Comparative study of crack path evolution under bending fatigue strain of two corrosion resistant materials

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Abstract

The behavior of materials is often defined when they are in service. Several parameters, such as dynamic mechanical solicitations and working environment, are of importance. In some cases, materials are subjected to fatigue in due time under the influence of mechanical loads and the effect of medium. Aluminum alloys and stainless steel are two corrosion resistant materials which are used in navy, aeronautic and medical manufactures. To study the behavior of these materials on corrosion fatigue, we have carried specimens to air fatigue and in several medium at different stress frequencies.

For aluminium specimens, we observed a phenomenon of decohesion between grains called as exfoliation corrosion. This can be explained by the fact that the damages are concentrated with the notches, where there is a high stress concentration.

For 316L stainless steel, one can point out the linearity and the uniformity of this crack both on the surface and inside the. This can be related to the uniform shape of area on which is applied the load. A decreasing in the load frequency is accompanied by an increasing of the crack opening, over the whole fatigue test. For a same number of cycles, specimen is much longer solicited mechanically and exposed to the chemical medium, at low frequency than at the higher one. It’s known that even if the amplitude of strain at the crack tip is not affected by the load frequency, it changes periodically with time.

1. Introduction

The behavior of materials is often defined when they are in service. Several parameters, such as dynamic mechanical solicitations and working environment, are of importance. In some cases, materials are subjected to fatigue in due time under the influence of mechanical loads and the effect of medium.

This phenomenon called corrosion fatigue is important for any design and many studies focused at the effect of different parameters, such as media [1, 2], load [3], temperature [4] and cyclic stress frequency [5, 6]. Austenitic stainless steel AISI316L is among the materials used in conditions of corrosion fatigue happening in several domains such as nuclear power, surgical implantology and chirurgical devices. In the navy structures, the aluminium alloys are of great interest because of their light weight and their corrosion resistance in the hydrochloric solutions [7]. In aeronautic structures, the exact cost of corrosion remains difficult to be quantified because of many indirect contributing parts such as that corresponding to the ground remaining time of the planes during unforeseen repairs (AOG, Aircraft One Ground). However, R. Kinzie [8] tried to carry out a follow up of the associated costs to corrosion between 1990 and 2002.

In order to know the behaviour of corrosion fatigue; we have studied the effect of notch size on fatigue in a 0.9 % NaCl medium and the effect of medium on fatigue. The fatigue test is made by cyclic bending. As part of the same work; we planned to study the effect of the stress frequency on corrosion fatigue behaviour in 0.9 % NaCl medium at room temperature for 316L stainless steel and 3.5% NaCl for aluminium alloy.

2. Materials and procedure

Two materials are used: an AW2024 aluminium alloy and AISI316L stainless steel. Aluminium samples are flat sheets of 150x10x3mm size. The stainless steel sheets are 75x10x1mm size.

The aluminium alloy used for the tests of fatigue presents the microstructure illustrated in figure 1. We can observe a formation of plans of grains by a uniform orientation of these last. The microstructure of the stainless is constituted of regular grains (Figure 2).

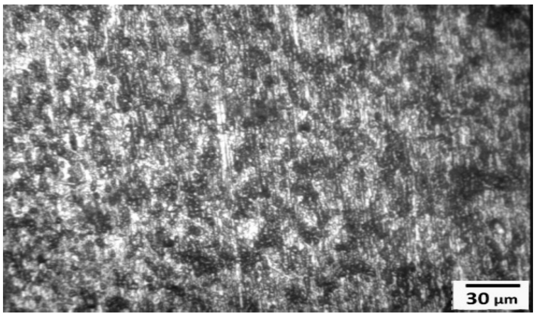

Figure.1: Microstructure of AW2024 with enlarging of 650.

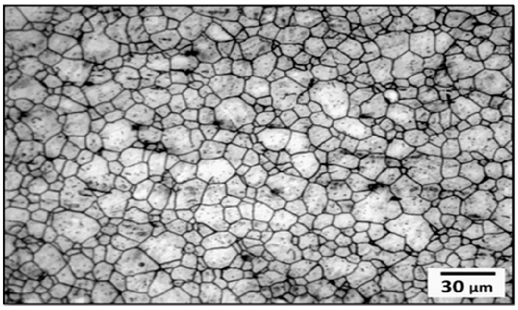

Figure.2: Microstructure of 316L stainless steel with enlarging of 650

Before beginning the tests of corrosion fatigue, a mechanical notch of 1mm of width and is realized in the middle of the specimens. Tests of fatigue are made by three points cyclic bending with a frequency of 0.5, 0.1 and 02 Hz, respectively, and a value of R equal to 0. The maximal applied load is equal to 19MPa for aluminium alloy and 200MPa for 316L stainless steel. The measurement of crack size is made by means of an optical microscope, each two hours interval, with interruption of the test during ten minutes. During these tests, the specimen is immersed, at room temperature, in a stirred and aerated NaCl solution

3. Experimental and numerical results.

The effect of medium and of stress frequency is highlighted below, for both the two materials.

3.1. Effect of medium

a. Aluminium alloy

Under cyclic solicitations, the first cracks appear on the notch (figure 3). As a result of the coupling of fatigue and corrosion, these cracks propagate both along the surface and inside the depth until a critical size leading to failure [9]. The size of the cracks, measured after different number of cycles, are indicated in table1 and concerns the two media.

Table. 1. Evolution of the crack size according to time for aluminium alloy

Cycles' number N	43200	49500	56700	63900	71100	78300
Crack size in µm (pure fatigue)	16,94	32,24	40,91	56,61	66,95	85,12
Crack size in µm (corrosion fatigue)	28,13	53,21	62,65	70,25	83,47	94,23

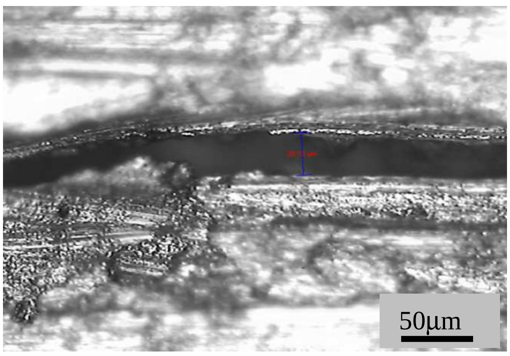

Figure 3. Initiation cracks on aluminium alloy

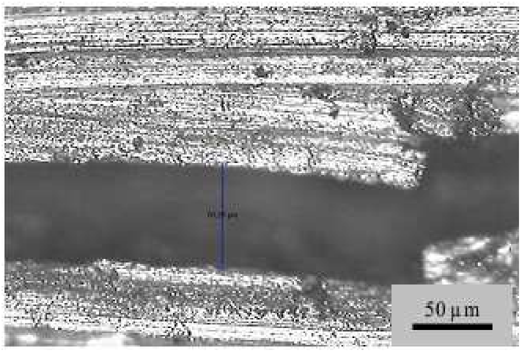

Figure 4. Crack propagation of aluminium alloy

The crack increases with the number of cycles of fatigue. It grows both on the surface of the sheet and inside it, but for this last route it seems to follow some grain boundaries (figure 4). This can be explained by the fact that the damages of specimen are concentrated inside the notches, where it exist a high stress concentration. The fracture shape is described as a decohesion between long grains, expressing the so called exfoliation corrosion. This one is due to the typical microstructure of the aluminum alloy. Moreover, the crack is worsened by the mechanical request, but this phenomenon is not observed at fatigue on air.

The evolution of the size crack with the number of cycles (figure 5), obtained for the same number of cycles, shows that the chlorine medium accelerates the size of the crack. The first crack appears since 40000 cycles for both cases. We notice that for the same number of cycles, the size of crack is bigger in the presence of the corrosive medium than that gets tired of it in the air.

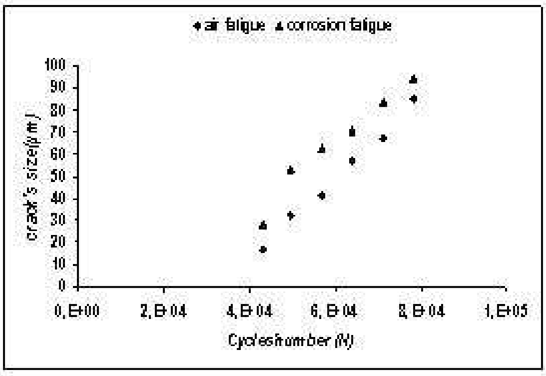

Figure.5: Evolution of the size of cracks with the number of cycles of fatigue.

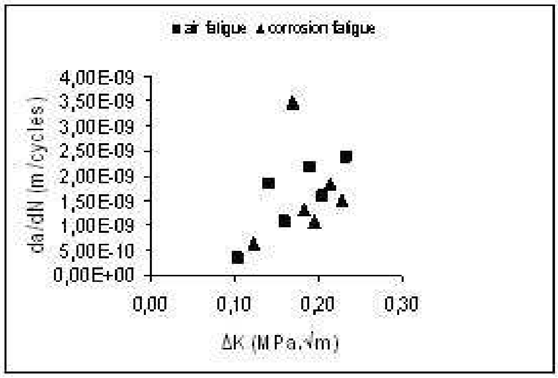

Figure.6: Propagation rate of cracks for the fatigue corrosion.

When the amplitude of the stress intensity factor K rises; the propagation rate rises also (figure 6). However, a singular point is observed, after 49500 cycles, and can be linked to the microstructural behavior of the aluminum alloy. This difference is due to the effect of the corrosive medium, because in all the cases, the crack initiation calls either upon the existence of a defect of surface, or with a slipping mechanism of atomic plans at the places where the stress are strongest, but the corrosive medium allows the continuation of the mechanism of deformation by eliminating the barriers. One can conclude from it that, in the zones of stress concentration, fatigue crack initiation and pitting occurs at the same time. There will be then a competition between the growth of the corrosion pit (dissolution) and the growth of the fatigue crack notch.

b. 316L stainless steel

The size of the cracks, measured after different number of cycles, are indicated in table 2 and concerns the two media.

Table2. Evolution of the crack size according to time for 316L stainless steel

N(cycles)	0	7200	14400	21600	36000	43200	50400	57600
a(µm) for air fatigue	50	52	53.5	56	60	62,5	65,0	67,7
a(µm) for corrosion fatigue	50	54	57,5	63	76,5	87,4	105,0	154

The evolution of the size crack with the number of cycles (figure 7) shows that the physiological medium accelerates cracking after 50000 cycles. After 10000 cycles, the size of crack due to corrosion fatigue equals 2 or 3 times the size of crack of that due to air fatigue. This shows the influence of the environment on the fatigue behaviour of the steel. On another part, one can observe that the evolution of the size of cracking is slightly slow in the case of air fatigue (figure 8), considering that the applied stress is much lower than the yield stress. Once the crack takes a critical size called pit-to-crack transition, the surface exposed to corrosion becomes more important that let the propagation of the cracks becoming more detrimental.

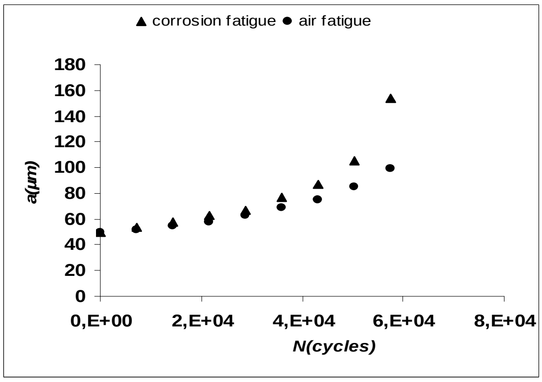

Figure 7. Evolution of crack size according to the number of cycles.

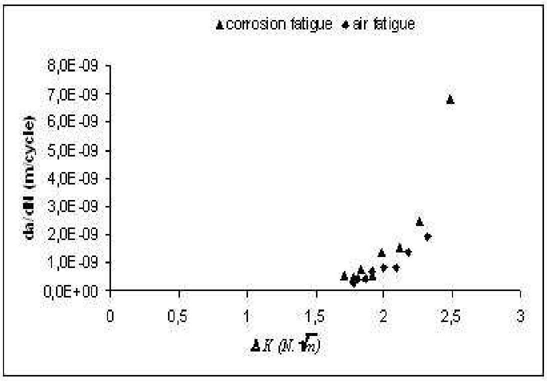

Figure 8. Crack growth rate according stress intensity factor

3.2. Effect of stress frequency

a. Aluminium alloy

The difference in the evolution due to the stress frequency, as seen in the figure 9, is to be linked to the dimension of the sheets used in the study. In fact, the necessary time to achieve a given size of the crack must be raised, when the length of the sheet is shortened.

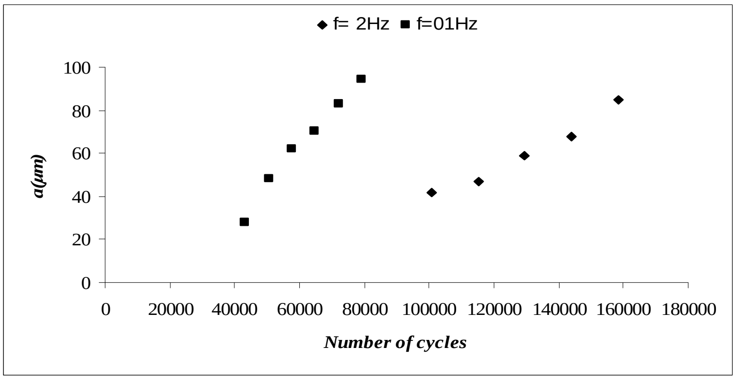

Figure9**.** Effect of the stress frequency on the evolution of crack size.

b. 316L stainless steel

The observation of the crack shape on stainless steel denotes a great homogeneity in the depth of the sheet, as well as on its surface. This can be related to the uniform shape of area on which is applied the load. The test made at a frequency of 1Hz indicated that the initiation of the crack from a pit of corrosion become detectable only after 17 hours (figure 9). The initial size, estimated to 15µm, reached the value of 37µm after 34 hours. This growth is however slower in comparison with that noticed at a stress frequency of 2Hz. This observation is more visible when we focus in the depth of the sheet than in the surface. Furthermore, the irregular shape of the crack can be explained by the electrochemical attack which is higher at 1Hz than at 2Hz [9]. For a stress frequency equal to 0.5Hz, crack initiation is observed at 30 hours and is higher on the surface than on depth [11].

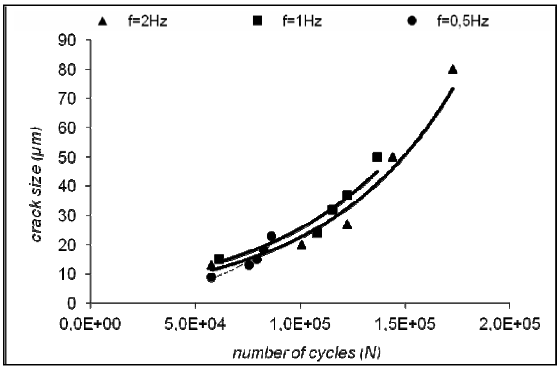

Figure 9. Evolution of crack size according number of cycles.

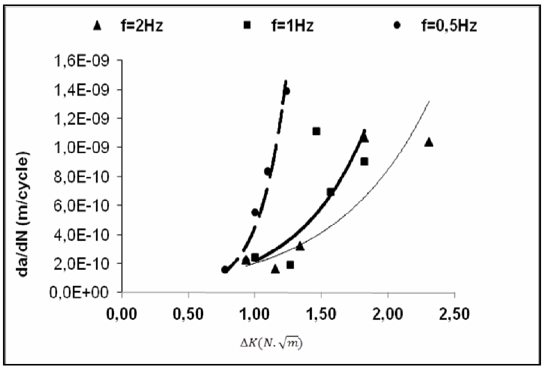

Figure 10. Crack growth rate according stress intensity factor.

The nature and rate of crack can be estimated from the stress intensity factor ΔK by using the model of Newman and Raju. This model takes into account the geometrical shape in mechanical aspects and proposes a 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 $\Delta\sigma$ is related to the notch size by the relation of Newman [12].

The figure 10 indicates that a decrease in the load frequency is accompanied by an increasing of the crack opening, over the whole fatigue test. For a same number of cycles, the sample is much longer solicited mechanically and exposed to the chemical medium, for the low frequency than the higher one. It's known that even if the amplitude of strain at the crack tip doesn't depend on the load frequency, it changes periodically with time. The degradation of the sheet, due a synergy effect, is then important.

The propagation rate indicates two regions. The first corresponds to the growth, the second to the propagation. Here also, the crack initiation from the pit of corrosion is not detectable for the same reason. The action of corrosive medium is important. Once the value of stress intensity factor increases, the mechanical aspect becomes important and the propagation rate increases when frequency is more significant.

The evolution of the propagation rate with the stress intensity factor confirms the former discussion. This time, we have to consider that the amplitude of strain rate at the crack tip decreases with decreasing frequency. This may decrease the dissolve current density, because of reducing physical defects that are responsible of corrosion. But at the same time, the effective exposition time to the aggressive medium is longer when the frequency decreases [13]. This allows us to explain the increase of the corrosion current and then of the propagation rate.

4. Conclusion

The effect of the load frequency on the opening at the crack tip and its propagation rate has been highlighted by the three-point bending test. The main reason of crack initiation on the parts of aluminium alloy subjected to corrosion fatigue is the appearance of pits, particularly in the zones subjected to strong maximum stresses. The pitting occurs around the metal precipitate phases zones. This phenomenon is comparable with the crack initiation of fatigue in the vicinity of inclusions and can be attached to the maximum stress, and then with the stress intensity factor. The addition of an aggressive medium leads us to a phenomenon of synergy with the pure fatigue [14].

The stainless steel plates, pre-notched with a chemical pit, are much more subject to the chemical attack, at the first stage of the corrosion-fatigue test. It takes more than 10 hours to observe the initiation of the crack. Since this point, lower is the load frequency; higher are the crack size and its propagation. This has been linked, from one side, to the change of the strain at the crack tip and, from another side, to a longer time of mechanical and chemical attack of the material. The time appears then a more significant factor than the number of cycles of corrosion-fatigue.

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