NRL Report 8042

Effects of Flowing Natural Seawater and Electrochemical Potential on Fatigue-Crack Growth in Several High-Strength Marine Alloys

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August 30, 1976

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NRL [redacted] 8042	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	Final rept.
4. TITLE: EFFECTS OF FLOWING NATURAL SEAWATER AND ELECTROCHEMICAL POTENTIAL ON FATIGUE-CRACK GROWTH IN SEVERAL HIGH-STRENGTH MARINE ALLOYS	5. TYPE OF REPORT & PERIOD COVERED: Final report on one phase of a continuing NRL Problem
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): T. W. Crooker, F. D. Bogar[redacted] W. R. Cares	8. CONTRACT OR GRANT NUMBER(s): 15p.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Research Laboratory, Washington, D.C. 20375	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NRL Problem M01-24, Project RR 022-01-46
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Arlington, Va. 22217	12. REPORT DATE: Aug[redacted]76
	13. NUMBER OF PAGES: 14
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

16 NRL-M01-24, RR022-01

18. SUPPLEMENTARY NOTES

17 RR022-01-46

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fatigue	Steel
Corrosion	Titanium
Crack growth	Aluminum
High-strength alloys	Seawater
Fracture mechanics	Electrochemistry

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Fatigue crack propagation was studied on samples of four high-strength marine alloys to determine the sensitivity of fatigue-crack growth rates to seawater and electrochemical potential. The materials studied included HY-130 steel, 17-4 PH steel in several combinations of melt processing and temper, Ti-6Al-2Cb-1Ta-0.8Mo, and 5456-H116 aluminum. Fatigue testing was conducted at low cyclic frequency, and the fatigue data are presented in terms of fatigue-crack growth rate (da/dN) versus crack-tip stress-intensity factor range (ΔK). Test specimens were exposed to fresh

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flowing natural seawater under freely corroding and potentiostat-controlled electrochemical conditions while undergoing corrosion-fatigue testing. The results of this investigation reveal significantly distinct differences among the four alloys under the conditions of corrosion fatigue. Both seawater and potential acted to accelerate crack growth rates in the ferrous alloys, which proved to be much more sensitive to seawater and negative potential than the nonferrous alloys studied. The titanium alloy exhibited no measurable sensitivity to either seawater or negative potential. The aluminum alloy exhibited only moderate sensitivity to seawater and beneficial effects from both positive and negative potentials. These exploratory studies indicate that high-strength marine alloys exhibit widely differing responses to corrosion-fatigue crack growth and that high-strength steels currently aimed for marine service are among the alloys most deleteriously affected.

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EFFECTS OF FLOWING NATURAL SEAWATER AND ELECTROCHEMICAL POTENTIAL ON FATIGUE-CRACK GROWTH IN SEVERAL HIGH-STRENGTH MARINE ALLOYS

INTRODUCTION

The Navy has initiated development of new classes of advanced surface ships, such as hydrofoil and surface-effect ships, which require weight-critical structures. These weight-critical structures demand the use of high-strength marine alloys which are inherently more highly flaw sensitive than the more forgiving traditional naval materials and thus more susceptible to such failure mechanisms as fatigue, environmental crack growth, and fracture. Experience to date with early prototype ships strongly suggests that fatigue and environmental crack growth do pose genuine threats to the structural integrity of these new classes of high-performance ships [1]. The present study was undertaken to begin development of the technology base on the effects of flowing natural seawater and electrochemical potential on fatigue-crack growth in several candidate high-strength marine alloys for advanced-ship applications.

At present little is known regarding the combined effects of seawater and potential on fatigue-crack growth in marine alloys. However experience to date with existing prototype ships has demonstrated the necessity for crack-growth estimates in establishing design criteria and maintenance intervals during service. Therefore information of the type presented herein is directly applicable to current problems in advanced ship design.

DESCRIPTION OF MATERIALS

The materials studied in this investigation included HY-130 steel, three samples of 17-4 PH steel, Ti-6Al-2Cb-1Ta-0.8Mo, and 5456-H116 aluminum. All of the materials studied were received as 25.4-mm-thick (1-in.) rolled plate. The three samples of 17-4 PH consisted of a vacuum-melted (VM) material in the H1050 temper plus an argon-oxygen-melted (AOM) material in the H1050 and H1150 tempers. The fatigue-crack-propagation characteristics of these three 17-4 PH steels in an ambient air environment are described in detail in Ref. 2, and similar information on the HY-130 steel is reported in Ref. 3. The tensile properties of the six materials studied are given in Table 1.

EXPERIMENTAL PROCEDURES

All of the corrosion-fatigue data reported herein were obtained in flowing fresh natural seawater at the NRL Marine Corrosion Research Laboratory in Key West, Florida. Fatigue-crack growth tests were conducted using single-edge-notch cantilever specimens (Fig. 1) except for limited reference data taken from Refs. 2 and 3 as noted. Fracture

Manuscript submitted July 29, 1976.

Table 1 — Tensile Properties

Material	0.2% Yield Strength		Ultimate Tensile Strength		Elong. (%)	R.A. (%)
	MPa	ksi	MPa	ksi		
HY-130	1015	147.2	1054	152.9	18.8	20.0
17-4 PH VM-H1050	1059	153.6	1105	160.3	16.0	62.0
17-4 PH AOM-H1050	1124	163.0	1178	170.8	12.5	47.2
17-4 PH AOM-H1150	931	135.0	1025	148.6	14.2	48.0
Ti-6Al-2Cb-1Ta-0.8Mo	789	114.5	865	125.5	12.0	27.6
5456-H116	214	31.1	371	53.8	22.7	20.0

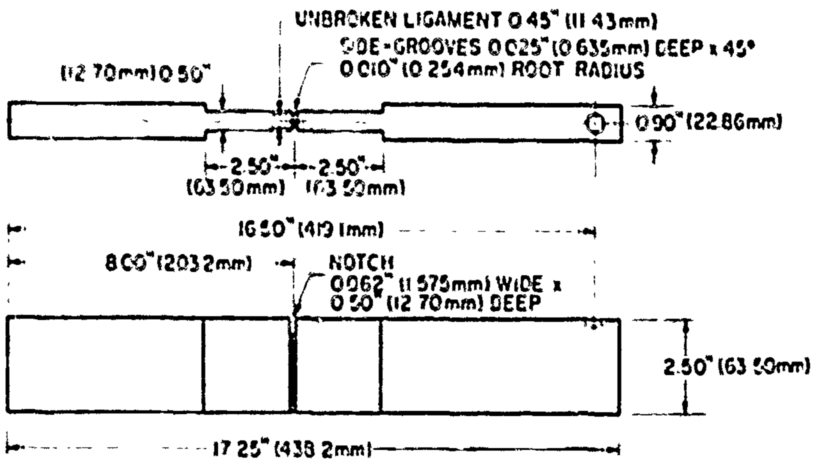

Fig. 1 — Details of the single-edge-notch cantilever specimen

mechanics stress-intensity factors for the cantilever specimens were calculated using the Kies expression [4]. All specimens were oriented with the edge crack parallel to the final rolling direction of the material, in the ASTM-designated T-L orientation [5].

The cantilever specimens were cycled under constant load, zero-to-tension, with the stress ratio R = 0. All tests were conducted at a cyclic frequency of 10 cpm (0.167 Hz), unless otherwise noted. One corrosion-fatigue test on HY-130 steel was conducted at 1 cpm (0.0167 Hz), and some ambient-air-environment reference data for 17-4 PH and HY-130 steels taken at higher frequencies are included from Refs. 2 and 3. Although the electrohydraulic testing machines used for the corrosion-fatigue tests conducted at the NRL Key West Laboratory did not feature closed-loop control systems, the waveforms employed can be considered to be approximately triangular for comparison purposes.

For the corrosion-fatigue tests natural seawater was taken directly from the ocean and immediately passed through a polyurethane enclosure cell, placed around the specimen test section, in a single-pass mode at a flow rate of about 200 ml/min. The corrosion

Table 2 – Freely Corroding Potentials Versus Ag/AgCl

Material	Potential (mV)
HY-130 steel	-665
17-4 PH VM steel	-300
17-4 PH OAM steel	-200
5456-H116 aluminum	-950
Ti-6Al-2Cb-1Ta-0.8Mo	-300

cell had a Plexiglas viewing area for optical observation of crack growth. The length of the fatigue crack was measured by a slide-mounted optical micrometer focused on the root surface of one side-groove of the specimen.

Electrochemical potentials were applied by means of a potentiostat device. Potentials were measured versus an Ag/AgCl reference electrode. The freely corroding potentials of the various materials studies are given in Table 2.

RESULTS

The results of this investigation are shown in Figs. 2 through 7. These figures are logarithmic plots of crack growth rate (da/dN) versus stress-intensity factor range (ΔK) for the six materials included in this investigation. Each plot includes a reference curve generated in a laboratory-ambient-air environment (relative humidity ≈ 50 percent) plus data generated in flowing natural seawater under freely corroding conditions and under various applied electrochemical potentials.

A wide variety of responses to seawater and electrochemical potential were noted among the six materials:

- No effect of either seawater or negative potential (Ti-6Al-2Cb-1Ta-0.8Mo),

- Deleterious effect of seawater with no effect of negative potential (17-4 PH VM steel),

- Deleterious effect of seawater with beneficial effect of either positive or negative potential (5456-H116 aluminum),

- Deleterious effect of seawater with deleterious effect of negative potential (17-4 PH AOM steels),

- Deleterious effect of seawater and negative potential with a further deleterious effect of reduced cyclic frequency (HY-130 steel).

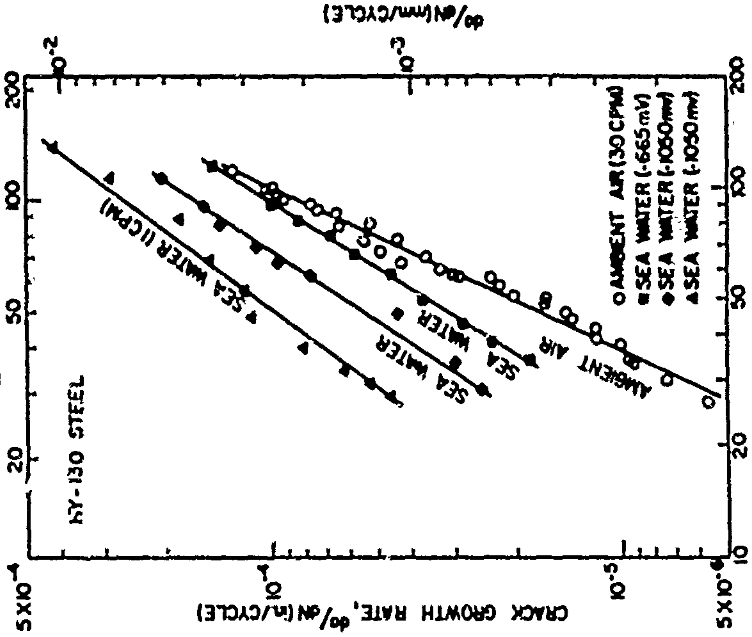

Fig. 2 — Corrosion-fatigue crack growth for HY-130 steel

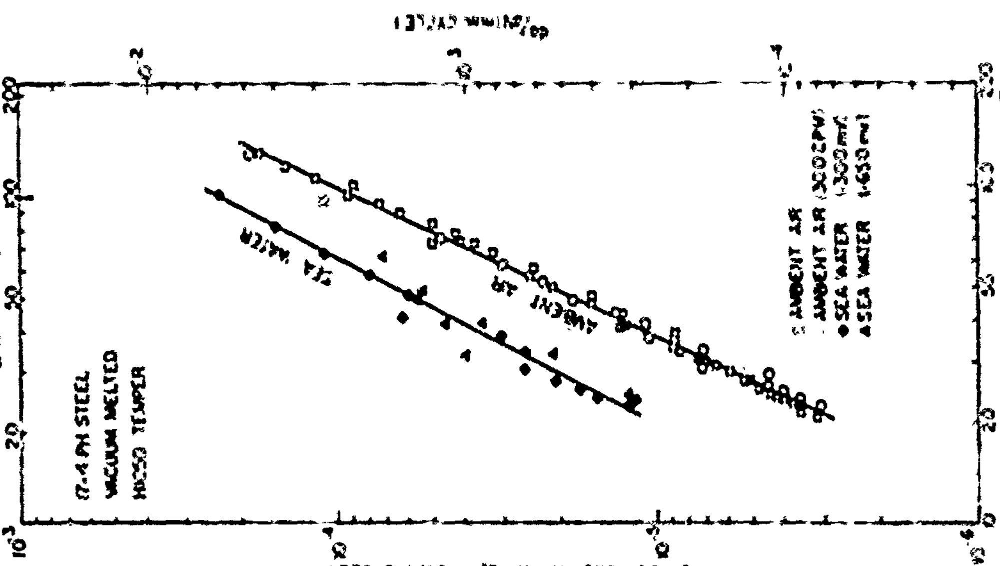

Fig. 3 — Corrosion-fatigue crack growth for 17-4 PH VM-H1050 steel

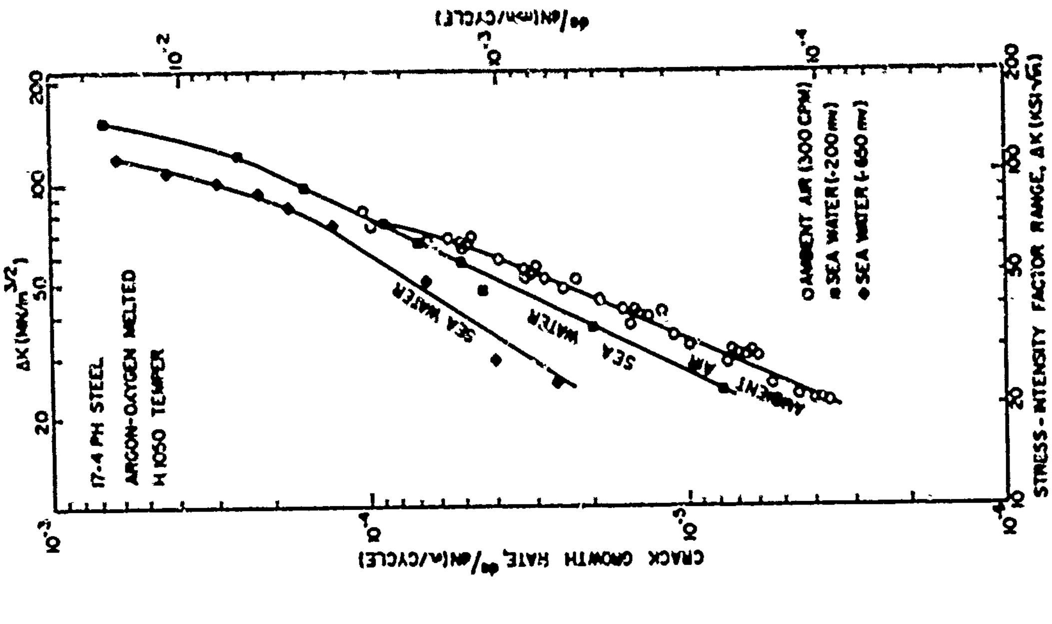

Fig. 4 — Corrosion-fatigue crack growth for 17-4 PH AOM-H1050 steel

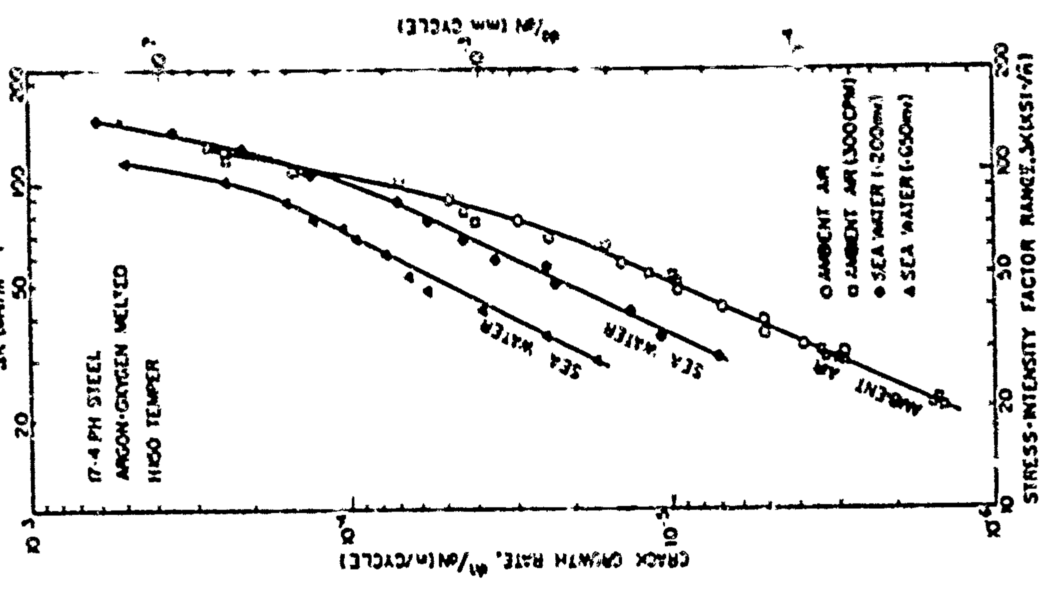

Fig. 5 — Corrosion-fatigue crack growth for 17-4 PH AOM-H1150 steel

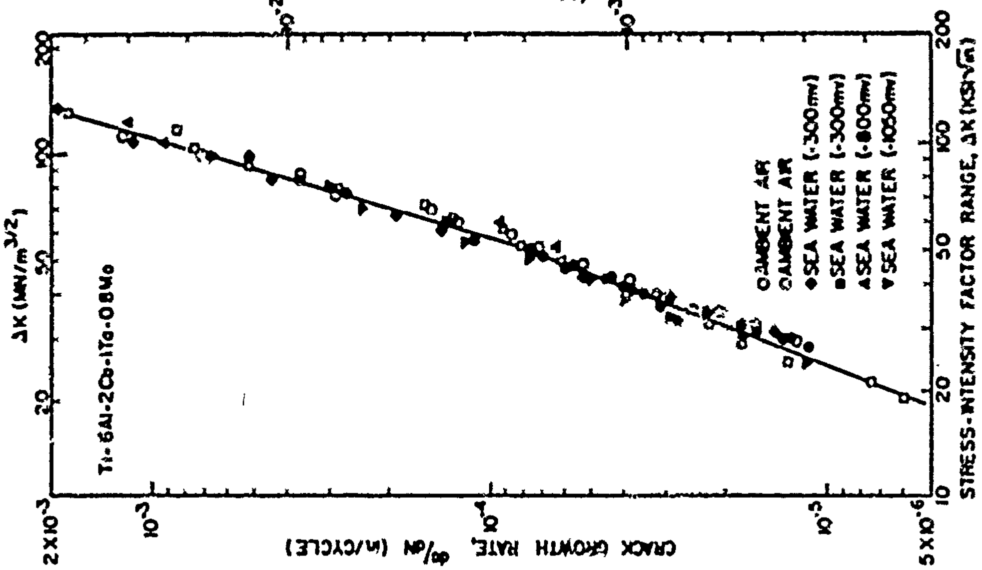

Fig. 6—Corrosion-fatigue crack growth for Ti-6Al-2Cb-1Ta-0.8Mo alloy

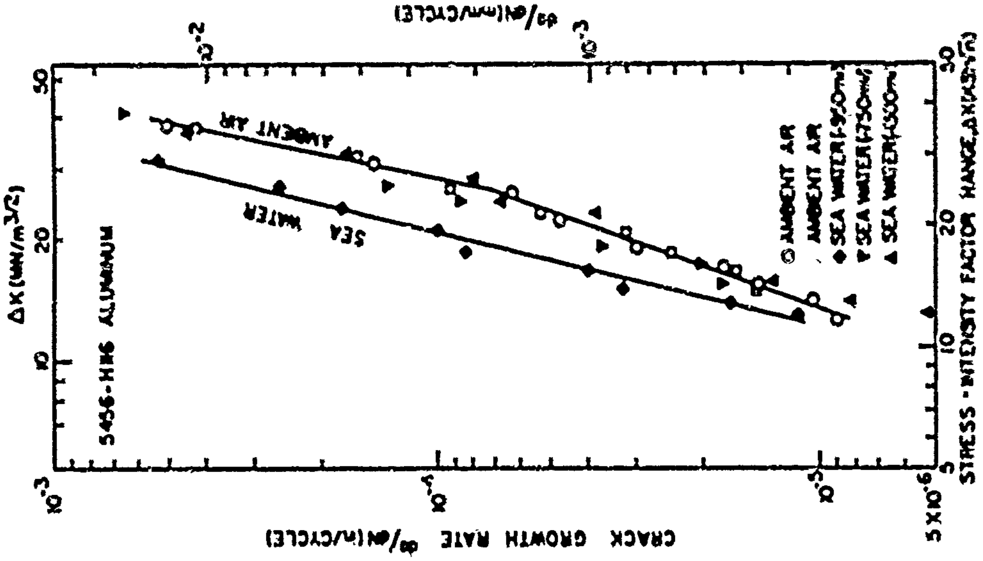

Fig. 7 — Corrosion-fatigue crack growth for 5456-H116 aluminum alloy

The magnitudes of the environmentally and electrochemically induced accelerations in crack growth rates varied from negligible to an order of magnitude, with the greatest accelerations occurring in the ferrous alloys at lower ΔK values under negative potential and at reduced cyclic frequency.

DISCUSSION

Ambient Air Environment

The da/dN-versus-ΔK curves generated in an ambient air environment provide the reference basis against which environmental and electrochemical effects are judged. Wherever possible, these reference curves are based on data from more than one test or have been compared against data from other investigators. For instance the HY-130 ambient-air reference curve shown in Fig. 2 was taken from data on part-through-cracked and center-through-cracked specimens at a frequency of 30 cpm as reported in Ref. 3. Subsequently additional tests were performed on this material using compact tension specimens cycled at 300 cpm which confirmed these results in ambient air, as reported in Ref. 6. For the 17-4 PH VM-H1050 material (Fig. 3) the reference curve consists of data generated using single-edge-notch cantilever specimens cycled at 10 cpm at the NRL field laboratory in Key West plus data generated using pin-loaded single-edge-notch tension specimens cycled at 300 cpm at the NRL main laboratory in Washington, as reported in Ref. 2. A similar combination of data are used to provide the reference curve for the 17-4 PH AOM-H1150 material (Fig. 5). For the Ti-6Al-2Cb-1Ta-0.8Mo alloy (Fig. 6) the data generated in this investigation are in excellent agreement with the results of other studies on this material conducted under Navy sponsorship [7,8]. Finally for the 5456-H116 alloy (Fig. 7) the ambient air reference curve is in good agreement with previous work on a 5456-H321 alloy reported in Ref. 9.

Freely Corroding Seawater Environment

With the exception of the Ti-6Al-2Cb-1Ta-0.8Mo alloy, all of the materials studied exhibited some degree of environmentally accelerated crack growth rates in the natural seawater environment under freely corroding conditions. The most significantly affected material under these conditions was the 17-4 PH VM-H1050 steel (Fig. 3), which exhibited increases in crack growth rates by as much as a factor of 5 due to freely corroding seawater. For the remaining materials (HY-130 steel, 17-4 PH AOM steels in both tempers, and the 5456-H116 aluminum) the freely corroding natural seawater environment resulted in an approximate doubling of crack growth rates.

However in judging these effects for the 17-4 PH steels, it must be kept in mind that the air-environment reference curves for these materials differ significantly. This aspect has been discussed in detail in Ref. 2, where it was noted that AOM-H1050 material exhibits notably poorer resistance to fatigue crack growth in ambient air than the other two 17-4 PH steels. Thus this material (Fig. 4) has an air-environment reference curve which lies well above the reference curves for the other two 17-4 PH steels (Figs. 3 and 5). Therefore it would appear that the freely corroding seawater has somewhat of an equalizing effect on these 17-4 PH steels, more strongly affecting the initially superior materials and less strongly affecting the initially inferior material.

Potentiostated Seawater Environment

The application of electrochemical potential to specimens of the various materials being fatigued in seawater provided marked differences in response among the alloys under investigation. This strongly suggests that the mechanisms of environmentally accelerated fatigue-crack growth differ among the various materials.

With the exception of one test on the aluminum alloy, all of the potentials applied by means of the potentiostat device were more negative than the freely corroding potentials. For the ferrous alloys, negative potentials of the magnitudes examined here are of great practical significance for advanced-ship applications. Cathodic protection systems using zinc anodes or coupling between steel f-- and an aluminum hull are encountered in marine structures and produce negative potentials in the range of values used in these studies.

For three of the four ferrous materials studied, negative potential had a markedly adverse effect on crack growth rates, generally accelerating crack growth rates by a factor of 2 or more over those measured under freely corroding conditions. Overall the combined effects of seawater and negative electrochemical potential tended to accelerate crack growth rates by a factor of approximately 5 in the HY-130 steel and the two 17-4 PH AOM steels. Effects of this magnitude become highly significant in crack growth estimates for design purposes. However in some situations such crack-growth-acceleration effects are difficult to avoid, because some degree of negative potential is often necessary to reduce surface pitting or crevice corrosion in ferrous alloys.

Unlike the other steels examined, the 17-4 PH VM material (Fig. 3) did not exhibit acceleration in crack growth rate due to negative potential. No explanation for this behavior is readily available. However two observ .ions are relevent. First, this material did respond more strongly to freely corroding conditions than the other steels studied. Also, an apparent lack of response to negative potential in this steel has also been noted in another investigation [8].

The HY-130 steel (Fig. 2) exhibited further increases in crack growth rates by reducing the cyclic frequency under pot ..iostated conditions to 1 cpm, resulting in crack growth rates as much as an order of m .nitude greater than those measured in ambient air in this material. Frequency effects ' this type are well recognized in steels [10-12]. In fact the crack growth rates seen here are in good agreement with those measured in HY-80 steel by Gallagher at similar values of ΔK, frequency, and potential [10]. Both Gallagher [10] and Vosikovsky [12] have shown that crack growth rates even continue to increase at cyclic frequencies below 1 cpm, with some of Vosikovsky's data on a low-alloy steel showing increases in crack growth rates by as much as a factor of 100 over ambient air data due to the combined influences of saltwater, negative potential, and low cyclic frequency below 1 cpm.

The responses of the nonferrous alloys to potential were quite different. The Ti-6Al-2Cb-1Ta-0.8Mo alloy exhibited no response either to seawater or seawater plus potential, thus indicating its attractiveness as a marine alloy. The aluminum alloy exhibited a moderate acceleration in crack growth rates due to freely corroding seawater, but the application of either negative or positive potentials in seawater had beneficial effects and reduced crack growth rates back to values near the ambient-air reference curve. These observations are in contrast to those of Speidel et al. on 7079-T651 aluminum [13], where potentials negative from the freely corroding potential were seen to reduce crack growth rates in corrosion fatigue and positive potentials produced an acceleration. However further interpretation of many of the observations presented cannot be rationalized without an understanding of the mechanisms involved.

Comparisons With SCC Characteristics

Some general comparisons with the stress-corrosion-cracking (SCC) characteristics of the materials studied are in order. It has become customary to delineate corrosion-fatigue crack propagation into two regimes involving K_{max} levels below or above K_{Iscc} [10]. Fatigue cycling above K_{Iscc} implies significantly accelerated crack growth rates resulting from the dual superposition of an SCC mechanism plus a fatigue mechanism [14], whereas cycling below K_{Iscc} implies a lesser degree of environmental acceleration resulting from a singular mechanism of crack growth.

Although only one of the actual materials studied in this investigation was specifically tested to determine its K_{Iscc} characteristics, a review of existing data on similar materials suggests that nearly all of the da/dN-versus-ΔK data from this study involve corrosion-fatigue cycling below K_{Iscc}.

Fujii [15] has done an extensive study on SCC in vacuum-melted 17-4 PH steels as a function of yield strength and potential using the same plate sample of materials as was used in this study. His data suggest that for the H1050 temper used in this study, the K_{Iscc} values for both the freely corroding and -650 mV conditions lie above 110 MPa $m^{1/2}$ (100 ksi$\sqrt{in.}$) and thus beyond the upper limit of the corrosion-fatigue curve for this material, as shown in Fig. 3. For the 17-4 PH AOM materials and the HY-130 steel, published data [16] plus recent unpublished work [17] suggest that all but the very upper portions of the corrosion-fatigue da/dN-versus-ΔK curves in Figs. 2, 3, and 5 lie below the estimated K_{Iscc} values. For the nonferrous alloys studied, related information on SCC characteristics of these materials suggests that they exhibit little or no sensitivity to SCC [18,19].

SUMMARY AND CONCLUSIONS

Corrosion-fatigue crack growth studies were conducted on a selected group of high-strength marine alloys in flowing natural seawater under low cyclic frequency at various controlled levels of electrochemical potential. The materials studied included: HY-130 steel, vacuum-melted 17-4 PH steel in the H1050 temper, argon-oxygen-melted 17-4 PH steel in the H1050 and H1150 tempers, Ti-6Al-2Cb-1Ta-0.8Mo, and 5456-H116 aluminum alloy. The results are presented in terms of a da/dN-versus-ΔK fracture mechanics format. These results have shown that:

- The corrosion-fatigue response of these alloys to natural seawater and electrochemical potential varies widely, depending on the particular alloy. Effects range from negligible to seriously deleterious;

• Generally the high-strength steels (HY-130 and 17-4 PH) currently committed to Navy programs are among the most seriously affected by corrosion-fatigue;

• The nonferrous marine alloys (Ti-6Al-2Cb-1Ta-0.8Mo and 5456-H116 aluminum) exhibited highly promising responses to the conditions of corrosion fatigue used in this investigation

ACKNOWLEDGMENTS

The authors acknowledge the assistance of C. W. Billow, G. W. Jackson, and W. E. King in preparing specimens and conducting tests. The financial support of the Naval Materiel Command is gratefully acknowledged.

REFERENCES

1. H.H. Vanderveldt, T.W. Crooker, and J.A. Corrado, "Structural Integrity Technology for Advanced Surface Ships," *Naval Engineers J.* 88 (No. 2), 97-105 (Apr. 1976).
2. T.W. Crooker, D.F. Hasson, and G.R. Yoder, "Micro-Mechanistic Interpretation of Cyclic Crack Growth Behavior in 17-4 PH Stainless Steels," *Fractography-Microscopic Cracking Processes*, ASTM STP 600, American Society for Testing and Materials, 1976, pp. 205-219.
3. A.M. Sullivan and T.W. Crooker, "Analysis of Fatigue-Crack Growth in a High-Strength Steel — Part 1: Stress Level and Stress Ratio Effects at Constant Amplitude," ASME Transactions, *J. Pressure Vessel Technology* 98, Series J (No. 2), 179-184 (May 1976).
4. J.A. Kies, H.L. Smith, H.E. Romine, and H. Bernstein, "Fracture Testing of Weldments," pp. 328-353 in *Fracture Touchness Testing and Its Applications*, ASTM STP 381, American Society for Testing and Materials, 1965.
5. R.J. Goode, "Identification of Fracture Plane Orientation," *Materials Research and Standards* 12 (No. 9), 31-32 (Sept. 1972).
6. A.M. Sullivan and T.W. Crooker, "A Crack-Opening-Displacement Technique for Crack Length Measurement in Fatigue Crack Growth Rate Testing—Development and Evaluation," *Engineering Fracture Mechanics*, publication pending.
7. H.L. Smith, Naval Research Laboratory, private communication.
8. D.D. Miller, The Boeing Company, private communication.
9. T.W. Crooker, "Fatigue and Corrosion-Fatigue Crack Propagation in Intermediate-Strength Aluminum Alloys," ASME Trans., *J. Engineering Materials and Technology* 95, Series H (No. 3), 150-156 (July 1973).
10. J.P. Gallagher, "Corrosion Fatigue Crack Growth Behavior Above and Below K_{Iscc}," NRL Report 7064, May 28, 1970.

11. J.M. Barsom, "Corrosion-Fatigue Crack Propagation Below K_{Iscc}," *Engineering Fracture Mechanics* 3, 15-25 (1971).

12. O. Vosikovsky, "Fatigue-Crack Growth in an X-65 Line-Pipe Steel at Low Cyclic Frequencies in Aqueous Environments," ASME Trans., *J. Engineering Materials and Technology* 97, Series H (No. 4), 298-304 (Oct. 1975).

13. M.O. Speidel, M.J. Blackburn, T.R. Beck, and J.A. Feeney, "Corrosion Fatigue and Stress Corrosion Crack Growth in High Strength Aluminum Alloys, Magnesium Alloys, and Titinium Alloys Exposed to Aqueous Solutions," pp. 324-343 in *Corrosion Fatigue*, National Association of Corrosion Engineers, 1972.

14. R.P. Wei and J.D. Landes, "Correlation Between Sustained-Load and Fatigue Crack Growth in High-Strength Steels," *Materials Research and Standards* 9 (No. 7), 25-27, 44, 46 (July 1969).

15. C.T. Fujii, "Stress Corrosion Cracking Properties of 17-4 PH Steel," in *New Approaches to Stress Corrosion Cracking*, ASTM STP 610, American Society for Testing and Materials, 1976 (pending).

16. G. Sandoz, "High Strength Steels" pp. 79-133 in *Stress Corrosion Cracking in High Strength Steels and in Titanium and Aluminum Alloys*, edited by B.F. Brown, Naval Research Laboratory, 1972.

17. C.T. Fujii, Naval Research Laboratory, private communication.

18. C.T. Fujii, "Stress Corrosion Cracking Properties of Thin-Plate Titanium Alloys," Report of NRL Progress, February 1976, pp. 10-12.

19. F.D. Bogar and C.T. Fujii, "Stress Corrosion Cracking Properties of Two Aluminum-Magnesium Alloys," NRL Memorandum Report 2724, Jan. 1974.