HYDROGEN ASSISTED CRACKING OF HIGH-STRENGTH STEELS FOR CIVIL ENGINEERING PURPOSES

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Progressive cold drawing in eutectoid steels affects the material microstructure producing orientation and packing of the pearlite lamellae, as well as orientation and enlargement of the pearlite colonies. In this paper the consequences of this evolution on the hydrogen induced fracture behaviour of the steels is studied. Results show that cold drawing produces anisotropy in the steel, so that the resistance to hydrogen assisted cracking is a directional property dependent on the angle with the cold drawing direction.

INTRODUCTION

In hydrogen assisted cracking of prestressing steel wires for civil engineering the combined action of the stress field and the environment produces a decrease of fracture resistance in the material. Previous work (Parkins et al. (1), Lancha (2), Toribio et al. (3)) deals with the influence of factors such as the electrochemical potential or the hydrostatic stress. An additional important parameter is the microstructure of the material, since the manufacturing process by cold drawing in several passes generates strong plastic deformations and induces material anisotropy as a consequence of the markedly oriented microstructure.

This paper deals with the influence of the cold drawing process —and its associated microstructural changes— on the fracture behaviour of pearlitic steels surrounded by a hydrogen environment. The research is based on previous metallographic examinations in this kind of steel (Toribio and Ovejero (4,5)) studying the microstructural evolution throughout the progressive cold drawing sequence in the two main microstructural levels: the pearlite colony and the pearlite lamellae. In addition, slow strain rate tests in a hydrogen environment were performed to evaluate the influence of the afore said microstructural arrangement on the posterior hydrogen assisted cracking behaviour of the steel.

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MATERIALS

Seven pearlitic steels were used in this work. Their chemical composition is given in Table 1. All the steels were obtained from a real manufacturing process by cold drawing which was stopped, so that each wire corresponds to a different stage of the process. The name of each steel indicates the number of cold drawing steps which has undergone, as shown in Table 2, together with the diameter (D_i) of each wire and the yield strength (σ_{02}). A clear improvement of (traditional) mechanical properties as the cold drawing proceeds is achieved. However, the consequences of this manufacturing technique from the point of view of the hydrogen embrittlement susceptibility of the steels are not well known and require further research.

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

C	Mn	Si	P	S	Cr	V	Al
0.80	0.69	0.23	0.012	0.009	0.265	0.060	0.004

TABLE 2 – Nomenclature, diameter and yield strength of the wires

Nomenclature	A0	A1	A2	A3	A4	A5	A6
D_i (mm)	12.00	10.80	9.75	8.90	8.15	7.50	7.00
σ_{02} (GPa)	0.686	1.100	1.157	1.212	1.239	1.271	1.506

EXPERIMENTAL PROCEDURE

To evaluate the fracture behaviour of the steels under hydrogen embrittlement environmental conditions, slow strain rate tests were performed on transversely precracked rods immersed in an aqueous environment. The relationship between crack depth and diameter of the rod was chosen as $a/D = 0.30$ for all the diameters. Specimens were precracked by axial fatigue in air, in such a way that the maximum stress intensity factor in the final stage was always $K_{max} = 0.30\ K_{IC}$ (where K_{IC} is the fracture toughness). After fatigue precracking, the specimens were coated with an insulator, except for a small band around the crack, to protect the rest of the sample against the corrosive solution. The aggressive environment was an aqueous solution of 1 g/l $Ca(OH)_2$ and 0.1 g/l NaCl, with a controlled pH of 12.5. The slow strain rate tests were conducted with constant applied displacement rate proportional to each wire diameter so that the smallest rate was $1.7\ x10^{-3}$ mm/min for the fully drawn rod (steel 6: 7mm diameter) and the highest was $3.0\ x10^{-3}$ mm/min for the hot rolled bar (steel 0: 12mm diameter). All the tests were performed at constant electrochemical potential with the value $E = -1200$ mV SCE (cathodic) to evaluate the steel susceptibility to hydrogen assisted cracking.

EXPERIMENTAL RESULTS

A progressive change in the macroscopic topography as the cold drawing increases was observed in all fracture surfaces after the hydrogen embrittlement tests. Fig. 1 offers a 3D-view of these fracture surfaces, showing that mixed mode crack growth appears for a certain cold drawing level, and it is associated with crack deflection which starts just at the tip of the fatigue precrack, i.e., a deviation in crack growth —from its initial fatigue crack growth path— appears at the very early beginning of the hydrogen embrittlement test in the most heavily drawn steels.

As sketched in Fig. 1, in the first steps of cold drawing (steels A0 and A1) the crack growth develops in mode I in both fatigue precracking and hydrogen-assisted cracking. In steel A2 there is a slight deflection in the hydrogen-assisted crack, and such a deflection is not uniform along the crack front, but it produces a wavy crack at different levels, and finally follows again the direction perpendicular to the wire axis. The same happens in steel A3, but in this case the deviation angle is higher. For the most heavily drawn steels (A4 to A6) the crack deflection takes place suddenly after the fatigue precrack and the deviation angle is even higher and more or less uniform along the whole crack front.

With regard to the microscopic fracture modes, the crack propagation path presented features of slow crack growth associated with hydrogen-assisted damage in all cases, although the specific features changed from one steel to another as a consequence of the mixed-mode crack growth. All of them resemble each other and may be classified as *hydrogen-damage topography*, although the shear appearance is more evident when the mode II component increases, i.e., in the most heavily drawn steels (Fig. 2). After the environmentally damaged zone, the final stage of tensile fracture develops by cleavage, it being macroscopically transverse to the wire axis in all steels (i.e., parallel to the fatigue precrack).

DISCUSSION

Previous works (4,5) analyzed the microstructural evolution with cold drawing in these steels. Results demonstrated the progressive orientation of the pearlite colonies and the pearlite lamellae in the cold drawing direction, which suggest a possible relation between the deflection of the (macroscopic) hydrogen-assisted crack and the microstructure of the material (in the two microstructural levels of the colony and the lamellae) which is markedly oriented in the last stages of cold drawing, thus inducing resistant anisotropy in the steel.

Fig. 3 shows a plot of the evolution with cold drawing of the orientation angle of the pearlite lamellae (angle α between the transverse axis of the wire and the direction marked by the lamellae in the longitudinal metallographic section) and the orientation angle of the pearlite colonies (angle α' between the transverse axis of the wire and the major axis of the pearlite colony, modelled as an ellipsoid). In both cases there is an increasing trend with cold drawing, i.e., both pearlite lamellae and colonies become increasingly aligned to the cold drawing direction (4,5). Fig. 4 offers the evolution with cold drawing of macroscopic parameters characteristic of the crack path (fracture profile defined by the deflection angle θ and the mixed mode step height h), showing that both increase with cold drawing in the same manner as the microscopic characteristics given in Fig. 3.

In the most slightly drawn steels (A0 and A1) a more or less random angular distribution is observed at the two basic microstructural levels, which indicates that the material is isotropic or quasi-isotropic and explains why the macroscopic hydrogen-assisted crack grows in mode I, since this is the most favourable direction. The steels with an intermediate degree of cold drawing (A2 and A3) exhibit crack deflection associated with mixed mode propagation and a wavy crack front; this is a consequence of the slight microstructural orientation of both the pearlite colonies and lamellae (angles α and α'). In the most heavily drawn steels (A4 to A6) the crack deflection is more pronounced, and the mixed mode takes place suddenly after the fatigue precrack, the deviation angle θ and the step height h reaching their maximum values; this is associated with a markedly oriented microstructure in the cold drawing direction (very high angles α and α' of the pearlite lamellae and colonies) and its corresponding anisotropic properties with regard to hydrogen assisted cracking as a consequence of this "fibrous" or "plated" arrangement. The most heavily drawn materials behave as fiber-reinforced composites (or laminates) from the materials science point of view.

CONCLUSION

The microstructural changes undergone by the pearlitic steels during industrial cold drawing have direct consequences in the posterior hydrogen-assisted cracking behaviour. The orientation of both pearlite colonies and lamellae influences the macroscopic crack propagation path in a hydrogen environment following the most favourable crack propagation direction. As a consequence, a transverse crack changes its propagation direction approaching the wire axis and producing a mixed mode propagation in the way that the deviation angle in relation to the original propagation direction is an increasing function of the cold drawing degree produced by manufacturing.

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REFERENCES

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

(2) Lancha, A.M., Ph. D. Thesis, Complutense University of Madrid, 1987.

(3) Toribio, J., Lancha, A.M. and Elices, M., Metall. Trans. A, Vol. 23A, 1992, pp. 1573-1584.

(4) Toribio, J. and Ovejero, E., Mater. Sci. Engng., Vol. A234-236, 1997, pp. 579-582.

(5) Toribio, J. and Ovejero, E., Mech. Time-Dependent Mater., in press.

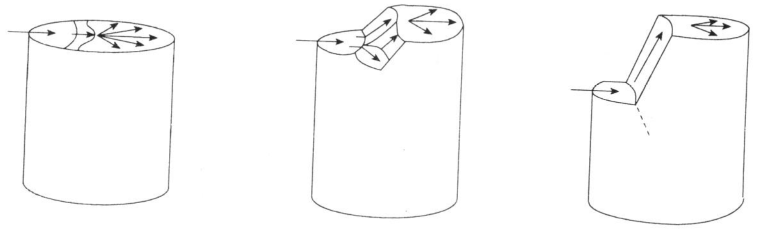

Figure 1. Fracture surfaces of steels with increasing degree of cold drawing.

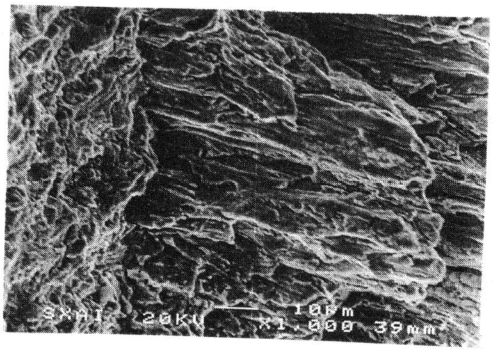

Figure 2. Hydrogen-damage topography, with shear appearance, in the most heavily drawn steel.

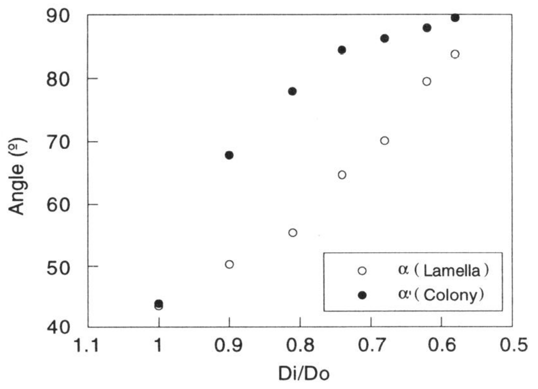

Figure 3. Evolution with cold drawing of the microstructure of the steels (orientation angle of the pearlite lamellae and colonies).

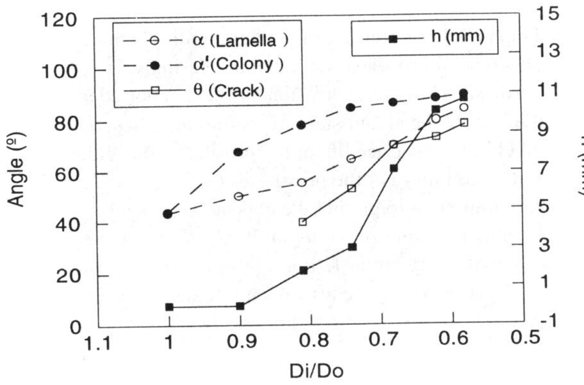

Figure 4. Evolution with cold drawing of the macroscopic crack path (deflection angle and mixed mode step height).