MANIFESTATIONS OF NON-UNIQUENESS OF THE CRACK GROWTH KINETICS CURVE IN ENVIRONMENTALLY ASSISTED CRACKING

V. Kharin and J. Toribio

Universidad de La Coruña (ULC)
Departamento de Ciencia de Materiales
ETSI Caminos, Campus de Elviña, 15192 La Coruña, Spain

Abstract. This paper describes some manifestations of non-uniqueness of the crack growth kinetics (CGK) curve in environmentally assisted cracking (EAC): crack growth rate (CGR) as a function of stress intensity factor (SIF). Considering the CGK curve as the basic item in the fracture mechanics approach to EAC, one would expect that this concept had an intrinsic character, dependent only on the specific material and environment, but not on other variables. However, attention should be paid to the influence of other factors of mechanical nature: fatigue pre-cracking, overloads, crack tip acuity, initial loading/straining, displacement rate, way of approaching the threshold level or test interruption. Some possible source factors of non-uniqueness are commented.

Resumen. Este artículo describe algunas manifestaciones de no unicidad en la curva de cinética de crecimiento de fisuras por corrosión bajo tensión: velocidad de crecimiento de fisuras en función del factor de intensidad de tensiones. Considerando dicha curva como el elemento básico de la mecánica de fractura en ambientes agresivos, cabría esperar que este concepto tuviese carácter intrínseco, dependiente sólo del material y ambiente específicos, y no de otras variables mecánicas. Sin embargo, debe prestarse atención a la influencia de otros factores de naturaleza mecánica: pre-fisuración por fatiga, sobrecargas, forma del extremo de la fisura, carga/deformación inicial, velocidad de deformación, modo de aproximación al umbral o interrupción del ensayo. Se comentan también algunos factores que potencialmente pueden ser causa de la no unicidad.

1. INTRODUCTION

One of the main objectives of fracture research is to develop the predictive ability regarding time evolution of damage in a component under mutual influence of loading and particular environmental conditions. As the minimal desired predictive capability, it must be ensured the *transferability* of laboratory specimen testing data for assessment of crack growths and failures that could occur in structures in service. The efforts to achieve this goal are based on the concept of *similitude* (cf. [1]). This relies on discovering some representative variables which are capable of matching a diversity of evolutions of cracking process by establishing between them some key configuration-independent inter-relations, which acquire the meaning of constitutive-type equations for material-environment system, and thus must possess uniqueness. In addition, these variables must be susceptible of being practically evaluated (effectively controlled), i.e. either directly measured or calculated in reliable manner.

Phenomenological fracture mechanics —within the framework of its grounding general idea of the autonomy of the crack tip region in loaded solid— provides a set of parameters and their functional relations which are able to characterise and quantify the behaviour of macroscopic cracks in materials, and not just represent particular manifestations of the process in single solids, e.g., laboratory test specimens or specific structural members.

Fracture mechanics approach to characterisation and implementation of environmentally assisted cracking (EAC) into structural reliability assessment codes is based in the general idea that the crack growth rate (CGR) depends solely on the stress intensity factor (SIF) level [2], and the particular idea that a SIF value does exist (threshold level) below which no propagation occurs, or at least a pseudo-threshold level below which CGR is negligible from the engineering point of view, thus permitting an estimation of the safety margin of the particular engineering structure against corrosion phenomena in general, or hydrogen embrittlement in particular.

The key element of this approach is the *crack growth kinetics* (CGK) curve: *crack growth rate* (CGR or v) versus *stress intensity factor* (SIF or K) This CGK curve is considered to be the law of crack growth reflecting the behaviour of cracks dependent *solely* on the specific couple *material -environment*. Therefore, it is not supposed to depend on other variables of mechanical nature such as pre-loading history on the sample or crack tip acuity.

Typical shape of CGK curve has three stages, on the basis of few characteristic values and three distinctive behavioural regions. The curve starts from the point of (apparently) zero crack growth rate with characteristic limit value of SIF for crack non-propagation (stress intensity factor threshold K_{th}) followed by the strongly SIF dependent stage I of CGK curve with sharply increasing CGR. Region II has a moderate variation of CGR, often with nearly SIF independent value of CGR v_{II}. The last region (III) of CGK curve is again strongly SIF dependent, and it ends when the limit value of crack growth resistance —fracture toughness— of material K_C is reached. This corresponds to the onset of postcritical (unstable) crack propagation, and it proceeds with no need of environmental assistance. Therefore, the fracture toughness value K_C is apparently a material constant unaffected by the environment. For hydrogen assisted cracking (HAC) processes this has experimental confirmation [3].

Both the threshold SIF (K_{th}) and the CGK curve* are considered to be the primary material's quantities representing the behaviour of cracks in a specific material-environment system. The former determines the limit condition (maximum SIF, i.e., maximum load for a given crack geometry) for the crack non-propagation, whereas the latter allows an evaluation of the durations of subcritical crack extension in solids, i.e., structure lives [3,4].

The afore mentioned concepts of fracture mechanics in aggressive environments are supposed to have the *intrinsic character* dependent solely on the specific material and the environment, thus having universal significance for the whole variety of solid-crack configurations and loadings modes. They are commonly adopted as the most valuable and representative characteristics for materials evaluation and for safe load and structure life assessments under certain set of environmental conditions (environmental chemistry, temperature, etc.) [2].

This approach to handle EAC is considered to be well founded and effective. The essential precaution was set up only to ensure *simultaneously* the mechanical and physico-chemical *autonomy* of the crack tip region characterisation [4], i.e., with the use of local variables being directly responsible for the situation near the crack tip. In other words, apart from taking care of the proper use of any of the fracture mechanics parameters, SIF in particular, to define the mechanical driving force for crack extension or, accordingly, the self-similar stress-strain state around physical fracture process zone (FPZ) at the crack tip, one should also use appropriate characterising parameters which in the same manner govern *environmental* action exactly in the process zone, its hydrogenation in the case of HAC [4]. Provided these two preconditions are satisfied, the CGK curve is supposed to acquire an intrinsic character: a *unique* EAC-resistance curve of a material for specified environmental conditions and, correspondingly, the threshold SIF becomes the physical constant for this material-environment system.

The uniqueness of the CGK curve grants the similitude of the crack tip events and, consequently, of crack behaviours in both test specimens and real structures in service, and thus provides transferability of laboratory testing data and opens the way for reasonable predictions of crack extension under different circumstances. This is very important matter as far as the extent that CGK curve is indeed unique, the fracture mechanics approach to EAC analysis is valid. When uniqueness exists, i.e., crack growth is totally controlled solely by SIF and local environmental variables, then any discrepancy between predicted and observed behaviour should be related to roughness in analysis or experimental scatter, but not due to the concept. Otherwise essential weakness of the concept itself makes the predictions less reliable and calls for more constraints to be imposed on the testing to obtain characteristic values of the crack growth parameters under aggressive environment (cf. [1]).

The vast body of experimental data supports the concept of uniqueness of the CGK curve (see, e.g., comprehensive reviews in [5] for HAC). However, this clear and rather widely used approach have been shown to be not generally valid. Several experimental findings (explained in next sections of this paper) brought doubts concerning the intrinsic character of the mentioned basic quantities, thus showing a limitation of current fracture mechanics treatment of EAC.

Although for the moment the common approach to EAC (and HAC in particular) within the ordinary framework of standard linear elastic fracture mechanics (LEFM) seems to be the best solution of the problem of quantification of this phenomenon, in a lot of observations the non-uniqueness of the CGK curves have been well documented *for situations where SIF-controlled small-scale-yielding (SSY) conditions at the crack tip were maintained.* Hereafter the summary of experimental findings is presented concerning the threshold SIF value and CGK curve as a whole.

* It is clear that the idea of CGK curve embraces the notion of threshold SIF as far as the latter corresponds to zero crack growth rate. Nevertheless, this value used to be considered separately for the reasons of importance and convenience and because it has often got individual theoretical and experimental treatment.

2. NON-UNIQUENESS OF THRESHOLD SIF K_{th}

As mentioned above, the threshold SIF value (K_{th}) is usually considered as the constant of the material-environment system provided some precautions are maintained regarding procedure of creation of the initial crack during fatigue pre-cracking procedure. Here is followed obviously the analogy with evaluation of standard fracture toughness characteristic of materials K_c, according to which precracking should be accomplished with maximum SIF value in fatigue cycles (K_{max}) not exceeding the magnitude of $0.6K_c$. Correspondingly, to obtain valid K_{th} values it was supposed to be sufficient to perform the final stage of fatigue pre-cracking with lower cyclic SIF K_{max} than expected value of K_{th}. However, in ulterior paragraphs it is shown a rather complicated dependence of experimental threshold SIF values on the fatigue pre-cracking regime. Thus, the extent to which the threshold SIF is a property of only the material and the environmental influence becomes an open issue.

The observed effects may be summarised as follows:

A1) *Fatigue precracking of specimens* requires a great deal of attention to ensure that the test results are not influenced by residual plastic regions in the vicinity of the crack tip, particularly for steels with low resistance to stress corrosion cracking [6]. Threshold values are higher when the fatigue precracking SIF (maximum value at the final stage) exceeds the initial SIF in the EAC test.

A2) There is a clear effect of the *fatigue stress intensity range ΔK* on the threshold level [7]. For the same value of K_{max}, lower values of K_{th} were found for lower magnitudes of the SIF range ΔK at the final stage of fatigue precracking. EAC tests were performed using the method of step-wise load rising and specimen holding at constant load, monitoring the maximum value of SIF when crack still remains non-propagating.

A3) The meaning and evaluation of thresholds in EAC was analyzed in previous works [8,9], dealing with the influence of the *maximum fatigue pre-cracking SIF* (K_{max}) on the threshold SIF (K_{th}). Results for hydrogen assisted cracking (HAC) demonstrated the influence of the fatigue pre-cracking procedure on the measured threshold. For $K_{max} = 0.25K_c$, the threshold stress intensity factor for HAC is $K_{IHAC} = 0.35K_c$. For $K_{max} = 0.50K_c$, the threshold is $K_{IHAC} = 0.58K_c$.

A4) The influence of the *maximum fatigue pre-cracking SIF* (K_{max}) on the threshold SIF for localized anodic dissolution (LAD) was also analyzed [8,9]. For $K_{max} = 0.25K_c$, the threshold stress intensity factor for LAD is $K_{ILAD} = 0.75K_c$. For $K_{max} = 0.50K_c$, the threshold is so high that even for $K_I = 0.95K_c$ no propagation can be detected, which means that the EAC process is negligible in this case, thus emphasizing the very important role of fatigue pre-cracking conditions ($K_{ILAD} \approx 0.96\ K_c$).

A5) The other manifestation of non-uniqueness of the K_{th} value for given environment-material system is the effect of *overloads* [10,11] happened before or during the environmentally assisted cracking test. The higher the value of SIF produced by an overload, the more increase in the subsequently determined stress intensity threshold. This is consistent with the afore mentioned K_{max}-effect.

A6) The influence of *crack tip radius* on the threshold SIF for EAC was analyzed in [12,13], where strong variations in the threshold SIF were found for different values of the crack tip radius, which denotes the role of crack tip acuity in the initiation and development of the EAC process.

A7) The influence of *initial loading or straining conditions* (initial *K/CTOD*) on K_{th} is not clear, since threshold value fit into the same scattering band for different values of initial SIF [14]. However, such a band is unacceptably wide, which seems to denote some kind of mechanical action —not purely environmental— on the threshold value. This effect could be related with the crack tip acuity, residual stresses or crack tip plasticity.

A8) It was experienced [15] the dependence of K_{th} values on *the way of its approaching in tests*. Namely, the tests performed with step-wise load rising (*crack initiation* techniques, where the EAC was approached from the lower values of sustained applied SIF) provided lower K_{th} values than experiments performed using *crack arrest* technique during which threshold is achieved in the course of EAC process in specimens with diminishing $K(l)$ values, i.e. it is approached from the greater SIF magnitudes.

A9) The effect of *crack tip opening displacement (CTOD) rate* on crack propagation in ductile alloy-aqueous environment systems was analyzed in [16]. It follows that the commonly quoted values of stress intensity threshold for the onset of environmental enhancement of cracking, apply *only* to static load conditions, and if there is a superimposed dynamic load then K_{th} will decrease, i.e., the faster the loading rate the lower the threshold value.

A10) Threshold SIF is extremely influenced by the *externally-applied displacement rate* (which can be expressed in the form of CTOD rate). As a general trend, the faster the displacement rate the higher the threshold value [14], which is consistent with an explanation based on pure kinetics of environmental attack at the crack tip and contradicts previous paragraph. A characteristic displacement rate seems to exist at which there is transition from very low to rather high threshold values.

One comment should be made regarding kinematic concepts. Externally applied displacement rate is only a control variable in any EAC test. The relevant variable is the local strain rate at the crack tip, since this is the exact location where the EAC- process happens [17].

3. NON-UNIQUENESS OF CGK CURVE $v=v(K)$

Alike regarding threshold SIF value for EAC, there are several experimental observations which demonstrate clearly the failure of the uniqueness of the CGK curve as the representative of the cracking behaviour in the given material-environment system. This absence of uniqueness of CGK curve have been demonstrated for different materials in various environments in the whole range of SIF variation, from threshold value to critical SIF (or fracture toughness). They may be summarised as follows.

B1) A discovered factor able to produce non-uniqueness of CGK curves is the *effect of pre-cracking procedure* [8,9]. Increasing of the maximum SIF K_{max} at the final stage of fatigue pre-cracking procedure causes decelerating effect on crack propagation, thus affecting the *whole* CGK curve and modifying the microscopic crack growth topographies. This conclusion is valid for both HAC and LAD.

B2) Experimental CGK curves display dependence on *preliminary loading in air* [18]. Holding of the specimen at some initial applied value of SIF K_0 without action of environment was found to cause systematical shifting of the CGK curve in the direction of diminishing of CGR with rising duration of this pre-holding under load.

B3) The effect of *initial crack tip acuity* (crack tip radius and blunting effect) on the crack growth rate under sustained load in environmentally assisted cracking is analyzed in reference [19], showing a non negligible effect on the whole CGK curve, produced by mechanical and geometrical factors.

B4) CGK curves for the same material-environment combination may display systematic variations depending on the *initial value of SIF $K_0>K_{th}$* at the onset of particular EAC test run [18,20]. In typical behaviours of this phenomenon, in contrast to the idea of uniqueness of CGK curve, the shape of the v-K curve transforms significantly. It shifts to higher crack velocities at the same SIF values if EAC tests started with greater values of initial applied SIF.

B5) Similarly to the threshold analysis, the influence of *initial loading/straining conditions* (initial K/CTOD) on the CGR (v) is not clear, since v values fit into the same scattering band for different values of initial SIF, although a slight effect can be detected, so as CGR values are a little bit higher for the lower values of initial SIF [14].

B6) With regard to the influence of *crack tip opening displacement (CTOD) rate* on the whole CGK curve, previous work in ductile alloy-aqueous environment systems [16] showed that an increase of loading rate produces an elevation of the CGK curve in general, and therefore a raise of the plateau-value the CGR, i.e., that corresponding to region II.

B7) Another related effect can also be described [14]. CGR is extremely influenced by the *externally-applied displacement rate* (which can be expressed in the form of CTOD rate). As a general trend, the faster the displacement rate the higher the plateau-value of the CGR, this conclusion being valid for both ultra-slow and fast tests, although for medium-speed tests the trend could be the opposite.

B8) Another clear manifestation of nonuniqueness of CGK curves is given by *interruption of EAC tests* with recess periods of both mechanical loading and environmental influence [18]. EAC tests started with some value of initial applied SIF K_0 were interrupted at some point S with SIF K_S, and then were renewed with the same value of initial SIF K_0. This fact produced significant diminishing of the CGR in the whole range of SIF variation, i.e. even after exceeding the value K_S of termination of preliminary cracking stage and out of the region of influence of primary plastic zone.

This appears to be even more striking if we take into account that these behaviours are not limited only to the crack propagation within specific (extraordinary) plastic zone produced by overloads or other peculiarities of the immediate pre-history of plastic zone formation during particular runs of EAC, but has a definitive influence on the *whole* subsequent crack propagation.

4. SUPPOSED SOURCE FACTORS OF CGK CURVE NON-UNIQUENESS

The previous observations may be summarised as follows. CGK curves $v=v(K)$ as a whole and threshold SIF values K_{th} in particular are able to vary significantly due to different cracking pre-histories (e.g., pre-EAC fatigue cracking regimes) and because of different paths of the proceeding of EAC itself Spectacular manifestations are several times increase of the apparent threshold SIF for HAC due to fatigue precracking with high values of the top SIF K_{max} of zero-tension cycles and overload retardation effects on HAC proceeding. Different crack growth rates may be experienced under the same K value depending on the tendency of SIF variation with crack extension, i.e., the sign of the gradient dK/dl during particular course of EAC in general (or HAC in particular). As a matter of fact, this indicates that common fracture mechanics approach is not fully capable of treating crack growth processes that can occur in service. Because of these findings the extent to which the threshold SIF and CGK curve are material properties becomes currently an open issue.which requires further research. Next paragraphs try to offer a preliminary search of supposed source factors of CGK curve non-uniqueness.

4.1. Mechanical factors

1. The basic assumption of fracture mechanics is violated for growing cracks: self-similar single-parameter controlled stress-strain fields exist only when

inelastic region is contained within an annular zone surrounding the crack tip. In fact, a growing crack leaves a wake of residual plasticity behind it, the previous condition cannot be satisfied.

2. For SSY conditions and under the same SIF, stress-strain state for stationary and growing cracks can differ from each other. For growing crack in comparison with stationary crack, stress concentration rises and strain concentration diminishes.

3. Fatigue pre-cracking conditions (previous history of loading) clearly affect the ulterior EAC behaviour, due to such a factors as plastic zone size, compressive residual stresses and crack tip acuity (initial CTOD).

4.2. Environmental factors

1. Electrochemical conditions at the crack tip are characterised with specific values of local pH and potential at the crack tip. Hydrogen assisted cracking and localized anodic dissolution can act simultaneously, which may alter crack tip bluntness and affect the stress-strain field, thus affecting the overall EAC process.

2. Some important variables of environmental nature are hydrogen-related factors, since hydrogen can be present at very different electrochemical conditions at the crack tip. Hydrogen diffusion coefficient and hydrogen solubility can change with dislocation density, and thus it is dependent on the accumulated plastic strain in the vicinity of the crack tip.

3. The effect of pre-cracking procedure (K_{max},...) may be significant on crack width (crack closure factor), and therefore on crack tip chemistry and thus on local electro-chemical conditions. Environmental conditions in the channel of the crack are described by charge-mass transport equations containing the crack width as one of the governing parameters to control local pH and potential at the crack tip.

5. CONCLUDING REMARKS

Errors can appear in determination of the basic EAC-resistance characteristics of materials, and what is worst, these errors can lead to non-conservative estimates of structural strength and life. And conversely, the possibility of slower crack growth under nominally the same intensity of stress-strain state near a crack tip indicates existence of a potential reserve of toughness that can be exploited. Thus, some benefits may be expected regarding improvement of structural performance with the use of crack-retardation phenomena.

Therefore, a need arises for re-assessment of the basic ideas of EAC quantification. This calls for more detailed analysis and modelling of the phenomenon, identifying potential origins and extents of variability of crack behaviour under nominally equivalent conditions. The contribution to a better understanding of the meaning of conventional approaches, together with the sources of their breakdown, clarifying the limits of validity and discovering the ways of improvement of testing and evaluation should be welcome, both from the scientific point of view and for practical and economical reasons.

Acknowledgements

This work was funded by the Spanish DGICYT (Grant CE94-001) and *Xunta de Galicia* (Grant XUGA 11801A93). One of the authors (V. Kharin) is also indebted to the Spanish Office of NATO Scientific Affairs Division for supporting his stay as a Visiting Professor at the University of La Coruña (Spain).

6. REFERENCES

[1] Kanninen M.F., and Popelar, C.H. Advanced Fracture Mechanics, Oxford Univ. Press, New York (1985).

[2] ASM Metals Handbook (Vol. 13: Corrosion). ASM, Metals Park, OH (1987).

[3] Panasyuk, V., Andrejkiv, A., and Kharin, V., "Theoretical analysis of crack growth in metals under hydrogen effect", Soviet Materials Science, **17** (4), pp. 61-75 (1981).

[4] Panasyuk, V., and Kharin, V., "The influence of hydrogenating environments on crack propagation in metals", in: Environment Assisted Fatigue, Mech. Eng. Publ., London, pp. 123-144 (1990).

[5] Nelson, H.G. "Hydrogen embrittlement", in Treatise on Materials Science and Technology, Vol. 25: Embrittlement of Engineering Alloys (Edited by C.L. Briant and S.K. Banerji), pp. 275-359, Academic Press, New York (1983).

[6] Judy Jr., R.W., King Jr., W.E., Hauser II, J.A. and Crooker, T.W., "Influence of experimental variables on the measurement of stress corrosion cracking properties of high-strength steels", ASTM STP 1049, 410-422 (1990).

[7] Nikiforchin, G.N., Tsyrulnik, A.T., Timifeev, B.T., Kvasnitsa, R.B. and Fedorova, V.A., "The effect of a preformed fatigue crack tip geometry on the K_{ISCC} level", Soviet Materials Sciience, **22** (6), pp. 63-68 (1986).

[8] Toribio, J., Lancha, A.M. and Elices, M., "Factors influencing stress corrosion cracking of high strength pearlitic steels", Corros. Sci., **35**, 521-530 (1993).

[9] Toribio, J., and Lancha, A.M., "Stress corrosion testing with pre-cracked specimens: influence of the pre-cracking procedure", in ECF10-Structural Integrity: Experiments-Models-Applications (Ed.

K. H Schwalbe and C. Berger), pp. 669-678 (1994).

[10] Jones, O., in: Fracture'77 (ICF4), **2**, 269, Pergamon Press, Oxford (1977).

[11] Hanisch, A.H., and Burck, L.H., Corrosion, **38**, 330 (1982).

[12] Chu, W.Y., Hsiao, C.M. and Li, S.Q., "A new engineering fracture toughness parameter K_{ISCC} (ρ)", Scripta Metall. **13**, 1057-1062 (1979).

[13] Ray, K.K. and Gao, G.R., "A new test principle for determining threshold stress intensity factor KIEAC in environmentally assisted cracking", Int. J. Fracture **61**, R69-R75 (1993).

[14] Dietzel, W. and Schwalbe, K.-H., "Aplication of the rising displacement test to SCC investigations", ASTM STP 1210, 134-148 (1993).

[15] Baus, A., Charbonnier, J.C., Lieurade, H.-P., et al, "Etude par la mecanique de la rupture de la tenacite, de la fissuration par fatigue et de la fissuration par corrosion sous contrainte d'aciers a tres haute resistance", Rev. Met., **72**, pp. 891-935 (1975).

[16] Ford, F.P., "Stress corrosion cracking of iron-base alloys in aqueous environments", in Treatise on Materials Science and Technology, Vol. 25: Embrittlement of Engineering Alloys (Edited by C.L. Briant and S.K. Banerji), pp. 235-274, Academic Press, New York (1983).

[17] Toribio, J., "The use of precracked and notched slow strain rate specimens", ASTM STP 1210, 105-122 (1993).

[18] Romaniv O., and Nikiforchin, G., Mechanics of Corrosion Fracture of Engineering Alloys, Metallurgiya, Moscow (1986); in Russian.

[19] Walter, R.J., and Chandler, W.T., "The role of crack blunting in sustained load crack growth", Scripta Met., **13**, pp. 975-976 (1979).

[20] Romaniv, O.N., Nikiforchin, G.N., and Deev N.A., "Kinetic effects in the mechanics of delayed fracture of high strength alloys", Soviet Materials Sciience, **12** (4), pp. 9-24 (1976).