# Fatigue Life Prediction of Titanium Specimens With TiO<sub>2</sub> Surface

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*Abstract:* - Most of mechanical components in the engineering are frequently subjected to multiaxial loading, which also applies to medical engineering. The cyclic-loading can lead to sudden fatigue failure. In present work the fatigue life of cylindrical titanium components made from titanium alloy Grade 23 is studied. This type of material is often used for dental implants. The surface treatment is used to improve biocompatibility of implants. The preferred surface treatment is titanium dioxide deposition. Contrary to well known surface layers used in industry whose main task improvement of resistance to the fatigue, corrosion and wear, the goal of deposition is to improve acceptability of implants by human body and the surface treatment can even reduce fatigue resistance. This reduction of fatigue resistance is undesirable. This problem leads engineers to find optimal solution.

*Key-Words:* - Fatigue life, Titanium alloys, Biaxial loading, Surface treatment, Titanium dioxide, Biocompatibility

#### **1** Introduction

In material science, fatigue life is progressive and localized structural damage that occurs when a material is subjected to cyclic loading [1,2,3,4,5]. The nominal maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the materials. Fatigue occurs when a material is subjected to repeated loading and unloading. If the loads are above a certain threshold, microscopic cracks will begin to form at the surface. Eventually a crack will reach a critical size, and the structure will suddenly fracture.

An example of such periodic stress can be a dental implant [6]. The dental implant consists of a ceramic crown that is attached to a threaded thorn. This thorn with thread is inserted in the housing box, which is ingrown in the bone of the jaw.

In this work we don't pay attention to the biological causes of the implant failure, in which the body rejects the implant as a foreign body. This is often related to various inflammations and other diseases [6,7,8,9]. In this work we will deal with the mechanical causes of the implant failure.

respectively one of them, fatigue failure of a threaded thorn caused by cyclic loading. The thorn with thread is practically an example of cylindrical specimen with notch under bending- torsion loading.

By changing surface layer properties of machinery parts it is possible to increase considerably their load-capacity. In case of implants the first task of surface treatment is improved biocompatibility, i.e the material of implant can release harmfull particles in the body and various body fluids can settle down and stiffen on the surface of implant. These stiff biological sediments on the implants surface are very often reason for implants rejection by the body.

The preferred surface treatment is titanium dioxide deposition [7]. The  $TiO_2$  surface is an example of nanosurface with rare and for implants important self-cleaning properties. The effect of self-cleaning significantly increases the likelihood of receiving the implant by the human body.

On other hand positive effect of dioxide surface on the fatigue resistance of implant is disputable. With regard to it and intensive cyclic loading of dental implant, it is necessarily study this problem.

## 2 Experimental Procedure

The most of implants used in dental medicane are manufactured from titanium alloys. Probably the most appropriate titanium alloy is Ti-6Al-4V ELI alloy. The abbreviation ELI means Extra-Low Interstitials, i.e this alloy is processed by special technology that reduced number of interstitial atoms. The reason for reduction of interstitial atoms is that its diffusion in the body. The interstitial atoms of vanadium are harmfull and these harmfull atoms can easily penetrate in the body.

The alloy Ti-6Al-4V ELI (Grade 23) is very close to the alloy Ti-6Al-4V, which is intended for industrial use, and its mechanical properties are practically the same. The mechanical properties of materials are: Elastic modulus E = 113.8 MPa, ultimate strength  $\sigma_u = 893$  MPa, yield stress  $\sigma_y = 827$  MPa, crack growth properties are characterised by constants  $C = 7.8 \cdot 10^{-14}$  and m = 4.9. These two constant are known from the Paris-Erdogan law. Crack growth properties were measured according to ASTM E647 [9]. The TiO<sub>2</sub> surface was formed by Plasma Immersion Ion.

The plasma immersion technique can be described thus: the surface of sample or the surface substrate is exposed to the plasma beam and that a relatively high substrate bias voltage is applied. The substrate bias is usually pulsed and so saturated by particles for refining the surface.

The fatigue experiments were made by means of the multiaxial-test machine MZGS-100 of the Polish provenience. Specimens were loaded at the room temperature up to final rupture. The applied loading of frequency 29Hz comprised symmetric (R = -1) sinusoidal bending and torsion and their synchronous in-phase combination.

## **3** Multiaxial Fatigue

In reality, majority of mechanical parts in engineering are subjected to the multiaxial loading, which is combination of simple loading modes such as, torsion, bending or tension. One of the most difficult tasks in design against fatigue and fracture is to translate the information gathered from uniaxial fatigue and fracture tests on engineering materials into applications involving complex states of cyclic stress-strain conditions. Many multiaxial fatigue criteria have been represented in the literature [5,10,11,12,13,14,15,16] but there is no generally accepted criterion for multiaxial loading now.

In this paper thirteen classical and advanced multiaxial criteria were utilized to predict the fatigue life under combined bending-torsion. When the individual components of stress tensor are inphase during the loading, the fatigue life is usually shorter than thatin case of out-of-phase loading. The normal and shear stress components  $\sigma_a$  and  $\tau_a$ , acting in a critical volume, control the fatigue life under combined bending-torsion loading. When these components are known, the prediction of biaxial fatigue life using uniaxial data is basically possible. The multiaxial criteria divide the stress space to the safe and the unsafe parts. The points bellow the boundary line lie in the safe region whereas the points above the line are in the unsafe region. The most general form of fatigue criteria can be written as an inequality:

$$a \cdot f(\tau_a) + b \cdot g(\sigma_a) \le \sigma_c, \qquad (1)$$

where *a* and *b* are parameters obtained from two uniaxial fatigue limits (e.g. fatigue limit in fully reversed torsion  $\tau_c$  and in repeated tension  $\sigma_c$ ). The linear combination of shear stress  $\tau_a$  and normal stress  $\sigma_a$  in Eq.1 can be replaced by a quadratic form. If the load data of the left–hand side LHS of Eq.1 correspond the to experimentally determineded fatigue limit, the ideal state of equality should be achieved. The accuracy of the fatigue life prediction by means of multiaxial criteria can be expressed by the so-called error index *I*:

$$I = \left(\frac{LHS - RHS}{RHS}\right) \cdot 100\%, \qquad (2)$$

where RHS is the right-hand side of the inequality. The error index expresses a percentage of deviation from the real fatigue life. The ideal prediction leads to LHS = RHS, i.e. I = 0. The positive value of the error index means, that the criterion yields conservative results, that the real fatigue life is higher than that calculated and, therefore, the prediction lies on the safe side of the boundary line.

Scope of this article does not allow a deeper analysis of all the compared criteria, and for this reason are discussed only some of the selected criteria. As the examples of classical fatigue criteria were tested criteria proposed by Gough and Pollard, McDiarmid, Matake or Kakun-Kawado criteria [5] The Gough - Pollard criterion is probably the oldest multiaxial criteria proposed in the thirties of the twentieth century. Gough and Pollard [5] suggested an empirical ellipse formula as a multiaxial fatigue criterion. This relationship is suitable for ductile materials:

$$\left(\frac{\sigma_a}{\sigma_c}\right)^2 + \left(\frac{\tau_a}{\tau_c}\right)^2 \le 1,$$
(3)

In the case of brittle materials (for example cast irons) we used modified Gough - Pollard criteria in the form [5]:

$$\left(\frac{\sigma_a}{\sigma_c}\right)^2 \left(\frac{\sigma_c}{\tau_c} - 1\right) + \frac{\sigma_a}{\sigma_c} \left(2 - \frac{\sigma_c}{\tau_c}\right) + \left(\frac{\sigma_a}{\sigma_c}\right) \le 1, \quad (4)$$

The McDiarmid [13,14] criterion is frequently used, because criterion is implemented in commercial fatigue software (for example MSC.Fatigue or FE-Fatigue). McDiarmid identifies the plane of maximum shear stress range. Damage is computed on this plane by combining the shear stress and normal stress. The McDiarmid criterion can be written according to convention used here generally (see Eq. 1):

$$\frac{\sigma_C . \tau_{a,\max}}{t_{AB}} + \frac{\sigma_C}{2R_m} \le \sigma_C, \qquad (5)$$

Where the  $R_m$  is the ultimate strength. Subscript *a* mean amplitude and subscript *max* denotes maximum value of stress. The subscript *AB* in this criterion represents choice between  $t_A$  a  $t_B$  fatigue limits corresponding to load conditions leading to cracks growing parallel to the surface (system A) or inwards from the surface (system B). This distinction between two cracking systems is not usually defined. In the case of plane bending combined with torsion is generally fulfilled equality  $t_{AB} = t_I$  [5,13,14].

The Matake criterion can be expressed as:

$$a_M \tau_{a,MSSR} + b_M \sigma_{\max,MSSR} \le \sigma_c.$$
(6)

Subscript MSSR by normal shear stress criterion means critical plane set according to Maximum Shear Stress (or Strain) Range criteria. Parameters  $a_M$  and  $b_M$  in this criteria are defined as  $a_M = \kappa$  and  $b_M = 2 - \kappa$ . Variable  $\kappa$  is fatigue limits ratio  $\kappa = \sigma_c / \tau_c$ .

The Kakuna-Kawada criteria [5] criterion can be written as:

$$a_K \sqrt{J_{2,a}} + b_K \sigma_{H,a} + c_K \sigma_{H,m} \le \tau_c, \qquad (7)$$

where the  $J_{2,a}$  is the second invariant of stress tensor deviator. The  $\sigma_{H,a}$  and  $\sigma_{H,m}$  are amplitude and mean value of hydrostatic stress.

The example of advanced stress based multiaxial criteria are Papadopoulos (integral approach) [10,11,15] or Goncalves, Arajo and Mamiya criteria GAM [16]. In Papadopoulos criterion (integral approach) are both input variables (shear stress and normal stress) integred over all planes [10,11,15]:

$$\sqrt{a_P \iiint T_a^2 d\chi \sin \psi d\psi d\varphi} + b_P \cdot \sigma_{H,\max} \le \sigma_c,(8)$$

The  $T_a = (T_a(\varphi, \psi, \chi))$  is amplitude of resolved stress. The  $\varphi$ ,  $\psi$  and  $\chi$  are Euler angles. The  $\sigma_{H,\max}$  is maximum value of hydrostatic stress. The parameters  $a_P$  and  $b_P$  are defined as:

$$a_P = \frac{5\kappa^2}{8\pi^2} \tag{9}$$

And

$$b_P = 3 - 3\kappa \,. \tag{10}$$

Criterion proposed by Goncalves, Araujo and Mamiya is quite new [18]. It is based on a construction of minimum circumscribed ellipsoid over the load path in five-dimensional deviatoric Ilyushin space. The Gonçalves Araujo and Mamiya criterion is expressed as:

$$a_{GAM} \sqrt{\sum_{i=1}^{5} d_i^2} + b_{GAM} \sigma_{1,\max} \le \sigma_c, \qquad (11)$$

where parameters  $d_i$  can be determined from minimum and maximum values of the transformed deviatoric stress tensor:

$$d_{i} = \frac{1}{2} \left( \max s_{i}(t) - \max s_{i}(t) \right), \tag{12}$$

The parameters  $a_{GAM}$  and  $b_{GAM}$  are defined as:

$$a_{GAM} = \frac{\kappa - 1}{\sqrt{2} \left( 1 - \frac{1}{\sqrt{3}} \right)}$$
(13)

and

$$b_{GAM} = \frac{\sqrt{3} - \kappa}{\sqrt{3} - 1} \,. \tag{14}$$

### 4 Results

The calculated error indexes are shown in Table 1. For all studied criteria were calculated average  $I_{avr}$ and absolute average *I<sub>ABS,avr</sub>* values of error indexies. The comparison of multiaxial criteria data relevealed that the Matake criterion was the most successful in the fatigue life prediction for surface threated specimens. If we consider the complex of fatigue prediction criteria, such as Padopoulosovo criterion and their possible use in professional software for industrial computing can be considered a suitable criterion proposed by Goncalves, Araujo and Mamiya [16]. This criteria is very suitable for implementation in software designed for industrial practice, which will be implemented in mass calculations of fatigue strength. Because, the calculations made by the following criteria are substantially faster than that in the case of criteria Papadopulos or other.

#### **5** Conclusion

The application of titanium dioxide surface implemented by plasma immersion leads to small decrease (between 5% to 10%) in the fatigue resistance in the low cycle region. This fatigue decrease is not important. So there it is not reason to use thread for implant without treatment, because there is greater risk for implant failure from biological reason than from the fatigue loading.

However, the fatigue strength dramatically drops when the peak stress in the cycle reaches the strength of the  $TiO_2$  particles. It is therefore necessary to spread the  $TiO_2$  particles evenly over the surface.

The comparison of multiaxial criteria revealed that the Matake criterion was the most successful in the fatigue life prediction. The average value of the error index (taking into account the sign) is the lowest one ( $I_{avr} = -0.21$ ). Also the average absolute value of the error index ( $I_{ABS,avr} = 7.93$  %) is second lowest.

Multiaxial criteria	Error indexes	
	I <sub>avr</sub> [%]	$I_{ABS,avr}$ [%]
Mod. Gough - Pollard	-5,83	9,21
Mod. Gough – Pollard – for brittle materials	-0,36	8,78
Findley	-0,78	9,62
Matake	-0,21	7,32
McDiarmid	1,79	8,47
Spagnoli	-0,45	8,03
Papadopoulos-Critical Plane Approach	-8.2	17,23
Marin	4,28	8,72
Sines	13,65	12,32
Crossland	-3,47	8,65
Kakun - Kawado	-2,49	8,65
Dang Van	-1,55	8,95
Papadopoulos – Integral Approach	-2,35	8.46
GAM	-2,25	7,93

Tab. 1 Average  $I_{avr}$  and absolute average  $I_{ABS,avr}$  values of error indexies.

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