Stress-corrosion of cold drawn prestressing steels

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Abstract

This paper evaluates the anisotropic stress-corrosion behaviour of high-strength cold-drawn prestressing steel wires. To this end, two eutectoid steels in the form of a hot rolled bar and cold drawn wire were tested. While a tensile crack in the hot rolled bar always propagates in mode I, in the cold drawn wire an initially mode I crack deviates significantly from its normal mode I growth plane and approaches the wire axis or cold drawing direction, thus producing a mixed mode propagation. In hydrogen-assisted cracking the deviation happens just after the fatigue pre-crack, whereas in localized anodic dissolution the material is able to undergo mode I cracking before the deflection takes place. An explanation of such behaviour can be found in the pearlitic microstructure of the steels. This microstructural arrangement is randomly oriented in the case of the hot rolled bar and markedly oriented in the wire axis direction in the case of the cold drawn wire. Thus both materials behave as composites at the microstructural level and their plated structure (oriented or not) would explain the different behaviour in a corrosive environment.

Keywords: stress-corrosion cracking, pearlitic steel, steelmaking, manufacturing, cold drawing, anisotropic fracture behaviour, fracture micromechanisms.

1 Introduction

Stress corrosion cracking (SCC) of high-strength prestressing steel is a problem of major technological concern since it can increase the risk of failure of concrete structures. This paper analyses a wide set of SCC laboratory experiments of pearlitic steel wires before and after cold drawing, i.e., the previous (base) hot rolled material and the fully drawn prestressing steel wire (final commercial product used in prestressed concrete, a material of the highest
interest in structural engineering). A discussion is presented to rationalise the anisotropic SCC behaviour of cold drawn prestressing steel on the basis of its oriented pearlitic microstructure, to formulate micromechanical models of macroscopic SCC behaviour and to provide the engineer with design tools in damage tolerance and structural integrity analyses of prestressed concrete structures.

2 Materials and effect of cold drawing

A high strength eutectoid steel supplied from commercial stock by EMESA was used in this work. It is the steel used in the production of cold drawn wire for prestressed concrete. The chemical composition is given in Table 1. This steel was tested in two conditions: firstly, as hot rolled patented cylindrical bars of 12 mm diameter, and secondly, as a commercial 7 mm diameter cold drawn prestressing wire obtained from the bar.

Table 1: Chemical composition (wt %) of the steel.

<table>
<thead>
<tr>
<th>Mo</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.74</td>
<td>0.70</td>
<td>0.20</td>
<td>0.016</td>
<td>0.023</td>
<td>0.01</td>
<td>0.01</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The mechanical properties of both the bar and the wire are presented in Table 2. The fracture toughness $K_{IC}$ was determined using cylindrical pre-cracked specimens obtained from the bar and the wire—for which the plane strain condition is achieved at the inner points of the crack—together with an expression for the maximum stress intensity factor at the deepest point of the crack (assumed semi-elliptical) calculated by using the Finite Element Method (FEM) combined with a Virtual Crack Extension technique.

Table 2: Mechanical properties of the bar and the wire.

<table>
<thead>
<tr>
<th>Steel</th>
<th>Young's Modulus (GPa)</th>
<th>Yield Strength (MPa)</th>
<th>U.T.S. (MPa)</th>
<th>Elongation under UTS (%)</th>
<th>Fracture toughness (MPa m$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hot rolled bar</td>
<td>195</td>
<td>725</td>
<td>1300</td>
<td>8.0</td>
<td>53</td>
</tr>
<tr>
<td>2. Cold drawn wire</td>
<td>190</td>
<td>1500</td>
<td>1830</td>
<td>5.8</td>
<td>84</td>
</tr>
</tbody>
</table>

The microstructure of both steels consists of fine pearlite with an interlamellar spacing of 0.1 mm. Fig. 1 shows the microstructure of both the hot rolled patented bar and the cold drawn wire in transverse and longitudinal cross sections. While the hot rolled bar has a randomly-oriented microstructure in both transverse and longitudinal sections (Figs. 1a and 1c), the cold drawn wire presents a randomly-oriented appearance in the transverse cross section (Fig. 1b), but a marked orientation in the longitudinal cross section (Fig. 1d), which implies an effect of manufacturing on the resulting microstructure. Thus the cold
drawn wire presents features consisting mainly of alternate lamellae of ferrite and cementite aligned parallel or quasi-parallel to the wire axis or cold drawing direction. The consequence will be a highly anisotropic behaviour.

Figure 1: Microstructure of both the hot rolled and the cold drawn steels in transverse and longitudinal metallographic sections: (a) hot rolled-transverse, (b) cold drawn-transverse, (c) hot rolled-longitudinal, (d) cold drawn-longitudinal.

3 Stress corrosion tests

To evaluate the stress-corrosion behaviour of the steels in aggressive media, slow strain rate tests (SSRT) were performed on transversely pre-cracked rods immersed in aqueous environment under electrochemical control. Precracking of the samples was carried out by axial fatigue in air environment, using different fatigue loads during the last step. The maximum stress intensity factor \( K \)-levels in fatigue were \( K_{\text{max}} = 0.28 \ K_{\text{IC}}, 0.45 \ K_{\text{IC}}, 0.60 \ K_{\text{IC}} \) and \( 0.80 \ K_{\text{IC}} \), where \( K_{\text{IC}} \) is the fracture toughness of the material in air.

3.1 Engineering approach: fracture load

The macroscopic effects of the environment on fracture were quantified through the ratio of the failure load in the solution (critical value \( F_c \)) to the failure load in air (reference value \( F_0 \)), as depicted in Fig. 2. All results showed the well known anodic and cathodic regimes of environment-sensitive cracking: for higher
potentials (E = –400 mV SCE) the anodic regime, associated with localized anodic dissolution (LAD); for lower potentials (E = –1200 mV SCE) the cathodic regime, associated with hydrogen assisted cracking (HAC). Since the results do not substantially depend on pH, only the average results for the three pH values used in the tests are shown in the plot of Fig. 2.

![Graph](image)

Figure 2: Macroscopic results of the slow strain rate tests, quantified through the ratio of the failure load in the solution (critical value $F_C$) to the failure load in air (reference value $F_0$), for both materials (HR: hot rolled, CD: cold drawn) and the two environmental conditions (HAC: hydrogen assisted cracking, LAD: localized anodic dissolution). The plot shows the average results in the tests.

An important $K_{\text{max}}$-effect is observed due to compressive residual stresses in the vicinity of the crack tip during fatigue pre-cracking of the samples. This phenomenon has been discussed in previous works [1], the main conclusion being that high values of $K_{\text{max}}$ produce strong compressive residual stresses in the vicinity of the crack tip, thus delaying the hydrogen entry (in HAC) or the metal dissolution (in LAD).

Both the hot rolled bar and the cold drawn wire are more susceptible to HAC than to LAD (in engineering macroscopic terms). The cold drawing process is beneficial against LAD phenomena, since it clearly increases the fracture load in the anodic regime. However, cold drawing is damaging against HAC processes, since it lowers the fracture load in a hydrogen environment (cathodic regime) for the whole range of $K_{\text{max}}$-values.

3.2 Physical approach: microscopic fracture modes

Fig. 3 gives the microscopic fracture modes associated with the different materials and environmental conditions. In HAC conditions (cathodic regime) the hot-rolled bar fails in mode I associated with the so called tearing topography surface (TTS) fracture mode [2,3] followed by cleavage-like propagation, whereas the cold drawn wire exhibits a shear topography with some evidence of
isolated cleavage facets, and the crack approaches the axis direction producing a mixed mode stress state (longitudinal splitting or delamination). There are two embryos of fracture located symmetrically in relation to the initial crack plane (at an angle of about 80º), but only one of them becomes the final fracture path, and thus the initial crack branching progresses along only one of the branches, probably for statistical reasons, which makes it the fracture path of lower fracture resistance or that with the higher concentration of hydrogen.

Figure 3: Microscopic modes of fracture for an intermediate $K_{\text{max}}$-level of 0.45 $K_{\text{IC}}$: (a) hot rolled bar under HAC conditions showing TTS, (b) cold drawn wire under HAC conditions showing shear topography and isolated cleavage facets, (c) hot rolled bar under LAD conditions showing cleavage, (d) cold drawn wire under LAD conditions showing mode I dissolution and crack deflection).

Under LAD conditions (anodic regime) the hot-rolled bar fails in mode I by cleavage-like topography whereas the cold drawn wire exhibits a short mode I crack growth path (50 µm in depth), and a posterior crack deflection with a deviation angle of about 80º from the initial crack path in mode I. Thus the mixed mode crack growth associated with longitudinal splitting or delamination also appears in anodic (pure stress corrosion cracking) conditions.

3.3 Fracture mechanics approach: critical stress intensity factor

Important differences arise when a crack deviation from its initial plane appears and a mixed mode propagation takes place in the form of crack branching (in the case of HAC) or crack deflection (in the case of LAD), as shown in Fig. 4. As a matter of fact, the stress corrosion resistance of the cold drawn steel is strongly dependent on the capacity of it to undergo mode I cracking across the more
resistant microstructural paths, since when the crack deviates from its original direction it follows a path of minimum resistance to stress corrosion cracking associated with the very oriented microstructure of the cold drawn steel.

![Figure 4](image)

**Figure 4:** Schema showing the environment-sensitive cracking modes: (a) hot rolled bar in HAC conditions, (b) cold drawn wire in HAC conditions, (c) hot rolled bar in LAD conditions, (d) cold drawn wire in LAD conditions.

**Table 3:** Summary of results of the slow strain rate tests ($K_{\text{max}} = 0.28 K_{\text{IC}}$). The subindex $c$ indicates critical (failure) instant in the tests in aggressive solution and the subindex $0$ refers to the pre-crack length before the tests ($a_0$) or to the reference fracture value in air ($F_0, K_0$).

<table>
<thead>
<tr>
<th>Crack path</th>
<th>Env.</th>
<th>Mater.</th>
<th>Critical crack</th>
<th>Critical load</th>
<th>Critical SIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAC</td>
<td>HR</td>
<td>$a_c \approx a_0 + \alpha_{\text{TTS}}$</td>
<td>$F_C/F_0 = 0.56$</td>
<td>$K_C/K_0 = 0.56$</td>
<td>Mode I</td>
</tr>
<tr>
<td>CD</td>
<td>$a_c \approx a_0$</td>
<td>$F_C/F_0 = 0.56$</td>
<td>$K_C/K_0 = 0.56$</td>
<td>Mixed mode* [Branching]</td>
<td></td>
</tr>
<tr>
<td>LAD</td>
<td>HR</td>
<td>$a_c \approx a_0$</td>
<td>$F_C/F_0 = 0.70$</td>
<td>$K_C/K_0 = 0.70$</td>
<td>Mode I</td>
</tr>
<tr>
<td>CD</td>
<td>$a_c = a_0 + \alpha_{\text{LAD}}$</td>
<td>$F_C/F_0 = 0.96$</td>
<td>$K_C/K_0$</td>
<td>Mixed mode* [Mode I+Deflection]</td>
<td></td>
</tr>
</tbody>
</table>

HAC: hydrogen assisted cracking
LAD: localized anodic dissolution
TTS: tearing topography surface
SIF: stress intensity factor $K$

The environmental effects on fracture of the considered materials can be analyzed in Table 3 which summarizes the results of the slow strain rate tests for the slightest fatigue pre-cracking regime ($K_{\text{max}} = 0.28 K_{\text{IC}}$), i.e., for that which
produces the minimum previous mechanical pre-damage before the stress corrosion tests and thus allows the maximum degree of environmental damage.

In the case of HAC (cf. Fig. 4 and Table 3) the hot rolled bar exhibits better behaviour than the cold drawn wire since, although the fracture load is the same when compared with its respective value in air, the ratio of stress intensity values in aggressive medium (hydrogen) to the reference value in air is higher in the hot rolled material as a consequence of the subcritical crack growth by TTS along the original crack growth direction in mode I.

For LAD (cf. Fig. 4 and Table 3) the situation is the opposite, and in this case the effect of cold drawing on stress corrosion (LAD) performance of the steels is clearly beneficial because of the fact that the subcritical crack growth in mode I (x_{LAD}) extends the time to failure and therefore raises the fracture load before the crack deflection (and the subsequent mixed mode propagation associated with this deviation from the initial cracking path) takes place during the environment sensitive tests.

3.4 Effect of cold drawing on SCC behaviour

In HAC, both the hot rolled and the cold drawn materials suffer a marked reduction of fracture load due to hydrogen degradation, and a subsequent reduction of critical stress intensity factor $K_{HAC}$ ("apparent toughness") which is $K_{HAC}/K_0 \approx 0.56$ in the cold drawn wire and $K_{HAC}/K_0 > 0.56$ in the hot rolled bar as a consequence of the subcritical mode I cracking by TTS (cf. Table 3).

In the case of LAD the situation is not so clear. The hot rolled bar exhibits a marked reduction of "apparent toughness" in relation to the actual toughness in air ($K_{LAD}/K_0 \approx 0.70$) in spite of the cleavage fracture micromechanism operating in both cases. As a matter of fact, although the cleavage topography is predominant in both situations, for the fracture in air ($K_0$) it is mechanical cleavage, whereas for the fracture in corrosive medium ($K_{LAD}$) it could be the so-called film-induced cleavage [4], that is, a brittle film which injects a crack into the substrate, thus producing cleavage fracture.

With regard to the critical stress intensity factor for LAD in the cold drawn wire, it could be even higher than the corresponding value in air ($K_{LAD}/K_0 > 0.96$). It can be explained by the blunting of the crack tip caused by the anodic dissolution that produces an apparently higher critical K-value. This crack-tip blunting is enhanced by the oriented microstructure of the drawn material (specially at the ferrite/cementite interface) and it can block the film-induced cleavage mechanism which otherwise would be operative (e.g. in the case of the hot rolled material).

The fundamental idea summarizing the results of the cold drawn steel is that such a material is highly susceptible to HAC —even more than the hot rolled initial material— but at the same time extremely resistant to LAD (without appreciable loss of fracture load). This elevated LAD resistance is associated with a clear increment of time to failure and is achieved because of the important fact that —in spite of the clear orientation of the steel microstructure— the crack is able to propagate in mode I breaking the strongest links, blunting the crack tip and blocking the film-induced cleavage mechanism. This is the key point related to the cold drawn wire: that the crack is able to undergo mode I cracking before final fracture, thus increasing both the critical stress intensity factor and the time...
to failure. In further sections of the paper, a micromechanical model is proposed to explain this stress-corrosion behaviour of the cold drawn steel.

4 Micromechanics of SCC in the cold drawn material

4.1 Material anisotropy

A composite engineering approach is used to model the oriented microstructure of the cold drawn wire as a fiber-reinforced composite. Such a microstructural arrangement has consequences of both a mechanical and a chemical nature:

(i) Strength anisotropy (mechanical anisotropy), i.e., fracture toughness $K_{IC}$ (or similar strength parameter) as a function of the orientation angle: $K_{IC} = K_{IC}(\theta)$, where $\theta$ is the common fracture mechanics angle. In particular, the fracture toughness values in direction perpendicular and parallel to the fibers are:

$$K_{IC\perp} = K_{IC}(0=0^\circ)$$ for fibers fracture (transverse fracture) (1)

$$K_{IC\parallel} = K_{IC}(\theta=90^\circ)$$ for longitudinal splitting (2)

the former is the fracture toughness for breaking the fibers in the model (fracture of the plates or the lamellae in the real material), whereas the latter is the fracture toughness for delamination or debonding of any microstructural elements at any scale in the steel.

It may be assumed that $K_{IC\perp}$ is clearly higher than $K_{IC\parallel}$:

$$K_{IC\perp} >> K_{IC\parallel}$$ (3)

(ii) Chemical anisotropy, i.e., hydrogen diffusion coefficient $D$ as a function of the orientation angle: $D = D(\theta)$, $\theta$ having the same meaning as above. This coefficient is a key item in HAC processes in pearlitic steels where stress-assisted diffusion has been shown to be the main hydrogen transport mechanism [5]. In particular, the diffusion coefficients in direction perpendicular and parallel to the fibers are respectively:

$$D_{\perp} = D(\theta=0^\circ)$$ diffusion in the transverse (crack) direction (4)

$$D_{\parallel} = D(\theta=90^\circ)$$ diffusion in the longitudinal direction (5)

The former corresponds to diffusion in the crack direction, perpendicular to the fibers (or lamellae or plates, according to the modelling), and the latter is associated with diffusion parallel to the fibers.

Considering again microstructural reasons, $D_{\parallel}$ is clearly higher than $D_{\perp}$, i.e.

$$D_{\parallel} >> D_{\perp}$$ (6)

which indicates that hydrogen tends to diffuse in the direction $\theta=90^\circ$, thus creating a pre-damage at the microscopic level.

4.2 Micromechanisms of HAC

Hydrogen tends to diffuse, in an isotropic material, towards the points located at $\theta=0$ and the crack grows in mode I. When the material is anisotropic, such as the cold drawn wire, although the maximum hydrostatic stress is located at $\theta=0$
(polar angle form the crack tip), there are two important reasons for the crack deviation from its initial propagation path in mode I:

(i) strength anisotropy of the cold drawn wire (lower toughness in the wire axis direction)

(ii) chemical anisotropy (higher hydrogen diffusion coefficient in the wire axis direction), so that hydrogen diffuses faster in the longitudinal direction ($D_{\parallel}$ relatively high) than in the transverse direction ($D_{\perp}$ relatively low).

With regard to the critical mechanism of failure in HAC, two micromechanisms could be operative, according to [6]:

(i) Hydrogen enhanced localized plasticity (HELP)

(ii) Hydrogen enhanced delamination (HEDE)

The original term in [6] was hydrogen enhanced decohesion, with the same acronym HEDE, but in this work the term delamination is more adequate.

With regard to HELP, its importance in the HAC of prestressing steel is probably low, since the lamellar structure of the steel (markedly oriented, analogous to a fiber-reinforced material or a laminate at the microscopical level) probably delays or even blocks the dislocation movement which otherwise could be operative in an isotropic material. In a lamellar structure such as that of the cold drawn wire, the cementite plates act as obstacles to the movement of dislocations, so they can block (or diminish) the dislocation multiplication.

In the matter of HEDE, its importance in the HAC of prestressing steel is probably high for the same reason as explained above, i.e., the lamellar structure of the steel (markedly oriented) which produces anisotropy regarding fracture and hydrogen diffusion, so that hydrogen diffuses mainly in the direction of the plates and can weaken the bonds or interfaces between the ferrite and the cementite lamellae (which are the weakest links even before the hydrogen presence) thus contributing to the hydrogen-induced fracture by delamination or debonding between two similar microstructural units.

4.3 Micromechanisms of LAD

A question arises here as to why the crack does not change its propagation path in spite of the clearly oriented microstructure of the steel. The explanation could lie in the local (or crack-tip) strain rate required to promote the anodic dissolution process which is achieved only at the crack tip in the $\theta=0$ direction (i.e., the crack plane) due to the stress-strain distribution in its vicinity.

Then, why does the crack finally change its propagation direction after a certain subcritical crack growth by LAD in mode I? Because of the presence in the heavily drawn material of extremely slender pearlitic pseudocolonies which are potential fracture sites for two reasons:

(i) the very high local interlamellar spacing which makes them weaker or potentially fracturable by shear cracking of pearlitic plates according to the mechanism proposed by Miller and Smith [7].

(ii) the presence of some microcracks and defects consisting of plates prefractured in the pseudocolony during the manufacturing process (cold drawing) as a consequence of the very high stresses applied on the wire.
The mechanism of LAD in cold drawn steel could be explained as follows: dissolution is produced in mode I along a distance. The crack continues in mode I along the initial plane and only deviates when it the afore-mentioned pearlitic pseudocolonies and final fracture takes place for purely mechanical reasons.

5 Conclusions

The cold drawn steel is strongly susceptible to HAC—even more than the hot rolled initial material—but at the same time extremely resistant to LAD, Thus, although the stress corrosion properties of the two steels are similar in the transversal direction, the cold drawn wire exhibits a dramatic reduction of HAC resistance in the longitudinal direction.

The reason for the afore-said macroscopic behaviour is the pearlitic microstructure of the cold drawn steel which becomes oriented in the wire axis direction as a direct consequence of cold drawing. This happens at the two basic microstructural levels: the pearlitic colony and the pearlite lamellae.

Acknowledgements

The author wishes to thank the present financial support of his research at the University of Salamanca provided by the following institutions: Spanish Ministry for Scientific and Technological Research MCYT-FEDER (Grant MAT2002-01831), FEDER-INTERREG III (Grant RTCT-B-Z/SP2.P18), Junta de Castilla y León (JCYL; Grant SA078/04) and Spanish Foundation “Memoria de D. Samuel Solórzano Barruso”.

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