

FATIGUE CRACK GROWTH IN CORROSIVE ENVIRONMENTS

V. V. PANASYUK, L. V. RATYCH and I. N. DMYTRAKH

Physicomechanical Institute, Ukrainian Academy of Sciences, 5 Nauchnaya St, Lvov-47, U.S.S.R.

(Received in final form 12 September 1983)

Abstract—An analysis is presented of factors causing fatigue crack resistance in metals exposed to liquid corrosive environments. A new approach involving invariant diagrams is proposed that takes simultaneous account of the stress-strain state and the electrochemical conditions at the tip of a crack. Variations in electrochemical conditions at the tip of a stationary crack and the relationship between the electrochemical conditions at the crack tip and the fatigue crack growth rate in aqueous corrosive environments are discussed with the aid of these diagrams.

NOMENCLATURE

- F = load
- M = bending moment
- a = crack length
- N = number of cycles
- v = crack growth rate
- v_e = fatigue crack growth rate in corrosion environment
- K_I = stress intensity factor for a Mode I crack
- $K_I, K_{I_{\max}}$ = initial level of K_I and maximum value of K_I
- ΔK = stress intensity factor range
- K_c = critical value of K_I for a material of given thickness
- K_{IC} = critical value of K_I under plane strain conditions
- K_{ISCC} = threshold value of K_I under plane strain conditions in a corrosive environment
- t = time
- S = fracture surface
- $C_1, C_2 \dots C_i$ = material constants
- $A_1, A_2 \dots A_j$ = parameters defining physicochemical processes at a crack tip
- $B_1, B_2 \dots B_k$ = parameters characterising the state of the fracture surface
- pH_e = hydrogen ion exponent of the environment
- pH_t = value of pH at the crack tip
- pH_x = value of pH within a crack at a distance x from the specimen surface
- pH_{ts} = value of pH at the tip of a stationary crack under static loading
- pH_{tc} = value of pH at the tip of a propagating crack under cyclic loading
- pH_{tc}^o = value of pH_{tc} at the moment a crack opens
- pH_{tc}^c = value of pH_{tc} at the moment a crack closes
- ΔpH_{tc} = variation of pH_{tc} within a loading cycle
- ϕ = metal electrode potential
- ϕ_s = value of ϕ on the specimen surface
- ϕ_t = value of ϕ at the crack tip
- ϕ_x = value of ϕ at a distance x from the specimen surface
- ϕ_{ts} = value of ϕ at the tip of a stationary crack under static loading
- ϕ_{tc} = value of ϕ at the tip of a propagating crack under cyclic loading
- ϕ_{tc}^o = value of ϕ_{tc} at the moment a crack opens
- ϕ_{tc}^c = value of ϕ_{tc} at the moment a crack closes
- $\Delta \phi_{tc}$ = variation of ϕ_{tc} within a loading cycle.

INTRODUCTION

The effect of static or cyclic loads on metallic materials in conjunction with corrosive environments is known to result in the rapid growth of cracks. The growth behaviour of these cracks is described by static corrosion crack resistance (SCCR) or cyclic corrosion crack resistance (CCCR) diagrams which reflect the dependence of the crack growth rate on the maximum stress intensity factor (or the stress intensity factor range) (Fig. 1). Such diagrams are constructed from experiments using specimens of a particular form (such as plate, bar or beam) containing an artificially introduced (central, lateral, surface) crack.

In the past decade numerous papers have been published (see reviews [1–8]) and several conferences have been held on the effect of various factors (such as structure, loading, temperature, environment, composition etc. [9–12]) on the cyclic crack resistance of materials. In particular, it has been established that, unlike fatigue cyclic crack growth resistance (FCGR) diagrams in an inert environment, vacuum or air, the stress corrosion crack resistance (SCCR) and the cyclic corrosion crack resistance (CCCR) diagrams are sensitive to initial loading conditions, initial crack length etc. [13, 14]. The value of the stress intensity factor is known to be dependent on these factors as well. Thus it appears that the stress-strain conditions at the tip of a crack have not an unambiguous influence on the crack resistance of materials exposed to corrosive environments. Therefore the SCCR and CCCR diagrams constructed by conventional methods (with no account of the electrochemical conditions at the tip of a crack) appear not to be invariant diagrams. This perhaps makes them less useful for evaluating the crack resistance of materials exposed to corrosive environments.

In this paper both theoretical and experimental considerations are developed to define invariant values of the resistance of a material to crack growth in a corrosive environment.

THEORY

It is known that the fracture of a material in an inert environment is best defined by the level of stresses and strains created in it. Hence we can assume that stress intensity

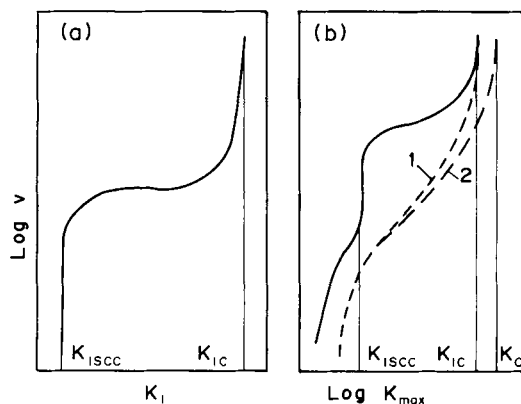


Fig. 1. Corrosion crack-resistance diagrams for materials under (a) static and (b) cyclic loading; solid lines. Curve 1—inert environment; self modelling requirements observed; Curve 2—inert environments; self modelling requirements not observed.

factors quantify the entire process of fracture near the tip of a propagating crack, i.e. each value of the stress intensity factor would correspond to a definite growth rate of the crack in a solid being deformed under prescribed loading conditions [15]. Then, if the requirements for self-modelling (i.e. the plastic strain region near the crack tip is small) were satisfied and the crack growth rate vs stress intensity factor was measured in inert environments by available experimental procedures [16], the necessary data would be obtained for constructing an invariant FCGR diagram reflecting the characteristic material properties. This is supported by numerous experimental investigations e.g. [1, 2]. If the self-modelling requirement is not fulfilled in inert environments, the FCGR diagrams will be shifted to some degree (Fig. 1, curve 2). This shift will occur at large values of stress intensity factors when it is difficult to model exact stress-strain states in small specimens.

When a material is exposed to a corrosive environment the mechanical factors cease to play a dominant role in the fracture behaviour because of physicochemical interactions between the material and the environment which occur continuously. This interaction is dependent on the stress-strain behaviour of the material, the specimen external surface state and the fracture surface features, environment chemistry and environment electrochemical characteristics; and the interaction occurs at different rates on the surface of a specimen and at the tip of a crack. As shown by available (yet few) theoretical [17–19] and experimental [20–25] investigations, this appears to be due to the electrochemical conditions, in particular the values of the hydrogen ion exponent pH (see Table 1) at the crack tip which differ essentially from those on the surface of the specimen. For a give material–environment system the differences are dependent upon the time of material exposure to the environment, the crack length, the external polarization potential and other factors. Hence the corrosive environment may have different influences on the formation of a prefracture zone at the crack tip. This effect has not previously been taken into account when defining static or cyclic crack resistance of materials exposed to corrosive environments. Procedures have usually been developed for inert environments and electrochemical conditions have been controlled only on the surface of a specimen and not at the crack tip. Since these conditions are different, the SCCR and CCCR diagrams are also found to be different.

In our papers [26–30] a detailed statement of this problem is given and the means of solution presented. In particular a model is proposed which takes into account the effect of environment on the development of a prefracture zone near the tip of a crack in a

Table 1.

Material	Environment	pH _e	pH _{ts}	Reference
AISI 4340 steel	3.5% NaCl	5.7	3.5–3.9	[20]
304 steel	Boiling solution of MgCl ₂	4.5	1	[21]
12Kh 18N10T steel	3.0% NaCl	6.5	1.7–1.8	[22]
45 steel	3.0% NaCl	6.5	5.8	[23]
15KhNSMF steel	3.0% NaCl	6.5	2.5	[23]
45kHN2MF A steel	3.0% NaCl	—	3.5	[24]
7075T aluminium alloy	3.5% NaCl	6.5	3.5	[20]
D16 aluminium alloy	3.0% NaCl	6.5	2.1–2.2	[22]
AT3 titanium alloy	3.0% NaCl	6.5	0.7–0.8	[22]
Ti8Al1Mo1Y alloy	3.5% NaCl	6.5	1.7	[20]
U7,5Nb2,5Zr alloy	0.6% NaCl	9.5	1.2	[25]

material deformed in a corrosive environment. The basis of this model is that the crack growth rate v_e depends not only on parameters such as the maximum value of the stress intensity factor, $K_{\max}$, but also on the $A_f(t)$ and $B_k(S)$ parameters characterizing respectively the physicochemical interaction as a function of time t and the state of fresh fracture surfaces S near the crack tip i.e.

$$v_e = f[C_1, C_2, \dots, C_i; K_{\max}; A_1(t), A_2(t), \dots, A_f(t); B_1(S), B_2(S), \dots, B_k(S)] \quad (1)$$

where C_i are the crack resistance constants of the material.

When constructing SCCR and CCCR diagrams, equation (1) should be used. To choose particular values of $A_f(t)$ and $B_k(S)$ and a particular structure of equation (1), extensive studies of various material–environment systems are required to be performed. In some cases additional restrictions may be imposed on the above parameters. For example, on the basis of published available data it can be assumed that for metals exposed to aqueous corrosive environments, electrochemical processes occurring at the tip of the crack are adequately defined by the crack tip environment hydrogen ion exponent pH_t and the metal electrode potential ϕ_t . Therefore to characterize the fracture zone in a material deformed in a corrosive environment (Fig. 2) we shall use three parameters namely $K_{\max}$, pH_t and ϕ_t . Thus equation (1) can be simplified to

$$v_e = f(C_1, C_2, \dots, C_i; K_{\max}; \text{pH}_t, \phi_t) \quad (2)$$

for calculation of the growth rate of a fatigue crack in a material in contact with an aqueous corrosive environment where the surface state of a specimen is characterized by the parameters pH_e and ϕ_s .

Thus it follows from equation (2) that for invariant SCCR and CCR diagrams to be constructed for materials in an aqueous corrosive environment, constant values of pH_t and ϕ_t are required. We have developed a procedure which provides not only a stabilized mechanical stress–strain state of the material but also the control and stabilization of the electrochemical conditions at the crack tip, i.e. $\text{pH}_t = \text{const}$ and $\phi_t = \text{const}$, during crack growth in a given material.

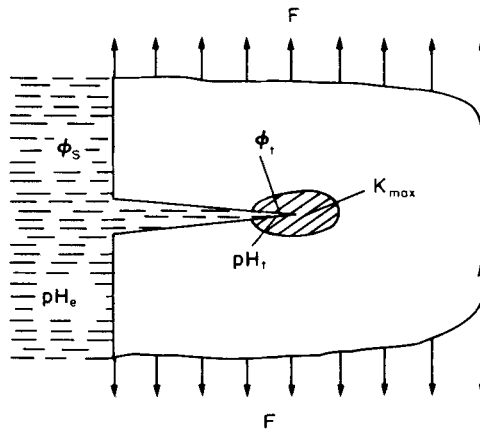


Fig. 2. Schematic of factors defining the state of material near the tip of a crack in a corrosive environment.

EXPERIMENTAL PROCEDURE

To study static and cyclic crack growth resistance of a material exposed to a corrosive environment, a rectangular section beam specimen with an edge crack is used that has a cylindrically drilled hold in the plane of crack propagation [31] to permit a capillary sensing instrument to be installed [32]. With reference to Fig. 3, a specimen (1) inside the chamber (2), is mounted in grips (3) of a pure bend testing machine which applied a moment M . Load is measured by resistance strain gauges (4) attached to the machine grips. Signals are fed to a Type KSP4 automatic potentiometer (5). Two auxiliary platinum electrodes (6) are placed symmetrically on both sides of the specimen in the plane of crack propagation and a control capillary (7) is put into the chamber. A measuring capillary tube (8) is installed into the specimen hole (Fig. 3, section A-A). As the crack grows the measuring capillary is adjusted by means of a device (9) in such a way that the capillary tube is in contact with the environment at the tip of the crack. One end of the measuring capillary tube is connected electrolytically, via a saturated solution of KCL contained in a vessel (14), to a standard reference chlorsilver electrode (10) and the other end is connected to a bleeder (12). The electrodes are connected to a Type P-5827 potentiostat (15). Stabilization and control of the stress-strain states of the material at the crack

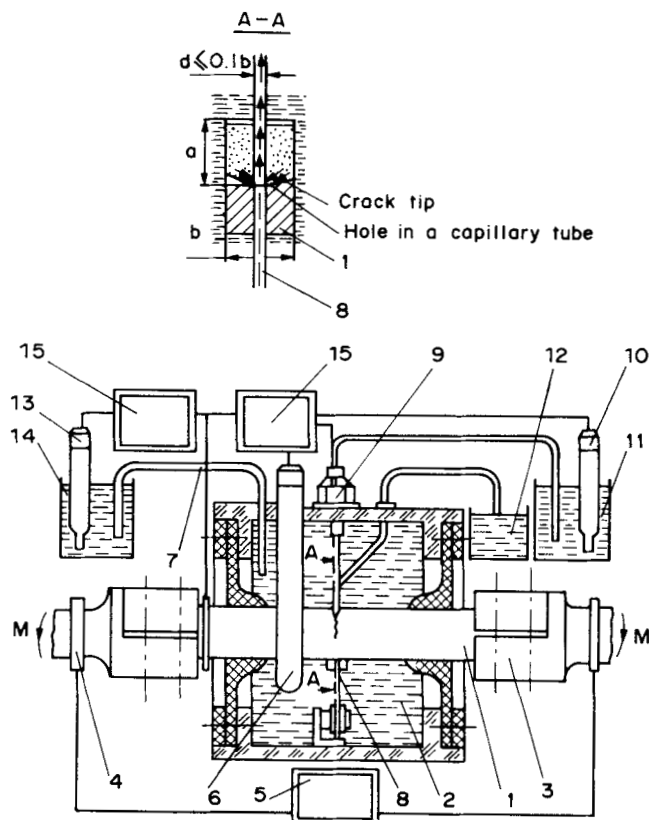


Fig. 3. Schematic of a machine for static or cyclic corrosion crack growth resistance testing of rectangular beam specimens taking account of electrochemical conditions at the tip of a crack.

tip is as described elsewhere [34]. Specimen sizes are chosen taking into account the compliance of the test machine–specimen system.

The metal electrode potential at the tip of a propagating crack (which is controlled via the potentiostat by means of the measuring capillary tube) is kept constant by varying the polarization current in the platinum electrode–specimen circuit.

The pH_i value at the tip of a propagating crack, corresponding to the pH_e value of the environment in the test chamber, is stabilized by pouring off continuously the environment from the crack tip into the bleeder via the holes and hollow part of the measuring capillary tube.

For known stress–strain states characterized by the stress intensity factor, the above procedure allows studies of electrochemical conditions to be performed at the tip of a stationary crack (under static load), an opening–closing crack (under cyclic load) and a propagating crack (when the crack length increases) as well as along the crack sides (the crack length) under conditions of free corrosion potential or when external polarization potential is applied. Thus diagrams can be made up of static or cyclic crack growth resistance of material exposed to an aqueous corrosive environment for constant electrochemical conditions at the tip of a crack.

RESULTS

We now consider some results obtained on 40Kh13 steel beam specimens of 10 × 20 × 150 mm size. Tests were performed in a 1% solution of H₃BO₃ in distilled water with KOH additions with pH values up to 8. Similar specimens of 20SF steel have been tested in a 3% solution of NaCl (pH = 6.7).

Electrochemical conditions at the tip of a stationary crack (under static loading)

Tests performed on the above pre-fatigue cracked specimens loaded to the same initial value of the stress intensity factor $K_I = K_i$ ($K_i < K_{ISCC}$) show (Fig. 4) that electrochemical conditions at the crack tip characterized by pH_{ts} and ϕ_{ts} differ essentially from those on the specimen surface characterized respectively by pH_e and ϕ_s , and they vary continuously with time of material exposure to the environment. A minimum value of pH_{ts} at the crack tip is achieved with time, the achievement being more rapid the longer is the crack. At the moment when pH_{ts(min)} is achieved at the tip of a crack variation of pH and ϕ along the crack length can be described by

$$\begin{aligned} \text{pH}_x &= \text{pH}_e [1 - (x/a)^{m_1} \exp(n_1(x/a))] \\ \phi_x &= \phi_s [1 + (x/a)^{m_2} \exp(n_2(x/a))] \end{aligned} \quad (3)$$

where $m_1 = 0.40$, $m_2 = 1.12$, $n_1 = -0.34$, $n_2 = -1.22$ for the system under consideration.

Application of the external polarization potential ϕ_s causes the electrochemical conditions at the crack tip to vary, the variation being more considerable the shorter the crack (Fig. 5). For each crack length there is a range of ϕ_s values which exert the greatest effect on ϕ_i . This range should therefore be taken into account when defining optimum conditions for providing cathodic and anodic protection against the corrosion fatigue failure of materials.

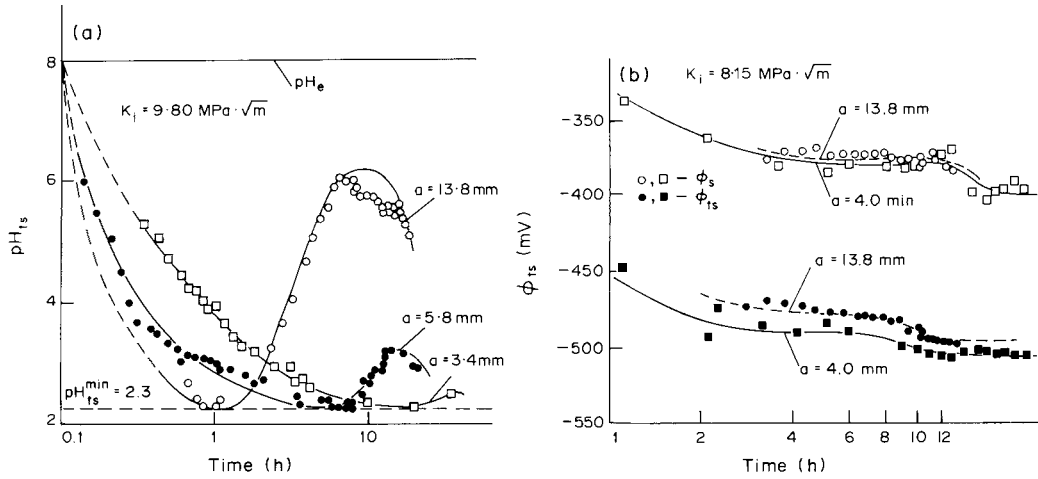


Fig. 4. Time dependence of (a) hydrogen ion exponent pH_{ts} and (b) metal electrode potential ϕ_{ts} at the tip of a stationary crack (under static loading) for various crack lengths, for beam specimens of 40Kh13 steel exposed to an aqueous solution with a pH value of 8.

The electrochemical conditions at the tip of a propagating crack (under cyclic loading)

Direct measurements of pH and ϕ at the tip of a fatigue crack (pH_{tc} , ϕ_{tc}) during its growth show (Fig. 6) that electrochemical conditions at the crack tip vary continuously, the variation being essentially sensitive to initial conditions near the tip of the crack. For the system studied, the value of $pH_{tc(\min)}$ appears to be much less than $pH_{ts(\min)}$ i.e. for a stationary crack (under static loading). The values of pH_{tc} and ϕ_{tc} at the moment the crack opens, pH_{tc}^o and ϕ_{tc}^o , have been found to vary in the following way: note that the

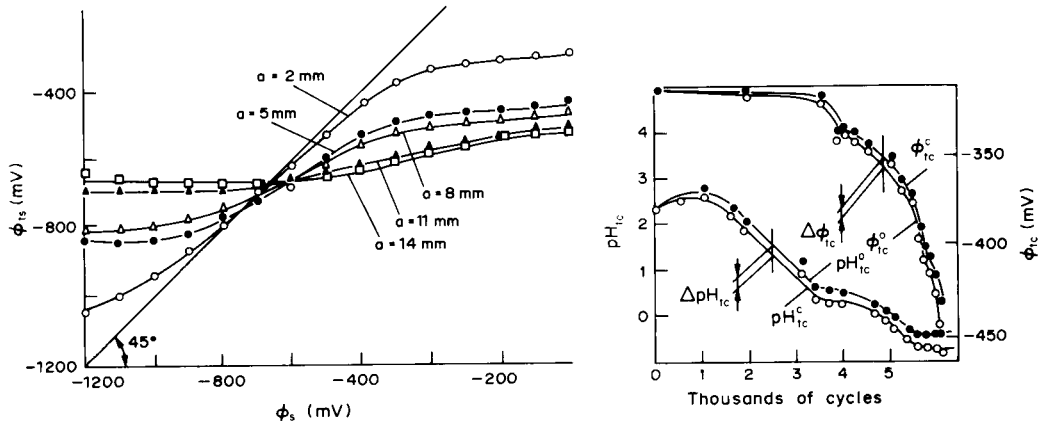


Fig. 5. Effect of external polarization potential ϕ_s on electrode potential at the tip of a stationary crack (under static loading) for different crack lengths in beam specimens of 40Kh13 steel exposed to an aqueous solution with a pH value of 8.

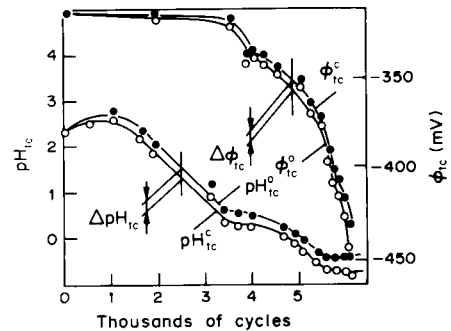


Fig. 6. Variation of hydrogen ion exponent pH and metal electrode potential ϕ at the tip of a propagating crack under cyclic loading of 40Kh13 steel beam specimens exposed to an aqueous solution with a pH value of 8.

variables ΔpH_{ic} and $\Delta \phi_{ic}$ (which increase and depend on the range of the stress intensity factor, ΔK) are superimposed on the pH and ϕ values at the crack tip and decrease continuously with time, t , from the moment the crack closes (pH_{ic}^c and ϕ_{ic}^c) i.e.:

$$\begin{aligned} pH_{ic}^o(N) &= pH_{ic}^c(t) + \Delta pH_{ic}(\Delta K); \quad t = t(N); \\ \phi_{ic}^o(N) &= \phi_{ic}^c(t) + \Delta \phi_{ic}(\Delta K); \quad \Delta K = \Delta K(N). \end{aligned} \quad (4)$$

The relationship between the fatigue crack growth rate and electrochemical conditions at the crack tip in a deformed solid

Our studies show that in a deformed solid the growth rate of a fatigue rate is directly related to electrochemical conditions at the crack tip. This is manifested by the fact that each fatigue crack growth rate in the CCCR-diagram corresponds to definite electrochemical conditions at the crack tip (Fig. 7); each area of the CCCR diagram corresponding to a definite area of variation of electrochemical conditions at the crack tip. Hence electrochemical conditions at the tip of a fatigue crack characterized by parameters pH, and ϕ , along with the stress strain state characterized by the stress intensity factor K_I , are seen to determine the growth rate of a fatigue crack in a corrosive environment. These factors and associated processes appear to cause acceleration of crack growth in a corrosive environment as compared with air conditions.

Thus it appears that to obtain reproducible data on the growth rate of a fatigue crack in a corrosive environment it is necessary to provide identical electrochemical conditions as the crack grows. Therefore if electrochemical conditions at the crack tip are kept constant during cyclic crack growth resistance tests [35] an invariant diagram of cyclic growth resistance can be obtained for a given system (Fig. 8) but conventional procedures (which are not able to provide $pH_i = \text{const}$ and $\phi_i = \text{const}$ conditions) yields noninvariant diagrams. Obtaining invariant diagrams allows cyclic crack growth resistance characteristics of a material to be defined for a given material–environment system. This appears

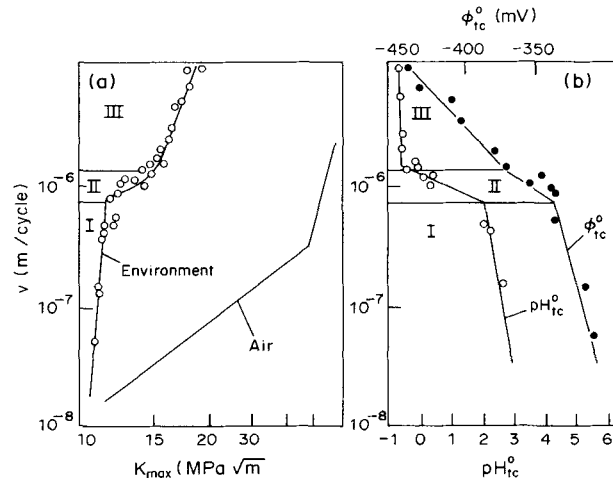


Fig. 7. Cyclic crack growth resistance diagrams. (a) As a function of K_{max} in air and an aqueous solution with a pH value of 8; (b) variation of hydrogen ion exponent pH_{ic}^o and metal electrode potential ϕ_{ic}^o .

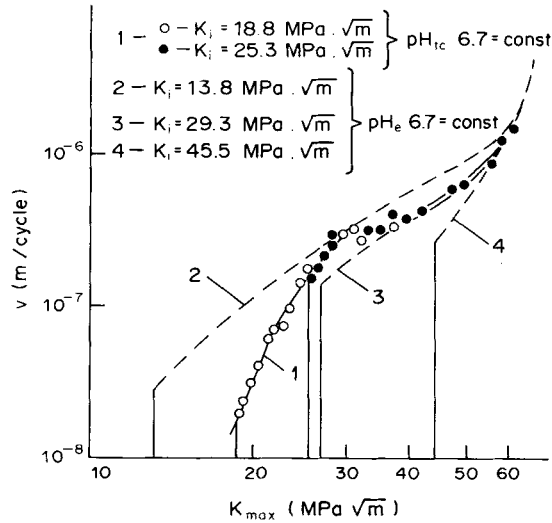


Fig. 8. Invariant ($pH_{ic} = 6.7 = \text{const}$) and noninvariant ($pH_e = 6.7 = \text{const}$) diagrams of cyclic crack growth resistance of a 20SF steel exposed to 3% NaCl solution at various initial levels of stress intensity factor (loading frequency 0.33 Hz, stress ratio $R = 0$, environmental temperature 25°C).

to be very useful when evaluating the service life of structural members exposed to a corrosive environment.

CONCLUSIONS

A procedure is proposed to define crack resistance of a material exposed to a corrosive environment. Studies performed using this procedure show that the environment hydrogen ion exponent pH_i and the metal electrode potential ϕ_i , characterizing electrochemical conditions at the tip of a crack, together with a stress intensity factor K_i allow the fatigue crack growth rate to be determined in a deformed solid exposed to a corrosive environment. Keeping pH_i and ϕ_i constant is considered to be a primary requirement for invariant diagrams of cyclic corrosion crack growth resistance of materials to be obtained.

REFERENCES

1. James L. A. (1976) Fatigue-crack propagation in austenitic stainless steels. *Atom. Energy Rev.* **14**, 37-86.
2. Lindley T. C., Richards C. F. and Ritchie R. O. (1976) Mechanics and mechanisms of fatigue crack growth in metals: a review. *Metall. Met. Form.* **43**, 268-274, 276, 278, 280.
3. Ritchie R. O. (1979) Near-threshold fatigue-crack propagation in steels. *Int. Met. Rev.* **24**, 205-230.
4. Romaniv O. M., Gladkij Ya. N. and Zyma Yu. V. (1978) The effect of structural factors on kinetics of fatigue cracks in structural materials. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials), **14**, No. 2, 3-15 (in Russian).
5. Romaniv O. M. (1981) Mechanics of corrosion failure: summary and future development. *Visnyk AN URSR* (Proceedings of the Ukrainian Academy of Sciences) **2**, 29-40 (in Ukrainian).
6. Yarema S. Ya., Popovitch V. V. and Zyma Yu. V. (1982) The effect of structure on the resistance

- to fatigue crack growth in 65G steel. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **18**, No. 1, 16–30 (in Russian).
7. Hudson C. M. and Seward S. K. (1976) A literary review and inventory of the effects of environment on fatigue behaviour of metals. *Engng Fract. Mech.* **8**, 315–329.
 8. Panasyuk V. V. (1982) On the up-to-date problems of fracture mechanics. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **18**, No. 2, 7–27 (in Russian).
 9. *Corrosion Fatigue: Chemistry, Mechanics and Microstructure* (1972) NACE, Houston, TX.
 10. *The Influence of Environment on Fatigue* (1977) Institution of Mechanical Engineers, London.
 11. *Advances in Research on Strength and Fracture of Materials* (1978) Pergamon Press, Oxford.
 12. *Proceedings of the 1st USSR-Great Britain Seminar on Corrosion Fatigue of Metals* (1982) Naukova Dumka, Kiev (in Russian).
 13. Romaniv O. M., Nikiforchyn G. N. and Dejev N. A. (1976) Kinetic effects in mechanics of delayed fracture of high-strength alloys. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **12**, No. 4, 9–24 (in Russian).
 14. Landes J. D. and Wei L. P. (1973) The kinetics of subcritical crack growth under sustained loading. *Int. J. Fract.* **9**, 277–293.
 15. Yarema S. Ya. (1981) Growth of fatigue cracks. Methodical aspects of investigation. In *Methods and Means to Evaluate Crack Resistance of Structural Materials*, pp. 177–207. Naukova Dumka, Kiev (in Russian).
 16. Determination of metal resistance to crack propagation (metal crack toughness) under cyclic loading (methodical instructions) (1979). *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **15**, No. 3, 83–97 (in Russian).
 17. Taunt R. J. and Charnock W. (1978) Fluid compositions within fatigue cracks. *Mater. Sci. Engng* **23**, 219–228.
 18. Doig P. and Flewitt P. E. J. (1977) The electrode potential within a growing stress corrosion crack. *Proc. R. Soc. A* **357**, 439–452.
 19. Doig P. and Flewitt P. E. J. (1978) Limitations of potentiostatic control in stress corrosion crack growth measurements. *Met. Trans.* **9A**, 357–362.
 20. Marek M. and Hochman R. F. (1970) Stress corrosion cracking of austenitic stainless steel. *Corrosion* **26**, 5–6.
 21. Brawn B. F., Fujii C. T. and Dahlberg E. P. (1969) Methods for studying the solution chemistry within stress corrosion cracks. *J. Electrochem. Soc.* **116**, 218–219.
 22. Kurov O. V. and Melekhov R. K. (1979) On the potential and pH at the tip of a propagating corrosion crack. *Protect. Met.* **15**, 314–316 (in Russian).
 23. Kurov O. V. and Isajev N. S. (1979) On the similarity between corrosion conditions within a narrow slit and those within a stressed crack. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **15**, No. 6, 100–103 (in Russian).
 24. Romaniv, O. M., Nikiforchyn, G. N., Student, A. Z. and Tsirulnik, A. T. (1982) Two specific features of corrosion crack-resistance evaluation of structural alloys. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **18**, No. 1, 35–47 (in Russian).
 25. Zehr C. W. (1972) A study of intergranular cracking of V-7.5 wt% Nb-2.5 wt% Zr (Mulberry) alloy in aqueous chloride solutions. *Corrosion* **28**, 196–205.
 26. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1981) Concerning the procedure to study cyclic crack-resistance of structural materials in liquid environments. In *Mechanical Fatigue of Metals*, pp. 50–51. Naukova Dumka, Kiev (in Russian).
 27. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1982) Some problems in studying cyclic crack resistance of materials in liquid environments. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **18**, No. 6, 42–49 (in Russian).
 28. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1983) Determination of cyclic crack resistance of structural steel in corrosion environments. *Proc. USSR Acad. Sci.* **269**, 109–112 (in Russian).
 29. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1982) Concerning determination of electrochemical conditions within a propagating crack when studying crack-resistance of materials in corrosion environment. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **18**, No. 3, 42–49 (in Russian).
 30. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1983) Dependence of fatigue crack growth

- on electrochemical conditions at the crack tip for materials exposed to aqueous corrosion environments. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **19**, No. 4, 33–37 (in Russian).
31. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1982) A specimen for fracture toughness testing of materials. Certificate 926561 (USSR). *Bull. Invent.* **17**, 212 (in Russian).
 32. Dmytrakh I. N., Ratych L. V. and Panasyuk V. V. (1982) Electrolytic capillary for electrochemical study of material crack resistance. Certificate 934345 (USSR). *Bull. Invent.* **21**, 205 (in Russian).
 33. Freyman L. I., Makarov V. A. and Bryskin I. E. (1972) *Potentiostatic Methods of Corrosion Study and Electrochemical Protection*. Khimia, Leningrad (in Russian).
 34. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1978) Pure-bend testing machine for studying kinetics of a fatigue crack. *Fiziko-Khim. Mekh. Mat.* (Physicochemical Mechanics of Materials) **14**, No. 63–67 (in Russian).
 35. Panasyuk V. V., Ratych L. V. and Dmytrakh I. N. (1982) Type of Fracture Toughness testing of specimens with cracks in a corrosion environment. Certificate 911242 (USSR). *Bull. Invent.* **9**, 186 (in Russian).