A Fatigue-Life Prediction Methodology for Notched Aluminum-Magnesium Alloy in Gulf Seawater Environment

Z. Khan, M. Younas, and G. Zuhair

Local-strain and linear-elastic fracture-mechanics (LEFM) methodologies have been investigated for prediction of the corrosion-fatigue life of notched components of specially developed Al-2.5Mg alloys exposed to Arabian Gulf seawater environment. Corrosion-fatigue crack initiation life estimates were obtained using strain-life relationships; corrosion-fatigue crack propagation life estimates were obtained using LEFM relationships. The total corrosion-fatigue life was considered to be the sum of the crack initiation and crack propagation lives. Estimated corrosion-fatigue lives were compared with experimentally obtained corrosion-fatigue life data using center-notched specimens of three types of Al-2.5Mg alloys (containing different amounts of chromium) exposed to Arabian Gulf seawater environment. Two notch geometries, a circular notch (K_t = 2.42) and an elliptical notch (K_t = 4.2), were investigated. Good corrosion-fatigue life predictions can be obtained using local-strain and LEFM methodologies by determining the relevant material constants via a few simple fatigue tests on smooth specimens and a few crack-growth-rate tests in the environment at the frequency of interest.

Keywords

aluminum-magnesium alloy, crack initiation, crack propagation, fatigue, life prediction, seawater

1. Introduction

DURING the past decade, considerable effort has been directed at the development and application of quantitative methodologies to estimate the fatigue life of engineering components and structures exposed to the combined simultaneous action of cyclic loading and a corrosive environment. Most engineering structures and components contain notchlike geometric features or other notchlike discontinuities; therefore, the development of quantitative procedures to estimate the corrosion-fatigue life of notched members has been a primary goal.

Fatigue lives of notched members subjected to constant-amplitude loadings are assessed by a variety of analytical methods based on stress-life, local-strain, and linear-elastic fracture-mechanics (LEFM) concepts (Ref 1-8). Stress-life combined with a fatigue-strength reduction factor approach fails to account for plastic behavior at the notch region and to consider the propagation life regime, which may be of great significance to the total fatigue life. Therefore, stress-life analysis is considered to be very conservative and hence inappropriate for total fatigue-life evaluation of notched members (Ref 9).

The total fatigue life of a notched member essentially consists of two portions: a crack initiation life portion, controlled by notch plasticity, and a crack propagation life portion, controlled by nominal stress and crack length. Fatigue crack initiation life is considered to be the number of cycles consumed in the nucleation and growth of a small crack to a length where it becomes a dominant fatigue crack. Fatigue crack propagation life is considered to be the remaining number of cycles required to grow the initiated fatigue crack to final fracture. To account for both portions, local-strain and LEFM approaches have been extensively employed in fatigue-life analysis of notched members. For crack initiation life estimates, local strain is the most widely employed technique; LEFM has found wide acceptance for crack propagation life estimates.

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The prediction of fatigue life under the conjoint conditions of cyclic loading and a corrosive environment becomes quite complicated when the numerous mechanical, metallurgical, and environmental variables that contribute to the corrosion-fatigue process (Ref 10-12) are taken into consideration. However, from an engineering point of view, it is often assumed that the adverse effects of the environment can be included in fatigue-life estimation procedures by determining the material fatigue properties in the environment and the frequency of interest (Ref 13).

The present study investigates the applicability of local-strain and LEFM fatigue-life estimation methodologies to the corrosion-fatigue life estimation of notched members exposed to Arabian Gulf seawater environment. Three modified Al-2.5Mg alloys containing various amounts of chromium were selected. Two notched geometries—one, a circular notch with a low stress-concentration factor (K_t = 2.42), and the other, an elliptical notch with a higher factor (K_t = 4.2)—were investigated. Fatigue-life estimates are compared with experimental fatigue-life data obtained from center-notched specimens fatigued in air as well as in Arabian Gulf seawater environment.

1.1 *Initiation Life Calculations*

Fatigue crack initiation life analysis of notched members requires a method to estimate the local stresses and strains—σ and ε, respectively—at the notch root. For the current analysis, the local stress-strain response was estimated using a nominally elastic version of Neuber's rule (Ref 14):

$$\frac{(\Delta S K_t)^2}{E} = \Delta\sigma\Delta\varepsilon \qquad \text{(Eq 1)}$$

All symbols are defined in the Nomenclature section at the end of this paper. Equation 1 relates the stress and strain response at the notch to the nominal stress and strain. The equation of the hysteresis curve can be represented by:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \quad \text{(Eq 2)}$$

Combining Eq 1 and 2 gives:

$$\frac{\Delta\sigma^2}{2E} + \Delta\sigma\left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} = \frac{(K_t\Delta S)^2}{2E} \quad \text{(Eq 3)}$$

Thus, the values of $\Delta\sigma$ can be determined by solving Eq 3 through an iterative technique. Once the local stress and strain response has been determined, the strain-life equation

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f}{E}(2N_f)^b + \varepsilon_f(2N_f)^c \quad \text{(Eq 4)}$$

can be solved for the number of reversals to initiation, $2N_f$. To account for the presence of mean stress, σ_0, the strain-life equation is expressed as (Ref 14):

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f - \sigma_0)}{E}(2N_f)^b + \varepsilon_f\left[\frac{\sigma_f - \sigma_0}{\sigma_f}\right]^{c/b}(2N_f)^c \quad \text{(Eq 5)}$$

1.2 *Propagation Life Calculations*

Numerous fatigue crack propagation laws based on the LEFM concept have been proposed (Ref 15). Perhaps the most commonly used correlation between constant-amplitude fatigue crack growth rates (da/dN) and the crack-tip cyclic stress-intensity factor range (ΔK) needed for fatigue crack propagation life calculations is provided by Paris (Ref 16):

$$\frac{da}{dN} = C(\Delta K)^m \quad \text{(Eq 6)}$$

where C and m are constants that characterize material resistance to crack propagation and can be determined by the best fit to the crack growth test data. The crack growth life, N_p, can be estimated by integrating Eq 6 as:

$$N_p = \int_{a_i}^{a_f} \frac{da}{C(\Delta K)^m} \quad \text{(Eq 7)}$$

For the current analysis, a_i is assumed equal to the notch dimension perpendicular to the maximum nominal stress. This simple definition of the initial crack size eliminates the need to find a nonarbitrary initial crack length through sophisticated procedures. The final crack size, a_f, is calculated from the limiting load capability of the cracked member based on the yield strength of the material under investigation. Modifications of Eq 6 as proposed by Forman et al. (Ref 17) are utilized to include mean stress effects:

$$\frac{da}{dN} = \frac{C\Delta K^m}{(1 - R)K_c - \Delta K} \quad \text{(Eq 8)}$$

where K_c is the fracture toughness of the materials.

2. Experimental Procedure

This investigation studied three types of modified Al-2.5Mg alloys that were developed for application in seawater desalination plants in Saudi Arabia. These modified alloys contain different amounts of chromium, which is added to improve the corrosion resistance of aluminum-magnesium alloys. The three alloys (designated types I, II, and III) contain 0.01, 0.1, and 0.3 wt% Cr, respectively; all were in the H34 temper condition. The

Table 1 Chemical compositions of the modified aluminum-magnesium alloys

Alloy type	Composition, wt %								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
I	0.06	0.05	<0.01	0.10	2.53	<0.01	0.01	0.003	Bal.
II	0.05	0.05	<0.01	<0.01	2.47	0.10	0.02	0.003	Bal.
III	0.04	0.05	<0.01	<0.01	2.48	0.29	0.01	0.003	Bal.

Table 2 Monotonic mechanical properties of the modified aluminum-magnesium alloys (H34 temper condition)

Alloy type	Modulus of elasticity (E), MPa	Yield strength (σ_y), MPa	Tensile strength (σ_{uts}), MPa	Reduction in area, %
I	70×10^3	230	267	38.3
II	70×10^3	220	279	39.1
III	70×10^3	215	250	42.6

detailed chemical compositions of these alloys are given in Table 1, and their mechanical properties are listed in Table 2.

Smooth and center-notched fatigue test specimens were machined from 2 mm thick sheet stock of the three alloys, with the longer dimensions (loading axis) aligned parallel to the rolling direction. The center-notched specimens (175 by 38 by 2 mm) were used to obtain experimental fatigue-life data for comparison with the fatigue-life estimates. Two notch geometries, a circular hole ($K_t = 2.42$) and an elliptical notch ($K_t = 4.2$), were investigated. All fatigue tests were conducted on an Instron (Instron Corporation, Canton, MA) 8501 servohydraulic test system in both laboratory air and in Arabian Gulf seawater environment. Sinusoidal load cycling at a stress ratio of $R = 0.1$ and a frequency of 20 Hz was used for the tests. An acrylic chamber mounted at the midsection of the specimen was used to contain the salt water during fatigue testing under corrosive conditions. A small pump maintained water circulation inside the chamber.

Fully reversed strain-controlled fatigue testing utilizing smooth specimens provided the required fatigue properties for the fatigue crack initiation life calculations. The material constants for fatigue crack propagation life estimates were obtained from crack-growth-rate tests using center-notched specimens. The crack length, a, was measured optically using a Questar (Questar Corp., New Hope, PA) QM-100™ long-distance traveling microscope equipped with a digital-readout crack-measurement system. This system enabled crack measurements with an accuracy of 0.01 μm.

3. Results and Discussion

3.1 *Fatigue and Corrosion-Fatigue Studies*

Fatigue and corrosion-fatigue test results in air and in Arabian Gulf seawater environment for alloy types I, II, and III are shown in Fig. 1 to 4, where the best log-log fit lines have been

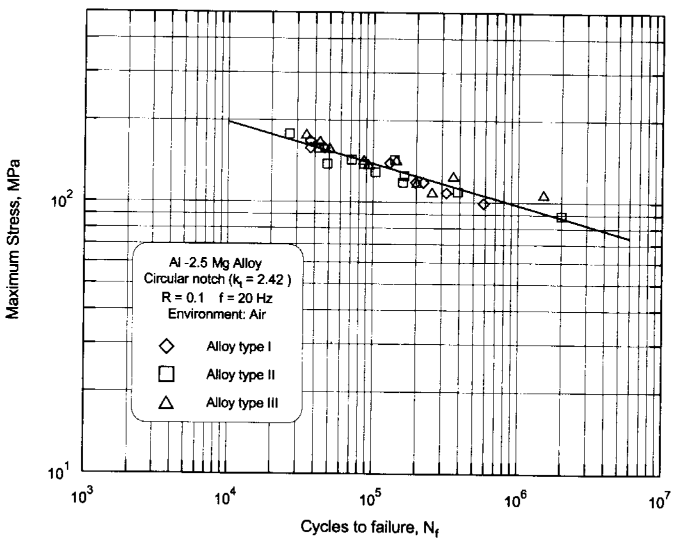


Fig. 1 Fatigue-life data for circular notched specimens in air

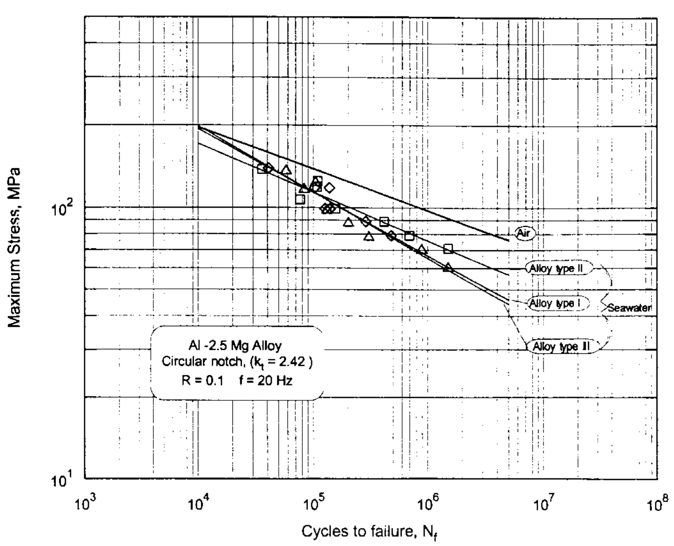


Fig. 2 Effect of corrosive environment on fatigue life of circular notched specimens

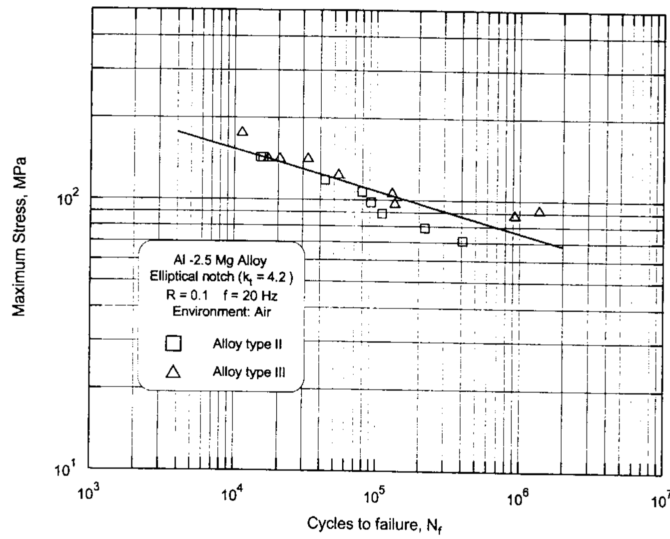


Fig. 3 Fatigue-life data for elliptically notched specimens in air

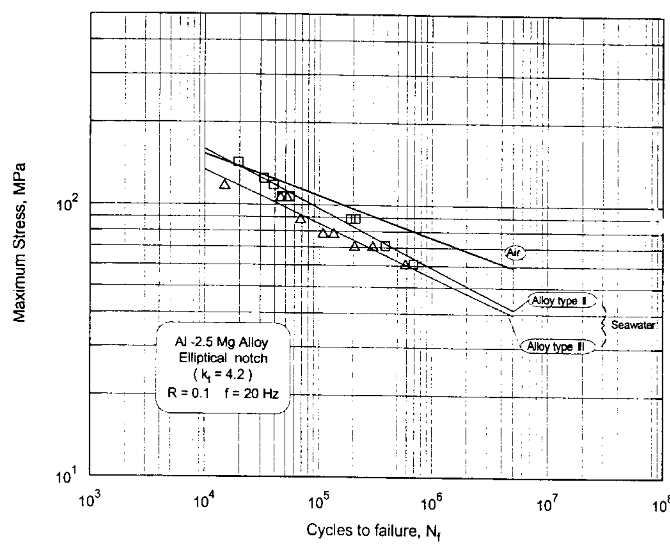


Fig. 4 Effect of corrosive environment on fatigue life of elliptically notched specimens

drawn through the data points. The fatigue test data for all three types of alloys (Fig. 1) suggest that the increase in chromium content has no noticeable effect on the fatigue strength of Al-2.5Mg alloy tested in laboratory air. However, chromium content has a significant influence on the corrosion-fatigue strength of all three types of alloys in Arabian Gulf seawater environment.

As shown in Fig. 2, the seawater environment reduces the corrosion-fatigue strength at 10^6 cycles by about 34% for alloy type I, which contains 0.01 wt% Cr. An increase in the chromium content to 0.1 wt% Cr (type II) results in a significant improvement in the corrosion-fatigue strength of Al-2.5Mg alloy. For type II the corrosion fatigue strength at 10^6 cycles is lowered by only about 25%, compared to almost 35% for type I. An increase to 0.3 wt% Cr, however, results in a severe degradation of corrosion-fatigue strength (Fig. 2). The corrosion-fatigue strength (at 10^6 cycles) for type III, containing 0.3 wt% Cr, is reduced by almost 38% in the seawater environment, which is even lower than that of type I.

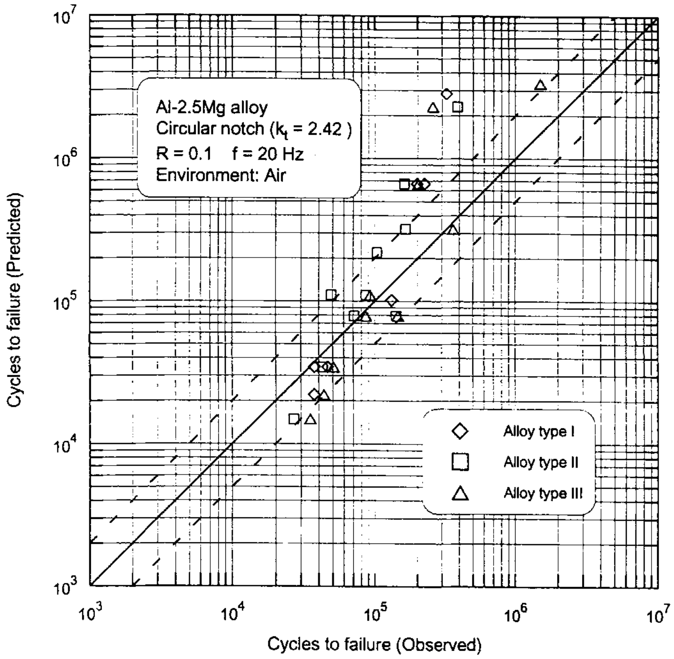


Fig. 5 Predicted versus experimental fatigue life in air for circular notched specimens

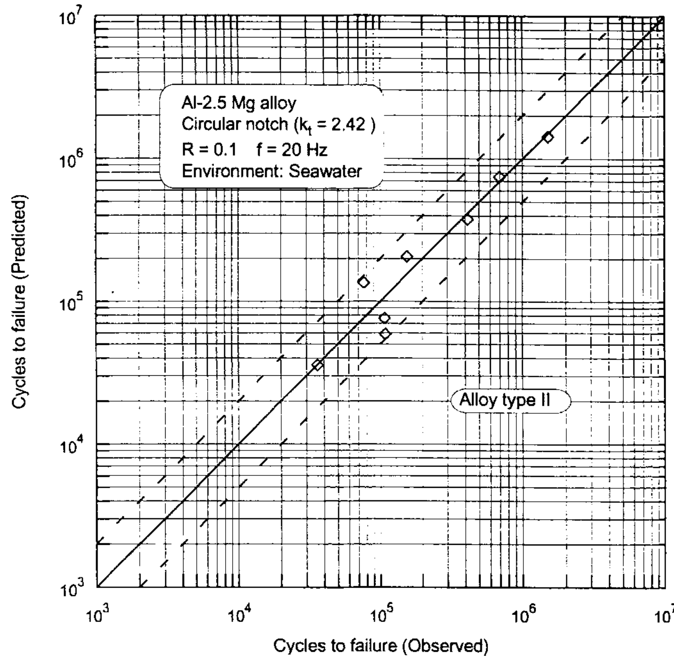


Fig. 7 Predicted versus experimental fatigue life in Arabian Gulf seawater for circular notched type II specimens

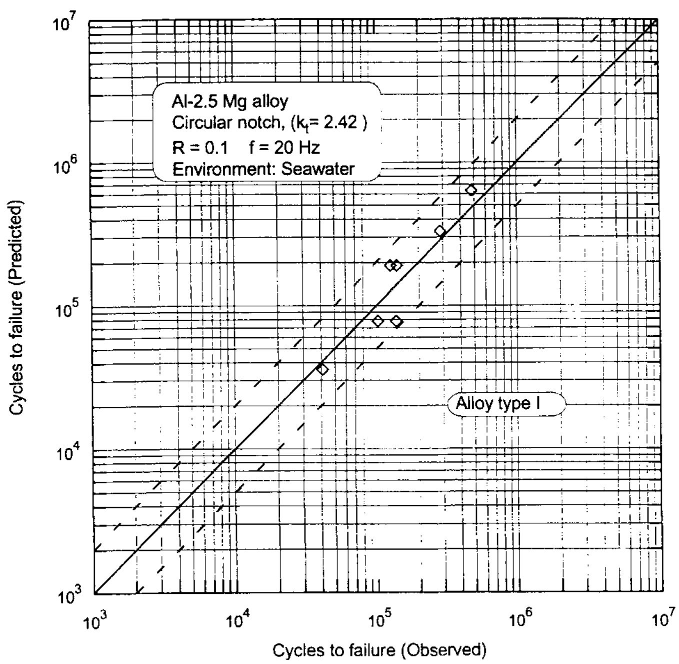


Fig. 6 Predicted versus experimental fatigue life in Arabian Gulf seawater for circular notched type I specimens

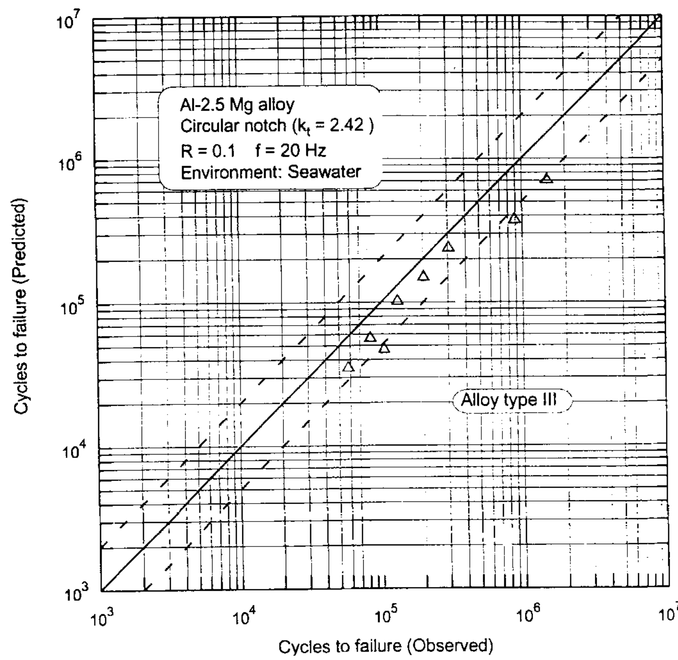


Fig. 8 Predicted versus experimental fatigue life in Arabian Gulf seawater for circular notched type III specimens

This degradation in corrosion-fatigue strength upon increasing the chromium content to 0.3 wt% is consistent with the results of an earlier study on the corrosion behavior of modified Al-2.5Mg alloys (Ref 18). This study shows a considerably higher corrosion rate (14.98 mpy) for type III than for alloy II (5.18 mpy). This observation, however, is inconsistent with the reported beneficial effect of 0.3 wt% Cr on the corrosion resistance of Al-2.5Mg alloys having temper conditions other than H34 (Ref 19). It seems reasonable to assume that perhaps the H34 temper treatment produces a weaker protective oxide film in the alloy containing 0.3 wt% Cr than in the alloy containing 0.1 wt% Cr. This weakening of the oxide film could have resulted from the possible formation of much coarser second-phase particles at a higher chromium concentration and the possible segregation of second-phase particles to the grain boundaries.

Figure 2 also shows that for circular notched specimens the corrosive environment has a more pronounced effect in the high-cycle (initiation-dominant) region than in the low-cycle (propagation-dominant) region for all three types of alloys. In the case of elliptically notched specimens, fatigue in air environment again shows no noticeable influence of chromium content (Fig. 3). The effects of the seawater environment on the corrosion-fatigue strength for elliptically notched type II and III specimens are presented in Fig. 4. The reduction in corrosion-fatigue strength for elliptically notched specimens is similar to that observed for the center-notched specimens. However, in the long-life region the severity of the degrading effect of 0.3 wt% Cr for elliptically notched specimen seems noticeably reduced. Corrosion-fatigue strength (at 10^6 cycles) for elliptically notched specimens for type III (containing 0.3 wt% Cr) is reduced by only about 30%, compared to 38% for the center-notched specimens. Based on this observation, it seems reasonable to suggest that the corrosive environment has a more pronounced effect in situations where a larger percentage of fatigue life is spent in crack initiation, as expected in the center (bluntly) notched specimens, than in situations where fatigue life is controlled by crack propagation, as expected in elliptically (sharply) notched specimens.

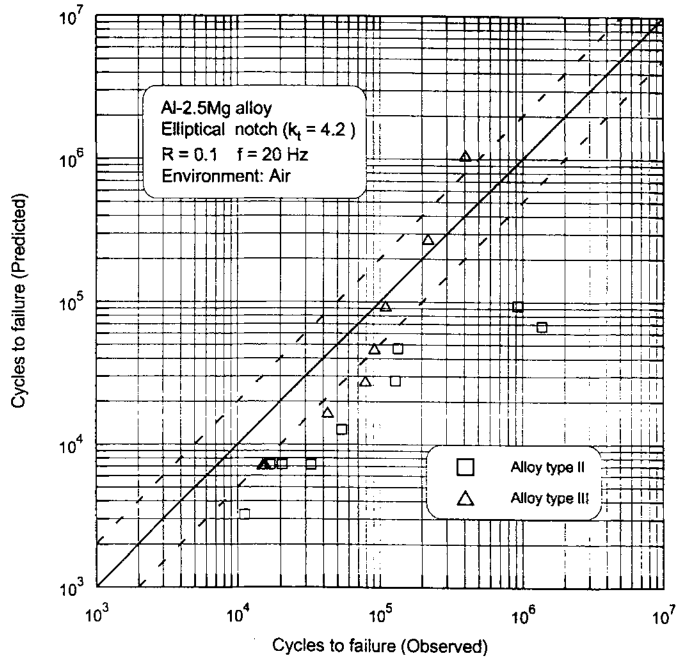


Fig. 9 Predicted versus experimental fatigue life in air for elliptically notched type I and II specimens

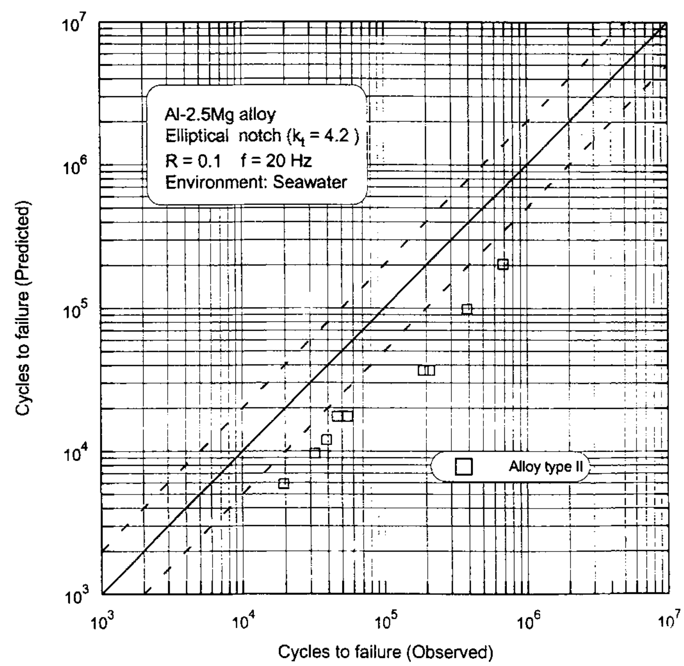


Fig. 10 Predicted versus experimental fatigue life in Arabian Gulf seawater for elliptically notched type II specimens

3.2 *Corrosion-Fatigue Life Predictions*

Comparisons of estimated fatigue lives and experimentally observed fatigue lives for circular notched specimens of alloy

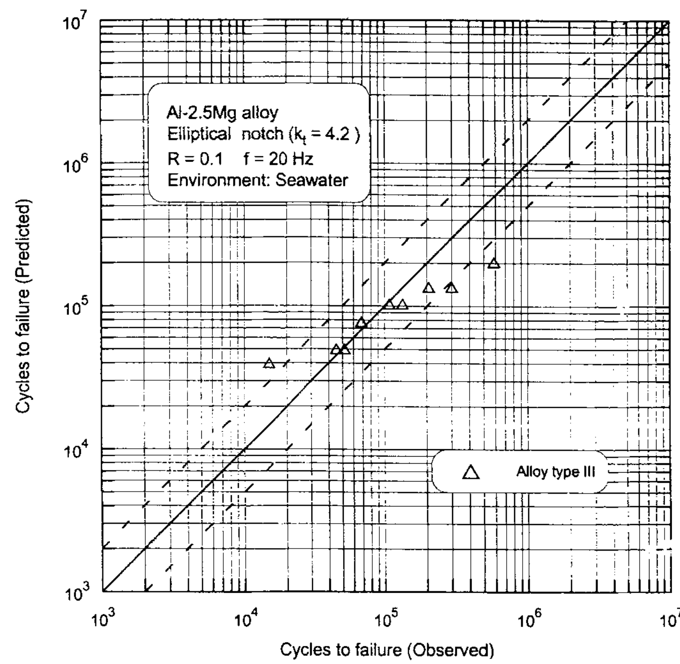
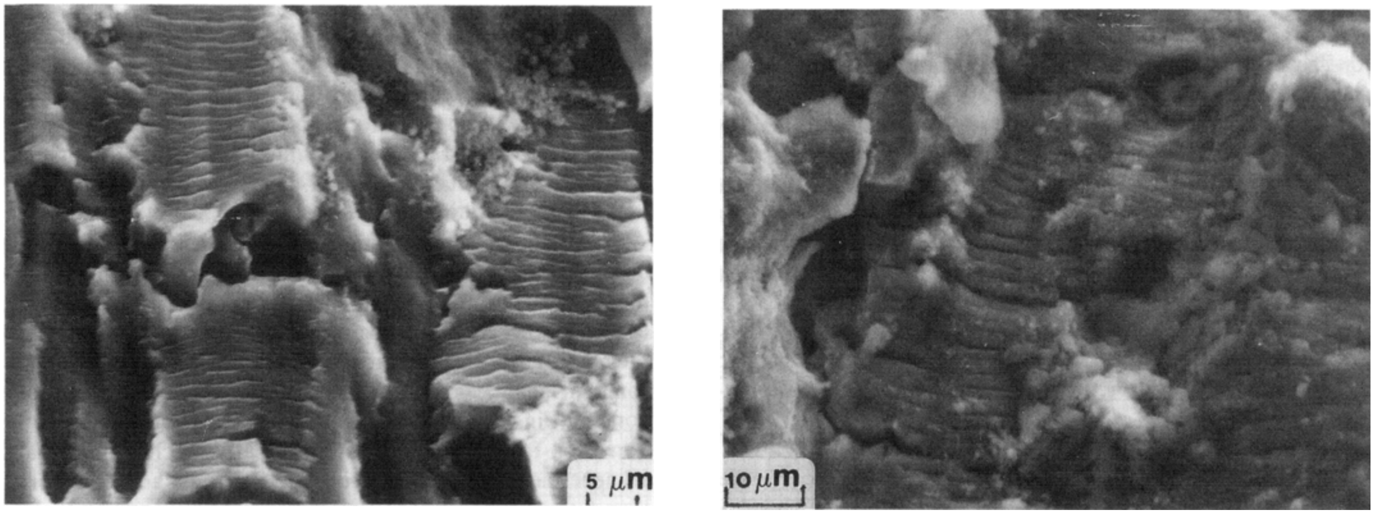


Fig. 11 Predicted versus experimental fatigue life in Arabian Gulf seawater for elliptically notched type III specimens



(a) (b)

Fig. 12 Scanning electron fractographs showing fatigue striations. (a) Air environment. (b) Arabian Gulf seawater environment

NOMENCLATURE

a	crack length (mm)	N_f	number of cycles to failure
a_i, a_f	initial and final (respectively) crack length (mm)	$2N_f$	number of reversals to failure
b	fatigue strength exponent	N_t, N_i, N_p	Total, initiation, and propagation (respectively) life estimates
c	fatigue ductility exponent	R	stress ratio ($\sigma_{min}/\sigma_{max}$)
C	Paris crack growth coefficient	ΔS	nominal stress range (MPa)
da/dN	fatigue crack growth rate (mm/cycle)	$\Delta\varepsilon$	total strain amplitude
E	modulus of elasticity (MPa)	ε_f'	fatigue ductility coefficient
ΔK	stress-intensity factor range (MPa$\sqrt{m}$)	$\Delta\sigma$	local stress range (MPa)
K'	cyclic strength coefficient (MPa)	σ_0	mean stress (MPa)
K_t	theoretical stress-concentration factor	σ_y	0.2% offset yield strength (MPa)
n'	cyclic strength exponent	σ_f	fatigue strength coefficient (MPa)

types I, II, and III in both air and Arabian Gulf seawater environment are shown in Fig. 5 to 8. Data points falling within the factor-of-two line on either side of the 45° diagonal are considered to represent excellent predictions. As Fig. 5 indicates, reasonably good fatigue-life estimates are obtained for the case of circular notched specimens in laboratory air environment for all three types of modified Al-2.5Mg alloy. Excellent corrosion-fatigue life estimates have also been obtained for all circular notched specimens in Arabian Gulf seawater environment (Fig. 6 to 8). All the points are observed to lie within the factor-of-two band for alloy types I and II. For type III, most of the points lie within the band.

Similar comparisons for elliptically notched specimens are shown in Fig. 9 to 11. Reasonably good fatigue-life predictions are obtained for laboratory air environment. Although most of the points are observed to be lying outside the factor-of-two band, the predictions are on the conservative (safe) side within the factor-of-three line and can still be considered to be good. All the corrosion-fatigue life predictions for elliptically notched type II specimens in Arabian Gulf seawater are found on the conservative side within a factor-of-four line (Fig. 10). Excellent corrosion-fatigue life predictions are obtained for elliptically notched type III specimens in the seawater environment (Fig. 11).

Detailed fracture surface analysis will be presented in a subsequent paper. For the present, the two fractographs in Fig. 12 show the fatigue striations in air and seawater environments. Figure 12(b) clearly demonstrates the corrosive attack of seawater in the fatigue crack growth region.

4. Conclusions

The fatigue resistance of a modified Al-2.5Mg alloy containing chromium is reduced in the presence of Arabian Gulf seawater environment. Increasing the chromium content from 0.01 to 0.1 wt% significantly increases the fatigue strength of the alloy. A further increase in the chromium content to 0.3 wt% severely degrades fatigue resistance.

Fatigue-life prediction methodology based on local-strain and LEFM concepts provides excellent corrosion-fatigue life estimates for notched members of Al-2.5Mg alloys exposed to Arabian Gulf seawater environment.

The effect of corrosive environment in the corrosion-fatigue life estimates can be included by determining the relevant material properties in the environment at the frequency of interest.

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