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MODELLING OF ENVIRONMENT EFFECT ON THE FATIGUE OF AN AISI 316L STEEL

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Résumé

L'analyse du comportement d'implants en acier inoxydable austénitique, soumis à des sollicitions dynamiques et exposés à un milieu physiologique, demeure importante afin de déterminer leur durée de vie. Dans ce but, des simulations de fatigue-corrosion d'éprouvettes pré - entaillées ont été effectuées. Les entailles initiales sont des piqûres stables obtenues par polarisation électrochimique dans une solution de $FeCl_2$. Les calculs ont été effectués en utilisant des conditions mécaniques et électrochimiques qui reproduisent celles observées sur des implants humains. Deux modèles de fatigue ont été appliqués : le modèle mécanique de Höeppner et le modèle mécano - chimique de Newman.

Les résultats numériques donnent le nombre de cycles menant à la transition de piqûre- fissure puis à la rupture complète. L'effet de la taille initiale d'entaille sur le comportement de fatigue de l'acier inoxydable est mis en relief. Les deux modèles de fatigue indiquent qu'une faible taille initiale de l'entaille augmente le nombre de cycles à rupture. La courbe de Wöhler, pour les deux milieux et pour différentes valeurs de la contrainte appliquée, montre que l'action mécanique a beaucoup plus d'influence pour les charges élevées, alors que l'action chimique est prédominante lorsque les charges mécaniques diminuent, réduisant ainsi considérablement la vie du matériel. La prévision de la vie doit également inclure l'effet d'autres paramètres tels que la fréquence de charges cycliques.

Mots clés **:** *Acier inoxydable austénitique, fatigue, corrosion, piqûres, air*

Abstract

The analysis of the behaviour of austenitic stainless steels, under dynamic stress in physiological medium, remains important in order to determine their lifetime when they are used in implantology. In this purpose, simulations of fatigue corrosion of pre-notched specimens were carried out. Input notch data were taken from stable pits obtained by preliminary polarization tests in a solution of $FeCl_2$, by taking two different concentrations (0,5 and 1M). Calculations were made using effective mechanical and electrochemical conditions observed on human body implants. Two fatigue models have been applied. Höeppner model is only a mechanical one, whereas Newman model adds chemical effect.

Numerical results indicates the number of cycles leading to critical size of pits-to-crack transition and then to failure. Furthermore, the effect of the initial notch size on fatigue behaviour of the stainless steel is highlighted. Both models indicate that decreasing initial notch size raises the number of cycles to failure. Adding chemical action to mechanical one accelerates the damage, in general. However, at higher sizes, one can observe a slowing down of the chemical effect. The curve of Wöhler for different mediums and values of applied stress shows that the mechanical action has much more influence when high loads are applied. As the stress applied decreases, the electrochemical effect becomes extensive and reduces considerably the lifetime of material. The prediction of lifetime needs thus to include the effect of other parameters, such as stress frequency, in order to compare it with real implant lifetime.

Keys words **:** *Austenitic stainless steel, fatigue, corrosion, pits, air*

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ملخص

ان تحليل السلوك الميكانيكي للحديد المقاوم للصدأ 316L تحت تأثيرات دورية ميكانيكية في وسط فيزيولوجي ذو أهمية قصوى لتحديد عمره عند استعماله كمثبت في جسم الانسان. لهذا الهدف تم القيام بمحاكاة الاجهاد - الصدأ لمخابيرمحقنة ابتدائيا عن طريق تجارب تقطيب في محلول $FeCl_2$ بتركيزين مختلفين لحساب. مختلف العوامل تم أخذ الشروط الميكانيكية والإلكتروكيميائية لحركة الجسم بعين الاعتبار، كذلك تم استخدام نموذجين للحساب الأول ميكانيكي لهوپنر أما الثاني فهو لنيومان ويأخذ العامل الكيميائي في الحسبان.

النتائج الرقمية أظهرت عدد الدورات المؤدي لتحول الدرزة الى شق ثم الى انكسار نهائي. إن تأثير الحجم الأولي للدرزة على عدد الدورات كبير جدا، إذ بينت الحسابات بكلا النموذجين أن صغر الحجم الأولي يزيد هذا العدد بينما كبره ينقص عدد الدورات وبالتالي مدة الحياة. كما أن زيادة العامل الكيميائي يقوم بتسريع الضرر لكن تزايد حجم الكسر يخفض من تأثير هذا العامل.كما أن رسم منحنيات ڤولر بين أن التأثير الميكانيكي أكثر اهمية منه عند تطبيق ثقل كبير لذلك فكلما نقص الثقل تسارع تآكل المادة كيميائيا.

لكل ذلك نستطيع القول أن افتراض عمر المثبتات يحتاج لدراسة تشمل مؤثرات أخرى كالتردد مثلا.

الكلمات المفتاحية **:** *حديد مقاوم للصدأ، اجهاد ،صدأ، درز، هواء*

When one introduces an implant into human body, such as plates allowing the fixing of the fractures, articular prostheses, dental implants, these materials find themselves under biological stress. This means that they will undergo, at the same time, a chemical and even a biochemical attack, by the biological environment, and a physical aggression by the mechanical environment. Moreover, the stresses acting on the implant are dynamic. For example, the articulation of the hip undergoes alternations of load [1].

The stainless steel remains the base metal of osteosynthesis, because of its generalized corrosion resistance, its ductility leading to mechanical deformation, and its low cost, thus its availability. The analysis of the behaviour of the austenitic stainless steels, under dynamic stress in physiological medium, remains important in order to determine their lifetime when they are used in implantology.

This study aims to determine the durability of such pre-notched steels plates, in artificial physiological conditions, under a dynamic stress, by considering the bending fatigue test. For the needs of modelling, we used two models for characterizing fatigue behaviour. Höeppner model is tested in air conditions (pure fatigue), whereas Newman model allowed us to characterize fatigue corrosion.

1. DESCRIPTION OF THE MODELS

1.1. Model of Höeppner.

Höeppner [2] proposed a model which estimates the number of cycles of fatigue so that a pit of corrosion can be transformed into a crack. The model gives then the critical size of the crack involving the failure of material. The model is based on the expression of the stress intensity factor K_{sf} for a pit considered as a crack. In the case of a fatigue test, the applied stress σ is related to the notch size a by the following relation :

$$K_{sf} = \sigma\sqrt{\pi a} \qquad (1)$$

The model of Höeppner is characterized by the correction of the previous formulae, by introducing a parameter Q, function of the size of pit and material [3]:

$$K_{sf} = 1.1\sigma\sqrt{\pi\frac{a}{Q}} \qquad (2)$$

Q is expressed by:

$$Q = \left(\frac{\pi}{2}\right)^2\left[\frac{3}{4}+\left(\frac{a}{2c}\right)^2\right]^2 - \frac{7}{33}\left(\frac{\sigma}{\sigma_{ys}}\right)^2 \qquad (3)$$

σ_{ys} represents the elastic limit of material and $2c$ the diameter of the pit.

Höeppner estimates that the factor K_{sf} of a pit is equal to the theoretical stress intensity factor ΔK_{scth} corresponding to the crack initiation. Therefore, the relation (2) determines the critical size of the pit that involves the beginning of the crack.

The Paris law gives the number of cycles making it possible to reach this depth of crack:

$$\frac{da}{dN} = C.\Delta K^{n} \qquad (4)$$

where C and n are material parameters and N the number of cycles.

1.2. Model of Newman and Raju [4, 5]

Newman and Raju took account of geometrical shape in mechanical aspects and proposed another calculation method of the threshold of the transition from corrosion pit to crack. It considers a hemispherical shape for the pits and includes the specimen plate dimensions. The applied stress σ is related to the notch size by the following relation:

$$\Delta K = \frac{2}{\pi}\Delta\sigma\sqrt{\pi a}\left[1.04+0.201\left(\frac{a}{h}\right)^2+0.106\left(\frac{a}{h}\right)^4\right].\left[1.1+0.35\left(\frac{a}{h}\right)^2\right] \qquad (5)$$

where a is the crack radius and h the sample plate thickness. The crack growth rate is still given by Paris formulae.

2. MATERIAL

The 316L austenitic stainless steel used has the following chemical composition (table 1).

Table 1 : Chemical's composition of 316L stainless steel

Fe %	Cr %	Ni %	Mo %	Mn %	S %
64,46	17,556	11,889	2,482	1,490	0,017

Potentiodynamic tests have been realised at the ambient temperature, in a chlorinated medium (respectively with 0,5 and 1M of $FeCl_2$), aerated and stirred. Sweeping in tension was carried out between -1000 and +1000mv, at a speed of 0,5mv/s. The pH of the solution was measured before and after tests and gives relatively equal values (3,3 to 3,5). The curves of polarization I = f(E) show the absence of an obvious transition active field – passive field and a value of potential of pitting which is next of 350 to 400mv/ECS [6]. These results are rather close to those known for this kind of steels [7, 8].

3. APPLICATION OF MODELS

The various results of the application of models to our study are indicated in table 2. The value taken for the stress applied is equal to 200MPa, which corresponds to the effort on of the hip articulation during walking [1].

The yield stress of the stainless steel is of 280MPa [1]. The notch used to start the mechanical stress corresponds to the pit obtained at the end of the electrochemical test. Because corrosion pits have different sizes, we have taken two hemispherical pits diameter, one of 150µm and the second of 250µm.

3.1. First case: pit diameter of 150 µm.

The average diameter of the pit - hemispherical notch is 150µm. The stress intensity factor for this pit is equal to 2,41MPa.m^{½}. To determine the critical size of the pit which can be considered as a crack, we take $K_{sf} = \Delta K_{scth}$ = 4,6MPa.m^{½} for the same applied load [3], that gives a pit size of 544µm, value considered equal to the depth of the crack. The number of cycles, necessary to reach this starting size from a pit of 150µm and for a load of 200MPa, is calculated from formulae (3), by taking $C = 4{,}343.10^{-10}$ and n = 3,794 for pure fatigue [9].

Concerning the corrosion fatigue, C and n are determined from crack growth rate curve of an austenitic stainless steel into an aggressive medium (3,5% NaCl), at room temperature [10]. Theses values are $C = 4{,}15.10^{-10}$ and n = 3,4. So, 20203 cycles are required for pure fatigue and 14644 cycles for corrosion fatigue. The crack develops itself and reaches a critical size for a stress intensity factor $K = \Delta K_{all}$ = 16MPa.m^{½} [3]. Because specimen thickness is only of 1mm, failure is observed at 21969 cycles for pure fatigue and 15781 cycles for corrosion fatigue.

3.2. Second case: pit diameter of 250µm

The average diameter of the hemispherical pit is 250µm. The critical size for it's transformation until the crack initiation is 544µm. The number of cycles that corresponds to this situation is of 11733 cycles for pure fatigue and 8658 cycles for corrosion fatigue. To reach failure, it does require 13286 cycles for pure fatigue and 9833 cycles for corrosion fatigue.

Table 2 : Stress intensity factors and cycles number corresponding to the two initial notch sizes.

Initial pit diameter	stage	a (mm)	da/dN (10^{-7}m/cycle)		N (cycles)	
			Model of Höeppner	Model of Newman	Model of Höeppner	Model of Newman
150 µm	Initiation	0,544	1,43	1,89	20203	14644
	Failure	1	4,46	10,3	21969	15781
250 µm	Initiation	0,544	1,68	1,89	11733	8658
	Failure	1	4,9	12,24	13286	9833

4. DISCUSSION OF RESULTS

Figure 1 shows that, for the same mechanical and geometrical conditions, it needs less number of cycles for the pit-to-crack transition when specimens are inside a corrosive medium than in air. As well as for pure fatigue, the following step, i.e. crack propagation acts in the same manner.

In figure 2, the crack growth rate is represented as a function of crack size because the sample thickness is only 1mm. Once the size of crack reaching this value, it is assumed that the failure is observed. The effect of the electrochemical action accelerates strongly these speeds. The fatigue corrosion rate is then a superposition of the rates of pure fatigue and corrosion [11].

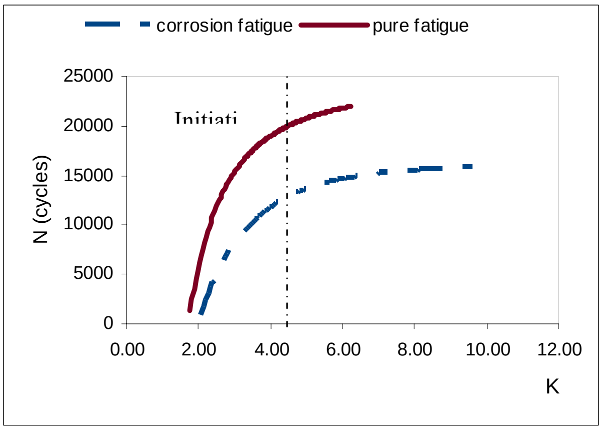

Figure 1 : Variation of the number of cycles versus stress intensity factor (initial pit diameter 150µm).

When mechanical action deforms crack, the area exposed to the corrosive environment becomes greater. Thus, corrosion rate rises and the quantity of waste material is more important and therefore accelerates the fatigue mechanism. At a greater crack size, environment effect is more dominant than mechanical one. Environment crack growth rate has the same behavior as in pure fatigue.

Moreover, as fatigue and chemical actions are applied simultaneously, a coupling phenomenon can be observed. Thus, corrosion fatigue can not be expressed by a simple summation of pure fatigue and corrosion processes [12]. We need to add a supplementary parameter $(da/dN)_e$ to give a more realistic description of the phenomena (formulae 6).

This parameter contains corrosion and interaction effects :

$$(da/dN)_{cf} = (da/dN)_{af} + (da/dN)_e \qquad (6)$$

where $(da/dN)_e$ has the same appearance as a fatigue term:

$$(da/dN)_e = A.a^m \qquad (7)$$

A and *m* parameters express the crack growth rate and are in dependence of material and environment. In our case their values are, from figure 2, respectively :

$$A = 6{,}1.10^{-7} \text{ and } m = 4{,}32.$$

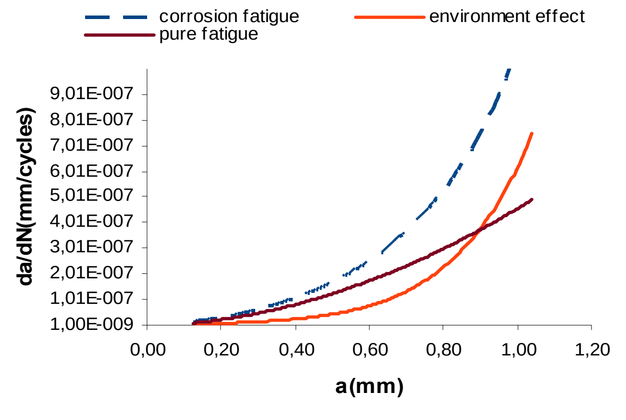

Figure 2 : Variation of the propagation rate with the crack size.

The Wöhler curve (figure 3) shows that the mechanical action is much more important when high loads are applied. As the stress applied decreases, the electrochemical effect becomes extensive and reduces considerably the lifetime of material. Many authors estimate that the associate reduction is almost the half of the value [13].

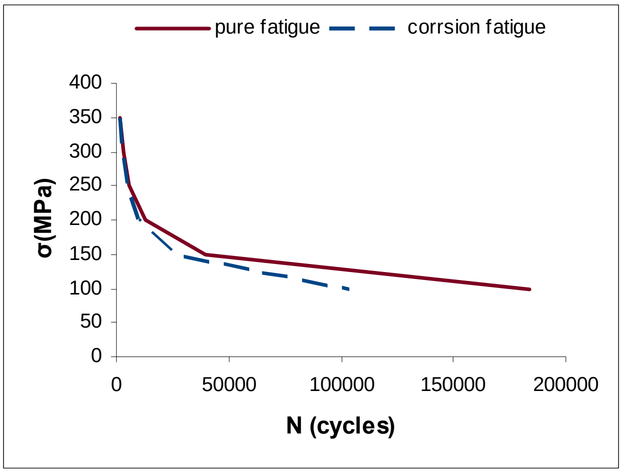

Figure 3 : Variation of the number of cycles with the applied stress.

Both Höeppner and Newman models indicate that decreasing initial notch size raises the number of cycles leading to failure (figure 4). Greater cracks have more effects on mechanical and chemical actions and accelerate their growth rate. But for small cracks, the mechanical effect is more important.

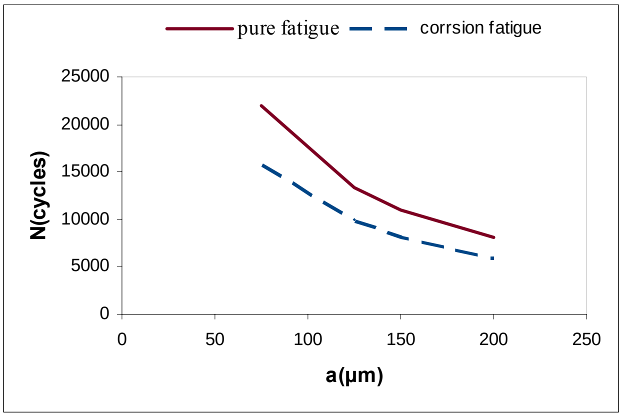

Figure 4 : Effect of initial pit size on the number of cycles to reach failure.

CONCLUSION.

The bending fatigue behaviour of an austenitic stainless steel plate, on which preliminary pits were formed, shows several aspects. The initial surface quality, related to the size of the pits, due to the concentration of the electrochemical medium first used, becomes detrimental when the pits are large. It is then significant to control the conditions of using the implants (friction, wear). In particular, the amplitudes of the effective mechanical stresses require an adapted design of the implants, in order to guarantee their durability.

The corrosion fatigue results of a detrimental and synergetic effect of the separate mechanisms. An additive term is necessary to relate the phenomena.

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