HYDROGEN ASSISTED CRACKING IN PEARLITIC STEEL: INFLUENCE OF YIELD STRENGTH

J. Toribio[1] **A.M. Lancha**[2] **and M. Elices**[3]

This paper compares the hydrogen assisted cracking (HAC)-behaviour of two prestressing steels of different yield strengths. Slow strain rate tests using pre-cracked specimens were performed in aqueous environment under several environmental conditions. Different fatigue pre-cracking loads were used to analyze the influence of the stress state in the vicinity of the crack tip on the hydrogen assisted cracking process. The results confirm the well known fact that the highest strength steel is the most susceptible to hydrogen embrittlement. A model of hydrogen diffusion in metals is proposed to explain these results on the basis of the stress-strain curve of the material.

INTRODUCTION

Prestressing steels, widely used for civil engineering purposes (e.g. prestressed concrete structures), usually work in aggressive environments, and can suffer stress corrosion cracking (SCC). As a mechanism of environmentally assisted cracking, hydrogen embrittlement —more properly hydrogen assisted cracking (HAC)— is a specific phenomenon which can be associated with all electrochemical conditions, not only under cathodic potentials but even under anodic ones, as described by Parkins *et al.*(1).

The present work compares experimental results on hydrogen assisted cracking of two prestressing steels of different yield strengths, to investigate the influence of this material parameter on their HAC-susceptibility. Consideration is given to the very important role of compressive residual stresses in the vicinity of crack tip after fatigue pre-cracking, which delay the hydrogen entry and therefore the embrittlement process.

[1] Department of Engineering, University of La Coruña, E.T.S.I. Caminos, Pol. de Sabón, Parc. 12-14, 15141 Arteixo, La Coruña, Spain.

[2] CIEMAT, Ciudad Universitaria, 28040 Madrid, Spain.

[3] Department of Materials Science, Polytechnical University of Madrid, E.T.S.I. Caminos, Ciudad Universitaria, 28040 Madrid, Spain.

EXPERIMENTAL

Two high strength eutectoid steels were used: a hot-rolled patented bar (steel 1) an a cold drawn wire (steel 2). The mechanical properties are presented in Table 1. The specimens were transversely pre-cracked rods of 12mm diameter (hot rolled) and 7mm diameter (cold drawn). The transverse pre-crack was produced by axial fatigue, as described below. The relationship between crack depth and cylinder diameter was the same for all specimens: $a/D=0.3$.

TABLE 1 – Mechanical properties of the bar and the wire

Steel	Type	E (GPa)	σ_Y (MPa)	UTS (MPa)	K_{IC}(MPa $m^{1/2}$)
1	Hot rolled	195	725	1300	53
2	Cold drawn	190	1500	1830	84

Samples were subjected to slow strain rate testing (SSRT), although two fracture tests in air environment were performed for each material. The applied displacement rate was 8.3×10^{-8} ms^{-1}, based on previous experience (1). The aggressive environment was an aqueous solution of 1 g/l $Ca(OH)_2$ plus 0.1 g/l NaCl to which HCl was added to adjust the pH value below the value of 12.5 for the base solution (pH = 12.5, 8 and 4 were chosen).

All tests were carried out at a constant potential E = -1200 mV SCE (cathodic). The experimental device is shown in Fig. 1, and consists of a potentiostat and a classical three electrode assembly. To evaluate the influence of the pre-cracking procedure, several types of samples were prepared by using different fatigue pre-cracking loads during the last step: 0.28 K_{IC}, 0.45 K_{IC}, 0.60 K_{IC} and 0.80 K_{IC}.

RESULTS

Results are practically independent of pH (Fig.2: hot rolled bar; Fig.3: cold drawn wire). For the hot rolled bar, the test severity decreases as the maximum fatigue load increases, and this occurs for all values of K_{max}. For the cold drawn wire, the effect is the same from the qualitative point of view (tendency), but not from the quantitative point of view (numerical values), because for all variability ranges of K_{max} the behaviour of the cold drawn steel is clearly below that of the hot rolled one. Moreover, there are certain K_{max}-values ($K_{max} < 0{,}50\ K_{IC}$) for which the effect of the maximum fatigue load on the susceptibility of the cold drawn wire to hydrogen embrittlement is negligible. The conclusion is that the cold drawing process is damaging from the HAC point of view. This fact confirms previous experimental results —not yet fully understood— obtained by Etienne and Wijngaard (2), and Tanaka *et al.* (3).

DISCUSSION

A plausible explanation of the different HAC-behaviour of both steels can be given on the basis of a hydrogen diffusion model which includes both the effects of hydrogen concentration and hydrostatic stress distribution, as previously formulated by Toribio and Elices (4). The hydrogen concentration at the crack tip (CT) is relevant, since there is a stress magnification at that point:

$$c_{CT} = c_0 \exp\left(\frac{V^* \sigma_{CT}}{RT}\right) \tag{1}$$

In order to model the residual stress distribution, Rice's model (5) is used. It is applicable to an elastic ideally plastic material under cyclic loading. Fig. 4 shows the stress distribution proposed by Rice for the minimum ($K=K_{min}$) and maximum ($K=K_{max}$) fatigue loads. In both cases the maximum and minimum stresses are equal to the yield strength of the material (with positive and negative sign, respectively). Distribution corresponding to $K=K_{min}$ represents the stress state after fatigue pre-cracking (prior to the HAC test). As depicted in this plot, residual stresses ahead of the crack tip are compressions.

The values of ω and $\Delta\omega$ are:

$$\omega = \frac{\pi}{8}\left(\frac{K_{max}}{\sigma_Y}\right)^2 \tag{2}$$

$$\Delta\omega = \frac{\pi}{32}\left(\frac{\Delta K}{\sigma_Y}\right)^2 \tag{3}$$

where σ_Y is the yield strength of the material, K_{max} the maximum stress intensity factor during fatigue pre-cracking (last step of loading, just prior to the fracture test), and ΔK the stress intensity range in that step ($\Delta K = K_{max} - K_{min}$). In all cases $K_{min} \cong 0$, and therefore $\Delta K \cong K_{max}$. Designating λ as the dimensionless ratio of the maximum stress intensity factor during fatigue pre-cracking to the fracture toughness ($\lambda = K_{max}/K_{IC}$), we have:

$$\omega = \frac{\pi}{8}\left(\frac{K_{IC}}{\sigma_Y}\right)^2 \lambda^2 \tag{4}$$

$$\Delta\omega = \frac{\pi}{32}\left(\frac{K_{IC}}{\sigma_Y}\right)^2 \lambda^2 \tag{5}$$

in which the ratio (K_{IC}/σ_Y) is a characteristic of the material. The depth of the maximum hydrostatic stress point, whose importance is determinant in hydrogen diffusion, is always at distance ω from the crack tip (Fig.4). Applying (4) and taking into account that the ratio (K_{IC}/σ_Y) is 0.073 $m^{1/2}$ for the hot rolled bar and 0.056 $m^{1/2}$ for the cold drawn wire, (see Table 1) such a depth is:

HOT ROLLED BAR: $\omega = 2.099\,\lambda^2$ (mm)
COLD DRAWN WIRE: $\omega = 1.232\,\lambda^2$ (mm)

where λ is the dimensionless ratio of K_{max} to K_{IC} (0.28, 0.45, 0.60 and 0.80). Value ω is clearly higher for the hot rolled bar. This length represents the distance which hydrogen has to cover to reach the critical point. Hydrogen concentration at such a point is higher for the cold drawn wire, since it is nearer the crack tip. As a consequence, the fracture load in hydrogen environment, expressed as a percentage of the fracture load in air, is lower for the cold drawn steel than for the hot rolled one, as depicted in Figs.2 and 3.

CONCLUSIONS

1. The different susceptibility to hydrogen embrittlement as a function of the yield strength is explained on the basis of a non-conventional hydrogen diffusion model, which includes not only hydrogen concentration, but also hydrostatic stress distribution in the sample.

2. Rice's model of residual stress distribution in the vicinity if the crack tip after fatigue pre-cracking gives the depth of the point at which the hydrostatic stress reaches a maximum value (very important in hydrogen diffusion), and therefore explains the higher susceptibility of the cold drawn wire to hydrogen embrittlement.

3. Compressive residual stresses generated in the vicinity of the crack tip during fatigue pre-cracking are relevant to determine the amount of hydrogen which fluxes into the sample, since those stresses delay the hydrogen diffusion.

ACKNOWLEDGEMENTS

One of the authors (J. Toribio) would like to thank the *Colegio de Ingenieros de Caminos, Canales y Puertos-Demarcación de Galicia,* Spain, for the financial support of technical trips during the final stages of this work.

REFERENCES

(1) Parkins, R.N., Elices, M., Sánchez-Gálvez, V. and Caballero, L., Corros. Sci., Vol. 22, 1982, pp. 379-405.

(2) Etienne, C.F.and Wijngaard, B.H., 'Comparison of stress corrosion testing of prestressing steel under constant load and constant strain rate', Proceedings3rd FIP Symposium, Madrid, 1981.

(3) Tanaka, Y., Yamaoka, Y.and Karauchi, M., 'Effects of tensile strength on the stress corrosion behavior of steel wires in NH_4SCN and NH_4NO_3 aqueous solutions', Proceedings 3rd FIP Symposium, Madrid, 1981.

(4) Toribio, J., and Elices, M., 'Role of diffusion in the hydrogen transport in metals', in 'Fracture Behaviour and Design of Materials and Structures (ECF8)', D. Firrao, Ed. (EMAS, West Midlands, 1990) pp.451-460.

(5) Rice, J.R., 'Mechanics of crack tip deformation and extension by fatigue', STP 415, (ASTM, Philadelphia, PA, 1967) pp.247-309.

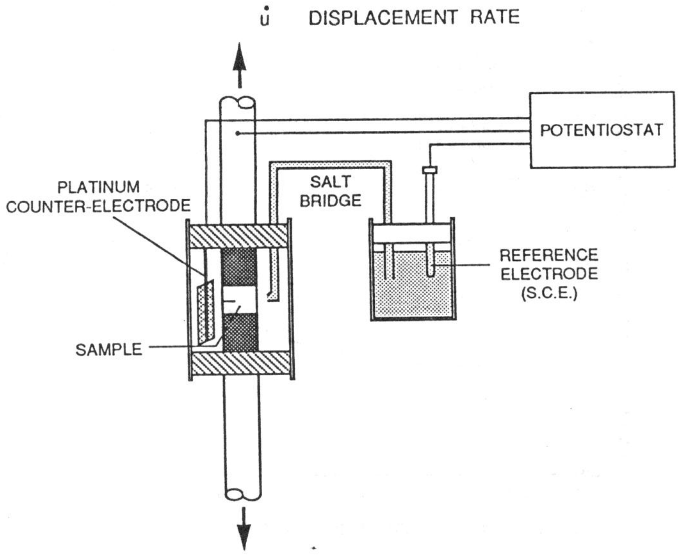

Figure 1. Experimental device

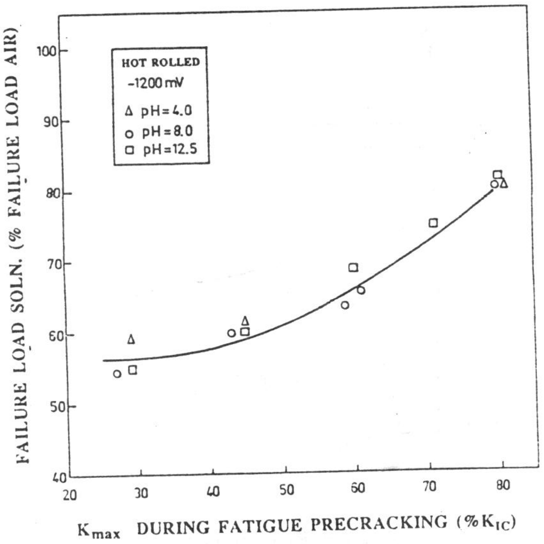

Figure 2. Results for the hot rolled bar

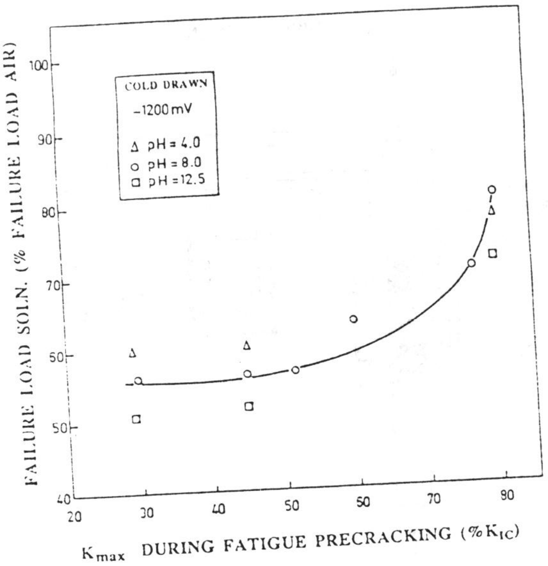

Figure 3. Results for the cold drawn wire

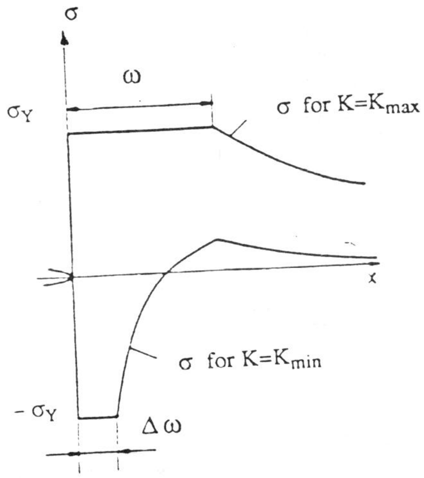

Figure 4. Rice's model