HYDROGEN–ASSISTED MICRO–DAMAGE IN PEARLITIC STEEL: EXPERIMENTAL EVALUATION AND MECHANICAL MODELLING

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Hydrogen-assisted micro-damage in pearlitic steel in the form of *tearing topography surface* (TTS) is modelled as a macroscopic crack that extends the original fatigue pre-crack and involves linear elastic fracture mechanics principles. In this case, the change from hydrogen-assisted micro-damage (TTS region) to cleavage-like topography takes place when a critical stress intensity factor (K_H) is reached, and this value depends on the amount of hydrogen which penetrated the vicinity of the actual crack tip (the fatigue pre-crack plus the TTS area). The value K_H is associated with a characteristic level of stress intensity factor in the crack growth kinetics curve.

INTRODUCTION

Analysis of hydrogen induced fracture of high-strength pearlitic steel (Toribio et al (1)) revealed the presence in the process zone of a non conventional microscopic fracture mode associated with hydrogen-assisted micro-damage. This particular micromechanical mode was identified by Thompson and Chesnutt (2) and Costa and Thompson (3) as tearing topography surface (TTS).

This papers offers a mechanical modelling of the TTS micro-fracture mode in pre-cracked specimens, by considering the progressive extension of the TTS zone as a macroscopic crack that extends the original fatigue pre-crack involving fracture mechanics principles. In this case, the change from TTS to cleavage-like topography takes place when a critical stress intensity factor (SIF) is reached.

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PHENOMENOLOGICAL ASPECTS

The analysis is based on experimental results (Toribio et al (4)) of hydrogen embrittlement of pre-cracked cylindrical samples of eutectoid pearlitic steel tested under simultaneous hydrogen charging. The main results showed phenomenological relations between the fracture load in hydrogen F_H (divided by its reference value in air F_O) and testing variables of an electro-chemical nature (pH and potential E) and mechanical character (K_{max}/K_O):

$$F_H/F_O = f\,(pH, E, K_{max}/K_O) \qquad (1)$$

where K_{max} is the maximum stress intensity factor (SIF) at the end of the last stage of fatigue pre-cracking and K_O the fracture toughness.

Fig. 1 shows the appearance of the fracture surface of the samples (4). Three regions are detected: the fatigue pre-crack, a transition topography consisting of hydrogen-assisted micro-damage (TTS) and finally the cleavage-like surface. Considering the TTS region as the area damaged by hydrogen, a damage depth a_H may be defined:

$$a_H = a_O + x_{TTS} \qquad (2)$$

where a_O represents the depth of the pre-crack (end of fatigue pre-cracking and beginning of the hydrogen embrittlement test), while x_{TTS} is the depth of the TTS zone, measured from the pre-crack border in direction perpendicular to the crack line (cf. Fig. 1).

Experimental evidence of the association between the TTS zone and the presence of hydrogen has been widely reported by Toribio et al (1,4,5) with regard to the specific features of the TTS region and their relationship with testing variables.

MACROSCOPIC CRACK MODEL

The macroscopic crack model is based on considering the characteristic TTS area as a macroscopic crack that extends the original fatigue pre-crack. The SIF for the total crack (fatigue pre-crack plus TTS) is:

$$K_H = M(a_H)\,\sigma_H\sqrt{\pi a_H} \qquad (3)$$

where $M(a_H)$ is the dimensionless SIF for the specific geometry, a_H is defined in (2) and σ_H is the remote stress. Considering the critical situation, i.e., the fracture instant in hydrogen environment, K_H

represents the *critical SIF in hydrogen environment*. For the case of fracture in air environment, the critical SIF is K_O, which represents the *fracture toughness of the material in air* (if it is assumed that the specimen constraint is high enough), and the ratio of K_H to K_O is:

$$\frac{K_H}{K_O} = \frac{M(a_O+x_{TTS})}{M(a_O)} \frac{\sigma_H}{\sigma_O} \sqrt{1+\frac{x_{TTS}}{a_O}} \tag{4}$$

To calculate the relationship (4) it is necessary to know the dimensionless SIF M for the geometry and loading mode under consideration: a cylinder subjected to tension with a part-through crack perpendicular to the tensile loading direction. The simplest expressions for the dimensionless SIF in this case were provided by Valiente (6) as a function of only one dimensionless parameter ξ:

$$M_1(\xi) = (0.473 - 3.286\,\xi + 14.797\,\xi^2)^{1/2}\,(\xi - \xi^2)^{-1/4} \tag{5}$$

$$M_2(\xi) = 1.4408 - 3.6364\,\xi + 19.3500\,\xi^2 - 34.7849\,\xi^3 + 36.8446\,\xi^4 \tag{6}$$

where ξ is the ratio a/D of the crack depth to the sample diameter. The two relations are obtained by a 3D finite element analysis. The function (5) for M_1 comes from the computation of the *global* energy release rate, whereas the function (6) for M_2 may be obtained computing the *local* SIF at the crack centre by using the stiffness derivative technique.

MODEL RESULTS

Table 1 shows the experimental results and the computations of the critical SIF in hydrogen (related to its value in air or fracture toughness). The results using the two dimensionless SIF values M_1 y M_2 are quite similar. The ratio K_H/K_O is always clearly below unity, demonstrating that the critical SIF in hydrogen depends on the amount of this element that penetrated the vicinity of the actual crack tip (including the fatigue pre-crack and the TTS area).

The influence of the fatigue pre-cracking load —with the subsequent distribution of compressive residual stresses in the vicinity of the crack tip— is reflected in Fig. 2, where a clear increase of the critical SIF in hydrogen (K_H) with the maximum SIF during the last stage of fatigue pre-cracking (K_{max}) is observed. This demonstrates clearly that the value K_H is *not* an intrinsic parameter of the material, but depends on the testing variables controlling the amount of hydrogen which penetrates the sample.

TABLE 1– Calculation of the critical SIF in hydrogen

pH	$\frac{K_{max}}{K_O}$	E (mV SCE)	$\frac{F_H}{F_O}$	x_{TTS} (μm)	$\frac{K_H}{K_O}$ (M_1)	$\frac{K_H}{K_O}$ (M_2)
4	0.28	−1400	0.50	320	0.56	0.55
		−1200	0.58	250	0.63	0.62
		−1000	0.64	70	0.65	0.65
	0.45	−1200	0.61	190	0.65	0.65
		−1050	0.67	10	0.67	0.67
	0.60	−1200	0.72	60	0.74	0.73
	0.80	−1200	0.80	12	0.80	0.80
8	0.28	−1200	0.53	180	0.56	0.56
		−1000	0.65	30	0.66	0.66
	0.45	−1200	0.60	150	0.63	0.63
		−1000	0.75	15	0.75	0.75
	0.60	−1200	0.67	90	0.68	0.68
	0.80	−1200	0.78	10	0.78	0.78
		−1000	0.88	10	0.88	0.88
12.5	0.28	−1200	0.55	170	0.59	0.58
	0.45	−1200	0.62	110	0.64	0.64
		−1100	0.75	70	0.77	0.76
		−1000	0.83	15	0.83	0.83
	0.60	−1200	0.70	80	0.72	0.72
	0.80	−1200	0.81	8	0.81	0.81

DISCUSSION

An important question is to elucidate the meaning of the parameter K_H, which can be done through the crack growth kinetics curve (da/dt-K) of the analyzed steel. This curve is represented in Fig. 3, taken from Ref. (1). Comparison of Figs. 2 and 3 provides insight into the significance of K_H. For $K_{max}/K_O = 0.25$ (Fig. 2) it is $K_H/K_O \cong 0.55$, while for the same fatigue pre-cracking load $K_{max}/K_{IC} = 0.25$ (Fig. 3) at $K/K_{IC} \cong 0.55$ there is a sudden increase of the crack growth rate accompanied by a change of the microscopic mode of fracture from TTS to cleavage (1). In analogous manner, for $K_{max}/K_O = 0.50$ (Fig. 2) it is $K_H/K_O \cong 0.65$, while for the same fatigue pre-cracking load $K_{max}/K_{IC} = 0.50$ (Fig. 3) at $K/K_{IC} \cong 0.65$ there is also a sudden increase of the crack growth rate accompanied by a change of the microscopic mode of fracture from TTS to cleavage (1).

CONCLUSIONS

This paper describes a simple mechanical model of the TTS micro-fractured zone in pre-cracked samples, considering the progressive spreading of the TTS zone as a macroscopic crack extending the original fatigue pre-crack in the framework of linear elastic fracture mechanics.

The critical SIF in hydrogen environment K_H depends on the amount of this element which penetrated the vicinity of the actual crack tip, shown to be clearly lower that the corresponding value in air (fracture toughness K_O).

The fracture parameter K_H is seen to be the *transition SIF* in the crack growth kinetics curve (da/dt-K) at which the crack growth rate progresses from the subcritical to the critical regime and the microscopic mode of fracture changes from the TTS mode to cleavage-like propagation.

ACKNOWLEDGEMENTS

This work was funded by the Spanish DGICYT (Grant UE94-001) and Xunta de Galicia (Grants XUGA 11801A93 and XUGA 11801B95). The author gratefully acknowledges this support, as well as the data provided by Dr. A.M. Lancha (CIEMAT, Spain).

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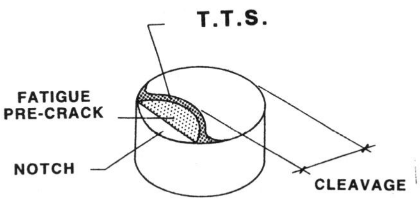

Figure 1 Fracture surface

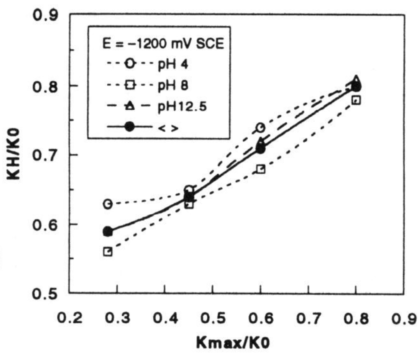

Figure 2 Influence of the fatigue pre-cracking load (K_{max}/K_o)

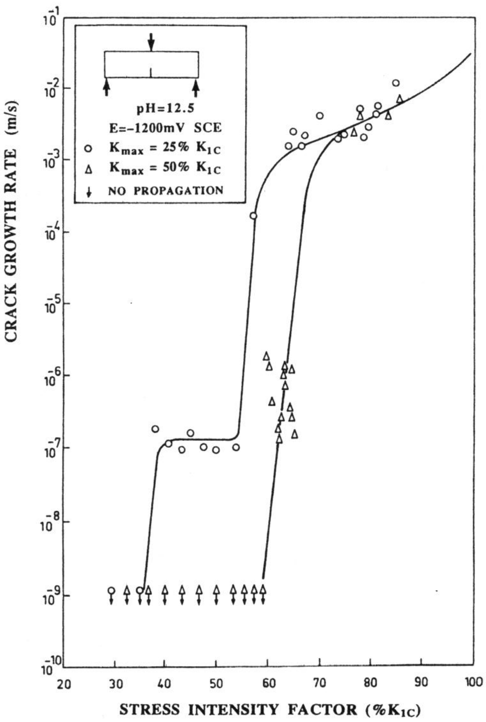

Figure 3 Crack growth kinetics curve (da/dt-K) for the same steel and environment (1).