Experimental evaluation of environmentally assisted cracking: the effect of compressive residual stresses at the crack tip

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Experimental evaluation of environmentally assisted cracking (EAC), or, in traditional form, stress corrosion cracking (SCC), is usually achieved in the framework of fracture mechanics, by means of constant load testing (CLT), constant strain testing (CST) or slow strain rate testing (SSRT). For this purpose, the only consensus standard currently fully developed has been provided by ISO, as a seven-part document entitled: "Corrosion of metals and alloys-stress corrosion testing" (ISO 7539) [1].

Although a variety of specimens (initially plain, notched and pre-cracked) can be used [2], a specific part of the standard is devoted to pre-cracked samples: ISO 7539-6: "Preparation and use of pre-cracked specimens" [3]. These specimens present clear advantages since they are quite realistic, and the effect of the environment is localized in the vicinity of the crack tip, apart from the fact that fracture mechanics techniques are applicable.

However, there is an additional variable, not sought, which produces spurious effects on results: compressive residual stresses in the vicinity of the crack tip, generated during fatigue pre-cracking of the samples. This effect was reported previously by Lancha and Elices [4] and Judy *et al.* [5]. Fatigue pre-cracking of specimens requires a great deal of care to ensure that experimental results are not influenced by compressive residual plastic regions, thereby producing a negative consequence in the form of unacceptable experimental scatter if the fatigue pre-cracking programme is not carefully controlled.

The effect of the maximum fatigue load during pre-cracking on experimental evaluation of EAC has been extensively analyzed by Toribio *et al.* [6], by means of tests (SSRT and CST) on high-strength pearlitic steel in aqueous solution after several fatigue programmes with different levels of maximum stress intensity factor (K_{max}) during the last stage of pre-cracking (the minimum stress intensity factor K_{min} was near zero in all cases). Tests were performed under different electrochemical conditions, covering a broad range from $E = -1200$ mV SCE to $E = -100$ mV SCE, so as to distinguish two different regimes of environmentally assisted cracking (EAC): a cathodic regime (below -900 mV SCE), in which the predominant mechanism is hydrogen assisted cracking (HAC), and an anodic regime (above -600 mV SCE), in which the main process is localized anodic dissolution (LAD).

The environmentally assisted cracking process (HAC or LAD) increases as the fatigue pre-cracking load decreases, i.e. the higher the maximum stress intensity factor (SIF) during fatigue pre-cracking (K_{max}), the higher the fracture load under aggressive environment. This fact demonstrates the very important role of residual stresses in EAC processes; those residual stresses, compressive type, are generated in the vicinity of the crack tip during fatigue pre- cracking of the samples. In the case of localized anodic dissolution, residual stresses modify the local strain at the crack tip, thus changing the balance between the creation and rupture of oxide film. For hydrogen embrittlement processes, compressive residual stresses delay the hydrogen ingress.

These K_{max}-effects, due to the compressive residual stresses in the vicinity of the crack tip generated during pre-cracking, were considered in the ISO 7539-6 Standard [3], which recommends that pre-cracking should be completed below the expected SCC threshold K_{ISCC}, if possible. However, this requirement is not clearly objective, since the threshold does not have an intrinsic character, but is affected by the pre-cracking procedure itself, as is demonstrated in the following paragraphs. The consequence from the experimental viewpoint is an undesirable increase in the scatter of results when the maximum fatigue pre-cracking load (K_{max}) is not properly controlled.

The meaning of thresholds in EAC was analysed in a previous work [7], dealing with the influence of the fatigue pre-cracking SIF (K_{max}) on the threshold SIF for environmentally assisted cracking (K_{IEAC}, or in traditional form K_{ISCC} or K_{th}), distinguishing between the anodic and cathodic regimes. Under cathodic regime (hydrogen assisted cracking: HAC) results are clearly dependent on maximum fatigue pre-cracking level (K_{max}). For $K_{max} = 0.25\, K_{IC}$, the threshold SIF for HAC is $K_{IHAC} = 0.35\, K_{IC}$. For $K_{max} = 0.50\, K_{IC}$ the threshold SIF for HAC is $K_{IHAC} = 0.58\, K_{IC}$ [7], where K_{IC} is the critical stress intensity factor of the material for the specific geometry used in the tests (prismatic three point bend specimens).

Under anodic regime (localized anodic dissolution: LAD) results also depend on K_{max}. For

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$K_{max} = 0.25\ K_{1C}$ the threshold SIF for LAD is $K_{ILAD} = 0.75\ K_{1C}$. For $K_{max} = 0.50\ K_{1C}$ the threshold for LAD is so high that even for $K_I = 0.95\ K_{1C}$ no propagation can be detected, which means that the environmental process is negligible in this case ($K_{ILAD} \simeq 0.96\ K_{1C}$). Pre-cracking conditions are so relevant under anodic regime (LAD), that they even impede the environmentally assisted cracking when K_{max} is high enough, and thus no actual threshold can be detected [7].

The analysis of both HAC and LAD phenomena demonstrates the very important role of residual stresses in the vicinity of the crack tip. These residual stresses, compressive type, are generated near the crack tip during the fatigue pre-cracking procedure, and produce an extremely high scatter in experimental results if they are not carefully controlled during the test. As a consequence, the important variable K_{max} should be included in the display of the EAC results, since it has been shown to be determinant in explaining the behaviour of the material under aggressive environment.

With regard to the concept of stress intensity threshold in environmentally assisted cracking (K_{IEAC}, K_{ISCC} or K_{th}) it does not seem to have an intrinsic character, but depends on certain variables such as the maximum stress intensity level during the last step of fatigue pre-cracking, which strongly influences the threshold itself, as shown in Fig. 1, where the threshold values for HAC (cathodic) and LAD (anodic) are plotted against the maximum stress intensity factor during fatigue pre-cracking (K_{max}). Values are divided by the critical stress intensity factor K_{1C}, and the rough tendencies are the following:

$$(K_{IHAC}/K_{1C}) = 0.12 + 0.92\ (K_{max}/K_{1C}) \quad (1)$$

$$(K_{ILAD}/K_{1C}) = 0.54 + 0.84\ (K_{max}/K_{1C}) \quad (2)$$

What is clear from Fig. 1 and Equations 1 and 2 is not only that the threshold value depends strongly on the maximum pre-cracking load, but also that the requirement of the ISO 7539-6 Standard is automatically reached, since the maximum stress intensity factor during the final stage of fatigue pre-cracking (K_{max}) is always below the actual stress corrosion cracking threshold (K_{IEAC}). So the problem is precisely an experimental fact: K_{max} is automatically below K_{IEAC} because this threshold value is too high due to the presence of compressive residual stresses in the vicinity of the crack tip. The original idea of ISO 7539-6 is to reach a tensile stress level well above that of the final stage of pre-cracking when crack growth starts because the threshold is exceeded. However, this situation is not possible in general because K_{max} and K_{IEAC} are really close in many cases (e.g. for HAC). Such a coupling between material strength and threshold stress intensity factor has also been detected by Astafjev and Kasatkin [8].

A simple model to explain these effects due to compressive residual stresses in the vicinity of the crack tip is that of Rice [9], summarized in Fig. 2. It is applicable to an elastic ideally plastic material, and gives the tress distributions in front of the crack tip for $K = K_{max}$ and $K = K_{min}$, the latter representing the residual stress distribution in the vicinity of the crack tip after fatigue pre-cracking of the samples. Following this model, the size of the plastic zone at the beginning of the EAC test (end of fatigue pre-cracking programme) is:

$$\Delta\omega = (\pi/32)\ (K_{max}/\sigma_Y)^2 \quad (3)$$

where σ_Y is the yield strength of the material, and pre-cracking stress distribution (that of the last peak of tensile load in fatigue) is recovered when the tensile load is applied in the fracture test, i.e. compressive residual stresses are deleted when the specimen is re-loaded up to the same tensile stress level as during fatigue.

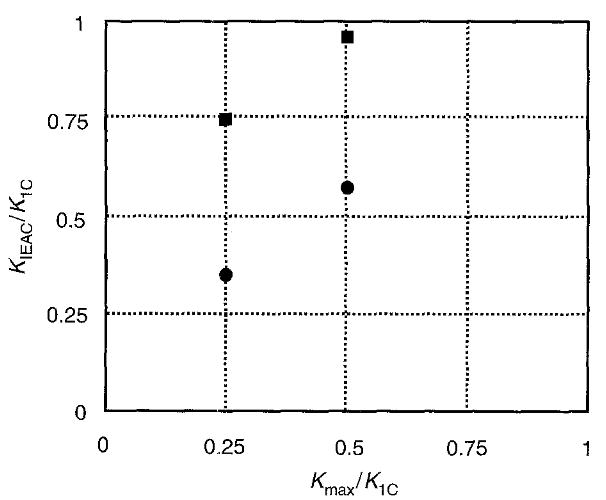

Figure 1 Threshold values (K_{IEAC}) versus maximum stress intensity factor during fatigue pre-cracking (K_{max}). Thresholds for hydrogen assisted cracking (K_{IHAC}) (●) and localized anodic dissolution (K_{ILAD}) (■) are distinguished.

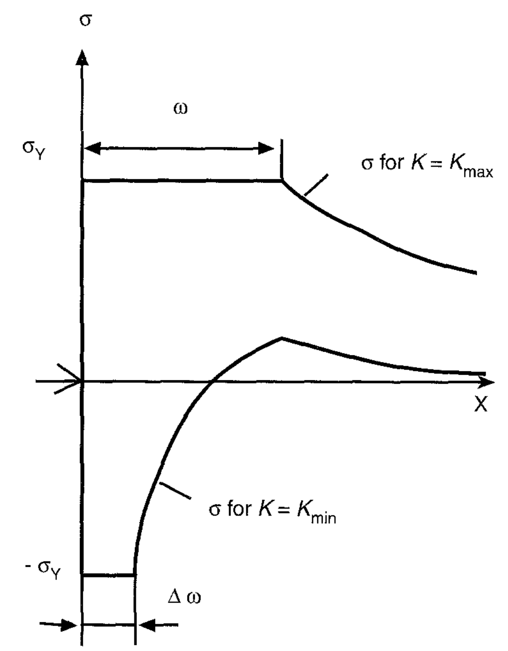

Figure 2 Stress distributions in front of the crack tip for $K = K_{max}$ and $K = K_{min}$, according to Rice's model [9] (elastic ideally plastic material). The latter represents the residual stress distribution after fatigue pre-cracking of the samples.

Consequently for EAC testing with pre-cracked specimens, SSRT in a cathodic regime (HAC) should be performed at the minimum possible strain rate, to allow enough time for hydrogen to diffuse after recovering the initial tensile stress distribution. CST and threshold measurement are particularly difficult because the initiation of cracking is strongly dependent on the plastic zone and the compressive residual stresses at the crack tip. The maximum stress intensity factor during the last stage of fatigue pre-cracking must be specified by the Standards as precisely as possible, since it dramatically affects the experimental results. The present requirement ($K_{max} < K_{IEAC}$) is automatically achieved, but it is not enough to guarantee experimental results independent of the fatigue pre-cracking load, as is demonstrated throughout this letter.

With regard to the difference between the two main mechanisms of EAC in aqueous environments (HAC and LAD), Fig. 3 shows a schematic drawing of the compressive residual stresses in the vicinity of the crack tip, to explain HAC and LAD behaviour, as well as the threshold levels. LAD is more susceptible than HAC to the effect of compressive prestressing of the crack tip by residual stresses generated during pre-cracking. The explanation lies in the specific localized character of LAD, which makes this phenomenon strongly dependent on compressive residual stress level precisely at the crack tip (single point). Conversely, HAC does not have so local a nature, since hydrogen diffuses towards the inner points, and the fracture phenomenon is extended over a process zone or fracture region (small, but not null) in the vicinity of the crack tip.

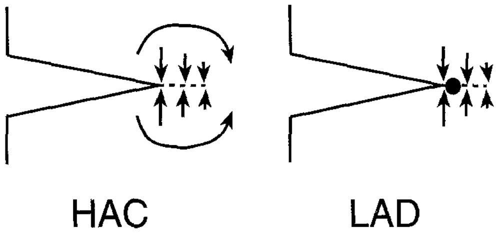

Figure 3 Schematic drawing showing compressive residual stresses in the vicinity of the crack tip, to explain HAC and LAD behaviour, as well as threshold levels.

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