STRESS CORROSION TESTING WITH NOTCHED SPECIMENS: CHOICE OF THE ADEQUATE KINEMATIC VARIABLE

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This paper focusses on the role of kinematic variables in slow strain rate testing with notched specimens. *Local or effective strain rate*, defined at the notch tip, is the relevant *damage variable* in environmentally assisted fracture processes, thus making the experimental results objective. *Global, nominal or applied strain rate*, defined over the whole sample, represents a *control variable* applied by the testing machine under displacement control. *Remote or external strain rate*, that applied far from the notch, is another *control variable* which can be applied by an extensometer placed outside the environmental cell. The convenience is shown of expressing the experimental results as a function of the local strain rate (damage variable) instead of any of the control variables, e.g. the global strain rate.

INTRODUCTION

Slow Strain Rate (SSR) testing is now a well recognized technique for measuring the susceptibility of metals to environmenttally induced fracture ((Parkins (1)), in spite of its inherent limitations regarding strain rate and potential dependence, as discussed by Beavers and Koch (2). Development of this method has lead to the International Standard *ISO 7539-7*: "Slow Strain Rate Testing" (3), which provides guidelines for this kind of SCC testing.

A variety of specimens (initially plain, notched and pre-cracked) can be used (cf. *ISO 7539-7*), but the advantages of notched samples in stress corrosion testing have been indicated by Caballero *et al.* (4). In the matter of hydrogen assisted fracture, notched specimens have been recommended by Thompson (5), and successfully used by Toribio and Elices (6) to elucidate the hydrogen transport mechanism in pearlitic steels.

This paper focusses on the role of kinematic variables, fundamental in SSR testing. The aim is to find the most adequate strain rate (local/global/remote) to make the experimental results objective, i.e., geometry-independent.

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EXPERIMENTAL

The material was a commercial pearlitic steel, whose chemical composition and mechanical properties appear in Table 1. The specimens were round notched samples of the four geometries shown in Figure 1.

TABLE 1 – Chemical composition (wt %) and mechanical properties of the steel

C	Mn	Si	P	S	E (GPa)	σ_Y (MPa)	UTS (MPa)	Ramberg-Osgood $\varepsilon = \sigma/E + (\sigma/P)^n$ P (MPa)	n
0.85	0.60	0.26	0.010	0.030	199	600	1151	2100	4.9

The SSR technique (1,2) was used, with crosshead speeds from 10^{-9} to 10^{-5} m/s. The environment was an aqueous solution of 1g/l $Ca(OH)_2$ + 0.1 g/l NaCl (pH=12.5). A potential of −1200 mV SCE (cathodic) was applied under potentiostatic control. Susceptibility to hydrogen was measured through the ratio of the failure load in hydrogen to that in air, as recommended by ISO Standard (3).

Figure 2 shows the SSR results, expressed as a function of crosshead speed or testing displacement rate. Results of quasi-static tests —independent of the strain rate— are omitted, to show the kinematic dependence: hydrogen embrittlement decreases as the displacement rate rises. The experimental scatter is too high, and results depend strongly on notch geometry, losing objective significance.

The next sections are devoted to a discussion of the relevant variables governing the process, to find those which reduce the experimental scatter and make the experimental results objective (geometry-independent). Emphasis is placed on the role of local strain rate, a topic previously addressed by Lidbury (7) and Garud (8) for cracked specimens.

KINEMATIC VARIABLES

Local strain is associated with a local reference length B, small enough to guarantee the convergence, parallel to the bar axis and placed next to the notch tip:

$$\varepsilon_L = \Delta B/B = u_L/B \tag{1}$$

where the enlargement ΔB of the local reference length B is the relative displacement between its ends (local displacement u_L).

Global, nominal or applied strain is the relative displacement between the ends of a length L (global displacement u_G), divided by the sample diameter :

$$\varepsilon_G = u_G/D \tag{2}$$

Remote or external strain is that corresponding to a remote reference length B', small enough to guarantee the convergence, placed far from the notch:

$$\varepsilon_R = \Delta B'/B' = u_R/B' \tag{3}$$

Local or effective strain rate is the damage variable governing the environment-sensitive fracture. It can be computed by derivation of (1):

$$\dot{\varepsilon}_L = \frac{u_L{}^{i+1} - u_L{}^{i}}{B\ \Delta t} \tag{4}$$

where i and i+1 represent consecutive load steps and Δt the time interval.

Global, nominal or applied strain rate is derived from (2), and is the control variable in a tests under displacement control:

$$\dot{\varepsilon}_G = \frac{u_G{}^{i+1} - u_G{}^{i}}{D\ \Delta t} \tag{5}$$

Remote or external strain rate is that applied far from the notch, and can also be the control variable in a test under strain control by means of an extensometer placed outside the environmental cell. Its expression is given by derivation of (3):

$$\dot{\varepsilon}_R = \frac{u_R{}^{i+1} - u_R{}^{i}}{B'\ \Delta t} \tag{6}$$

ANALYSIS OF RESULTS

In Figure 3, the dimensionless failure load in solution is represented as a function of global strain rate, defined over a distance L=4D. This variable is calculated over the whole sample, whereas crosshead speed is measured at the testing grips, thereby including the compliance of the testing machine. The scatter in Figure 3 still remains unacceptable. A similar conclusion would be drawn if results were expressed as a function of remote strain rate, since both are only experimental *control variables*, but not actual damage variables.

Figure 4 offers the failure load in solution as a function of the average value of the local strain rate in the vicinity of the notch tip, calculated as described by Toribio and Elices (9) with the depth of the maximum hydrostatic stress point x_S. The scatter is acceptable, and results for all geometries fit into the same band, which emphasizes the relevant role of local strain rate, making the experimental results objective. This band represents the kinematic relationship —independent of geometry— between the failure load in hydrogen and the local strain rate, which thus represents the actual *damage variable*.

Figure 4 also demonstrates that susceptibility to stress corrosion cracking can be measured through the ratio of the failure load in aggressive environment to the same variable in air (easy to measure), as recommended by the *ISO 7539-7* standard. However, when higher accuracy is needed, the computation of stress levels in the vicinity of the notch tip is unavoidable (cf. Ref. 9).

The most adequate notched geometries for testing the hydrogen embrittlement susceptibility of high strength pearlitic steels seem to be those in which the maximum hydrostatic stress point is near the notch tip (geometries A and C: Shallow notches with blunt or sharp radius), since in those cases the point towards which hydrogen diffuses is near the notch tip (x_S is small) and the hydrogen embrittlement effect is clearly detectable, even at not too low strain rates.

CONCLUSIONS

1. Results of SSR tests on notched samples of high strength pearlitic steel under hydrogen embrittlement conditions were analyzed to elucidate the most relevant kinematic variable.

2. Local, global and remote strain rates were considered. The first is the damage variable in environmentally assisted fracture, whereas the other two can be *control variables* in the experiments.

3. Scatter is too high when the results are expressed as a function of crosshead speed or testing displacement rate. The scatter remains unacceptable when results are plotted against global strain rate.

4. Experimental results fit into the same band when expressed as a function of the local strain rate in the vicinity of the notch tip, which is the relevant kinematic variable (*damage variable*)

5. Susceptibility to stress corrosion cracking can be measured through the ratio of the failure load in aggressive environment to the same variable in air, as recommended by the ISO 7539-7 standard.

6. The most adequate notched geometries for hydrogen embrittlement testing are those in which the maximum hydrostatic stress point is near the notch tip: shallow notches with blunt or sharp radius.

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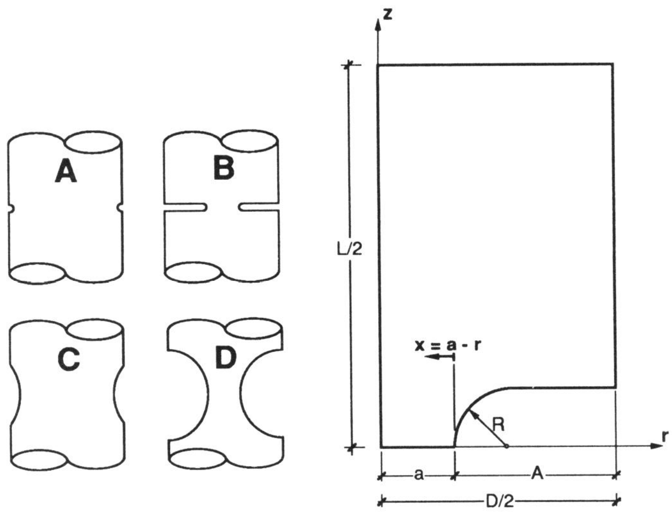

Figure 1. Dimensions of the SSR specimens (Geometry *A* : R/D = 0.03, A/D = 0.10; Geometry *B* : R/D = 0.05, A/D = 0.39; Geometry *C* : R/D = 0.36, A/D = 0.10; Geometry *D* : R/D = 0.40, A/D = 0.39; D=11.25 in all specimens).

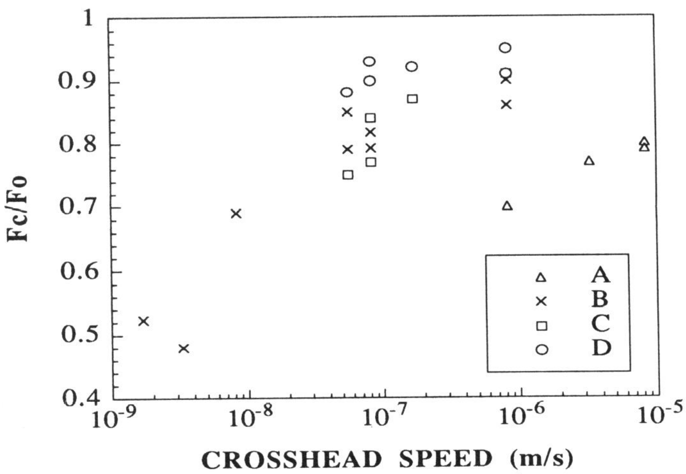

Figure 2. Results of the SSR tests, in a plot representing failure load in hydrogen (divided by the same in air) vs. crosshead speed applied by the testing machine. Results of quasi-static tests (independent of the strain rate) are omitted.

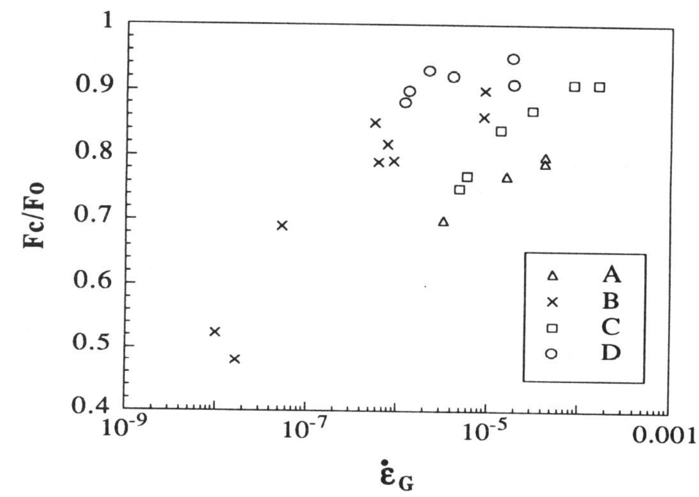

Figure 3. Results of the SSR tests, expressed as a function of the global strain rate. Results of quasi-static tests (independent of the strain rate) are not given.

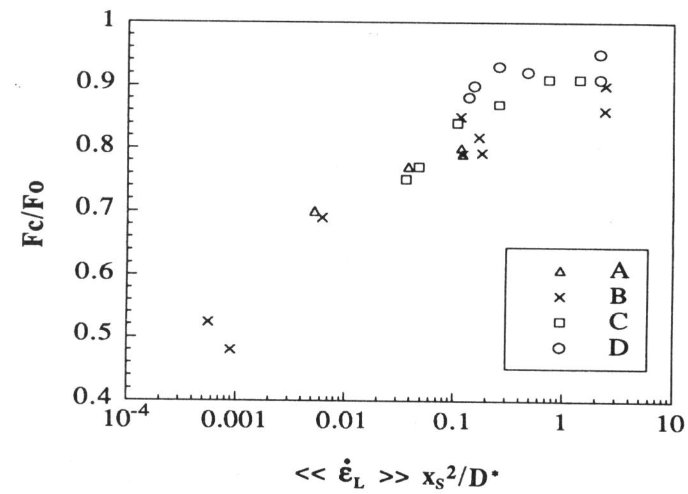

Figure 4. Results of the SSR tests, expressed as a function of the local strain rate. Results of quasi-static tests (independent of the strain rate) are not given.