Effect of initial notch size on fatigue corrosion of an AISI 316L STEEL

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ABSTRACT

In order to study the dynamic behaviour of austenitic stainless steel (316L) implants into physiological medium, simulations of fatigue corrosion of pre-notched specimens were carried out. Input notch data were taken from stable pits obtained from preliminary polarization tests. Calculations were made using effective mechanical and electrochemical conditions observed on human body implants. Two fatigue models have been applied. Hoeppner model is only a mechanical one, whereas Lindley 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 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.

Key words: austenitic stainless steel, fatigue, corrosion, pits, crack

1. INTRODUCTION

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 prenotched steels plates, in artificial physiological conditions, under a dynamic stress, by considering the bending fatigue test.

For the needs for modelling, we used two models for characterizing fatigue behaviour. Hoeppner model is tested in air conditions (pure fatigue) whereas Lindly model allowed us to characterize fatigue corrosion.

2. DESCRIPTION OF THE MODELS

2.1. Model of Hoeppner.

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

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

The model of Hoeppner is characterized by the correction of the preceding formula, 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.

Hoeppner estimates that the factor K_{sf} of a pit is equal to the theoretical stress intensity factor ΔK_{scth} corresponding to the crack initiation. The relation (2) thus determines the critical size of the pit that starts the fissure.
The law of Paris 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, N the number of cycles.

2.2. Model of Lindly [2]

Lindly takes account of the chemical and mechanical aspects, and proposes another method of calculation of the threshold of transformation of the pit of corrosion into fissure. It considers that the pits are of elliptic form. The stress applied σ is associated to the notch size by the following relation:

$$\Delta K_{th} = \frac{\Delta\sigma\sqrt{(\pi a)\left[1.13 - 0.07\left(\frac{a}{c}\right)^{\frac{1}{2}}\right]}}{\left[1 + 1.47\left(\frac{a}{c}\right)^{1.64}\right]^{\frac{1}{2}}} \qquad (5)$$

3. MATERIAL

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

Table1. Chemical composition of 316L stainless steel.

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

It go through potentiodynamic tests, at the ambient temperature, in 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 test and gives relatively equal values (3,3 to 3,5). The curves of polarization I = f(E) show the absence of a clear transition active field – passive field and a value of potential of pitting which is next of. 350 - 400mv/ECS. These results are rather close to those known for this kind of steels [5].

4. APPLICATION OF MODELS.

The various results of the application of the model to our study are indicated in table 2.
The value taken for the stress applied is equal to 200MPa, what undergoes the articulation of the hip at the time of the 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.

4.1. Medium 0,5 M.

The average diameter of the pit - hemispherical notch is of 150 µm. The factor of intensity of stress for this pit is worth 2,41MPa.m $^{½.}$ To determine the critical size of the pit which can be simulated as a fissure, we take $K_{sf} = \Delta K_{scth}$ = 4,6MPa.m ^{½} for the same load applied [3] what gives a size of pit of 544 µm, that we consider as equal to the depth of the fissure. The number necessary of cycles to reach this size starting from a pit of 150 µm and for a load of 200MPa is calculated by formula (3), by taking C = 4,343 X 10^{-10} and N = 3,794 [6]. Calculation gives N=14987 cycles. The fissure grows in the face according to the number of cycles and reaches a critical size for a factor of intensity: $K_{=} \Delta K_{all}$ = 16MPa.m ^{½} [3]. The number of cycles is then equal to 18767 cycles, and the critical depth of the fissure is estimated of 6,58mm.

4.2. Medium 1M.

The average diameter of the hemispherical pit resulting from this medium is 250 µ m. the critical size for his transformation for the crack initiation is 544 µ m. The number of cycles that corresponds to this size is of 9247 cycles. To reach the critical size of the fissure (6,58mm), the number necessary of cycles is of 13027 cycles.

Figure 1 shows that the effect of the electrochemical medium accelerates strongly these speeds. The speed due to fatigue corrosion is a superposition of that of pure fatigue and that due to corrosion [7]. However, a great number of cycles is needs to reach the critical point of rupture, when the initial notch (pit) is small (figure 2). Thus, the lifetime of material depends on the concentration of the medium $FeCl_2$ used to obtain the pits and on the applied stress.
The curve of Wöhler (figure 3) shows that the mechanical action is much more influent when high loads are applied. As the stress applied decreases; the electrochemical effect becomes extensive and reduces considerably the lifetime of material.

Table2. Stress intensity factors and a number of cycles corresponding to the two mediums.

		ΔKscth (MPa.m½)	a (mm)	da/dN (10-7m/ cycle)		N (cycles)	
				Hoeppner	Lindly	Hoeppner	Lindly
Milieu 0,5 M	Amorçage	4.6	0.544	1,3256	1,64	14986	7952
	Rupture	16	6.58	162,57	161,49	18766	10358
Milieu 1M	Amorçage	4.6	0.544	1,3256	1,64	7987	5886
	Rupture	16	6.58	162,57	161,49	11314	8164

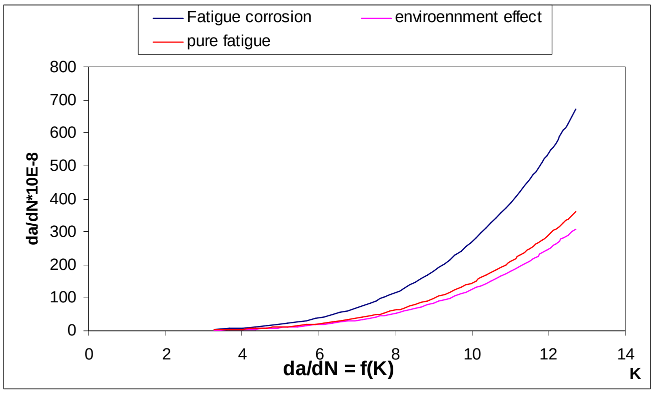

Figure1. *Variation of the propagation velocity according to the stress intensity factor*

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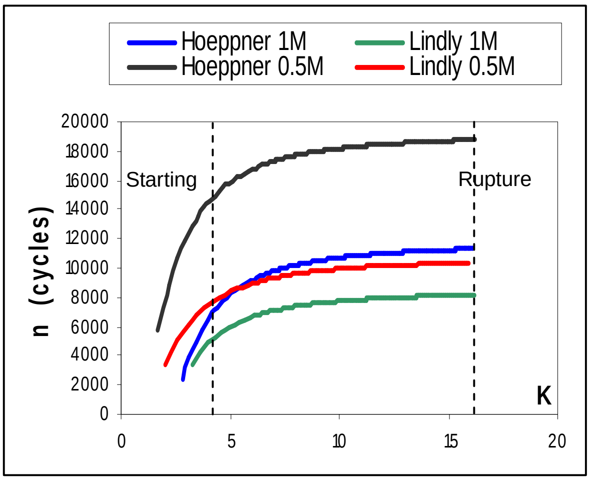

Figure2. *Variation of the number of cycles according to the depth of the notch*

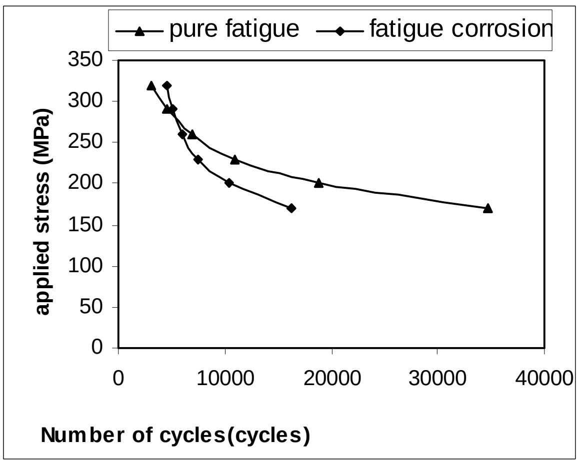

Figure3*. Variation of the number of cycles according to the applied stress*

We can deduce that the pits likely to occur on the human implants are much smaller than those taken in this study. This can explain the good resistance of the human implant in spite of the significant number of cycles (approximately 10^6 cycles) during mechanical stress.

5. CONCLUSION

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

6. REFERENCES

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