ON THE INTRINSIC CHARACTER OF THE CRACK GROWTH KINETICS CURVE

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Abstract. The paper analyzes ample experimental evidence of uncertainty of the threshold stress intensity factor (SIF) and the crack growth kinetics (CGK) curve in environmentally assisted cracking (EAC). These parameters —basic items in the fracture mechanics approach to EAC— are supposed to have an intrinsic character dependent *solely* on the specific material and the environment, i.e., to posses uniqueness. However, they are notably sensitive to the influence of a wide family of test/service variables, producing loss of confidence in materials testing and structural integrity assessment.

Resumen. Este artículo analiza numerosas evidencias experimentales de incertidumbre en el factor de intensidad de tensiones umbral y en la curva de cinética de crecimiento de fisuras en ambiente agresivo. De acuerdo con el tratamiento del fenómeno de fisuración en medios agresivos según la mecánica de fractura, se supone que los parámetros antedichos poseen carácter intrínseco, dependiendo *sólo* del material y del ambiente, es decir, gozan de la propiedad de unicidad. Sin embargo, en este trabajo se muestra la influencia sobre ellos de una serie de variables de ensayo/servicio, con la consiguiente disminución de la fiabilidad en ensayos de materiales y evaluación de la integridad estructural.

1. INTRODUCTION

One of the main tasks in studies of environmentally induced degradation of materials is to provide adequate evaluation of the susceptibility of a given material to cracking caused by particular conditions of harmful surroundings (specified environment composition, temperature and pressure, etc.). This also has to render predictive ability regarding evolution of cracks in structures under the double influence of loads and aggressive environment. As the minimum desired predictive capability, the *transferability* of laboratory specimen testing data must be ensured for assessment of crack growths and failures that could occur in structures in service. The ways to achieve this goal follow after the concept of *similitude* (cf. [1]). It relies on finding representative variables and establishing between them key configuration-independent inter-relations able to match a diversity of cracking process evolutions that can occur in service in a given material-environment system. They should acquire the significance of constitutive-type equations for that system, i.e., they must have *intrinsic character*, so that their shape and characteristic quantities must depend *solely* on the material and the environment. Thus, they must possess *uniqueness* for the material-environment couple. Phenomenological fracture mechanics offers the way to solve this matter within the framework of its general grounding concept of the autonomy of the crack tip region in a loaded solid. It is believed to be able to characterise (quantify) behaviours of cracks in materials in generally applicable terms, and not just to represent particular manifestations of the process in single solids, e.g., test specimens or specific structural members.

The customary fracture mechanics approach to characterisation and implementation of environmentally assisted cracking (EAC) into material evaluation and structural reliability assessment codes is based on the general idea [2,3] that crack growth rate (CGR) v depends solely on stress intensity factor (SIF) K, and the particular concept that a special value of SIF does exist —the threshold one K_{th}— below which no propagation occurs (or it is negligible from the engineering point of view). Crack growth kinetics (CGK) curve $v=v(K)$ (Figure 1) is considered to be the law of crack growth reflecting the behaviour of cracks dependent *solely* on the specific couple *material-environment*. Commonly, the *bulk environment* is referred to as the constituent of this couple. Obviously, the CGK curve allows one to evaluate durations of crack extension in solids, i.e., structural life, whereas the threshold SIF determines the limit condition (maximum SIF, i.e., maximum load for a given crack geometry) for crack non-propagation (unlimited durability) [3]. It is clear that the idea of CGK curve embraces the notion of threshold SIF since the latter one corresponds to zero crack growth rate (cf. Figure 1). However, this value is considered separately for reasons of importance, less sophisticated applications and because it has often had individual theoretical and experimental treatment. Cracking threshold is of essential worth for both materials evaluation and structural design applications as the quantifyer of resistivity against EAC. Obtaining CGK curves and threshold SIF values with the highest possible accuracy is of great interest in engineering.

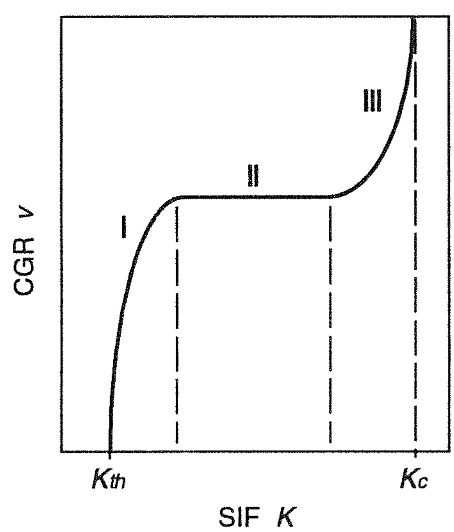

Fig. 1. Schematic CGK curve with three distinct stages of *v*-*K* dependence: strong *K*-dependence within regions I and III and plateau-like one within part II.

The *uniqueness* of crack growth resistance characteristics is a very important matter because if they are indeed unique then the fracture mechanics approach to EAC quantification is actually valid in assessment of materials degradation and structural life prediction. When uniqueness exists, then any discrepancy between predicted and observed behaviour should be attributed to roughness in analysis or experimental scatter, but not to the concept (cf. [1]). Otherwise *conceptual weakness* makes the predictions less reliable and calls for more constraints on testing to obtain reliable characteristic values of the crack growth resistance parameters under aggressive environment.

The significant body of experimental data supports the presumption of uniqueness of the fracture mechanics characteristics of EAC [4-9]. However, this customary and widely used approach is not generally valid. This comes not only from the limited efficacy of linear elastic fracture mechanics (LEFM) which fails when extended plastic zones appear near a crack. It is not restricted either to the known phenomenon of member thickness influence on crack growth resistance parameters. The latter is rationalised with the incorporation of the stress triaxiality factor representing plasticity constraint in the vicinity of the crack tip. Nevertheless, wide evidence is found of non-uniqueness of EAC characteristics in situations where SIF-controlled small-scale yielding (SSY) conditions at the crack tip were maintained, i.e., LEFM itself was applicable.

This paper gives a collection of manifestations of non-uniqueness of the CGK curve which produce uncertainty in EAC evaluation. This brings doubts concerning the intrinsic character of the basic quantities and demonstrates a shortcoming of current fracture mechanics treatment of EAC. In effect, this shows that the extent to which CGK curve and threshold SIF are the properties of *only* the material and the environment becomes an open issue and some problems on EAC evaluation using fracture mechanics still need resolution.

2. EVIDENCE OF UNCERTAINTY IN EVALUATION OF THRESHOLD SIF K_{th}

The following paragraphs discuss the influence of factors able to produce lack of uniqueness on threshold SIF results, thus causing uncertainty in its evaluation.

(Th-1) Fatigue Precracking

Fatigue precracking of specimens requires a great deal of attention to ensure that test results are not influenced by residual plastic regions in the vicinity of the crack tip, particularly for steels with low resistance to EAC [10]. Threshold values are higher when the precracking SIF exceeds the initially applied SIF in the ulterior EAC test.

The influence of fatigue precracking on threshold evaluation is detectable in very different electrochemical processes which promote cracking [11,12]. The effect of maximum cyclic SIF during the last stage of precracking (K_{max}) on measured threshold values is spectacular in both hydrogen assisted cracking (HAC) and localized anodic dissolution (LAD), as shown in Figure 2. A roughly linear increasing relationship between K_{th} and K_{max} is connoted [12].

The cyclic stress intensity range during fatigue ΔK affects very much the EAC threshold SIF K_{th} [13]. For the same K_{max} at the final stage of precracking, higher magnitudes of $\Delta K/K_{max}$ render significantly greater values of K_{th}. Furthermore, the increase of measured K_{th} is even higher if tests are performed with lower K_{max} at fixed $\Delta K/K_{max} = const$. This is sketched in Figure 3: for the precracking regimes A, B and C, the corresponding measured threshold values are ranged $K_{thA} < K_{thB} < K_{thC}$.

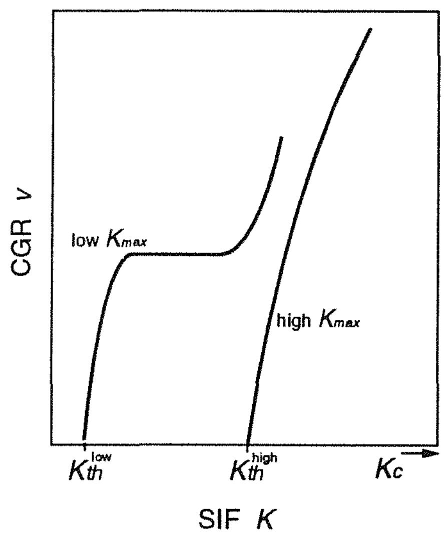

Fig. 2. Influence on threshold SIF and CGK curve of the maximum SIF during fatigue pre-cracking of specimens (K_{max})

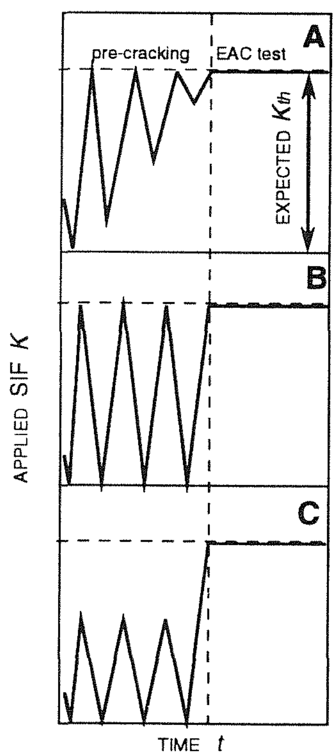

Fig. 3. Specimen loading histories affecting measured EAC thresholds.

(Th-2) Prior Overloads

Another manifestation of variability of measured K_{th} is the effect of single overloads before the EAC test. Prior overload in inert environment (e.g., argon or air) can cause an apparent increase of the threshold [14], the increase of K_{th} with overload SIF being approximately linear above a certain level of overload [15], as shown in Figure 4. This is consistent with the afore mentioned effect of maximum SIF given in Figure 2 if both are related to the maximum SIF ever attained in the pre-EAC history. Overloads and subsequent plastic zones also influence the evaluation of threshold through the effect on the incubation period for delayed cracking [16,17].

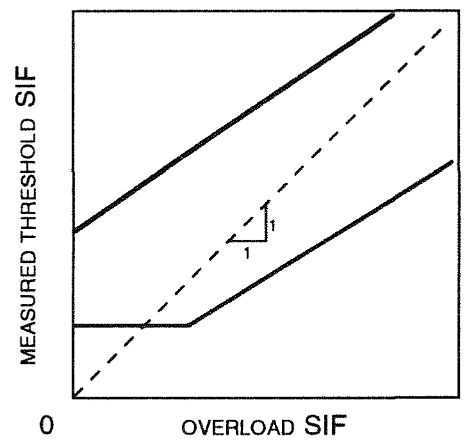

Fig. 4. Trends of measured K_{th} dependence on overload SIF value.

(Th-3) Crack Length

It has been shown in interlaboratory research programmes that the threshold SIF is clearly affected by the crack length [18], or at least the latter produces a really large scatter in K_{th}. Furthermore, it has been proved that threshold values for short cracks are lower than those for long cracks [19], as displayed in Figure 5. In these tests with edge crack lengths of several millimeters the estimated plastic zone sizes were 10-30 μm and thus the influence of specimen sides closeness on the near-tip elastoplastic field might be negligible. However, differences of crack tip electrochemistry were detected between short and long cracks.

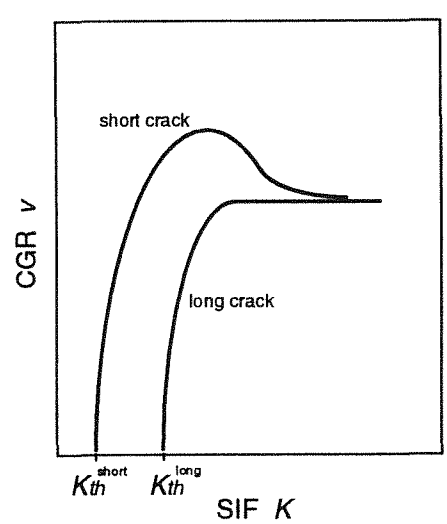

Fig. 5. Influence of crack length on threshold SIF and CGK curve.

(Th-4) Crack Bluntness

Initial crack tip radius ρ (i.e., crack bluntness) has a strong influence on the threshold SIF, as analyzed in [20,21], where strong variations of measured K_{th} with ρ were found (Figure 6). The threshold SIF increases as the crack tip radius increases, and this parameter also influences the procedure of measuring the threshold. This denotes the role of crack tip acuity in the initiation of the EAC process. A limit bluntness value ρ^* apparently exists below which such a effect disappears and the threshold value seems to be independent of the crack tip radius.

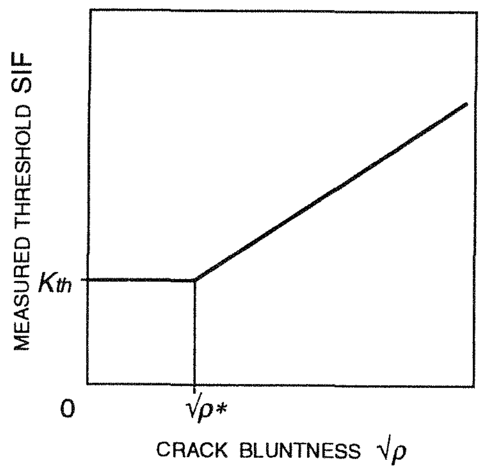

Fig. 6. Relationship between measured threshold SIF and initial crack bluntness ρ.

(Th-5) Threshold Approaching Technique

Two techniques can be used to approach the threshold [9]: *crack initiation* (from previous SIF values below the threshold) and *crack arrest* (from previous SIF values above the threshold). The measured threshold SIF associated with crack blunting is likely to be considerably higher for decreasing SIF measurements (crack arrest) than for increasing SIF measurement (crack initiation) [22]. However, other data show in some cases the opposite trend, i.e., lower threshold values are obtained when the crack arrest technique is used in testing [23].

(Th-6) Initial SIF

The influence of initial loading or straining conditions (initial SIF K_i) on K_{th} —which can be anticipated from test data when a crack self-arrest technique is used— does not seem to be clearly elucidated. CGK curves for self-retarding EAC displays deep drops of CGR with apparent threshold values fitting into some scatter band for different values of K_i [24]. This band is unacceptably wide, which seems to denote some kind of mechanical-environmental action on the threshold.

(Th-7) Displacement Rate

A key variable for EAC is the externally applied displacement rate, which can be expressed in the form of rate of loading, local strain (at the crack tip) or crack tip opening displacement (CTOD), as well as $K^{\bullet}$ under SSY. Its influence on the threshold is controversial, since papers [24,25] show that the threshold increases when the rate of elongation or loading rises, whereas [26,27] reveal the opposite trend, i.e., decreasing threshold for increasing CTOD rate.

The first of these trends of higher threshold values for faster displacement or loading rate is consistent with an explanation based on competition between physico-chemical kinetics of environmental attack at the crack tip and purely mechanical damage by rising crack tip strain. A characteristic displacement rate seems to exist at which there is a steep transition from very low to rather high apparent threshold values close to the fracture toughness of material K_C, as shown in Figure 7. The lower-shelf value corresponds to a maximum degree of environmental degradation of the material, whereas in the upper shelf there is not enough time to fully develop environmental decay, the maximum value (close to K_C) corresponding to mechanical damage with negligible participation of environmentally-assisted phenomena.

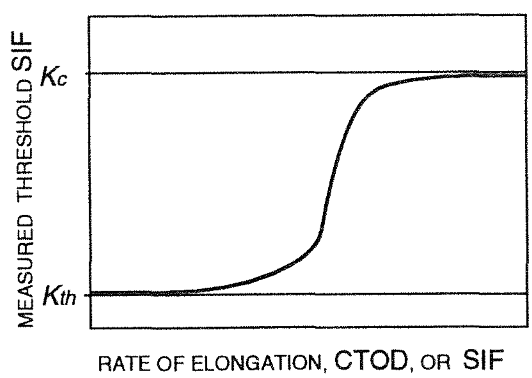

Fig. 7. Influence on the threshold K_{th} of the rate of elongation, CTOD or SIF.

According to the other tendency met in the literature, the commonly quoted values of threshold SIF for the onset of environmental enhancement of cracking apply *only* to sustained load conditions, and if there is any superimposed dynamic load then K_{th} may decrease. The threshold SIF is very sensitive to the CTOD rate — which can be related to the externally-applied displacement rate— in the form of decreasing threshold for increasing CTOD rate (Figure 8), which contradicts the previous paragraph. This kind of manifestation may result from instantaneous attainment at the crack tip of the most harmful situation during dynamical interaction of straining and environmental-related processes (creation of fresh metal surface affecting the in-crack electrochemistry, formation-rupture of brittle surface films, *etc.*).

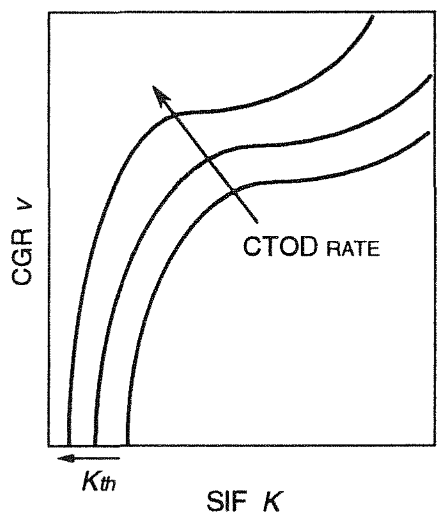

Fig. 8. Trend of variation of crack behaviour depending on CTOD rate (arrows indicate the direction of shifting of CGK curve and K_{th} with rising of CTOD rate).

3. EVIDENCE OF UNCERTAINTY IN EVALUATION OF CGK CURVE $v=v(K)$

The following paragraphs discuss the influence of factors able to produce lack of uniqueness on the CGK as a whole, thus causing uncertainty in its evaluation:

(V-1) Fatigue Precracking

Fatigue precracking can induce variability on the whole CGK curve in both HAC and LAD [11,12]. Increasing the maximum SIF K_{max} at the final stage of fatigue precracking produces a decelerating effect on crack propagation. It is not restricted to the onset of EAC (i.e., at the threshold level), but affects the entire CGK curve (Figure 2). Furthermore, this alteration of CGK is accompanied by a modification of the microscopic topographies on the fracture surface, which implies a change in the operative fracture micromechanisms.

(V-2) Prior Load Hold

Experimental CGK curves display a dependence on preliminary loading in air [28]. Holding of a specimen during time t_h at some initial applied value of SIF K_i under no environmental action was found to cause shifting of the CGK curve in the direction of diminishing CGR for rising duration of this pre-hold under load. The general trend for different hold times is given in Figure 9, showing that increasing times t_h produce decreasing CGR v.

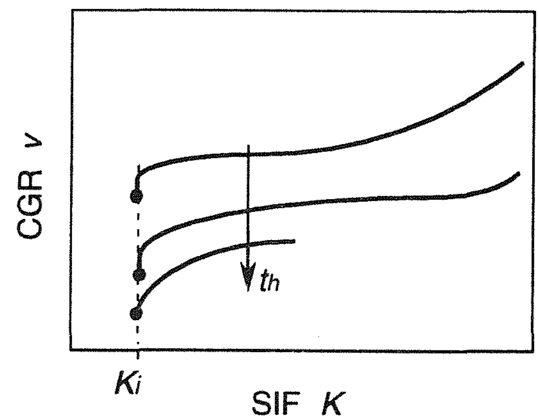

Fig.9. Schematic variation of CGK curve with duration of preliminary loading in air at about the same SIF K_i before EAC (arrow indicates the trend of variation of CGK curve with the increase of holding time t_h).

(V-3) Crack Length

Apart from the intense effect of crack length on the threshold level (higher K_{th} for longer cracks, cf. Figure 5) there is a detectable influence of crack length on the whole CGK curve, especially in the plateau region (stage II) corresponding to nearly constant velocity of crack propagation. The rates of crack growth for short cracks are higher than those for long cracks [19], as depicted in Figure 5. Moreover, in the case of short cracks there is no typical plateau with constant CGR, but a sort of pseudo-plateau in which CGR decreases as SIF increases.

(V-4) SIF Gradient

During crack growth, SIF varies with crack length a, and the gradient dK/da depends on cracked specimen geometry as well on the specific loading device (boundary conditions), e.g., gripping system used to maintain fixed load or fixed displacement.

For the same material-environment couple, significant discrepancy was found [29] between CGK curves obtained from EAC tests performed on specimens with different SIF gradient dK/da. For the lowest values of SIF (stage I of a typical CGK curve, cf. Figure 1), the results obtained under constant load (increasing SIF, $dK/da > 0$) and constant displacement (decreasing SIF, $dK/da < 0$) agree well. However, for higher values of applied SIF (within region II of the CGK curve), significantly lower crack velocities were obtained in constant displacement tests. Thus, test devices providing diminishing SIF with crack propagation ($dK/da < 0$) may lead to an underestimate of CGR in the plateau-like stage II of the CGK curve, as sketched in Figure 10. The effect is more pronounced in low strength materials.

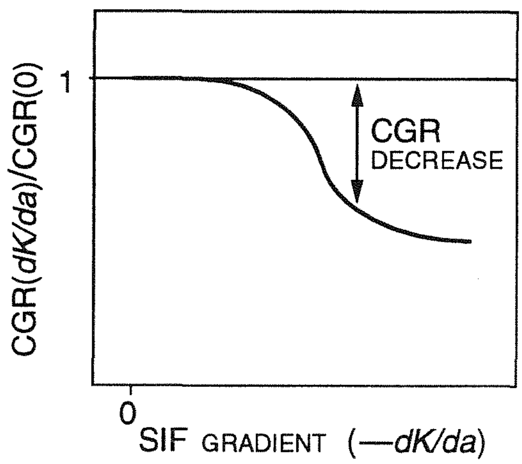

Fig. 10. Decrease in "plateau" CGR as a function of SIF gradient in terms of values related to crack velocities obtained under conditions of sustained SIF $K(a)$ = const, i.e., at $dK/da = 0$.

(V-5) Test Interruption

More evidence of the lack of CGK curve uniqueness is given by interrupted EAC tests with recess without load [28,30]. There crack growth was initiated at SIF K_i (Figure 11), run up to a certain point A of the CGK curve ($K_A > K_i$), then interrupted holding a specimen with no load, and after some period EAC was re-started at about the same initial value K_i (point A'). This produced significant decrease of CGR (cf. Figure 11) in a wide range of SIF variation, when the crack grew apparently beyond the region of influence of residual plastic zone at the test interruption point.

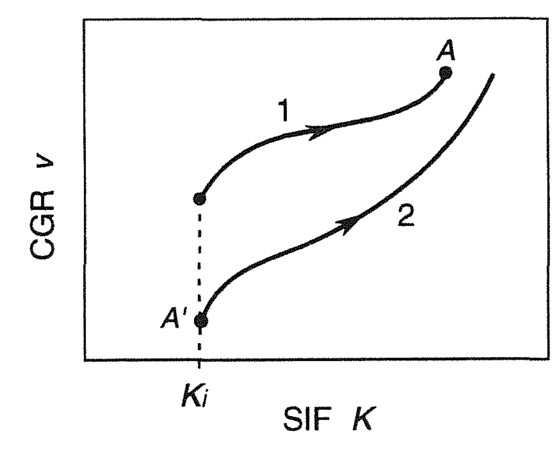

Fig. 11. The effect of test interruption and re-start on CGK curve appearance: curve 1 corresponds to initial run of EAC interrupted at point A; curve 2 relates to re-initiated cracking at A'.

(V-6) Initial SIF

CGK curves for the same material-environment system may display systematic variations depending on the initial value of applied SIF $K_i > K_{th}$ at the onset of the EAC test under rising SIF $K(a)$, i.e., when $dK/da > 0$ [23,28,30]. In contrast to the idea of uniqueness of the CGK curve, the shape of the $v(K)$-dependence transforms significantly. It often shifts to faster crack velocities at the same SIF values if EAC tests started from greater values of initially applied SIF $K_{i1} < K_{i2} < K_{i3} < K_{i4}$ (Figure 12) [28,30]. However, it is not the general trend of the effect which apparently depends on alloy microstructure and on the environment. Another kind of CGR variability was also reported [31] when $v(K)$-curves for distinct initial SIF reveal transient behaviour approaching gradually some reference CGK curve for $K > K_i$ (Figure 13).

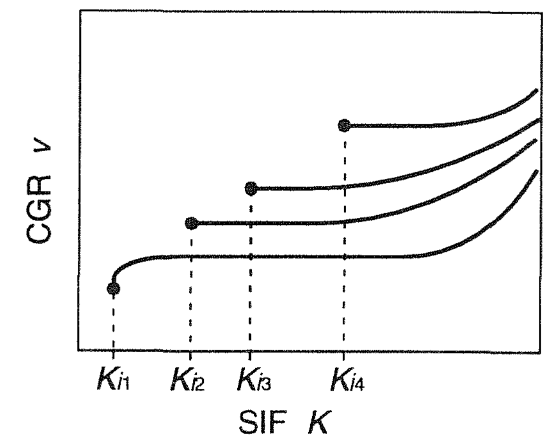

Fig. 12. The effect of initial loading condition — initial applied SIF K_i — on CGK curve.

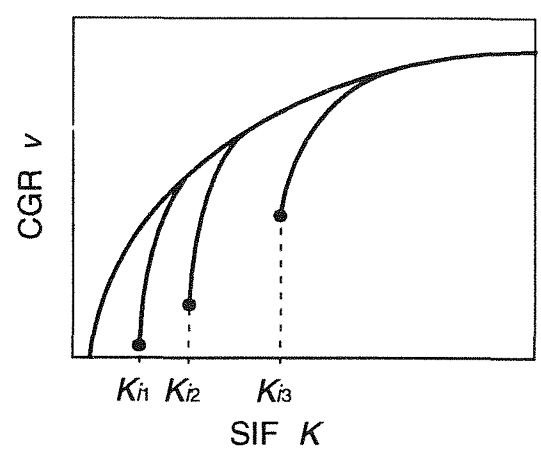

Fig. 13. Dependence of CGK curves on the initial SIF level, showing *transition periods*.

Similarly to the effect on cracking threshold (cf. item *Th-6* above), the influence of initial loading/straining conditions (initial SIF K_i) on CGK curve in tests with decreasing $K(a)$, i.e., when $dK/da < 0$, is not clear. CGR values fit into a wide scatter band for different values of initial SIF, although a slight trend can be detected, so that CGR values are a little bit higher for lower values of K_i [24].

Finally, in specimens loaded to maintain *constant* SIF $K = K_i > K_{th}$, transient periods were evidenced [31,32] of variable CGR v which gradually increased to certain steady-state value $v_{ss}(K)$ (Figure 14). Thus, in general, CGR is not a single-value function of SIF, rather for each value of K there is some definite band of crack velocities.

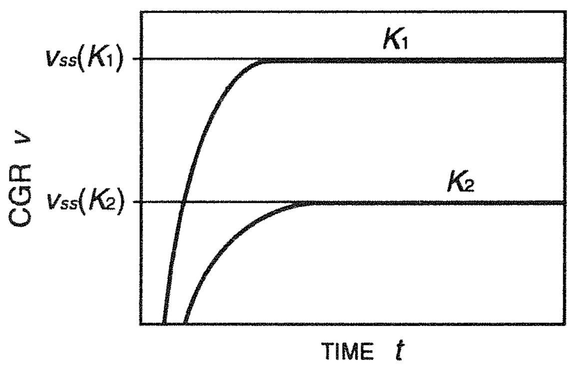

Fig. 14. Schematic variability of CGR during EAC tests under constant K conditions with different SIF values $K_1 > K_2$.

(V-7) Displacement Rate

With regard to the influence on CGR of the externally applied displacement rate or —accordingly— the rate of elongation, loading, SIF, crack tip strain or CTOD, previous work [26,27] showed that faster crack tip straining (in terms of CTOD rate) produces an elevation of the CGK curve as a whole (Figure 8). This trend is confirmed for ductile alloys with regard to stage II of CGK curve [33-36]. However, other data [24] display somewhat different CGR alteration due to increasing displacement rate: uplift of the stage II portion of the CGK curve and shifting of its near-threshold part I to higher SIF magnitudes (Figure 15).

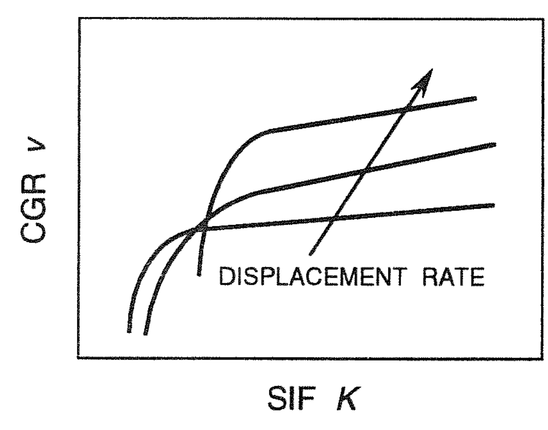

Fig. 15. Experienced trend of the influence of displacement rate on CGK curve.

As in the influence on the threshold value, this latter mode of behaviour seems to be associated with the range of rather slow strain rates whereas for faster loading the trend can change to the first one (cf. Figure 8). Nevertheless, despite the controversies with regard to the sign of the effect of straining rate on CGK curve, its quantitative significance has been well demonstrated.

Final comment

Among the reviewed effects, those associated with cracking history appear to be even more striking if we take into account that they do not seem to be limited only to the crack propagation through specific (extraordinary) plastic zone produced by overloads or other peculiarities of the immediate pre-history of plastic zone formation in particular cracking cases, but they have a definitive prolonged influence on the *whole* subsequent crack propagation beyond the area of influence of such special domains of residual plasticity.

In another paper in this volume [37], a rigorous local fracture mechanics approach to EAC —in which all influencing factors are treated autonomously, i.e., in terms of *local* values at the crack tip— is emphasised to advance towards a resolution of these problems. In addition, a *safe approach* is proposed for engineering design against EAC.

4. CONCLUSIONS

Uncertainty can appear in determination of the basic EAC-resistance characteristics of materials, and what is worse, it can invalid too optimistic material evaluation and consequently non-conservative estimation of structural strength.

In general, customary fracture mechanics approach to evaluate CGK curve and threshold SIF in EAC cannot pretend to render adequate *intrinsic* characteristics of a material-environment system (the latter considered in a global sense, i.e., as bulk environment).

The elucidated effects capable of originating a too wide diversity of cracking behaviours not covered by any single CGK curve call for additional restrictions to be imposed on testing to obtain reliable (conservative) values of crack growth resistance characteristics of materials.

Acknowledgements

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