Chapter 16
Corrosion Fatigue

16.1 Introduction

Corrosion fatigue by definition is fatigue in a corrosive environment. An aggressive environment can be harmful for the fatigue life of a structure, and protection against corrosion is necessary. Designers must consider corrosion in service, not only in view of fatigue. Corrosion is undesirable for reasons related to a safe and economic use of a structure during its service life. Corrosion can also be unacceptable in view of the appearance of a structure, i.e. for cosmetic reasons. Usually, corrosion prevention is considered to be a matter of selecting a corrosion resistant material or applying a suitable surface protection, such as paint or cadmium plating, etc. Unfortunately, these options do not guarantee good fatigue properties. Furthermore, several high-strength materials have a relatively poor corrosion resistance. Disastrous accidents have occurred due to fatigue cracks starting from corrosion damage, in several cases corrosion pits. Whenever corrosion damage can occur to the material surface of a dynamically loaded structure, corrosion fatigue can be a serious problem.

Corrosion fatigue should not be confused with stress corrosion, which is crack initiation and growth under a sustained load or residual stress. Usually, stress corrosion occurs along an intergranular crack growth path, whereas corrosion fatigue in many cases is still a transgranular crack growth phenomenon. Moreover, stress corrosion does not occur in many technical materials, whereas corrosion fatigue can occur in most materials. Corrosion fatigue is also not the same as fatigue of corroded material. Of course, corrosion damage can decrease the fatigue properties because it implies surface damage which will reduce the crack initiation life. The effect of the surface quality was discussed in Chapter 14. The problem considered in the present chapter is technically relevant if a corrosive environment is present during the entire life time of a structure. It implies that the crack initiation period and the crack growth period can be affected both.

As shown by the literature, corrosion fatigue was investigated in various experimental programs, primarily as a material problem. Constant-amplitude (CA) fatigue tests were carried out with closely controlled environments on simple laboratory specimens. The investigations have revealed that damage accumulation during corrosion fatigue is caused by the combined actions of fatigue and corrosion with mutual interactions. The type of material and the environment of the experiments is usually referred to as the material/environment system. Because corrosion is a time-dependent mechanism, it is obvious that the load frequency and the wave shape of the load cycles can be significant for corrosion fatigue.

Corrosion fatigue as a problem of a structure in service is characterized by variables which can be highly different from the material/environment system of laboratory research. The differences were discussed by Schütz in a publication with the title: "Corrosion fatigue. The forgotten factor in assessing durability" [1]. He emphasized the difference between laboratory experience and the exposure of a structure under variable-amplitude (VA) loading in service. Laboratory tests should be completed in an acceptable time period whereas a structure in service is exposed to a non-controlled environment and exposure times of years. The question then is how the basic understanding of corrosion fatigue obtained in fundamental research can be transferred into practical considerations for structural design against fatigue.

In the present chapter, results of laboratory investigations are discussed first (Section 16.2). It is a selection of observations which have contributed to reveal corrosion effects on fatigue, including frequency and wave shape effects. Illustrative results are presented, but it is not an extensive survey of the numerous investigations published in the literature. Practical aspects about corrosion fatigue problems are considered in Section 16.3. A case history is discussed in Section 16.4. The main topics of the present chapter are listed in Section 16.5.

16.2 Aspects of corrosion fatigue

In the previous chapter on fretting corrosion, it was said that fretting primarily affects the crack initiation period and not the crack growth period. However, as already discussed in Chapter 2 (Section 2.5.7), in a corrosive environment, both crack initiation and crack growth are affected by the environment. In some materials with a good corrosion resistance, it is possible that the effect of the environment on crack initiation is insignificant, while fatigue crack growth is accelerated. In such a case, it is just the other way round compared to fretting corrosion. This exceptional behavior has been observed for some Ti-alloys. However, in general, corrosion has an unfavorable influence on both crack initiation and crack growth. The contribution to crack initiation is largely a pure corrosion mechanism causing surface damage. The acceleration of crack growth by a corrosive environment is caused by some interaction between a corrosive mechanism, cyclic slip at the crack tip and a rupture mechanism (decohesion), which leads to an enhanced crack extension.

The large effect of a corrosive environment on an S-N curve was discussed in Section 2.5.7 and illustrated in Figure 2.29 by results for mild steel tested in air, water and salt water. A significant decrease of fatigue lives and fatigue strength is observed in this figure. The large reduction of the fatigue limit is most noteworthy. It implies that crack initiation is possible at low stress amplitudes, which would not have occurred without the corrosive environment. After crack initiation, the environment can enter the crack, reach the crack tip, and enhance the crack growth rate. The corrosion processes involved are chemical, electrochemical in liquid environments, or physical.

Corrosion is a time dependent process. As a consequence, corrosion fatigue should depend on the time scale of the load history. During fatigue at a low frequency, much more time is available for a corrosion mechanism than during fatigue at a high frequency. The frequency effect was also illustrated by the results of Figure 2.29.

Two types of environments should be considered:

1. *Gaseous environments*
   Some gaseous environments do not interact with the material during the fatigue process. The environment is considered to be inert. In this respect, the most pure inert environment is vacuum, which is technically significant for space applications. It is also used in research investigations to study fatigue without any interference from an

environment. The experimental problem is to obtain a very low vacuum pressure in order to be sure that effects on the fatigue mechanism are excluded. Fatigue tests have been carried out with a vacuum pressure as low as 0.1 Pa.[20] An alternative is to use an inert gas, e.g. argon or nitrogen. The gas then should be highly purified, which also implies that it should be an extremely dry gas without water vapor.

Fatigue tests in a laboratory are usually carried out in air. It is more carefully specified as "laboratory air" with data on the temperature (often labeled as room temperature, RT) and the relative humidity (RH). Results of fatigue tests in air are frequently used as a reference for comparison to fatigue in an aggressive environment. Such comparisons might suggest that air is a non-corrosive environment. However, this is not correct. Water vapor and oxygen are active agents during fatigue of several materials. Furthermore, decomposition of water vapor implies that hydrogen can also play some role in fatigue by entering the material.

2. *Liquid environments*

The most well-known liquid environment used in test programs is salt water. The detrimental effect of salt water was known long ago from industrial applications. Experiments on the effect of salt water were already carried out in the early 1930s by Gough and co-workers [2]. Results of this work are shown in Figure 16.1. The large reduction of the fatigue limit is most obvious. The technical relevance of liquid environments is easily understood. Many structures become wet, e.g. structures in the sea, structures outdoors by rain, otherwise by condensation of water vapor, etc. Near coast lines, water will contain salt. In many cases, the presence of water cannot be avoided, while water can contain several impurities which can affect corrosion fatigue. The corrosion mechanism in a liquid is electro-chemical. At a material surface, corrosion can contribute to crack nucleation to create the very first microcrack. As soon as a crack is present, the liquid environment enters the crack. Under cyclic loading, the crack acts as a pump due to cyclic opening and closing of the crack. The environment is drawn into the crack.

Corrosion fatigue has extensively been studied in various research programs reported in the literature. This has significantly contributed to the present

[20] 0.1 Pa = 0.1 N/m^2 = 10^{-6} bar $\approx 10^{-6}$ atmosphere. Another frequently used unit is torr, called after Torricelli of the mercury (Hg) barometer. The conversion is: 1 torr (= 1 mm Hg) = 133.3 Pa.

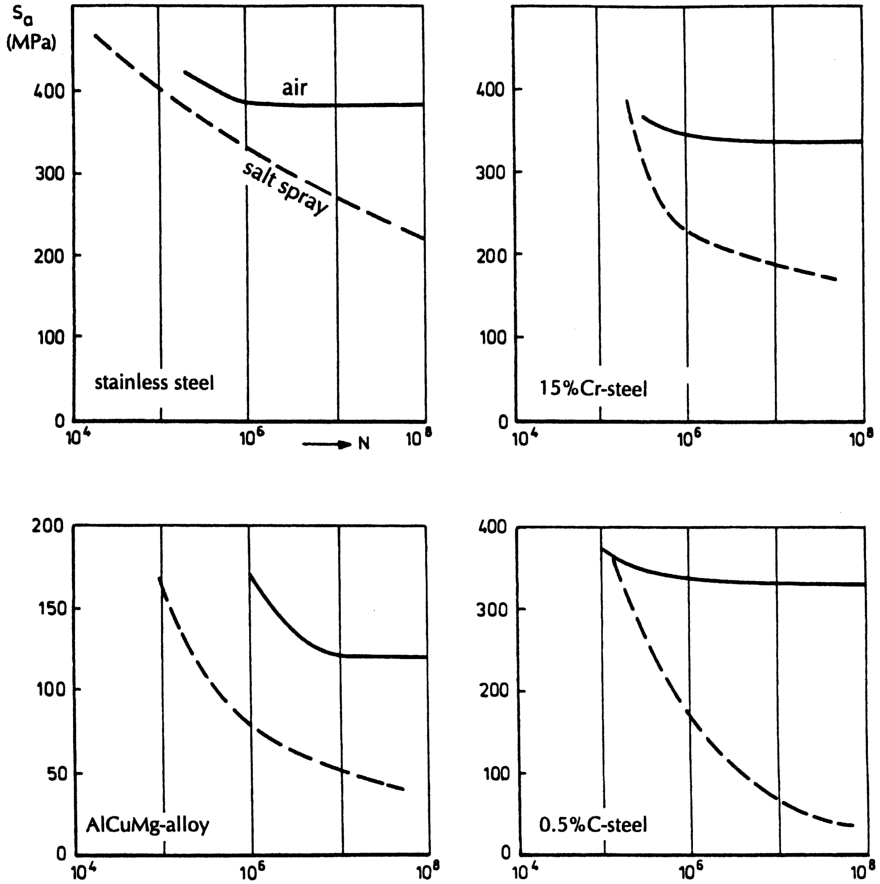

Fig. 16.1 Effect of salt water on S-N curves. Note the large reduction of fatigue limits. Results of Gough and Sopwith [2].

understanding of corrosion fatigue. It has also shown that corrosion fatigue is a rather complex phenomenon. Investigations on the fatigue mechanism under corrosive conditions are difficult. The number of variables involved is large, both with respect to materials and environments. The process zone is extremely small, e.g. crack initiation in a slip band, or crack extension at a crack tip. Dimensions of the crack extension in one cycle are in the μm range, or even in the sub-micron range. It is hard to make in situ observations other than by fractography in the electron microscope. However, the consequences of corrosion fatigue in terms of fatigue lives, fatigue limit, and crack growth rates can be measured. The discussion in this section is restricted to some simplified mechanistic aspects and trends shown in experiments. Aspects of the engineering significance are covered in Section 16.3.

16.2.1 Corrosion fatigue in gaseous environments

Most investigations on corrosion fatigue in gaseous environments were made on fatigue crack growth. Crack initiation, starting in slip bands at a free material surface, has been discussed in Chapter 2. It was pointed out that cyclic slip is causing intrusions (Figure 2.2), which create fresh metal surfaces exposed to the environment. For most technical materials, it implies that oxidation will occur immediately, which will interfere with subsequent cyclic slip. This very first microcrack growth should depend on the presence of oxygen in the environment. It is also possible that water vapor plays a role in this environmental process.

Fatigue tests in vacuum on pure metals have shown that cyclic slip is a more distributed phenomenon occurring at several places along the free surface. It is not hampered by an outside oxide layer on the metal. However, technical materials are always covered by some oxide layer, which usually is rather brittle. Cyclic slip during fatigue in air is more concentrated in a small number of slip bands. It still remains questionable whether gaseous environments can reduce the fatigue limit. However, as soon as microcracks are present, a gaseous environment enters the fatigue crack and an environmental effect on microcrack growth can occur. The effect was confirmed in experimental investigations on macrocracks. It has been shown that water vapor is of essential importance for fatigue crack growth in several materials, including steels and Al-alloys. Figure 16.2 shows results of Pao et al. [3] for fatigue crack growth in AISI 4340 steel ($S_U = 2082$ MPa) in a water vapor environment of a low pressure (585 Pa = 4.4 torr). A significant and systematic frequency effect occurred in the frequency range of 0.1 to 10 Hz. Apparently, a time-dependent mechanism is active during fatigue crack extension. It is generally associated with some hydrogen mechanism. Dissociation of water molecules produces OH^- and H^+ which can affect the cohesion strength at the crack tip. It is referred to as an embrittlement effect during fatigue crack growth. However, it remains a difficult problem to define in detail how this occurs. Moreover, it is not necessarily the same mechanism for different materials. The effect should not be considered to be the same as hydrogen embrittlement under sustained loading, which usually leads to an intergranular failure.

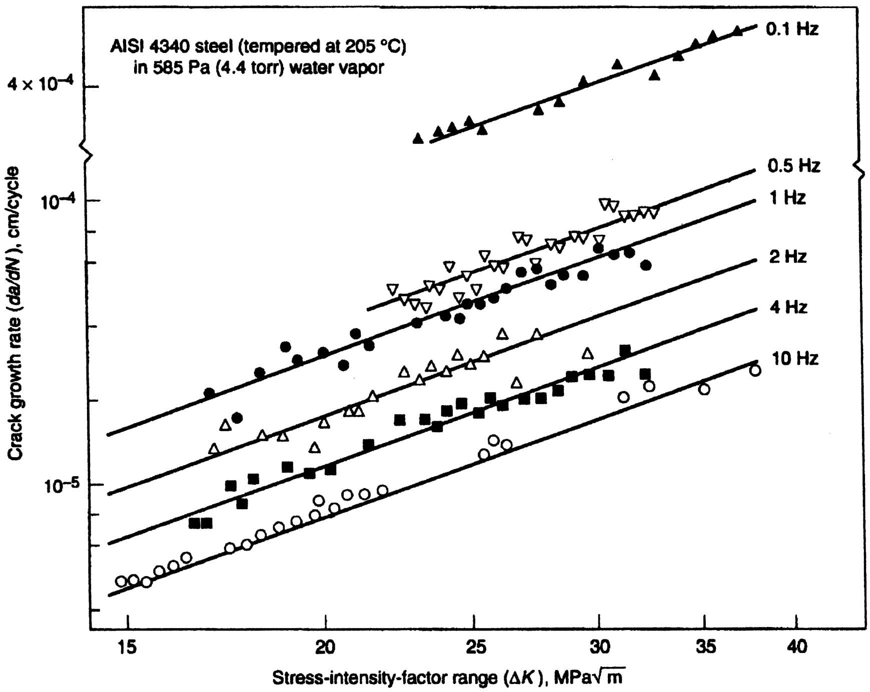

Fig. 16.2 Fatigue crack growth in a high-strength low-alloy steel in water vapor. Effect of frequency. Results of Pao et al. [3].

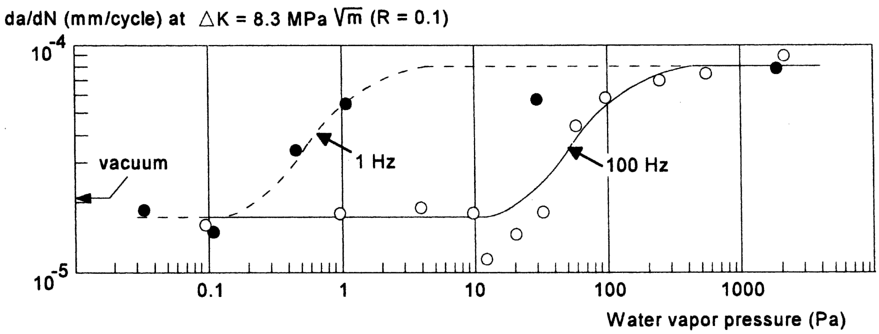

Fig. 16.3 Fatigue crack growth in an Al-alloy (RR58 ≈ 2618). Effect of water vapor pressure. Results of Bradshaw and Wheeler [4].

Similar indications on water vapor effects were observed in fatigue crack growth experiments on Al-alloys. Bradshaw and Wheeler carried out tests in water vapor of different pressure levels [4]. Crack growth rates obtained at a ΔK-level of 8.5 MPa$\sqrt{\text{m}}$ are shown in Figure 16.3. At a low water vapor pressure level, the crack growth rate was 0.16 μm/cycle, almost the same as the growth rate in vacuum at the same ΔK. With so little water vapor, it appears to be an inert environment. However, at higher water vapor pressures, the crack growth rate goes to a constant maximum level of about 0.8 μm/cycle, which is five times larger than at the low water vapor pressure level. The transition from the low to the high growth rate occurs in a similar S-curve for 1 and 100 Hz, but at 1 Hz at a 100 times lower pressure range than at 100 Hz. According to Bradshaw and Wheeler, it supports a dynamic adsorption model. More support for the significance of water vapor is coming from the observation that crack growth rates in Al-alloys are higher in humid inert gases than in dry air or dry oxygen.

An interesting observation was made by Broek [5], who found that the crack growth rate in Al-alloy sheet specimens (7075-T6) tested in air at −75°C was significantly lower than in air at RT. At such a low temperature, the water vapor pressure is very low, even at 100% RH, and this leads apparently to a lower crack growth rate. Although the lower ductility of this material at such a low temperature might enhance crack growth, the water vapor effect was predominant in reducing the growth rate.

16.2.2 Corrosion fatigue in liquid environments

Environmental effects

The most noteworthy effect of a liquid environment is the large reduction of the fatigue limit as illustrated by Figure 16.1. Under corrosive conditions fatigue cracks can be nucleated at very low amplitudes, whereas this does not occur if corrosion damage is not present. The initial contribution from corrosion is in creating surface damage. The corrosion pit shown in Figure 16.4 is severe surface damage. Dissolution of material has occurred. The picture also indicates an intergranular corrosive attack. Actually, it is a horrible notch, which should have a large effect on the fatigue limit. The effect of corrosion pits on the S-N curve was illustrated in Chapter 2 with Figure 2.28.

Corrosion damage is generated in the first part of the fatigue life. Surface corrosion damage implies that micronotches are present. Subsequent fatigue crack growth is again assisted by corrosion. Because this can occur at stress amplitudes far below the original fatigue limit, it still can take a large number of cycles until complete failure.

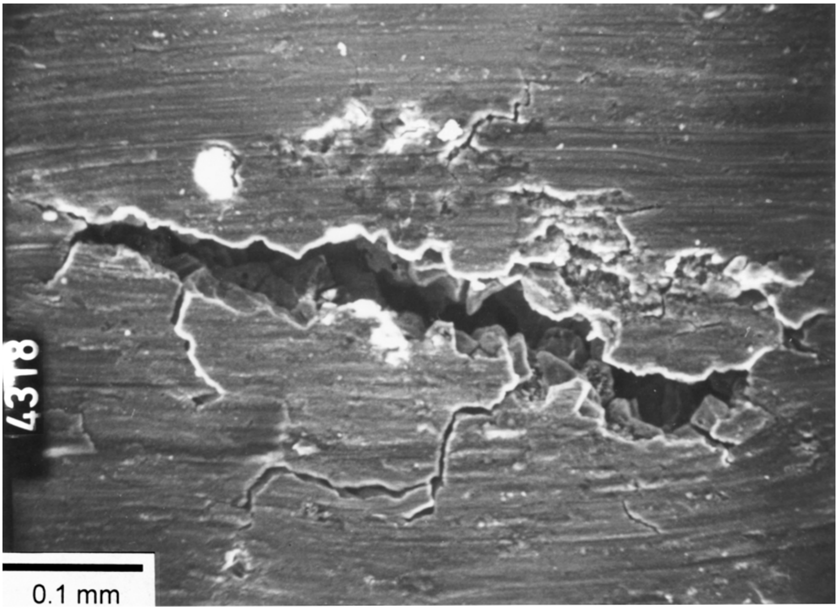

Fig. 16.4 Corrosion pit in an Al-alloy surface [6]. Tip to tip about 0.5 mm.

Investigations of macrocrack growth have indicated that corrosion in an aqueous environment significantly contributes to fatigue crack growth. The involvement of corrosion variables was borne out by effects on the fatigue crack growth rate when electrochemical conditions were modified. An obvious approach is to carry out comparative tests in different electrolytes. This was done by Duquette and Uhlig using deaerated water in comparison to non-deaerated water in tests on low-carbon steel specimens [7]. The results in Figure 16.5 show that deaerated water gave a better S-N curve than aerated water. The graph indicates that the same trend was also found for tests in a 3% NaCl solution. The S-N curve for fatigue in air in Figure 16.5 suggests that deaeration inhibits early corrosion damage of the material surface. This follows from the reduction of the fatigue limit, which is smaller in deaerated salt water than in aerated water. In deaerated water without salt, the reduction is even absent. But the test results also raise a question; why does deaerated water give a better fatigue life than air?

The corrosion aspect of fatigue crack growth in aqueous solutions is further confirmed by experiments with liquid corrosion inhibitors added to salt water. Crack growth rates in several high-strength steels were significantly reduced by the application of inhibitors as shown by results of Lynch et al. [8]. The corrosion activity is indeed dependent on the

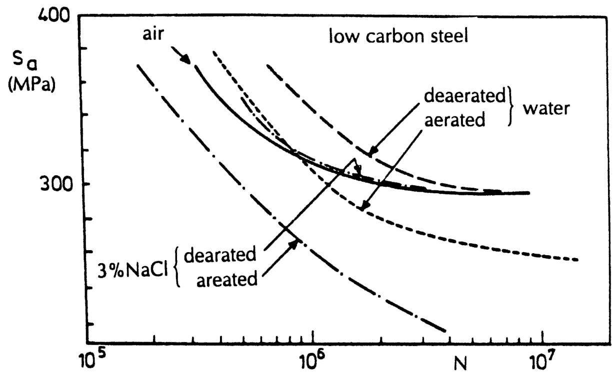

Fig. 16.5 S-N curves of low-carbon steel in water. Effect of deaerating water. Results of Duquette and Uhlig [7].

composition of the electrolyte at the crack tip. Pollution of water can also affect the corrosion fatigue behavior.

Furthermore, electrolytic corrosion is affected by application of an electrical potential on a specimen. Actually, this technique is used as a practical means for corrosion protection of structures operating in water or underground. The application of a potential voltage modifies the anodic or cathodic reaction. In laboratory fatigue experiments, it has been shown that an electrical potential imposed on a specimen can reduce surface corrosion damage, crack initiation and fatigue crack growth.

With respect to explaining faster fatigue crack growth in a liquid solution as compared to fatigue in air, different suggestions are proposed in the literature. Arguments adopted are associated with anodic dissolution phenomena at the crack tip, or again some hydrogen embrittlement mechanism. Plastic deformation at the crack tip can make the material of the crack tip zone more anodic than away from the tip. The crack tip zone then becomes more corrosion sensitive. Moreover, in salt water Cl-ions may weaken the cohesive strength of the material. The weakening can also be due to absorbed hydrogen produced as a result of the local corrosion activity.

Frequency and wave shape effects

Interesting results were published by Barsom [9], see Figure 16.6. He carried out crack growth tests on a maraging steel (12Ni-5Cr-3Mo, $S_U = 1290$ MPa) using different frequencies and wave shapes (positive and negative saw tooth wave shapes, see Figure 2.30). Tests in air did not reveal an influence of

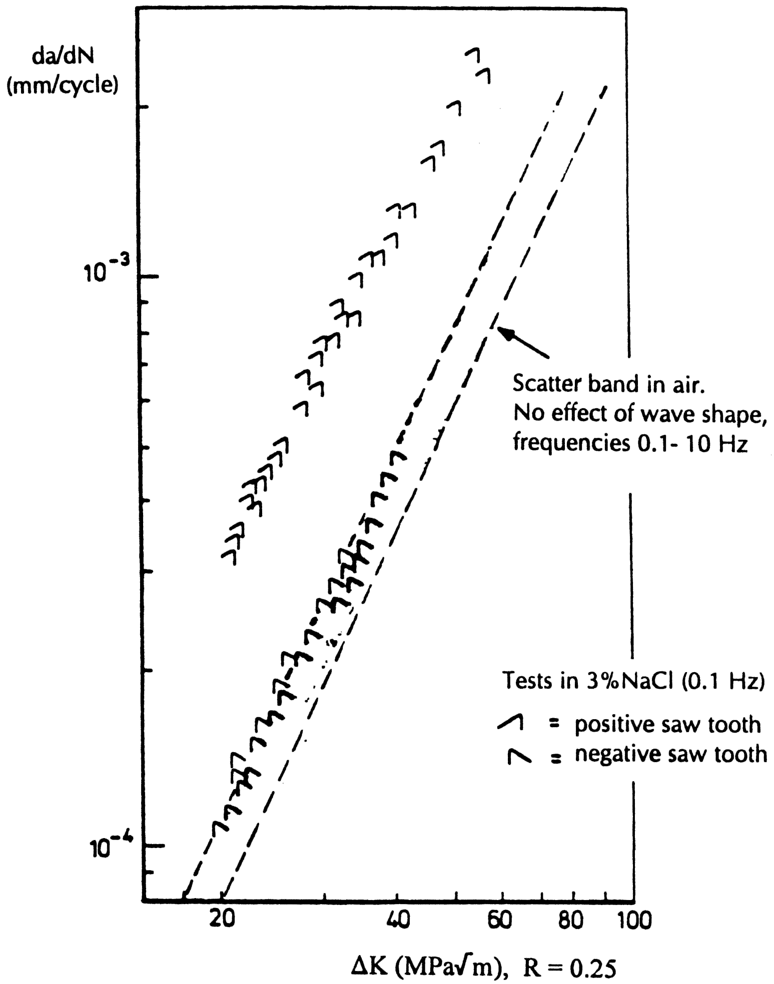

Fig. 16.6 Fatigue crack growth in a maraging steel (12Ni-5Cr-3Mo) with positive and negative saw tooth wave shapes. Results of Barsom [9].

these variables. In salt water, a significant frequency effect was found for sinusoidal load cycles with frequencies of 0.1, 1 and 10 Hz, respectively. Interesting results were obtained with positive and negative saw tooth cycles. The results for negative saw tooth cycles in salt water are practically within the scatter band of the test results in air (Figure 16.6). It suggests that corrosion did not accelerate crack growth. This was explained by the high loading rate when increasing the load from S_{min} to S_{max} in a very short time. In this part of the load cycle, crack extension must occur. In spite of the low overall frequency of 0.1 Hz, the loading part of the cycle is too short for a significant contribution of salt water to crack extension. However, in the tests with the positive saw tooth cycles, the load is increased from S_{min} to S_{max} very slowly; for 0.1 Hz in 10 seconds. There is ample time for the corrosive environment to interact with the crack extension mechanism during the increasing stress intensity at the crack tip. The crack growth rate was about three times faster than for the negative saw tooth cycles.

Another interesting question was addressed by Atkinson and Lindley [10]. They considered slow load cycles with hold times at the maximum load, see the wave shapes in Figure 16.7. The technical relevance is related to structures, for which the working load is maintained for a considerable period of time. Pressure vessels are a good example. The hold times at S_{max} in the test program were 0, 1 and 10 minutes respectively. Two loading rates were applied, characterized by the rise time and fall time, both being 100 seconds (wave shapes A-C) or 10 seconds (wave shapes D-F). Crack growth rates were measured at a constant ΔK-value of 50 MPa$\sqrt{\text{m}}$. The results in

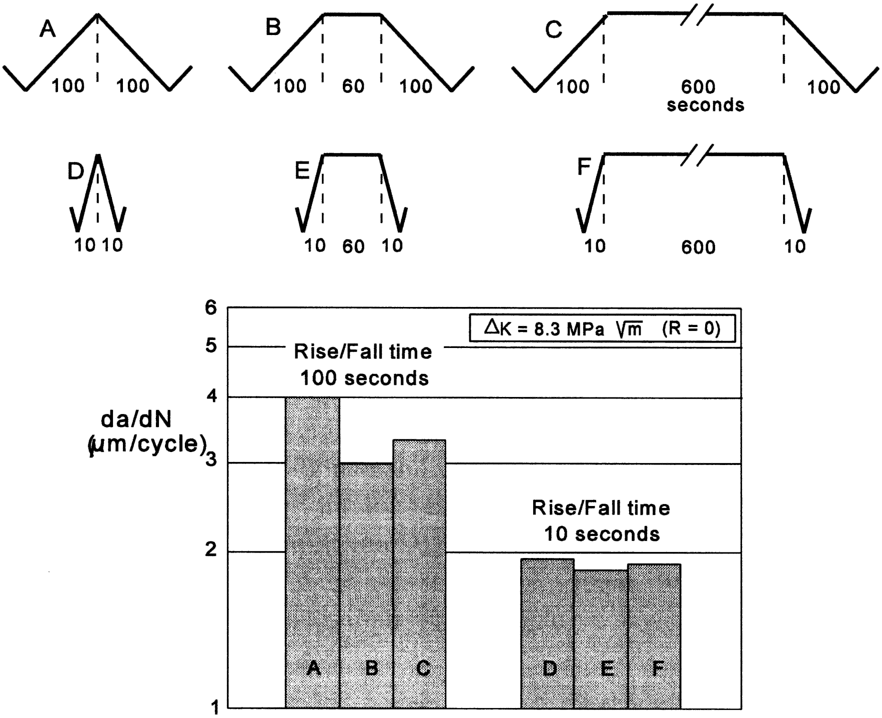

Fig. 16.7 Effect of hold times at maximum load on fatigue crack growth in 0.22C-stetel in lake water. Results of Atkinson and Lindley [10].

Figure 16.7 indicate a systematic influence of the rise time. The crack growth rate for increasing the load from minimum to maximum in 100 seconds was about two times larger than for a rise time of 10 seconds. However, the results for hold times at K_{max} of 1 or 10 minutes, or no hold time at all, did not indicate a systematic difference. It thus should be concluded that crack extension occurred during raising the load from minimum to maximum, and not during the hold time at K_{max}. If some crack extension might occur during the hold time period, it should be associated with stress corrosion. It then may be recalled that stress corrosion in many materials occurs along the grain boundaries (intergranular), whereas fatigue crack growth occurs through the grains (transgranural). It thus is not obvious that crack extension of corrosion fatigue and stress corrosion could be additive.

Comparative fatigue crack growth tests were carried out in Delft [11] on Al-alloy specimens (7075-T6) in salt water. The wave shapes are shown in Figure 16.8. Different rise times (time for raising the load from S_{min} to S_{max}) were used. Hold times were added at either S_{max} or S_{min}, see the inset figures in Figure 16.8. The crack growth tests were carried out at $S_{max} = 90$ MPa and $S_{min} = 30$ MPa ($R = 1/3$). The crack growth rates in Figure 16.8 are $\mathrm{d}a/\mathrm{d}N$-values at $\Delta K = 10$ MPa$\sqrt{\mathrm{m}}$ ($2a \approx 17.0$ mm

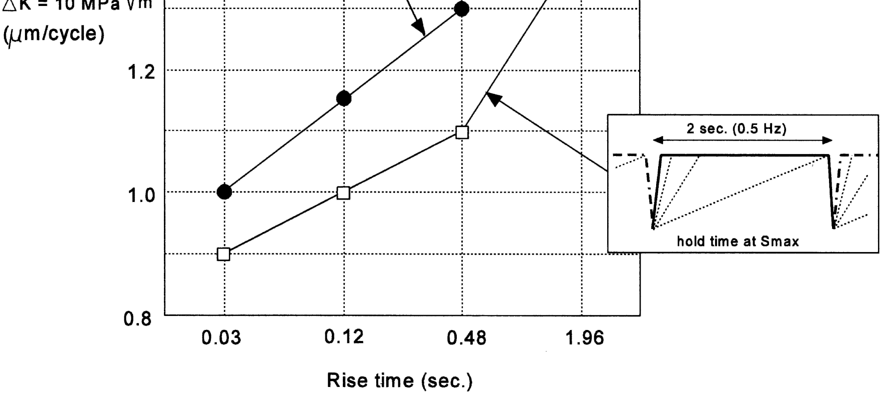

Fig. 16.8 Crack growth rate in 7075-6 specimens tested in salt water with different wave shapes. Effects of rise time and holding at S_{max} or S_{min} [11].

in a 100 mm wide specimen, average results of three similar tests). The crack growth rate increases for a longer rise time, i.e. a slower load increase. This trend agrees with the observation of Barsom and Atkinson and Lindley (Figures 16.6 and 16.7, respectively). However, the crack growth rate was lower for holding times at S_{max} as compared to the results for holding times at S_{min}, perhaps an unexpected trend. It was tried to clarify the trend by fractographic observations in the SEM. It turned out that holding at S_{max} caused secondary cracking in grain boundaries perpendicular to the crack front. These cracks are associated with a stress component in the thickness direction. It was generally observed that the fracture surface for holding at S_{max} had a more complex topography which was responsible for the slower crack growth.

Some additional comments on the crack growth mechanism

Perhaps unexpected, it was found by Komai that fatigue crack growth in low-carbon steel could be slower in salt water than in air [12]. It turned out that corrosion products filled the crack, which prevented a full crack closure at S_{min} and probably caused a smaller effective ΔK. Wanhill and Schra observed that corrosion could increase the threshold ΔK_{th} obtained in air for two Al-alloys (2024-T3 and 7475-T761), even more by sump water than by salt water [13]. The increase of ΔK_{th} was associated with jamming of the crack tip by corrosion products. Remarkably enough, Wanhill and Schra found that sump water considerably accelerated crack growth at higher ΔK-values (tests at 13 Hz). It should be expected that an increased mean stress will enhance the corrosion effect because the crack will be more open. This promotes the accessibility of the environment to the tip of the fatigue crack.

An increased temperature should also enhance the corrosion fatigue mechanism. In the temperature range were most liquid environments can exist, it is expected that activation of the corrosion mechanism could become more significant at an increased temperature, The information in the literature is limited, although increased crack growth rates in the temperature range of 10 to 60°C are occasionally reported, a trend which should be expected. This was confirmed by results of Atkinson and Lindley [14] obtained in fatigue crack growth tests on a carbon steel specimens loaded at $\Delta K = 50$ MPa$\sqrt{m}$ ($R = 0.05$). Crack growth rates for temperatures of 0, 25, 50, 75 and 100°C were 1.0, 2.0, 2.6, 3.6 and 4.6 μm/cycle respectively.

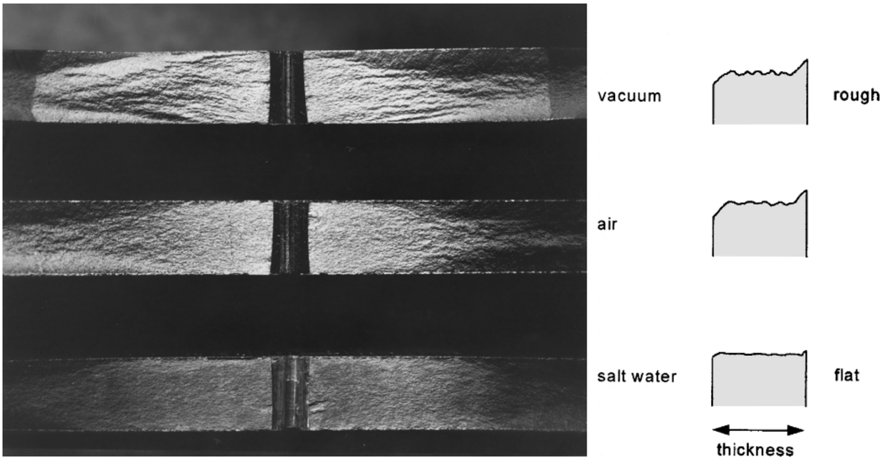

Fig. 16.9 Effect of environment on the fatigue fracture surfaces of fatigue cracks in center-cracked specimens of Al-alloy plate specimens, 7075-T6, thickness 6 mm [16]. $S_{max} = 98$ MPa, $R = 0.1$.

The above examples of corrosion fatigue test results illustrate that corrosion fatigue crack growth is a complex phenomenon, which can be quite different for different material/environment systems. In addition to various aspects of corrosion reactions, the role played by the configuration of the fracture surface is somewhat underexposed in the literature. Different corrosion fatigue mechanisms can cause different fatigue fracture surfaces, both microscopically and macroscopically. On a microscopic level, Stubbington and Forsyth [14] refer to two types of striations in Al-alloys, brittle striations, which are rather flat, and ductile striations, which are more undulated. Brittle striations occurred in an aggressive environment and ductile striations in air as an environment.

Different environments can also lead to macroscopically visible differences of the fracture surface. A noteworthy example is offered by the occurrence of shear lips, described in Section 2.6, see Figure 2.38. Shear lips at a free material surface have been observed on fatigue crack fractures in several steels and Al-alloys. Horibe et al. [15] carried out fatigue crack growth tests on low-carbon specimens in air and in salt water. The fracture surface had a more brittle appearance in salt water, while the transition to shear lips during crack growth was less evident than in air. In an aggressive environment, shear lip formation is suppressed. Apparently, an aggressive environment is promoting tensile decohesion, rather that shear decohesion occurring in the shear lips. A similar corrosion effect was observed in comparative tests on center-cracked Al-alloy specimens tested in vacuum, laboratory air, and salt water [16]. Crack growth in air was about two times faster than in vacuum, while in salt water it was again about three times faster than in air. The faster crack growth in the more aggressive environment could not be correlated with a larger ΔK_{eff} because crack closure measurements indicated the same S_{op} for the three environments.[21] The difference between the crack growth rates should thus be associated with environmental effects. However, the fracture surfaces obtained in the three environments were also different, see Figure 16.9. The fracture surface in vacuum showed the largest shear lips and a more undulated fracture surface over the full thickness. The smallest shear lips and the most flat fracture surface occurred in salt water. The fracture mechanisms are apparently different in the three environments, and a different crack growth resistance should thus be expected. In addition, a more flat fracture surface implies a straight crack front, whereas a corrugated fracture surface is associated with a tortuous crack front. The crack driving force ($\mathrm{d}U/\mathrm{d}a$) per unit length of the crack front will be smaller for an irregular fracture surface than for a flat fracture surface. In other words, the environmental effect on crack growth is not solely the result of a corrosion mechanism; the fatigue fracture characteristics are also involved.

16.3 Practical aspects of corrosion fatigue

In Section 16.2, several aspects of corrosion fatigue have been discussed and illustrated by experimental data. Some evident trends of these data are: (i) a large reduction of the fatigue limit can occur in liquid environments, (ii) crack growth rates may be significantly increased by a corrosive environment, and (iii) the load frequency and wave shape can have a significant effect on crack growth. It was also pointed out that the detrimental effects could be understood in terms of surface corrosion damage and enhanced crack growth rates by corrosion assisted crack extension during cyclic loading. These effects are dependent on the type of material and environment. The understanding was largely obtained in investigations in the laboratory, usually in CA tests on unnotched specimens or on crack growth specimens (MT and CT). The question remains how this understanding should be translated into design and production practices, and prevention

[21] Theoretically, an effect of the environment on the plastic zone size should not be expected. As a consequence, a similar crack opening stress level, and thus a similar ΔK_{eff}, appears to be logical.

of corrosion fatigue in service. As an example of this problem setting, the practical relevance of fatigue tests on aircraft Al-alloys specimens submersed in salt water is not directly obvious. After all, an aircraft is not a submarine. But some lessons can be learned from understanding the corrosion fatigue problem.

Corrosion can cause surface damage, which should be considered to be notches. In spite of a limited depth (a few tenths of millimeters), corrosion pits must be associated with high stress concentrations. Especially for high-strength materials, the corrosion damage can be disastrous. For instance, fatal accidents have occurred due to fatigue failures starting from a corrosion pit in the rotor system or the blades of helicopters. The characteristic feature was corrosion damage at the material surface of a notch which was open to the environment. Corrosion protection had been insufficient. The notch should not be accessible for the environment, or surface treatments should prevent crack growth from corrosion surface damage, e.g. shot peening or other surface treatments (Chapter 14).

It can be tried to make a prediction of the remaining fatigue life if a corrosion pit is present. The corrosion pit should then be represented by an equivalent initial flaw, and the life prediction is a fatigue crack growth prediction. Problems involved are associated with assumptions to be made. The initial flaw size is an important parameter. The crack growth rate is relatively low for a small crack as a result of the low stress intensity factor. As a consequence, assuming an initial crack depth of either 0.2 or 0.4 mm (0.008 or 0.016 inch) can imply a large difference for the predicted crack growth life. Another problem is the crack growth prediction. Which crack growth data will be used? The environment causing the surface damage can also affect subsequent crack growth. Furthermore, is the load spectrum sufficiently known? At best, an estimate of the order of magnitude of the remaining fatigue life is obtained from a prediction, although the estimate can be instructive for considering safety and economic aspects.

In Section 16.2, the discussion of corrosion fatigue was mainly concerned with CA tests on unnotched specimens or crack growth specimens. The results of such tests can still be relevant to notches in a structure if they are directly exposed to the environment, e.g. open holes and fillets. A good environmental accessibility also exists for welded structures in the sea. In other situations, the most fatigue critical locations are not in contact with a liquid environment, for instance inside closed box type structures, or in bolted and riveted joints depending on how these joints are designed and produced. However, it should not be overlooked that air also contains water vapor. It implies that water by condensation can be present at notches which can be reached by air. Furthermore, if plates are joined by bolts or rivets, crevices between the plates may not be fully airtight, and air can penetrate between the plates. Water can then be present also, and cyclic loading will help further penetration between the plates. It can lead to the well-known crevice corrosion. Industries have learned to recognize such problems by service experience. Because corrosion is generally undesirable, also if fatigue is not a problem, various ways have been developed to protect structures against different types of corrosion. At the same time, this is a protection against corrosion fatigue. Actually, it is commonly believed in the engineering world that the corrosion fatigue problem should primarily be handled as a corrosion problem. It thus implies avoidance of corrosion by proper design and material selection, supplemented by suitable surface treatments.

Sometimes, incidental fatigue cracks cannot be avoided. It then may be important to know if a corrosive environment will accelerate fatigue crack growth in service. If fatigue cracks are present, corrosion protection techniques applied to the material surface may be of little help because fatigue cracks can disrupt surface coatings. It could be tried to make a crack growth prediction, but the result should be considered with caution as said earlier. Safety factors are necessary, and the choice of these factors is a matter of judgment. An alternative is to carry out realistic service-simulation fatigue tests. The tests should be realistic, or at least conservative, with respect to the load history to be applied and the environment to be used. The specimen geometry should be representative for the structure under consideration. A realistic simulation of the load-time history can imply that experiments will require long testing times. In view of differences between service-simulation fatigue tests and the real service life conditions, a safety factor should still be considered. According to Schütz [1], a factor 2 may then be sufficient, but larger factors might be considered, depending on safety and economy arguments.

One variable mentioned in the previous section is the temperature which can affect corrosion reactions and increase the crack growth rate. Limited experimental evidence is available on this issue and it should be realized again that this evidence is coming from laboratory tests carried out at relatively high test frequencies in a short period. Engineering judgment as well as qualitative understanding of corrosion fatigue is essential to make decisions in such cases.

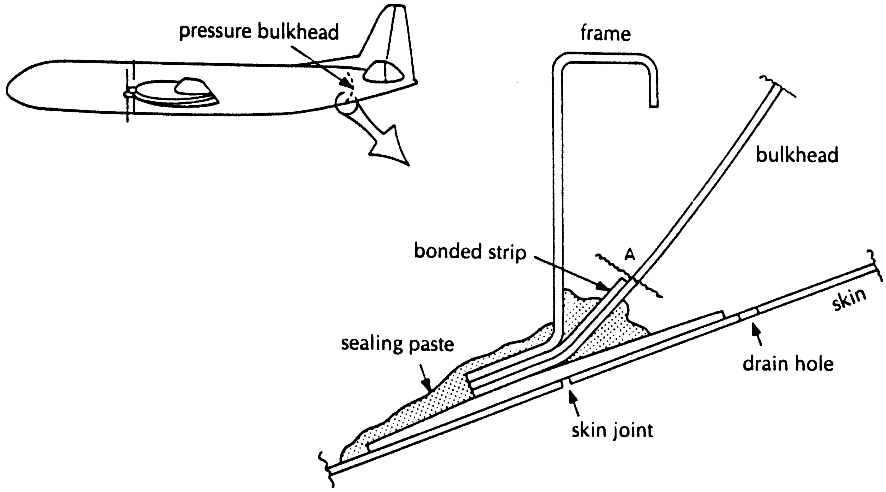

Fig. 16.10 Corrosion fatigue caused a catastrophic failure in a pressure bulkhead of a transport aircraft [17]. The failure occurred along the edge of the bonded strip at location A. Rivets are not shown in this figure.

16.4 A case history

In 1968 an aircraft crashed as a results of a pressure cabin failure occurring at cruising altitude. The accident investigation showed that the rear pressure bulkhead was blown out, which damaged the control system of the empennage rudder and elevators [17]. Nobody survived the accident, which resulted in 85 fatalities. Figure 16.10 shows the position of the rear pressure bulkhead in the aircraft, and a more detailed cross section of the structure at the fatigue critical location. The hemispherical dome of the pressure bulkhead is connected to the fuselage skin which is supported by a frame at the same location. The bulkhead is loaded by the cabin pressure which introduces a tensile membrane stress in the sheet material of the bulkhead. In general, each flight implies one load cycle on the joint of the pressure bulkhead to the fuselage skin. The joint is reinforced with a bonded strip along the edge of the pressure bulkhead. The designer was aware of the corrosive environment. Sump water can be collected in the lower part of the joint, i.e. between the bulkhead and the fuselage skin, and between the bulkhead and the frame.

Corrosion prevention is taken care of by a drain hole in the fuselage skin and by applying a sealing paste at the locations where crevice corrosion might occur. Corrosion fatigue cracks started at A and grew along the edge of the bonded strip. The environment inside the pressure cabin is humid air at room temperature. On the outside of the pressure bulkhead, the temperature at cruising altitude is very low; in the order of −50°C. As a result of the temperature difference between both sides of the pressure bulkhead, condensation of water vapor occurs at the inside of the bulkhead. Due to gravity, the condensed water flows down and is trapped in small quantities at the edge of the bonded strip, point A in Figure 16.10. This caused local corrosion damage which initiated fatigue cracks. After some circumferential crack growth, a catastrophic decompression failure occurred. The failure mode was corrosion fatigue.

Typical fatigue and corrosion prevention aspects were involved:

1. The material selection was not optimal. The crack growth properties and corrosion resistance of the Al-alloy involved were relatively poor.
2. From a fatigue point of view, the bonded strip is certainly a better solution then a riveted strip, because the notch effect is smaller. However, it was overlooked that the thin edge of the strip could trap water causing corrosion damage. It may be noted that the bonded strip is positioned at the inside of the pressure bulkhead. If the strip would have been bonded at the outside, it could not have trapped water.
3. The aircraft manufacturer applied sealing paste to the joint to avoid corrosion. If the sealing had included the edge of the bonded strip, corrosion fatigue should have been avoided.
4. Inspection of the location where corrosion fatigue started is difficult.

The case history illustrates that material selection, corrosion prevention and detail design can be important to avoid corrosion fatigue in service. Sump water is a well-known cause for corrosion problems in structures of steel and Al-alloys. Well-known examples are pockets in steel structures which collect stagnant water. The same can occur in the belly of a transport aircraft. Such circumstances should be avoided by a more clever design and corrosion protection.

16.5 Topics of the present chapter

1. Corrosion fatigue is a complex phenomenon due to the corrosion aspects involved. Detrimental effects of corrosion on crack initiation and crack growth under fatigue loading depend on the type of material and environment. Systematic effects have been recognized, but

these effects are not generally applicable to all material/environment combinations.

2. Corrosion fatigue effects are usually associated with material dissolution at the material surface and at the crack tip. At the material surface it will shorten the crack initiation period and substantially reduce the fatigue limit. At the crack tip it will accelerate crack growth which in addition may be increased by some weakening of the cohesive strength of the material at the crack tip.
3. Corrosion damage of the material surface and noteworthy corrosion pits, can lead to a large reduction of the fatigue limit.
4. Some typical aspects of corrosion fatigue are: (i) Damage contribution of corrosion to fatigue crack growth primarily occurs during crack extension in the load-increasing part of the load cycles. The loading rate in this part of the cycle is important. As a consequence, the load frequency can also be important. (ii) Holding times at maximum load are not necessarily contributing to crack extension. (iii) The water vapor pressure is an important variable of gaseous environments.
5. In most investigations, corrosion fatigue experiments were carried out as constant-amplitude tests on unnotched specimens or crack growth specimens under closely controlled environmental conditions. However, the conditions for corrosion fatigue of a structure in service are significantly different, especially with respect to the load-time history, the variable environment and long exposure times (years). These differences should be considered in practical problems.
6. Design considerations on corrosion fatigue are frequently based on the prevention of corrosion. It can be done by prevention of the access of the environment to fatigue critical locations of a structure, selection of a suitable corrosion resistant material, and application of material surface treatments.

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