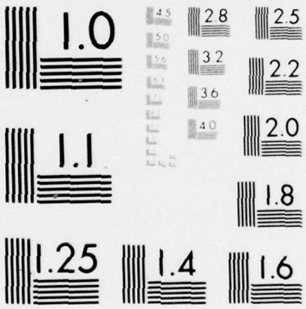
AD-A042 927 NAVAL RESEARCH LAB WASHINGTON D C F/G 11/6
CONDITIONS AFFECTING CRACK-GROWTH RATE: RELEVANCE TO TEST METHO--ETC(U)
JUN 77 A M SULLIVAN
UNCLASSIFIED NRL-8111 NL

1 OF 1
ADA042927

END
DATE
FILMED
9-77
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

NRL Report 8111

Conditions Affecting Fatigue-Crack-Growth Rate: Relevance to Test Method Selection and Data Interpretation

A. M. Sullivan

Strength of Metals Branch
Engineering Materials Division

June 7, 1977

NAVAL RESEARCH LABORATORY
Washington, D.C.

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Report 8111 | 2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CONDITIONS AFFECTING CRACK-GROWTH RATE: RELEVANCE TO TEST METHOD SELECTION AND DATA INTERPRETATION	5. TYPE OF REPORT & PERIOD COVERED Final report on one phase of a continuing NRL Problem 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) A.M. Sullivan	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem M01-57 Task No. ZF 54-591-001
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Navy Chief of Naval Material Washington, D.C. 20360	12. REPORT DATE June 7 1977 13. NUMBER OF PAGES 18
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)

18. SUPPLEMENTARY NOTES

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

Conditions of the material
Conditions of the test-environmental
Conditions of the test-mechanical
Fatigue crack-growth rate

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

The literature of fatigue and corrosion fatigue crack-growth rate contains many discrepancies. The many variables associated with fatigue crack-growth rate are classified, and their relative significance is discussed.

CONTENTS

CONDITIONS AFFECTING FATIGUE-CRACK-GROWTH RATE: RELEVANCE TO TEST METHOD SELECTION AND DATA INTERPRETATION

INTRODUCTION

Fatigue-crack-growth rate (FCGR) is of fundamental importance to structural integrity technology. The material of any structure subjected to repeated loading cycles is a candidate for the initiation and propagation of fatigue cracks. Since it is now generally recognized that virtually all structures will contain cracks or imperfections that can be considered cracklike defects, propagation will be the stage discussed here.

FCGR testing has a long but often unrecognized history. Crack-growth information was buried in "cycles-to-failure" fatigue data for many decades and was not specifically identified for engineering use. No adequate engineering representation existed until 1963, when Paris [1] showed that FCGR expressed as da/dN appeared to be a unique function of stress-intensity factor range ΔK, such that

$$da/dN = A\,\Delta K^{n}. \tag{1}$$

An extensive amount of data has since been collected and analyzed in this fracture mechanics format. Later, it became obvious that the log-log plots of Eq. (1) were actually sigmoidal, the linear approximation being valid only over the midrange (Fig. 1). Because this midrange generally coincides with service loading conditions, representation of FCGR by this simple Paris law remains of great practical importance.

However, even the most casual literature survey reveals glaring discrepancies between results of various investigations and their interpretation. It is well known that many factors can influence the crack-growth resistance of materials; these naturally enter into the design of laboratory tests for such properties. An attempt to classify some important variables associated with FCGR testing seems warranted. These will be discussed as

Conditions of the material
Conditions of the test —mechanical
Conditions of the test —environmental

and will be considered with respect to two environments:

1. Ambient air
2. Aqueous and saline (3.5 percent NaCl)

Manuscript submitted February 14, 1977.

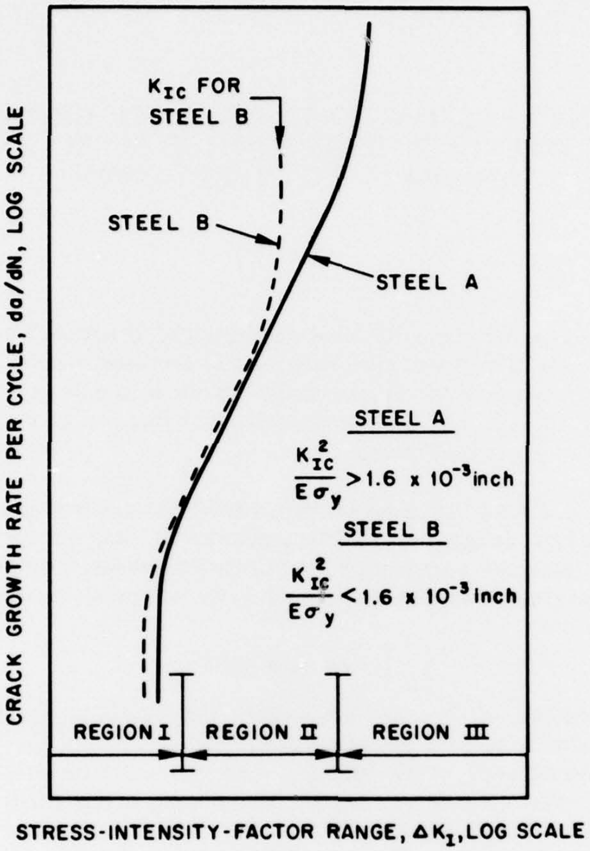


Fig. 1 – Schematic of $da/dN = A\Delta K^n$ as log da/dN vs log ΔK, showing sigmoidal nature of curve with linearity only in Region II. (Reprinted, with permission, from Ref. 2, p. 193. © 1973 American Society for Testing and Materials.)

CONDITIONS OF THE MATERIAL

Alloy System – Variations in the alloy system (steel, aluminum, and titanium) seem to influence somewhat the value of the exponent in Eq. (1).

Microstructure – Different values of the preexponential constant and exponent n in Eq. (1) may be characteristic of certain steel microstructures:

Martensitic:	$da/dN = 6.6 \times 10^{-9} \Delta K^{2.25}$ [3,4]
Ferritic-Pearlitic:	$da/dN = 0.36 \times 10^{-9} \Delta K^{3.00}$ [3]
Austentic Stainless:	$da/dN = 0.30 \times 10^{-9} \Delta K^{3.25}$ [5-7].

Deviations from these numerical values will be discussed later.

Thickness — Ambiguity and inconsistency characterize the literature of thickness effects on FCGR, since three types of response are documented:

1. No effect of thickness [8-11]
2. Growth accelerated by increased thickness [4,12]
3. Growth accelerated by decreased thickness [13,14].

Tests at NRL showed a slight increase in FCGR and considerable scatter in tests on specimens cut from an as-heat-treated plate of 5Ni-Cr-Mo-V steel. When this material was stress relieved after being cut, no effect of thickness was noted but FCGR was substantially increased [15] (Fig. 2). Further studies on A516-60 steel from a series of test specimens of varied thickness normalized, cut down, and stress relieved, again show no effect of thickness [16] (Fig. 3).

Processing History — The discussion of specimen thickness effects demonstrates that specimen processing affects FCGR. Lack of uniformity in such processing, together with a lack of reported processing information, is believed to have contributed largely to the ambiguities cited in this report. Sequences of processing can be described as follows:

1. Roll to size, heat treat, and test
2. Cut to size, heat treat, and test
3. Heat treat, cut to size, and test
4. Stress relieve prior to testing in (1), (2), or (3).

All of these require experimental investigation.

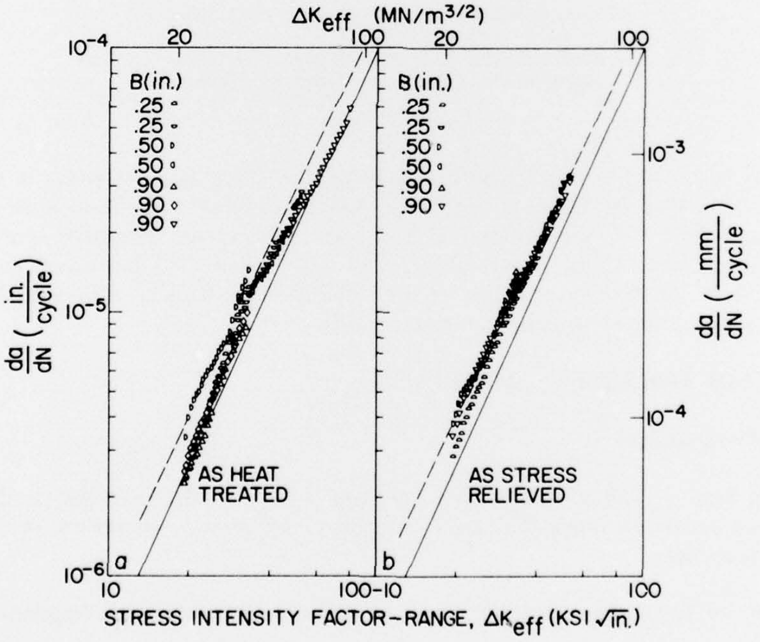


Fig. 2 — da/dN vs ΔK for 5Ni-Cr-Mo-V steel: effect of thickness in specimens tested as heat treated and stress relieved (Ref. 15, Fig. 2)

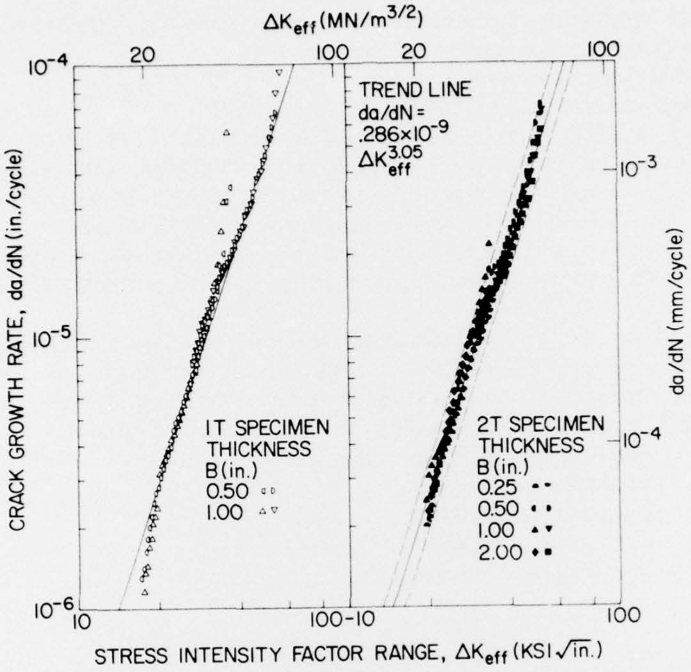


Fig. 3 – *da/dN* vs ΔK for A516-60 steel: effect of thickness in 1-T and 2-T WOL-type CT specimens (Ref. 16, Fig. 2c)

Yield Strength Level – Limited information on the effect of yield stress is available. Fatigue tests on 4340 steel tempered at a series of different temperatures show ambiguous results. Both Anctil and Kula [17] and Miller [18] find a variation in the exponent n of Eq. (1) with tempering temperature. On the other hand, Imhof and Barsom [19] find no effect of tempering temperature. A replot of these data can be seen in Fig. 4. Studies on a 17-4 stainless steel indicate little effect of tempering temperature on n [19].

CONDITIONS OF THE TEST – MECHANICAL

Ambient Air Environment

Specimen Type – The specimen type does not appear to affect the test results. In Fig. 5, data from three specimen types (CT, CCT, and SEN) are shown together with the trend line from the CT specimen.

Frequency – Tests in ambient air are apparently not affected by test frequency [20,21].

Waveform – No difference in test results were noted with sinusoidal, triangular, or square waveforms [20].

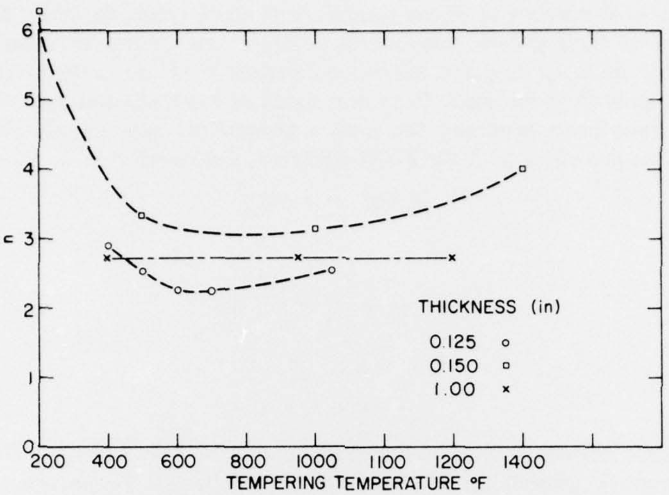


Fig. 4 – Exponent *n* vs tempering temperature for 4340 steel [17, 18]

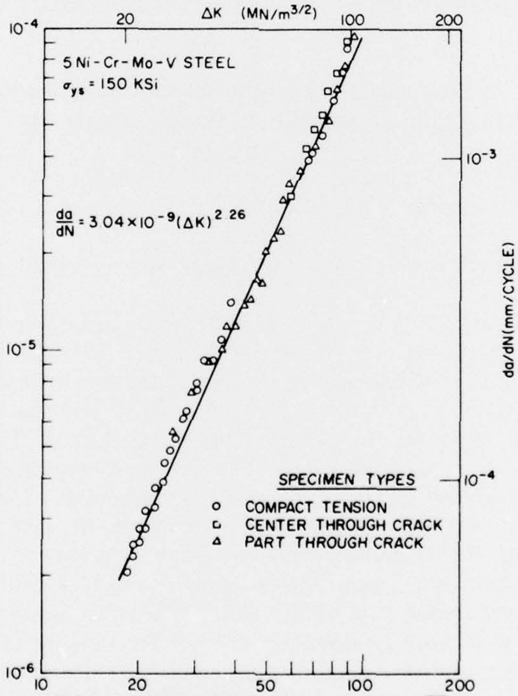


Fig. 5 – Results of tests from three specimen types: CT, CCT, and SEN (Ref. 15, Fig. 3).

Stress Ratio — The effect of stress ratio R is evident (Figs. 6a, 6b). At present the apparent acceleration of crack-growth rate cannot be explained. However, development of a generalized relationship incorporating the effects of different R values is important; it would allow estimates of crack growth to be made from one series of experimental determinations. Several complex models have been proposed for such a generalized relationship [23-27]. A simpler model [22] describes the effect of R for a 5Ni-Cr-Mo-V steel such that

$$da/dN = A \, \Delta K_{eff}^{n}$$

where

$$\Delta K_{eff} = \left[\frac{1 - bR}{1 - R} \right] \Delta K$$

$$\begin{aligned} b &= 0.85,\ R \geqslant 0 \\ &= 1.40,\ R \leqslant 0. \end{aligned}$$

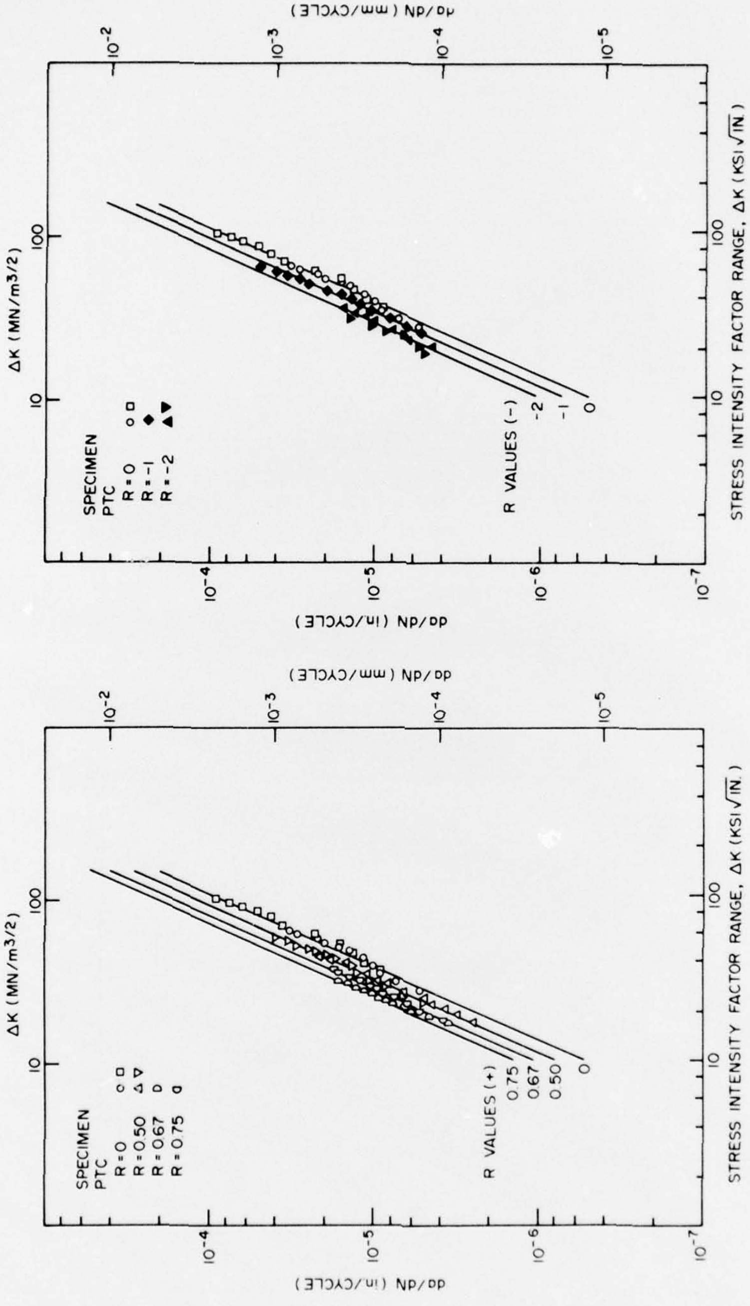
Stress Amplitude History — Recent literature reports both acceleration [28] and retardation [29,30] of fatigue-crack growth due to load sequence effects. To predict the latter, several models have been proposed [30-33]. One attempt to normalize da/dN from variable-amplitude loading studies uses a root-mean-square (rms) value of $\Delta\sigma$ for computing ΔK [34]. An equally successful effort at normalization of ten block loading profiles uses the simple mean value only [35].

Service Conditions — From the foregoing discussion of test conditions in ambient air, it can be seen that only stress ratio and amplitude (variable) have an immediate bearing on service conditions.

Aqueous and Saline Environment

Specimen Type — There is no evidence to suggest that specimen type influences FCGR.

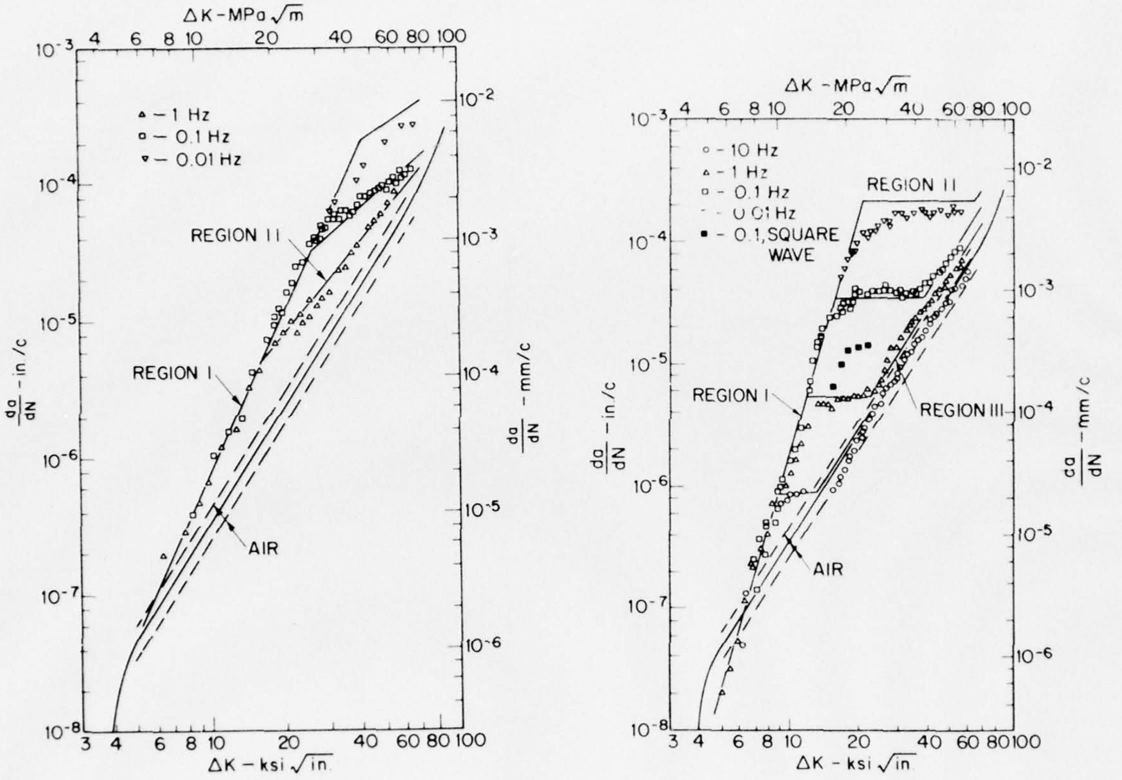
Frequency — This variable is highly important when testing is done in an aggressive environment. In general, the lower the frequency the more pronounced the increase in FCGR expressed as da/dN. Actually, of course, the time of crack growth to failure is greatly increased at lower frequencies. Good coverage of the effect of frequency has been made on X-65 line pipe steel by Vosikovsky [21], on HY-80 and 4340 by Gallagher [36], and on 4340 by Krafft [37]. Data from Ref. 21 cover approximately four orders of magnitude of da/dN and were obtained under conditions of free corrosion and cathodic potential. Three regions of growth are identified. Available data for a condition of free corrosion are seen in Fig. 7a and those for cathodic potential in Fig. 7b. Departure from the slope of Region I at higher values of da/dN as the frequency is reduced is evident. Also evident is the fact that the slope of Region I is higher in the NaCl environment than in air. Other results by Barsom concerning the effect of frequency confirm that it is more pronounced at lower frequencies [19,38]. What is surprising about these data, however, is that the authors are apparently discussing Region II environmental data and find no slope change from air data, (Figs. 8a, and 8b). Crooker and Lange [39], on the other hand, testing at higher values of da/dN and ΔK, show data obviously belonging to Region II in a 12Ni maraging steel (Fig. 9).



(a) R values ≥ 0 (Fig. 4a)

(b) R values ≤ 0 (Fig. 4b)

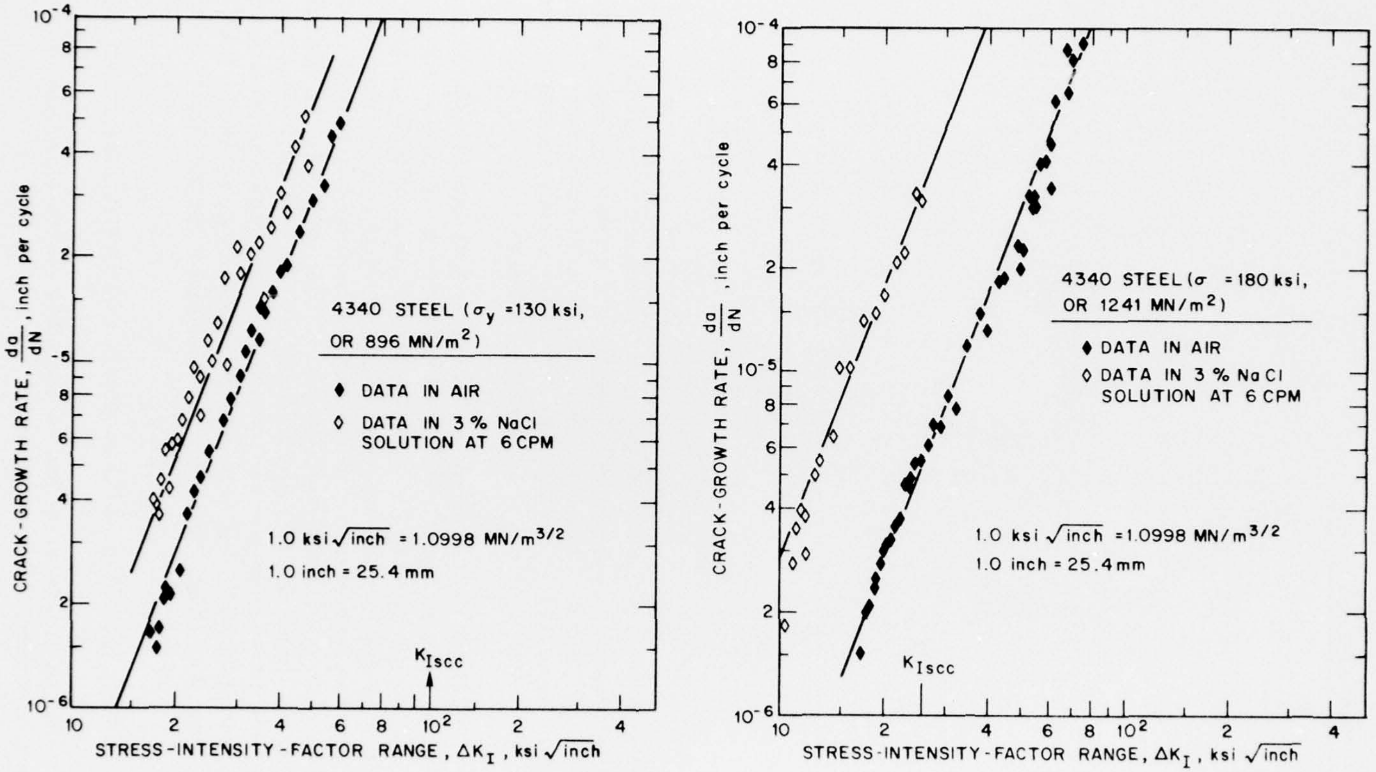
Fig. 6 – Comparison of control ($R = 0$) data and that produced over a range of R values [22]:



(a)

(b)

Fig. 7 – *da*/*dN* vs Δ*K* for *X*-65 line pipe steel in air and salt water [21]: (a) freely corroding (Fig. 3); (b) cathodic potential (Fig. 2). (Reprinted from O. Vosikovsky, Trans. ASME, Ser H, **97**, 298-304 (Oct. 1975). © 1975 American Society of Mechanical Engineers.)



(a)

(b)

Fig. 8 — da/dN vs ΔK in air and NaCl solution for 4340 steel [19]: (a) σ_{ys} = 130 ksi (896 MPa) (Fig. 16); (b) σ_{ys} = 180 ksi (1240 MPa) (Fig. 17). (Reprinted, with permission, from Ref. 19, pp 202, 203. © 1973 American Society for Testing and Materials.)

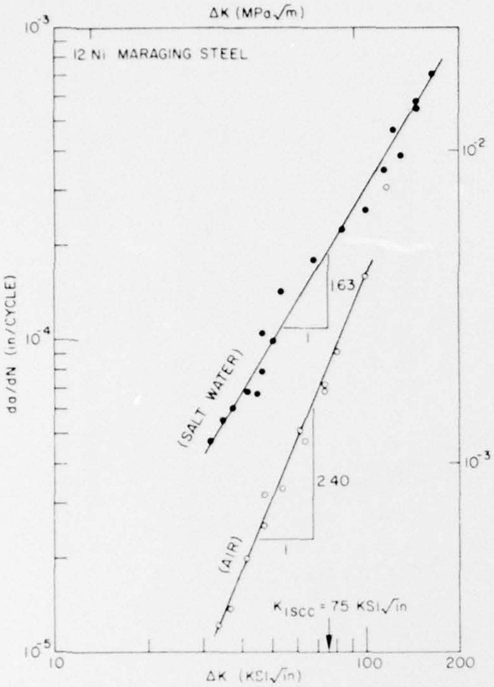


Fig. 9 – da/dN vs ΔK in air and NaCl solution for 12Ni maraging steel (Ref. 39, Fig. 5)

Reexamination of Imhoff and Barsom's data on 12Ni maraging steel [2] suggests that Region II behavior was commencing at the uppermost limit of his data and went unrecognized. Paris [40] shows behavior similar to that of Crooker and Lange for a D6a steel. The most obvious conclusion here is that, except for Vosikovsky [21], the experimenters did not cover a wide enough range of da/dN values to charaterize completely the effects of corrosive environments.

Waveform – In adverse environments the waveform does have an effect, but its exact consequence appears unresolved. Barsom [20] found that the environmental effects occurred only during increasing tensile stresses. Crack-growth rates under sinusoidal, triangular, or positive sawtooth waveforms showed environmental effects, but under square or negative sawtooth waveforms they were the same as in air. This result was confirmed by Pelloux on 7075-T73 aluminum in a discussion to the same Ref. 20 and by Crooker, et al. [41]. Another discussion to Ref. 20, however, by Hudak and Wei, indicated that tests on 7075-T651 using both positive and negative sawtooth forms were identical. To further complicate matters with respect to waveform, Vosikovsky [21] finds that with cathodic potential, da/dN values from a square waveform, while lower than those using a triangular waveform, are still higher than those in air.

Stress Ratio – No references to studies on the effect of stress ratio have been found.

Amplitude – No references to studies on the effect of variable-amplitude loading on FCGR in aqueous environments have been found.

Service Conditions — Here, frequency and waveform as well as stress ratio and amplitude may well represent variables in service conditions.

CONDITIONS OF THE TEST-ENVIRONMENTAL

Composition of contaminate solution.
Solution flowing or still.
Cathodic protection — sacrificial anode or potentiostat.

Recent experimental work has shown that in a flowing solution the corrosion fatigue-crack-growth rate (CFCGR) was the same under both freely corroding and cathodically protected conditions. In a still solution CFCGR was accelerated in the cathodically protected specimen.

SOME CAUSES OF DISCREPANCIES AND MISINTERPRETATIONS

Limited *da/dN* Range

Schematic diagrams of various curves of *da/dN* vs ΔK postulated [42] for corrosion fatigue are seen in Fig. 10. Figure 11 depicts behavior exhibited by certain nonferrous alloys [43]. By referring back to Figs. 7, 8a, 8b, and 9 we see that the data apparently do not fit the postulated forms. Discussion of the data in Fig. 9 shows quite clearly that the range of data was not sufficient to characterize the environmental effect. The four orders of magnitude shown in Fig. 7 are more representative. The limited ranges studied have also led to divisions into regions, which differ from author to author. This must be clarified.

Material Thickness

This subject has already been covered in some detail. Clearly, to assess service conditions, the material must be tested in the processed form it will be used. Further, to elucidate the mechanisms of crack growth, reports of research must include processing information.

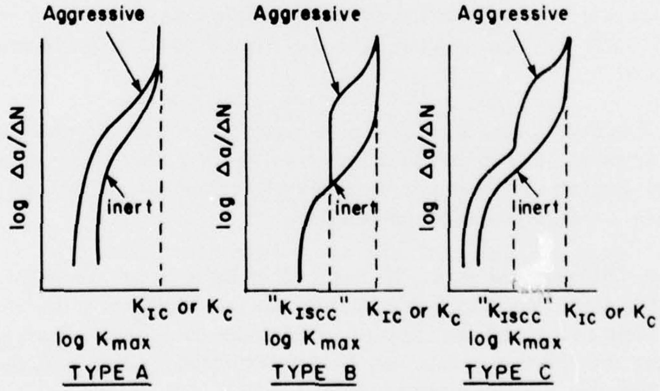


Fig. 10 — Types of corrosion fatigue crack-growth behavior. (Reprinted with permission, from Ref. 42, p. 387. © 1972 National Association of Corrosion Engineers.)

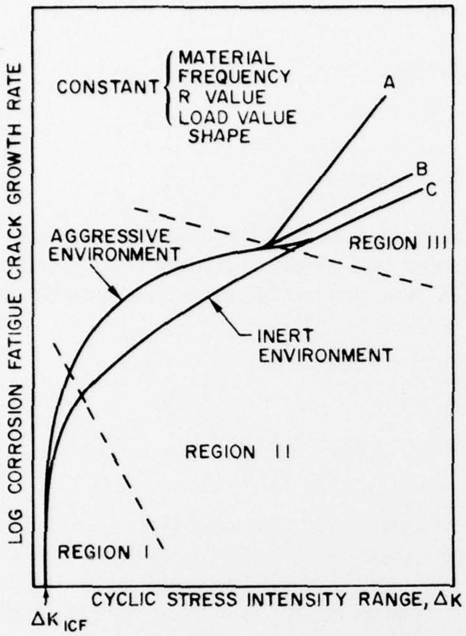


Fig. 11 – Schematic of the influence of stress intensity on corrosion fatigue crack-growth rate. (Reprinted, with permission, from Ref. 43, p. 326. © 1972 National Association of Corrosion Engineers.)

VALUES OF EXPONENT *n*

The previous statement that specific values of n can be associated with specific types of steel microstructures is misleading. Not only are there indications that n may vary with tempering temperature and K_{Ic} (not yield strength), but also data show clearly that n is altered by an adverse environment. The dogmatic statement that $n \simeq 2$ for martensitic steels is belied by the data of Ref. 37. Here Miller also suggests that the highest values of n may reflect the effect of the atmospheric humidity, although no fractorgraphic evidence is presented. However, it has been shown in 17-4 stainless [2] that changes in fracture mode can be reflected by changes in n. When the fracture mechanism is by ductile striations, $n \simeq 2.26$; when microvoid coalescence (MVC) and cleavage appear, $n \simeq 4.0$. This mode change is seen in air tests with increased values of R.

Vosikovsky, however, notes an increase in n when the fracture mode changes from ductile striations in air ($n = 2.82$) to brittle striation in NaCl. This observation pertains only to high ΔK values in Region II. However, in Region I increases are also noted, since $n = 3.95$ (free corrosion) and $n = 6.20$ (cathodic potential).

Barsom's data [20] all show values of $n \approx 2.25$ in both air or salt water. For one material only, 12Ni maraging steel, electron fractographic analysis indicates a fracture mode of ductile striations for the tests in air and flat, fine-textured plateaus or quasi-cleavage in the salt solution. The fact that the salt-water data can be reinterpreted to give a slope greater than 2 is more compatible with the fracture appearance.

CONCLUSIONS

1. More comprehensive and systematic characterization of materials is needed.

2. Increasing costs of material, machining, and labor handicap the research. Cooperation among laboratories with coordination by one would distribute the burden and increase the usefulness of the information.

3. To render such pooled information meaningful, a standardized test method is mandatory.

REFERENCES

1. P.C. Paris, "The Fracture Mechanics Approach to Fatigue," *Fatigue* —An Interdisciplinary Approach, Proceedings of the Tenth Sagamore Army Materials Research Conference, Aug. 13-16, 1963. Syracuse University Press, 1964, p. 107.
2. E.J. Imhof and J.M. Barsom, "Fatigue and Corrosion-Fatigue Crack Growth of 4340 Steel at Various Yield Strengths," *Progress in Flaw Growth and Fracture Toughness Testing*, ASTM STP 536, Philadelphia, Pa., pp. 182-205 (1973).
3. J.M. Barsom, "Fatigue-Crack Propagation in Steels of Various Yield Strengths," *Trans. ASME J. Eng. Ind.* (Ser. B) **93**(4), 1190-1196 (Nov. 1971).
4. J.M. Barsom, E.J. Imhof, Jr., and S.T. Rolfe, "Fatigue Crack Propagation in High Yield-Strength Steels," *Eng. Fracture Mech.* **2**, (4), 301-317 (June 1971).
5. L.A. James, "The Effect of Elevated Temperature Upon the Fatigue Crack Propagation Behavior of Two Aurstenitic Stainless Steels," *Mechanical Behavior of Materials*, Vol. III, The Society of Materials Science, Japan, 1972.
6. P. Shahinian, H.E. Watson, and H.H. Smith, "Fatigue Crack Growth in Selected Alloys for Reactor Applications," *J. Mater.* **7**(4), 527-535 (1972).
7. J.H. Weber and R.W. Hertzberg, "Effect of Thermomechanical Processing on Fatigue Crack Propagation," *Met. Trans.* **4**, 595-601 (Feb. 1973).
8. W.G. Clark, Jr., "Effect of Temperature and Section Size on Fatigue Crack Growth in Pressure Vessel Steel," *J. Mater.* **6**,(1), 134-149 (1971).
9. G.T. Hahn, R.G. Hoagland, and A.R. Rosenfield, "Local Yielding Attending Fatigue Crack Growth," Air Force Systems Command, Aerospace Research Laboratories Report ARL 71-0234, Nov. 1971.
10. C.E. Richards and T.C. Lindley, "The Influence of Stress Intensity and Microstructure on Fatigue Crack Propagation in Ferritic Materials," *Eng. Fracture Mech.* **4**(4), 951-978 (1972).
11. J.R. Griffiths and C.E. Richards, "The Influence of Thickness on Fatigue Crack Propagation Rates in a Low Alloy Steel Weld Metal Above and Below General Yield," *Mater. Sci. Eng.* **11**, 305-310 (1973).
12. F.A. Heiser and W. Mortimer, "Effect of Thickness and Orientation on Fatigue Crack Growth Rate in 4340 Steel," *Met. Trans.* **3**, 2119-2123 (1972).
13. W.G. Clark, Jr. and H.E. Trout, Jr., "Influence of Temperature and Section Size on Fatigue Crack Growth Behavior in Ni-Mo-V Alloy Steel," *Eng. Fracture Mech.* **2**(2), 107-123 (1970).
14. A.R. Jack and A.T. Price, "Effects of Thickness on Fatigue Crack Initiation and Growth in Notched Mild Steel Specimens," *Acta Metallurgica*, **20**, 857-866 (1972).
15. A.M. Sullivan and T.W. Crooker, "The Effects of Specimen Thickness on Fatigue Crack-Growth Rate in 5Ni-Cr-Mo-V Steel-Comparison of Heat-Treated and Stress Relieved Specimens," NRL Report 7936, Dec. 9, 1975.

16. A.M. Sullivan and T.W. Crooker, "The Effect of Section Size Upon the Fatigue Crack Growth Rate of A516-60 Pressure Vessel Steel," NRL Report 8004, Aug. 4, 1976.
17. A.P. Anctil and E.B. Kula, "Effect of Tempering Temperature on Fatigue-Crack Propagation in 4340 Steels," *Effects of Environment and Complex Load History on Fatigue Crack Propagation*, ASTM STP 462, Philadelphia, Pa., pp. 297-317 (1970).
18. G.A. Miller, "The Dependence of Fatigue Crack Growth Rate on the Stress Intensity Factor and the Mechanical Properties of Some High-Strength Steels," *Trans. ASM*, **61**, 1968, 442-448 (1968).
19. T.W. Crooker, D.F. Hasson, and G.R. Yoder, "A Fracture Mechanics and Fractrographic Study of Fatigue-Crack Propagation Resistance in 17-4 PH Stainless Steels," NRL Report 7910, July 17, 1975.
20. J.M. Barsom, "Effect of Cyclic Stress Form on Corrosion Fatigue Crack Propagation Below $K_{I_{scc}}$ in a High Yield Strength Steel," *Corrosion Fatigue* NACE-2, National Society of Corrosion Engineers, Houston, Texas, 1972, pp. 424-436.
21. O. Vosikovsky, "Fatigue Crack Growth in an X-65 Line-Pipe Steel at Low Cyclic Frequencies in Aqueous Environments," *Trans. ASME, J. Eng. Mater. Technol.* (Ser H), **97**, 298-304 (Oct. 1975).
22. A.M. Sullivan and T.W. Crooker, "Analysis of Fatigue-Crack Growth in a High Strength Steel — Part I: Stress Level and Stress Ratio Effects at Constant Amplitude," *Trans. ASME, J. Pressure Vessel Technol.* (Ser. J) **98**(2), 179-184 (May 1976).
23. R.G. Forman, V.E. Kearney, and R.M. Engle, "Numerical Analysis of Crack Propagation in Cyclic-Loaded Structures," *Trans. ASME, J.* Basic *Eng.* (Ser. D) **89**(3), 459-464 (Sept. 1967).
24. K. Walker, "The Effect of Stress Ratio During Crack Propagation and Fatigue for 2024-T3 and 7075-T6 Aluminum," *Effects of Environment and Complex Load History on Fatigue Life*, ASTM STP 462, Philadelphia, Pa., pp. 1-14 (1970).
25. W. Eiber, "The Significance of Fatigue Crack Closure," *Damage Tolerance in Aircraft Structures*, ASTM STP 486, pp. 230-242 (1971).
26. T.W. Crooker and D.J. Krause, "The Influence of Stress Ratio and Stress Level on Fatigue Crack Growth Rates in 140-ksi YS Steel," *Report of NRL Progress*, pp. 33-35 (Dec. 1972).
27. D.J. Krause and T.W. Crooker, "Effects of Constant-Amplitude Loading Parameters on Low-Cycle Fatigue-Crack Growth in a 140-150 ksi Yield Strength Steel," *Report of NRL Progress*, pp. 51-54 (Mar. 1973).
28. W.T. Matthews, F.I. Baratta, and G.W. Driscoll, "Experimental Observation of a Stress Intensity History Effect Upon Fatigue Crack Growth Rate," *Int. J. Fracture Mech.* 7(2), 224-227 (June 1971).
29. O. Jonas and R.P. Wei, "An Exploratory Study of Delay in Fatigue-Crack Growth," *Int. J. Fracture Mech.* 7(1), 116-118 (Mar. 1971).
30. O.E. Wheeler, "Spectrum Loading and Crack Growth," *Trans. ASME, J. Basic Eng.* (Ser. D) 181-186 **94**, (Mar. 1972).
31. J.D. Willenborg, R.M. Engle, and H.A. Wood, "A Crack Growth Retardation Model Using an Effective Stress Concept," Air Force Flight Dynamics Laboratory, TM-FBR-71-1, Jan. 1971.
32. T.D. Gray and J.P. Gallagher, "Predicting Fatigue Crack Retardation Following a Single Overload Using a Modified Wheeler Model," Eighth National Symposium on Fracture Mechanics, Providence, R.I., Aug. 26-28, 1974, pending publication as an ASTM STP.
33. J. Schijve, "The Prediction of Fatigue Crack Propagation Under Service Load-Time Histories," ICAF Symposium, London, England, July 18-20, 1973.

34. J.M. Barsom, "Fatigue Crack Growth Under Variable Amplitude Loading in ASTM A514-B Steel," *Progress in Flaw Growth and Fracture Toughness Testing*, ASTM STP 536, pp. 147-167 (1973).
35. A.M. Sullivan and T.W. Crooker, "Analysis of Fatigue-Crack Growth in a High-Strength Steel — Part II: Variable Amplitude Block Loading Effects," ASME Paper No. 75-WA/PVP-23, pending publication in *Trans. ASME, J. Pressure Vessel Technol.* Ser. J, **98**(3), 208 (Aug. 1976).
36. J.P. Gallagher, "Corrosion Fatigue Crack Growth Behavior Above and Below $K_{I_{scc}}$," NRL Report 7064, May 28, 1970.
37. J.M. Krafft and H.L. Smith, "Ligament Instability Model for Stress Corrosion and Fatigue Crack Propagation in an 4340 Steel," NRL Memorandum Report 2598, Apr. 1973.
38. J.M. Barsom, "The Dependence of Fatigue Crack Propagation on Strain Energy Release Rate and Crack Opening Displacement," in *Damage Tolerance in Aircraft Structures*, ASTM STP 486, pp. 1-15 (1971).
39. T.W. Crooker and E.A. Lange, "The Influence of Salt Water on Fatigue Crack Growth in High Strength Structural Steels," *Effects of Environment and Complex Load History on Fatigue Life*, ASTM STP 462, pp. 258-271 (1970).
40. Propagation of D6a Steel in Air and Distilled Water," *Stress Analysis and Growth of Cracks*, ASTM STP 513, pp. 196-217 (1972).
41. T.W. Crooker, F.D. Bogar, and K.R. Kondas, "Influence of Experimental Factors on Corrosion-Fatigue Crack Growth Rate in 17-4 PH Steel," *Report of NRL Progress*, pp. 21-23 (May 1976).
42. A.J. McEvily and R.P. Wei, "Fracture Mechanics and Corrosion Fatigue," *Corrosion Fatigue*, International Corrosion Conference Series NACE-2, National Association of Corrosion Engineers, Houston, Texas, 1972, pp. 381-395.
43. 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 Titanium Alloys Exposed to Aqueous Solutions," *Corrosion Fatigue*, International Corrosion Conference Series NACE-2, National Association of Corrosion Engineers, Houston, Texas, 1972, pp. 324-345.