

## ASPECTS OF ENVIRONMENTAL INTERACTION ON CORROSION FATIGUE BEHAVIOUR OF SAE 8620 STEEL

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**Abstract.** *The corrosion fatigue lifetime of materials can be predicted by simulating the multi-stage damage process with regard for action of both corrosion and mechanical factors. The pitting corrosion leading to fatigue crack nucleation and crack growth is considered to be among the most significant degradation mechanisms in aging structures. The influence of an aggressive environment (NaCl 3.5% aerated solution) on fatigue crack initiation behaviour was studied. This study comprised corrosion fatigue tests using specimens of structural SAE 8620 steel. The decreasing cyclic frequency (60 Hz to 11.7 Hz) effect on corrosion crack initiation behaviour was examined. The tests carried out under rotating-bending loading conditions at 11.7 Hz (700 rpm), showed that pitting corrosion caused by anodic attack was responsible for corrosion fatigue crack initiation.*

**Keywords:** *corrosion fatigue, pits, crack initiation, crack growth*

### 1. INTRODUCTION

The corrosion fatigue behaviour of metallic materials has attracted considerable attention from researchers throughout the world. Most engineering materials are, to a greater or lesser extent, susceptible to corrosion, in the form of either general or localized corrosion. The reduction in fatigue lifetime of components as a result of presence of an aggressive environment is becoming very common. This stems from the fact that corrosion fatigue is responsible for many service failures in a wide variety industries such as processing, naval, aircraft, automobilistic and energy generation. This has led to an important consideration to be encountered by design engineer for safer design (Shipilov, 2002; Murtaza and Akid, 1996).

The corrosion fatigue lifetime of metallics materials can be predicted by simulating the multi-stage damage process regarding the action of both corrosion and mechanical factors. In general, the corrosion fatigue life of metallics materials is controlled mainly by the initiation and propagation of small surface cracks. Several studies have examined pit initiation and growth behaviour during the corrosion fatigue process (Hu, 1999; Rokhlin *et al.*, 1999; Ebara, 2006; Wei *et al.*, 2006). It is well established that corrosion pits initiation and grow in the early stages of the corrosion fatigue process. Corrosion fatigue cracks start to grow from these corrosion pits and cause the final failure of the metallics structures (Shi and Mahadevan, 2003; Rajasankar and Iyer, 2006; Dolley *et al.*, 2000).

In the present study the SAE 8620 carbon steel was used due to its use in industries such as automobilistics and energy generation (Bayrakceken, 2006; Gomes *et al.*, 2005; Pinto, 1996).

### 2. EXPERIMENTAL PROCEDURES

#### 2.1. Material and specimens

In the present study the structural steel SAE 8620 was used. Its chemical composition is shown in Table 1. The main mechanical properties of this steel are listed in Table 2. The material was investigated in the received conditions.

Table 1 – Chemical composition of SAE 8620 steel (wt.%).

Ni	Cr	Mo	Mn	Cu	Al	Si	P	S	C	Fe
0.42	0.50	0.16	0.78	0.09	0.019	0.23	0.016	0.032	0.19	Bal.

Table 2 – Mechanical properties of SAE 8620 steel.

Yield strength (offset = 0.2%) (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Hardness (HV)	Hardness (HB)
464	634	20	66	202	192

In microstructural analysis the specimens were etched with Nital 2% and were analysed by software QUANTIKOV (Pinto, 1996). After the chemical, microstructural and mechanical characterization, fatigue specimens were machined to the configuration shown in Figure 1. The roughness surface ( $R_a$ ) of the gage sections of the all specimens were  $(0.09 \pm 0.02) \mu\text{m}$ .

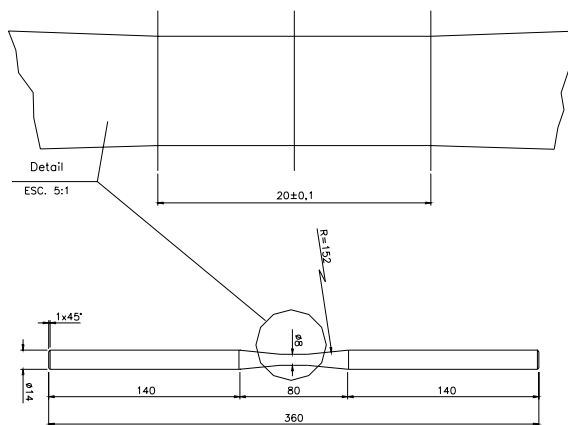


Figure 1. Fatigue test specimen configuration. Dimensions in mm.

## 2.2. Test procedure

Rotating-bending machine of the constant bending moment type was used in the present research. All fatigue tests were conducted at constant strain amplitudes and a frequency of 11.7 Hz (700 rpm) and 60 Hz (3600 rpm) with a stress ratio ( $R$ ) of -1.

The corrosion fatigue tests were conducted at 11.7 Hz and 60 Hz in a 0.6M NaCl solution made by marine salt and distilled water with pH 6.2. The aerated solution was circulated from and to a reservoir via corrosion cell fitted on the specimen at room temperature. The electrolyte (10 L) was pumped through the cell in a 0.3 L/h flow rate. The corrosion cell developed to conduct the aggressive environment tests are shown in Figure 2. The tests were conducted until the specimens broken with stress level between 10.8 MPa and 297 MPa at 11.7 Hz and between 208 MPa and 297 MPa at 60 Hz. The fatigue limit in long life regime above  $10^6$  cycles in SAE 8620 steel resulted in S-N-P (stress-number of cycles-probability) curves at 11.7 Hz.



Figure 2. Cell used in the corrosion fatigue tests in the aggressive environment.

After corrosion fatigue tests, the lateral fracture surfaces of the specimens were examined in detail using a JEOL JSM-5310 scanning electron microscope (SEM).

### 3. RESULTS AND DISCUSSION

#### 3.1. Microstructure

Figure 3 illustrates the microstructure of the SAE 8620 steel in cross section. Figure 3a shows a large amount of non-metallic inclusions dispersed in the metallic matrix. Figure 3b shows the ferritic-perlitic microstructure of the SAE 8620 steel with 55% of ferrite and medium size of grain of ferrite of 12µm. Figure 3c shows a non-metallic inclusion with medium size of 10µm. Fatigue crack initiation in inclusions on the material's surface may occur through the debonding of the inclusion from the matrix interface, separation of internal boundaries or through fracturing of the inclusion itself. This inclusions can act as sites for particle-induced corrosion pitting in the structure and serves to eliminate the initiation portion of its fatigue life (Dolley *et al.*, 2000; Murtaza and Akid, 2000). The interfacial separation matrix-inclusion is induced during the tensile loading. The fatigue lifetime is decreased by the presence of inclusions. The chemical composition of the inclusions was not identified at this time.

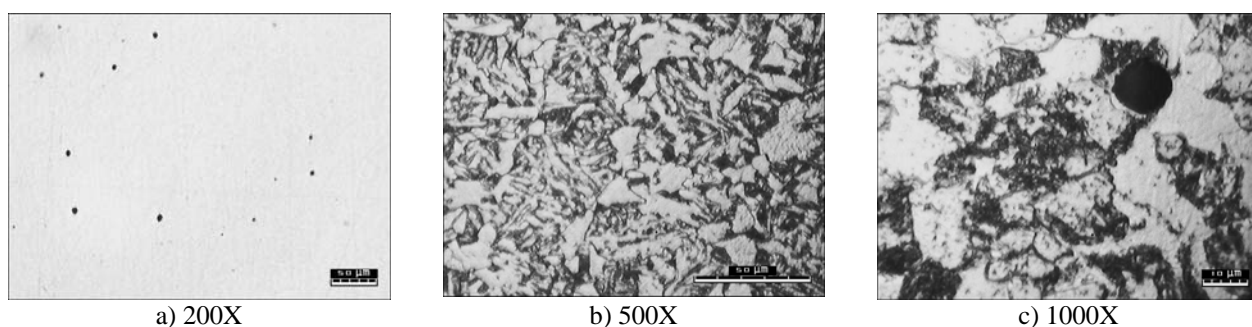


Figure 3. Micrograph of a cross section of SAE 8620 steel.

#### 3.2. Fatigue limit

The S-N-P curves were determined by regression with life date analysis using statistical software MINITAB for failure probability (p) of 0.01, 0.50 and 0.99. Figure 4 shows the S-N-P curves for SAE 8620 steel from fatigue tests carried out in 0.6M NaCl aerated solution at 11.7 Hz. The fatigue strength limit in this condition was 1.8 MPa.

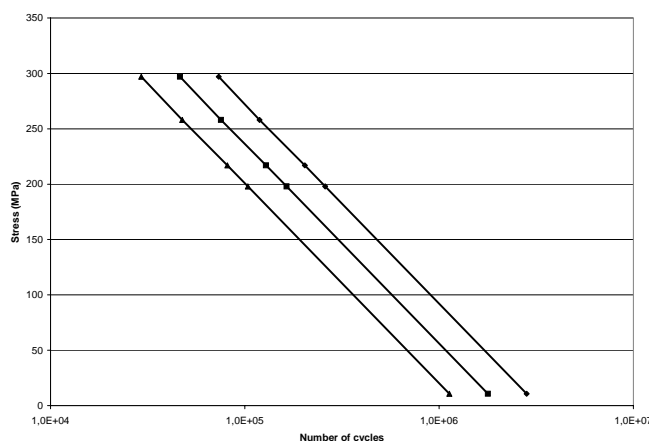


Figure 4. S-N-P curves of SAE 8620 in 0.6M NaCl aerated solution; 11.7 Hz and  $R = -1$ .

#### 3.3. Fatigue crack initiation

In the studies of the fatigue and corrosion fatigue, crack initiation mechanisms aimed to identify the preferential sites for crack initiation and microstructural particularities and/or peculiarities associated to these sites. These sites are possibly responsible for premature fatigue or corrosion fatigue crack initiation and contribute to reducing the fatigue life of the alloys.

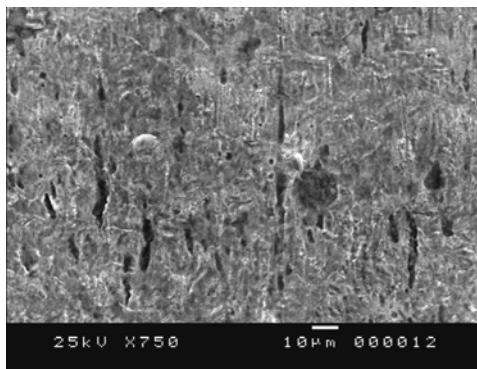
The results in literature (Gironès *et al.*, 2005; Turnbull *et al.*, 2006) report that the main stages of damage leading to environment-assisted fatigue failure from defect-free surfaces include: breakdown of the surface passive film, pit development and growth, transition from pitting to cracking, crack growth and crack coalescence. The environment

acts on the material through the surface, producing uniform or localized chemical attack by diffusive mass transfer (Scheiner and Hellmich, 2007).

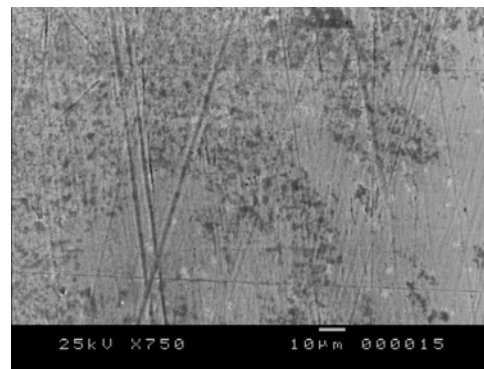
All alloys used in engineering develop surface passive films as a result of surface oxidation during processing. The degree of protection given by a surface film depends on the diffusion rates of various environmental constituents through the film and on the stability of the coating itself against environmental attack. The carbon steel with little or any alloying additions shows weak passive behaviour and is considered active when immersed in environments as benign as water. In these alloys, corrosion occurs very quickly following the immersion in aqueous environments. Additions of sufficient alloying elements such as Cr, Cu and Ni improve the corrosion resistance through the formation of a tightly adhered mixed oxide film on the surface of the alloy (Akid *et al.*, 2006; Sheir *et al.*, 2000). This increases the pitting resistance and more aggressive environments are required to break down the oxide film.

Localized corrosion (pits) on the surface of materials occur largely in passive metals or alloys in contact with neutral aqueous solutions containing aggressive anions such as chloride (Pan *et al.*, 2006). The pits formations are a major consideration for engineering components with high integrity surface finish. If a residual or applied mechanical stresses occur together with an aggressive environment, the early development of pits and subsequent cracks can play a major role in the total lifetime of a component (Giordani *et al.*, 2004). Various factors are important to corrosion fatigue behaviour. The effect of decreasing frequency on pit nucleation and growth can be observed in Figure 5. Figure 5 shows lateral surfaces of specimens after corrosion fatigue tests conducted using SAE 8620 carbon steel in 0.6M NaCl aerated solution. The tests were carried out under constants conditions but at different cycle test frequencies until the specimens are broken. Figure 5(a) shows the test carried out at 11.7 Hz and Figure 5(b) shows the test at 60 Hz.

The decreasing of frequency increases the exposure time of material to the environment. The corrosive environment favors the formation of geometric discontinuities on the surface of specimens, thereby favoring crack nucleation. As this process is time dependent, the influence of the aggressive environment on the material's fatigue life increases as the metallic material is subjected to prolonged exposure in a given environment.



(a)  $N_f = 135419$  cycles; time of exposure: 194 minutes.



(b)  $N_f = 175893$  cycles; time of exposure: 94 minutes.

Figure 5. Effect of frequency (time of exposure) on the fatigue corrosion behaviour of SAE 8620 steel in 0.6M NaCl aerated solution. The applied stress was 198 MPa and  $R = -1$ .

The aggressive environment evidently exerts a strong influence on the fatigue crack initiation. The geometric discontinuities (pits) cause stress and strain concentrations, favoring fatigue crack initiation in these regions (Rajasankar and Iyer, 2006). The initiation of a crack from a pit can be observed in Figure 6.

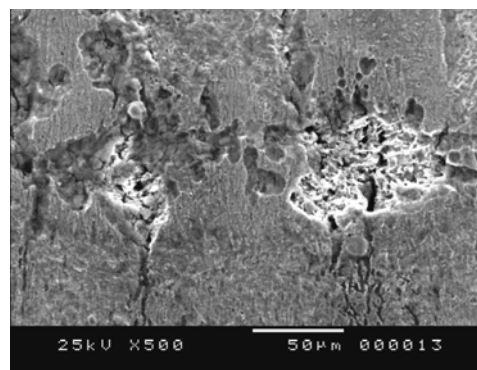


Figure 6. Fatigue crack initiation at corrosion pits observed in corrosion fatigue test on SAE 8620 in 0.6M NaCl solution. The stress applied was 198 MPa,  $R = -1$  and  $f = 11.7$  Hz.

In an aggressive environment, beyond the mechanical effect associated with stress and strain concentration on the pits, the effect of electrochemical corrosion exerts a special influence (Rajasankar and Iyer, 2006). Pitting corrosion is a highly localised type of corrosion caused by anodic attack (Giordani *et al.*, 2004). It is generally characterized by holes or pits in metal surface that have little or no uniform corrosion. The localized anodic attack that starts can become autocatalytic in nature. When this happens, the aggressive environment penetrates into the pits and therefore immediately comes into contact with the base metal, which acts as an anodic site in relation to the rest of the passive surface (the surrounding material that didn't suffer corrosion), promoting a process of anodic dissolution of the metal. An occluded electrochemical cell is then created inside this discontinuity. The anodic dissolution occurs through the formation of metallic ions  $Mn^+$  and an increase in the concentration of these cations in the electrolyte inside the discontinuity foster the electrostatic attraction of the aggressive chloride anions, presents in the used electrolyte (Scheiner and Hellmich, 2007). The hydrolysis of ions  $Mn^+$  leads to a great formation of ions  $H^+$ , resulting in a drop in the pH inside of the pit (Jakubowski, 1998). The migration of chloride anions towards the interior of the pits maintains the electrostatic balance. As a result, there is a continuous increase in the concentration of chloride anions inside of the pits and an accentuated drop of the pH of the electrolyte stagnated there (Makhlouf *et al.*, 2003). These factors, associated with the deficiency of oxygen in this region, consumed mainly by the metal repassivation reactions, creates a highly aggressive localized environment that reduces the stability of the passive film. This contributes to the acceleration of the anodic dissolution and makes the repassivation of the damaged region hindered. There is an establishment of an autocatalytic process by crevice corrosion. Additionally, anodic dissolution can be accelerated by the highly deformed condition of the matrix due to the concentration of strain in the vicinity of the discontinuity. The atoms in this region are in a higher energy state, requiring less activation energy to be removed from the crystalline lattice than the less damaged regions of the material. To complement this extremely unfavorable condition, anodic dissolution inside the geometric discontinuity can unblocked the slip interrupted by the accumulation or piling up of dislocations presents in this region, favoring the subsequent slipping and rendering the process autocatalytic (Giordani *et al.*, 2004). The transition from a pit to a crack is not governed solely by the stress intensity associated with the discontinuity (pit) and applied stress but is also determined by the local electrochemistry, which controls pit growth (Akid *et al.*, 2006). Geometric discontinuities associated with electrochemical factors can be as important as or even more significant than the factors relating to stress concentration, particularly at the initiation and in the early stage of fatigue crack propagation (Parkins, 1985). As illustrated in Figure 6, the geometric discontinuity that keeps the electrolyte more stagnated in its interior contributes to the development of a more aggressive electrolyte. In this case, the electrochemical factors of the localized corrosion is an important fatigue crack initiation factor.

Corrosion pits are typically smaller than a millimeter in depth and serve as micronotches with locally elevate the stress level. Furthermore, the pH level of the corrosive environment inside the pit can be more acidic than that in the bulk, causing possible acceleration in the rate of fatigue crack growth (Gironès *et al.*, 2005). Once that the stage of development and growth of pits and the initiation of a crack from a pit happened, the subsequent stage in the accumulation of damage under environment-assisted fatigue following the stage of the transition from a pit to a crack. Figure 7 shows the transition from a pit to a crack. The SAE 8620 steel is subjected to corrosion fatigue test in 0.6M NaCl aerated solution.

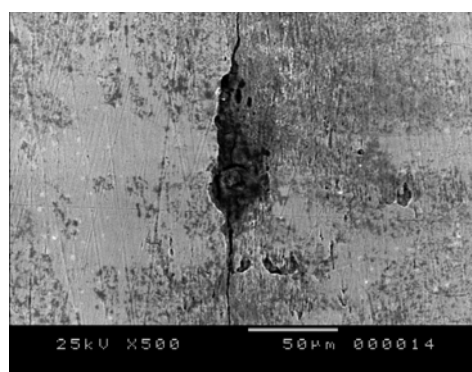


Figure 7. Transition from a pit to a crack observed in corrosion fatigue test on SAE 8620 steel in 0.6M NaCl solution. The applied stress was 198 MPa,  $R = -1$  and  $f = 60$  Hz.

The important effect of crack growth on fatigue life prediction has received more and more attention in recent years. The transition from a pit to a fatigue crack is considered to be an extremely important stage on fatigue lifetime and might be regarded as a damage mechanism transition point (Shi and Mahadevan, 2000). The interest is generated in studying the pit growth behaviour due to its influence on crack initiation life which forms significant portion of useful service life of structures under fatigue.

#### 4. CONCLUSIONS

As corrosion fatigue is a time-dependent phenomenon, loading frequency is an important parameter to take into account. In this sense, when increasing the frequency, the time that unprotected material is exposed to the aggressive environment becomes shorter and a less detrimental effect on the fatigue life should be expected.

The presence of pitting during the corrosion fatigue process is a critical point. Once a pits is formed, it may act as a stress raiser and thus, crack nucleation becomes localized at the root of the pit, where the environment is notably more aggressive than in the bulk. Pitting corrosion exhibits high frequency response and, therefore, likely to interact with damage mode due to the fatigue loads in causing additional damage to the structural components.

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