

Effect of Corrosive Environment on the Fatigue Crack Initiation and Propagation Behavior of Al 5454-H32

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Fatigue behavior of aluminum alloy 5454-H32 was studied under laboratory air and 3% NaCl solution environment using smooth cylindrical and notched plate specimens. Presence of 3% NaCl environment during fatigue loading drastically reduced alloy fatigue life. The deleterious effect was pronounced in both types of specimens in the long-life regions, where the fatigue lives were lowered by as much as a factor of 10. However, the sharply notched specimens showed only a modest reduction in fatigue life in corrosive environment. The severe influence of the corrosive environment in the long-life (low-stress) regime cannot be explained merely by the early initiation of the fatigue crack from surface pits; the environmental contribution in the early crack growth regime must also be considered an important factor. Fracture surface studies revealed extensive pitting and some secondary cracking in the crack initiation region. It was shown that lowered fatigue life in Al 5454-H32 occurs by early initiation of fatigue cracks from surface pits. In addition, a corrosion pitting and secondary cracking process may be operative in the small crack growth region. This could have enhanced the early crack growth rate and thus contributed to the lower fatigue life in the long-cycle region.

Keywords
Al 5454-H32, aluminum alloys, corrosion, fatigue

1. Introduction

IT is well known that the fatigue life of engineering alloys subjected to cyclic loading while exposed to a corrosive environment is drastically affected by the conjoint action of two synergistic processes: corrosion and fatigue. This failure mode, termed corrosion-fatigue, is a common cause of failure of many engineering components and structures operating in corrosive environments. In the presence of a corrosive environment, fatigue life is considered to be reduced due to early initiation of a fatigue crack or enhancement of fatigue crack propagation rates by the corrosive environment.

Much of the work on corrosion-fatigue during the past two decades has focused on characterizing the influence of corrosive environment on fatigue crack propagation (long crack propagation) behavior (Ref 1-15). A few studies have dealt with the characterization of corrosion-fatigue crack initiation behavior using smooth unnotched specimens (Ref 16-20). Due to the complex mechanical, metallurgical, and environmental issues involved in the synergistic corrosion-fatigue process, the two regimes of fatigue life—crack initiation and crack propagation—have been studied separately.

However, the fatigue life of a component operating in a corrosive environment may not necessarily be governed only by the crack propagation stage or only by the crack initiation stage. Rather, as is well established, the total fatigue life of many engineering components and structures essentially consists of both crack initiation (crack nucleation and small crack growth) and crack propagation (long crack growth) portions. Characterization of both fatigue crack initiation and long fatigue crack propagation behavior is essential to a full understanding of the fatigue behavior of a given material. This is especially so in situations where an aggressive environment is present during fatigue loading, as different stress-environment synergistic mechanisms may be operative during different stages of fatigue life.

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With the above points in mind, an investigation was undertaken of the influence of corrosive environment on both the crack initiation and crack propagation regimes of the fatigue life of an aluminum alloy. Both smooth unnotched and notched specimens were used. It was assumed that fatigue of smooth unnotched specimens and bluntly notched (low K_t) specimens in corrosive environment would essentially characterize the corrosion-fatigue crack initiation behavior of the alloy, and that fatigue of sharply notched (high K_t) specimens would characterize its corrosion-fatigue crack propagation behavior.

An aluminum-magnesium type 5454 alloy was chosen for the study. Aluminum-magnesium 5*xxx* series alloys are developed for use in marine environments, pressure vessels, desalination plants, and the petrochemical industry. Unlike its counterpart types 5456 and 5086, which have been extensively studied, type 5454 received only modest attention in terms of

Table 1 Chemical composition of Al 5454-H32

Element	Weight percent
Iron	0.40
Silicon	0.25
Copper	0.10
Manganese	0.5-1.0
Magnesium	2.4-3.0
Chromium	0.2-0.5
Zinc	0.25
Titanium	0.20

Table 2 Mechanical properties of Al 5454-H32

Modulus of elasticity (E), MPa	70.3×10^3
0.2% offset yield strength (σ_y), MPa	220
Ultimate tensile strength (σ_u), MPa	312
Reduction in area (RA), %	30.4

the characterization of its corrosion-fatigue behavior. Perhaps this was sufficient reason to choose this alloy for the present study.

2. Experimental Procedure

A commercial-grade aluminum 5454 alloy in the H32 temper condition was used for this study. This material was received in the form of 6 mm thick plate. The nominal composition and mechanical properties of the alloy are listed in Tables 1 and 2, respectively.

Smooth cylindrical specimens with a gage section diameter of 4.5 mm and a gage length of 12.5 mm were machined from the plate stock such that the longer dimension (loading axis) was parallel to the rolling direction. Center-notched specimens with dimensions of 305 by 50.8 by 6 mm were also machined from the same plate with a similar orientation as the smooth specimens. Two notch geometries, a 12 mm diam circular hole and a 12 mm elliptical notch, were investigated. The smooth specimens were mechanically polished to a final finish of 600-grit SiC. An approximately 25 mm wide area surrounding the notch at the midsection of the center-notched plate specimens was also polished to a 600-grit SiC finish.

Fatigue and corrosion-fatigue tests were conducted on a closed-loop electrohydraulic material testing system under load-controlled conditions with a constant-amplitude sinusoidal waveform cycling at a frequency of 10 Hz. A self-aligning hydraulic gripping system was used to grip the center-notched plate specimens, and a Woodsmetal grip was used to grip the smooth cylindrical specimens.

All corrosion-fatigue tests were carried out under fully submerged free-corroding conditions in a 3% NaCl solution environment at ambient temperature. The corrosive environment

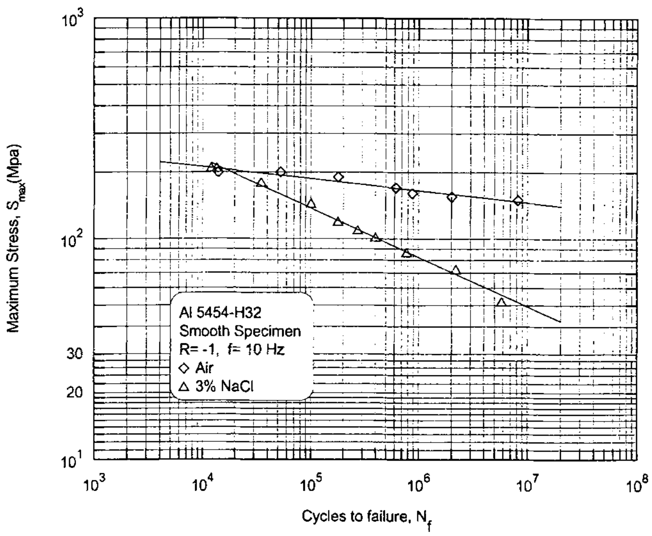


Fig. 1 Effect of 3% NaCl environment on the fatigue life of Al 5454-H32 for smooth specimens

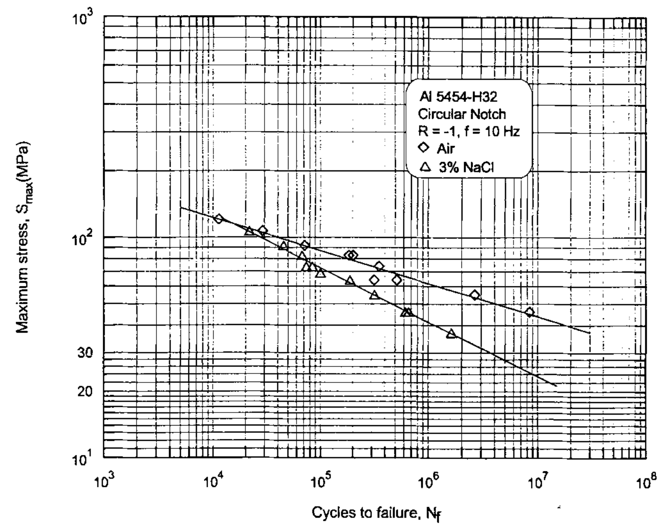


Fig. 2 Effect of 3% NaCl environment on the fatigue life of Al 5454-H32 for circular notched specimens

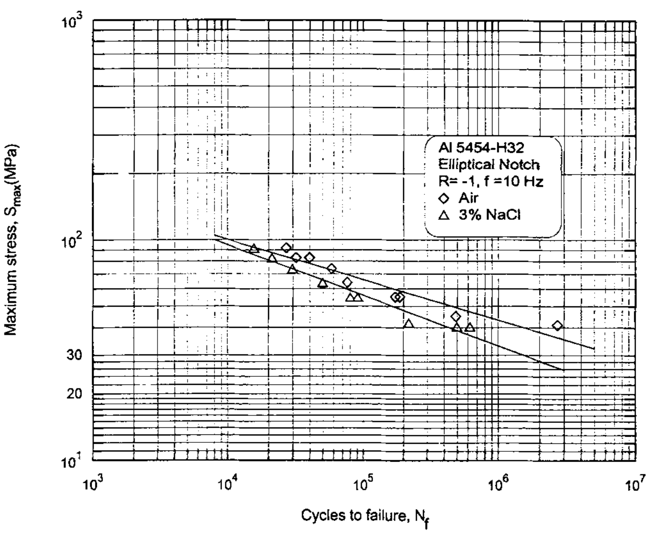


Fig. 3 Effect of 3% NaCl environment on the fatigue life of Al 5454-H32 for elliptically notched specimens

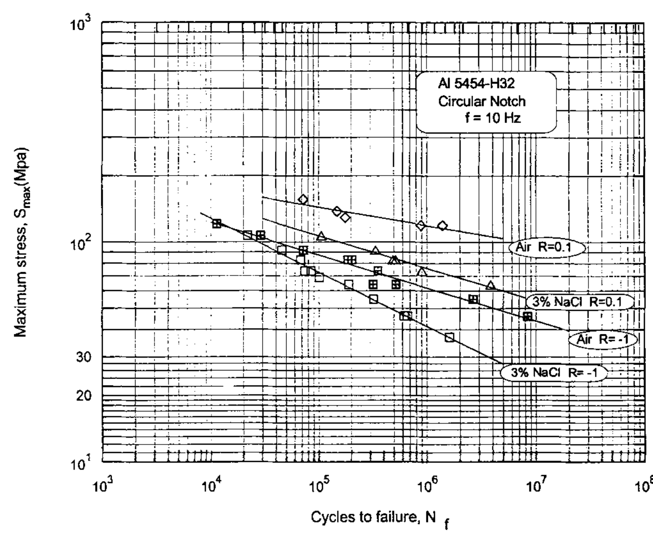


Fig. 4 Effect of stress ratio on the fatigue life of Al 5454-H32 in laboratory air and in 3% NaCl environment for circular

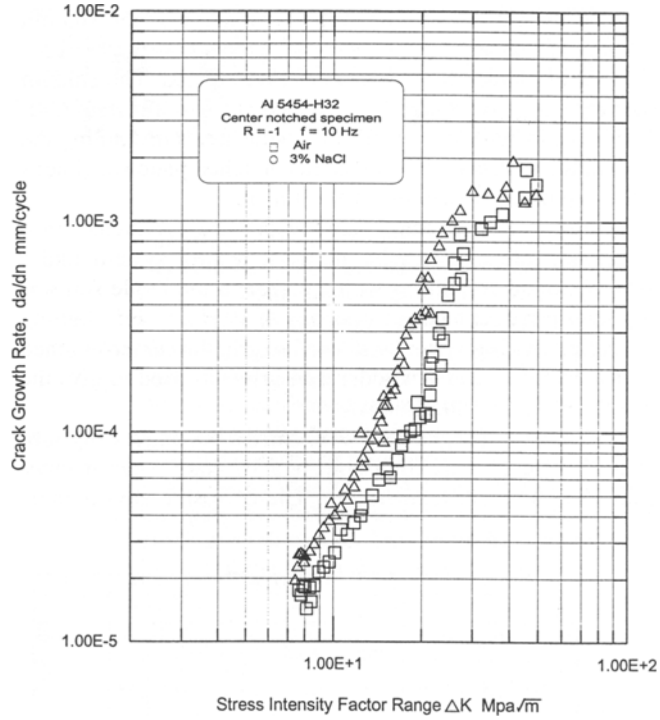


Fig. 5 Effect of 3% NaCl environment on fatigue crack growth rate for Al 5454-H32

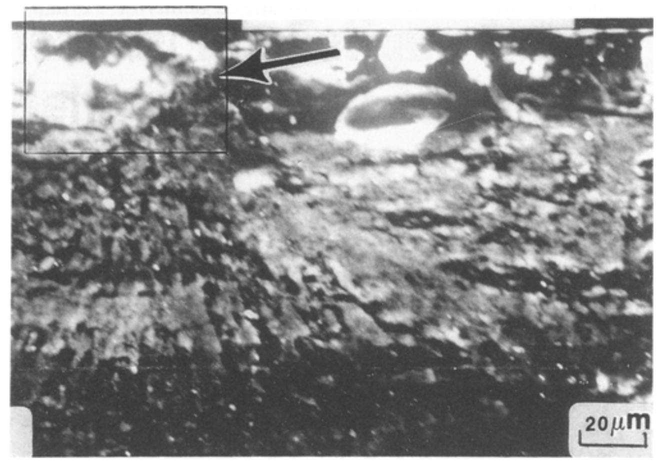


Fig. 6 Fatigue crack initiation from a corrosion pit (see upper left box at top surface) in 3% NaCl environment. Arrow points to the initiation site.

was contained in a Plexiglas immersion cell mounted in the midsection of the test specimen. The corrosive solution was periodically replenished to make up for evaporation during high-cycle tests. Crack growth was measured using an optical microscope mounted on a specially designed micrometer fixture that enabled crack measurements to an accuracy of 0.01 mm.

3. Results and Discussion

3.1 *Fatigue and Corrosion-Fatigue Tests*

Results of fatigue tests in laboratory air environment and corrosion-fatigue tests in 3% NaCl environment are shown in Fig. 1 to 5 for smooth, circular notched, and elliptically notched specimens. The figures show the fatigue-life data with the best log-log fit line drawn through the data points.

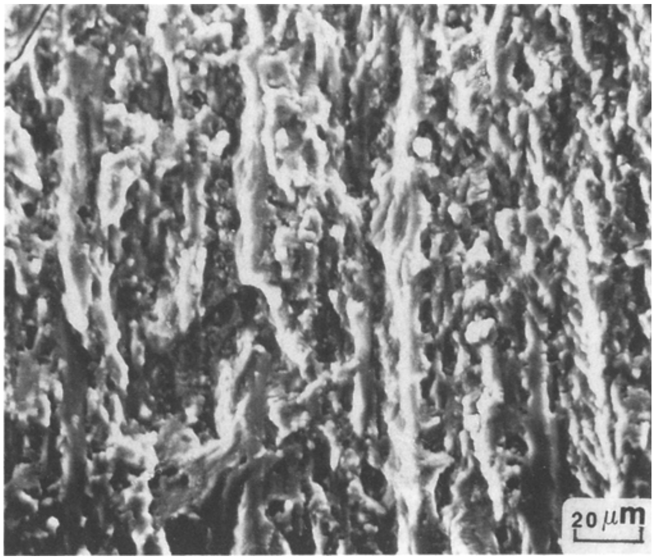
Figure 1 provides a direct comparison of the results of fatigue and corrosion-fatigue tests for smooth cylindrical specimens for $R = -1$ ($R = \sigma_{min}/\sigma_{max}$) loading at a frequency of 10 Hz. The deleterious effect of corrosive environment on the fatigue strength of the alloy is clearly demonstrated. The environmental effect is markedly greater in the high-cycle ($>10^5$ cycles) region than in the low-cycle region. At 10^7 cycles, the fatigue strength of the alloy is reduced by almost 70% in the presence of 3% NaCl environment as compared to the laboratory air environment.

The fatigue life in the high-cycle region is lowered by almost an order of magnitude in corrosive environment. However, the environmental effect becomes gradually less pronounced in the intermediate-life region and decreases to a negligible level in the low-cycle region. The apparent greater environmental sensitivity to corrosive environment in the high-cycle region is usually attributed to the longer exposure time available for corrosive attack compared to the very short time available in the low-cycle region.

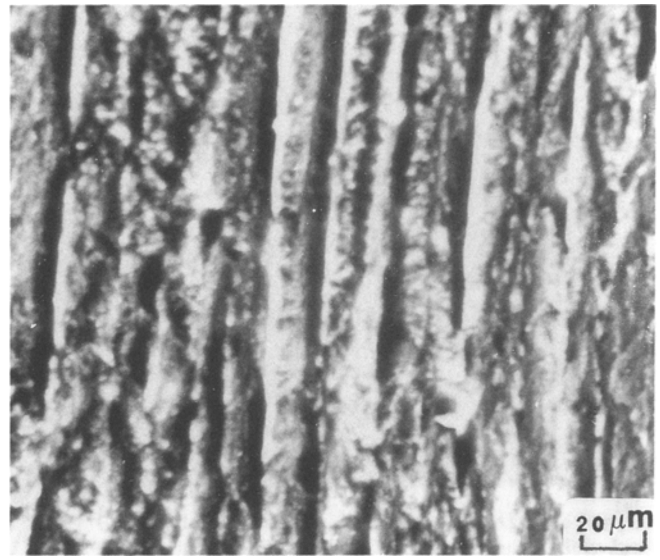
The environmental contribution to reduced fatigue life is considered to be early initiation of the fatigue crack, usually (but not necessarily) from the surface pits caused by the corrosive attack. However, the observed marked reduction in fatigue life by almost a factor of 10 for alloy Al 5454-H32 in 3% NaCl environment cannot be explained merely by early initiation of the fatigue crack from surface pits. Several investigators have pointed out that fatigue life, especially in the high-cycle (low-stress) region, may consist of three regimes: crack initiation (crack nucleation), small crack growth, and long crack growth. It then seems reasonable to suggest that as the corrosive environment is expected to affect the crack initiation and long crack propagation stages of fatigue life, it must also affect the small crack growth stage of fatigue life.

Cottis et al. (Ref 19) recently suggested that after initiation (nucleation) of the fatigue crack, fatigue life is essentially governed by three regimes: a short crack growth regime, a long crack growth regime, and a no-growth regime. Short crack growth is the growth that occurs below ΔK_{th}; long crack growth occurs once ΔK exceeds ΔK_{th}. The no-growth regime exists due to the very short crack length and low stress levels such as those present in the high-cycle regime. Cottis et al. suggested that the environmental contribution in the short crack growth and no-growth regimes may be an important factor in lowering fatigue strength.

It is thus also reasonable to suggest that for alloy 5454-H32, the observed severe reduction in fatigue life in the high-cycle region is attributable not only to early initiation of the fatigue crack from surface pits but also to possible enhancement of the early crack growth rate. In a study of corrosion-fatigue behavior of Al-Zn-Mg alloy, Magnin (Ref 20) has suggested that the main part of fatigue life in the low-stress, long-life regime is related to the nucleation and evolution of microcracks at the specimen surface.



(a)



(b)

Fig. 7 Fracture surface morphology in the vicinity of the crack initiation region. (a) Specimen fatigued in laboratory air. (b) Specimen fatigued in 3% NaCl environment. Extensive pitting and grain-boundary corrosion are evident in the corrosive environment.

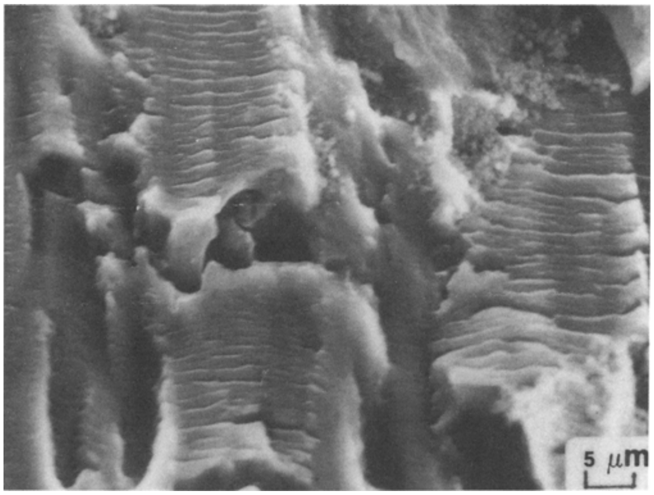
According to Magnin, an important role of the corrosive environment is to accelerate the microcracking process. Some researchers have shown that early crack growth is hindered by microstructural barriers, such as twins, grain boundaries, and second-phase particles. Cottis et al. (Ref 19) have proposed that in the presence of corrosive environment a pitting corrosion process may be involved, which helps to overcome these microstructural barriers and thus enhance the early crack growth rates at low stress levels such as those present in the high-cycle regime.

For the present alloy, the actual mechanism by which the environment affects early crack growth is unclear. However, fractographic studies indicate that early crack growth rates may have been enhanced by a pitting corrosion process similar to that suggested by Cottis et al. In Al 5454-H32, this pitting seems also to have led to secondary cracking (shown later in Fig. 8). It may be reasonable to suggest that in addition to pitting, secondary cracking may have contributed to the reduced fatigue life of Al 5454-H32 in the presence of 3% NaCl environment.

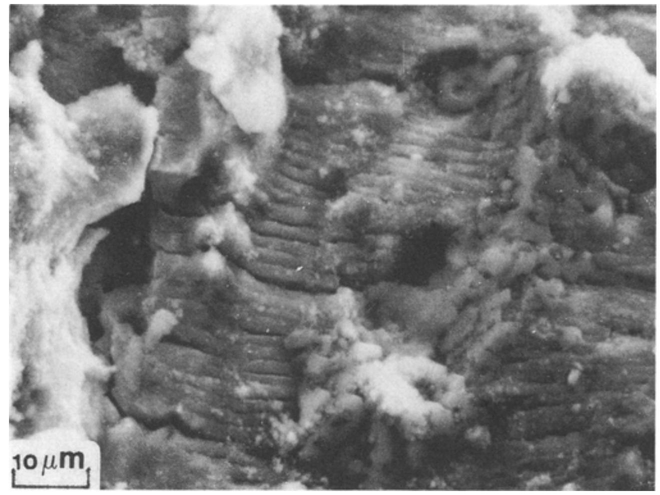
If it is true that the corrosive environment has a much more pronounced influence on the crack initiation behavior of the present alloy, then a blunt notched member, for which crack-initiation-dominant fatigue life is expected, would show similar trends of fatigue behavior under corrosive environment as those observed for smooth specimens. The results of fatigue and corrosion fatigue-tests for the circular (blunt, $K_t = 2.42$) notched specimens (Fig. 2) demonstrate that the effect of corrosive environment is indeed observed to be most significant in the high-cycle (crack-initiation-dominant) region. The data presented in Fig. 2 show that the fatigue strength at 10^7 cycles is reduced by almost 50% in 3% NaCl environment. The effect of corrosive environment becomes less pronounced in the intermediate-life region and becomes negligible in the low-cycle region, as was observed for smooth specimens.

Fig. 8 Secondary cracks emanating from corrosion pits found in the vicinity of the crack initiation region. The small arrows point to the secondary cracks; the larger arrow indicates the crack growth direction.

A sharply notched specimen, on the other hand, would experience early crack initiation due to the presence of high applied stresses and the high stress concentration at the notch root. Such a specimen would exhibit crack-propagation-dominant fatigue behavior. The effect of corrosive environment on the fatigue strength of a sharply notched specimen should then be similar to that observed in the intermediate- to low-cycle region. Figure 3, which displays corrosion-fatigue data for elliptically notched (sharp notch, $K_t = 5.1$) specimens, shows that the corrosive environment causes a roughly 25% reduction in fatigue strength at 10^7 cycles. The data for long crack propagation rate shown in Fig. 4 conform with the trend observed for elliptically notched members: An approximately threefold



(a)



(b)

Fig. 9 Fatigue striations in the crack propagation region. (a) Fatigue in laboratory air environment. (b) Fatigue in 3% NaCl environment

enhancement of fatigue crack propagation rates is observed in 3% NaCl environment compared to those observed in air. It is thus reasonable to assume that the corrosive environment is expected to cause most of the damage in situations where crack-initiation-dominant behavior is anticipated.

In order to examine the effect of stress ratio on the fatigue and corrosion-fatigue behavior of the alloy, a few circular notched specimens were tested at a stress ratio of $R = 0.1$ (Fig. 5). Since it is reasonable to assume that only tensile nominal load excursions are effective in crack propagation, the difference in the crack growth characteristics due to change in the stress ratio would be insignificant for a given maximum nominal load. The strain amplitudes considered to cause crack initiation are reduced by at least a factor of two for $R = 0.1$ loading as compared to $R = -1$ loading. A crack-initiation-dominant behavior is still expected for $R = 0.1$ loading, as observed for $R = -1$ loading. A look at Fig. 5 confirms this, where $R = 0.1$ loading can be seen to reduce fatigue strength by about a factor of two. The expected reduction in fatigue strength due to the presence of 3% NaCl environment is also evident.

3.2 *Fracture Surface Studies*

Fractographic studies in this investigation aimed at correlating the fracture surface morphology with the fatigue test results in order to identify environmental contributions during different portions of fatigue life.

Figure 6 shows the crack initiation region of a smooth cylindrical specimen fatigued in 3% NaCl environment. The arrow points to the crack initiation site marked by the converging river pattern. The fatigue crack clearly can be seen to originate from the corrosion pit (see the box in the upper left of Fig. 6). The crack then progressed with a semicircular crack front, as indicated by the ridge pattern.

Extensive pitting and grain-boundary pitting corrosion attributable to environmental attack are clearly visible in the initiation region shown in Fig. 7(b). Figure 8 reveals a large number of corrosion pits in the vicinity of the crack initiation region. A number of secondary cracks are also observed on the fracture surface. These secondary cracks (indicated by the small arrows) appear to originate from some of the corrosion pits. The actual mechanism by which this secondary cracking occurs is not clearly understood. There is, however, some indication that these secondary cracks possibly result from the notchlike effect of the corrosion pits, as shown in Fig. 8.

It is perhaps reasonable to assume that through such a pitting and secondary cracking process, the corrosive environment may have overcome the microstructural obstacles in the small crack growth regime and possibly in the no-growth regime to cause the observed degradation of fatigue life in the present alloy. This point can be supported by the findings of many investigators that the nonpropagating cracks in specimens fatigued in air or other inert environments become active through a pitting and notching effect if these specimens are exposed to a corrosive environment. Further investigation is certainly needed.

In the long crack growth region, no appreciable difference in the effects of the two environments on fracture surface morphology was noticed. Both fracture surfaces were marked by ductile fatigue striations (Fig. 9). The ductile-to-brittle transition of the striations usually attributed to the environmental effect by some investigators for other aluminum alloys was not found in the present investigation.

4. Conclusions

The presence of 3% NaCl solution during fatigue cycling severely reduces the fatigue life of aluminum alloy 5454-H32. The most deleterious effect (about 70% reduction in fatigue strength) is observed in the long-life (low-stress) regions, where a major portion of the fatigue life is spent in the crack initiation and early crack growth regimes. The long crack growth rates are only modestly enhanced.

Crack initiation life is severely reduced by the corrosive environment, which promotes early initiation of fatigue cracking via surface pitting and by probable enhancement of the early crack growth rate through a pitting and secondary cracking process.

Environment should be a serious consideration when evaluating the fatigue performance of Al 5454-H32 in situations where crack-initiation-dominant fatigue behavior is anticipated.

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