure 1. Fatigue curves in pure grade 4 titanium with and without surface treatment.

TESTING IN IMPLANTS

This section shows tested implants and the results obtained in the fatigue tests performed on them. Figure 2 shows the geometry of the implant tested and the way in which the load was applied. It is applied according to the UNE-EN ISO 14801 standard, which specifies that the force must be applied at an angle of 30 degrees from the axis of the implant and a load ratio of R = 0.1. The tests were carried out at a frequency of 10 Hz. There were tests conducted with maximum loads of 220, 200, 160, 150 and 140 N, which yielded lives of 9545, 14630, 56398, 182613 and 185723 cycles, respectively. One test with 130 N was interrupted after 5 10^6 without failure.

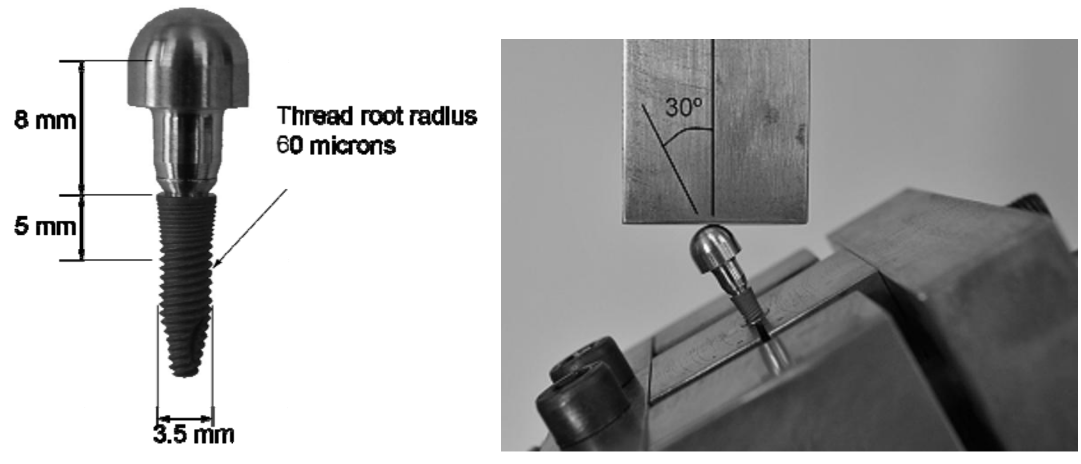

Figure 2. Geometry of the tested implant and the implant test setup.

NUMERICAL MODEL

The numerical model of the implant was performed in ANSYS. The purpose of this numerical model is to obtain the stresses and strains in the implant, as well as the SIF along the path of the crack. This information makes it possible to apply the calculation model described in the next section and obtain the fatigue life. The SIF was obtained using a weight function [14] in which the stress distribution is introduced in the plane where the crack grows, calculated by the finite element model.

The model of the implant, Fig. 3, required the use of a total of 311,064 solid187 10-node tetrahedral elements. The contact between the hemispheric load member and the pillar, as well as between the pillar and the body of the implant, was modelled using a "bounded" type contact. Conditions of null displacement were applied to the nodes located on the crests of the external thread of the implant body. This boundary condition in displacement was applied up to a certain height, specifically up to 5 mm below the platform of the implant body. Element density has been controlled in different parts of the model. There was a refinement of the mesh in the crack initiation area, where the size of the elements is 6 microns.

The model in the area around the place of crack initiation is elastoplastic, the rest being elastic. It was found that in the boundary zone between the two, the stress level was within the elastic regime, so that there were no sudden jumps in stress. Plasticity was modelled using kinematic hardening, with properties obtained from a test conducted in the laboratory.

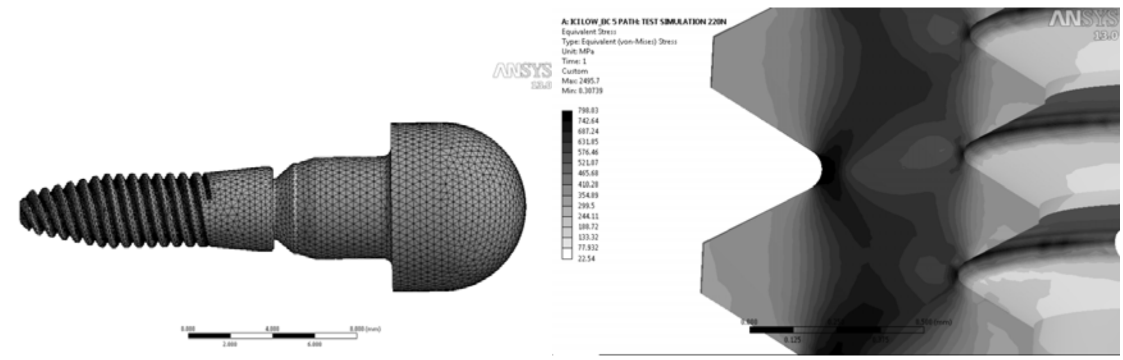

Figure 3. Model of the implant and von Mises stress distribution at the bottom of the thread.

Figure 3 also shows the distribution of the von Mises stress in the thread area. It should be taken into account that the implant is hollow and has an internal thread. This is the reason why the distance covered by the crack is so small. Figure 4 shows the evolution of the normal stress to the crack along the crack's path for the five load levels analysed. In all of them, there is a plastification at the bottom of the thread and the influence of the stress raiser reaches a depth of about 100 microns.

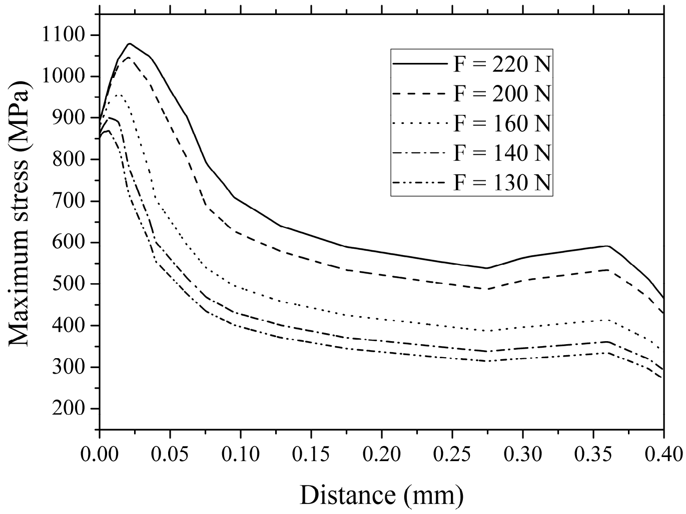

Figure 4. Normal stress to the crack in the five load levels analysed.

THEORETICAL MODEL

This paper uses a model for the prediction of life already proposed by the authors [12]. It bears the characteristic of combining the stages of initiation and propagation, without having to predefine the crack length at which the initiation ends and propagation begins. Each phase is analysed separately.

The initiation phase is analysed by determining the number of cycles required to generate a crack length *a*. This number is calculated from the stresses along the path followed by the crack and from a fatigue curve ε-N, which will be detailed later. The result is a curve, $a - N_i$, representing the cycles required to cause a crack of length *a*. In the propagation phase, there is a calculation of the number of cycles it takes to propagate a crack, from any length *a* up to failure, using fracture mechanics. To do this, the growth law is integrated from each crack length, *a*, until failure, yielding the curve ($a - N_p$). The sum of these two curves would provide the total life depending on what value is taken for the crack length separating the initiation and propagation phases. These two curves show that the initiation process dominates near surface, and the propagation process does so farther from it, so that the link between the two is found in the minimum of the total life curve described above. For this reason, and because it is the most conservative value, the minimum of the curve is taken as the solution.

Initiation phase

The model presented in this paper analyses the initiation phase based on the work of McClung et al. [15] for notches. The first step consists in obtaining a fatigue curve, $\varepsilon - N|_{a_t}$, in smooth unnotched specimens, to provide the number of cycles required to generate a crack of length a_t, as a function of the applied strain. For each level of strain,

ε_j, the number of cycles of this curve, $N_{\varepsilon_j a_t}$, is obtained by subtracting the growth of the crack from a_t to failure from the total number of cycles. Each curve, $\varepsilon - N|_{a_t}$, for different values of a_t will be called initiation curves.

In case of application of the model in a simple fatigue test, the number of cycles required to generate a crack of length, a_t, could be calculated using the appropriate curve, $\varepsilon - N|_{a_t}$. In the case of a component with a multiaxial state and stress gradient, the same process may be applied, but with some modifications. Firstly, this requires a multiaxial fatigue criterion; in this case, Fatemi-Socie [16] shall be used. Subsequently, the Fatemi-Socie parameter (*FS*) is calculated for each strain level in the initiation curves, $\varepsilon - N_i|_{a_t}$, obtained previously. With this, the new curves are constructed, $FS - N_i|_{a_t}$. On the other hand, when there is a notch, stress decreases rapidly with depth, from a maximum at the surface. Therefore, the estimated initiation life will be one or the other, based on where the damage parameter used is assessed. The option considered most appropriate is to calculate the average *FS* between the surface and the crack length a_t, and with it, to enter the curve $FS - N_i|_{a_t}$ and obtain the number of cycles required to generate a crack of length a_t. This option implies the hypothesis that an equal value for the average damage parameter in the area will produce the same number of cycles to initiate the crack of that length.

Propagation phase

Fracture mechanics are applied for the propagation phase, taking as initial length a generic length, *a*. The growth law used also attempts to model the growth of small cracks, since the defined initiation length can be in the order of microns. The way to do this is by introducing a modified growth threshold as a function of crack length [12].

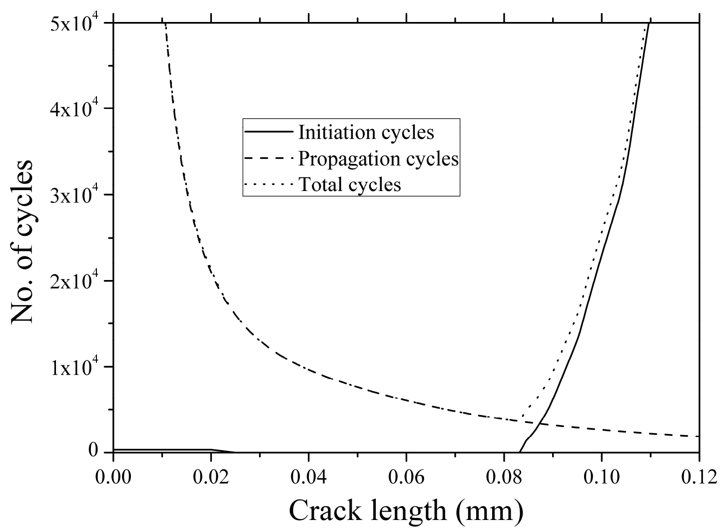

Figure 6. Application of the prediction model in the test with F = 220 N.

Combination of initiation and propagation

Once the two previously mentioned curves have been obtained, ($a - N_p$ y $a - N_i$), represented in Fig. 6 for test F = 220 N, they are both added, rendering a curve that represents the total life as a function of the value taken for initiation length. The minimum is taken as the fatigue life, and the point where the minimum occurs is taken as the initiation length. This model can be compared with others where the length from which propagation is taken is defined a priori. Applying this model would be equivalent to entering the graph in Fig. 6 with a predetermined crack length a, obtaining an initiation and a propagation life. The advantage of the proposed model is that it is more conservative and there is no need to make a decision regarding when one phase ends and the other begins.

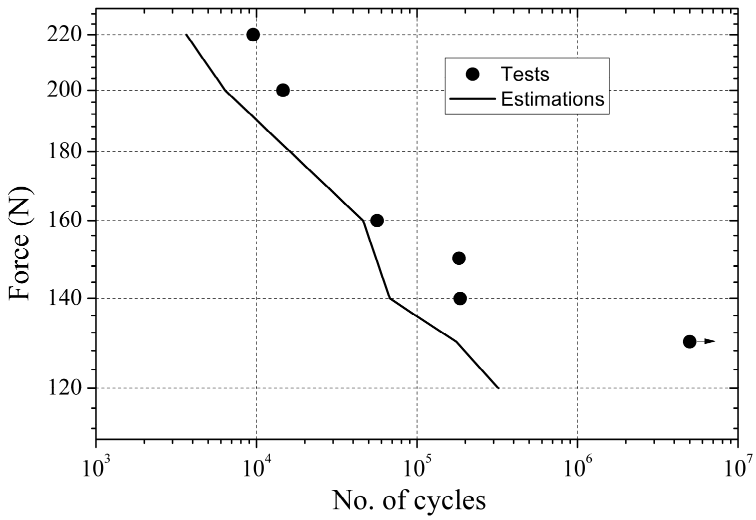

Figure 7. Fatigue tests in implants and theoretical estimates.

LIFE ESTIMATION AND COMPARISON OF RESULTS

Figure 7 shows the results of fatigue tests in the implants, together with theoretical predictions using the model explained in the previous section. The predictions are reasonable and somewhat conservative. The slope of the estimated curve is practically equal to the one obtained in the tests. It is important to highlight that the entire process of crack initiation and propagation takes place within less than half a millimetre, and that the model is able to reflect this in an acceptable manner.

Apart from the potential errors of the model, another reason for the differences obtained may be an error in material characterization, in both initiation and propagation, since the number of tests performed is relatively small. Consequently, in view of the results, it can be said that regardless of the reasonable fitting to the experiments, it is necessary to perform a higher number of characterization tests, as well as testing in complete implants. In the latter case, it will be interesting to have more results, both for each load level and for loads corresponding to longer lives.

CONCLUSIONS

The result of this study shows that the proposed life prediction model, also used in various other situations, is very versatile and robust, adapting to different circumstances.

Is important to emphasize that this model fits the life prediction of implants, elements which, given their small size, can present problems of scale. In any case, this study should be extended by a more complete characterization of the material and a greater number of verification tests in implants.

ACKNOWLEDGEMENTS

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