

Environmentally Assisted Cracking Paths in Cold Drawn Pearlitic Steel

J. Toribio and E. Ovejero

University of Salamanca, Campus Viriato, Avda. Requejo 33, 49022 Zamora, Spain.
E-mail: toribio@usal.es

ABSTRACT. *Progressive cold drawing in eutectoid steels produces a preferential orientation of the pearlitic microstructure in the wire axis or drawing direction. This affects the posterior behaviour of the steels under environmentally assisted cracking (EAC) conditions. The experimental results show that cold drawing induces strength anisotropy in the steel, and thus the resistance to EAC is a directional property that depends on the angle in relation to the drawing direction. Therefore, an initial transverse crack changes its propagation direction to approach that of the wire axis, thus producing mixed mode propagation, the deflection angle being an increasing function of the cold drawing degree. This experimental result may be explained by micro-mechanical considerations on the basis of the lamellar microstructure of the steels. A relationship is established between the microstructural angles and the deflection angles of the macroscopic crack in EAC, thus providing a materials science type relationship between the microstructure and the macroscopic crack paths.*

INTRODUCTION

High-strength prestressing steel wires are manufactured by cold drawing to increase both the yield strength and the ultimate tensile strength (UTS) of the steel and allow it to be used as the main constituent of prestressed concrete structural elements. The manufacture technique consisting of cumulative drawing of pearlitic wires through a series of dies with diameters progressively thinner produces important microstructural changes in the material which could influence its posterior performance. Evidence exists in the scientific literature showing the anisotropic fracture behaviour of prestressing steel in air [1], as well as in aggressive environments promoting environmentally assisted cracking (EAC) in the material [2-4].

This paper offers a materials science approach to the modelling of EAC behaviour of cold drawn prestressing steel wires. The approach is based on linking the microstructure of the steels (progressively oriented as a consequence of the manufacture process by cumulative cold drawing) with their macroscopic EAC behaviour (increasingly anisotropic as the degree of cold drawing increases). Special attention is paid to the evolution of the macroscopic crack path as the degree of cold drawing increases.

MATERIALS

Materials were high-strength steels taken from a real manufacturing process. Wires with different degrees of cold drawing were used. The different steels were named with digits 0 to 6 indicating the number of drawing steps undergone, so steel 0 is the hot rolled bar (base material) which is not cold drawn at all, and steel 6 represents the prestressing steel wire (final commercial product) which has suffered six cold drawing steps. Table 1 includes the diameter (D_i), the yield strength (σ_{02}) and the ultimate tensile strength (UTS) of the steels. There is a clear improvement of (traditional) mechanical properties as the cold drawing proceeds, but the consequences of this manufacture technique from the point of view of the fracture and EAC of the steels are not well known and require further research.

Table 1. Diameter (D_i), yield strength (σ_{02}) and UTS.

Steel	0	1	2	3	4	5	6
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
UTS (GPa)	1.175	1.294	1.347	1.509	1.521	1.526	1.762

MICROSTRUCTURAL EVOLUTION WITH COLD DRAWING

Metallographic techniques were applied to reveal the pearlitic microstructure of the progressively drawn steels. Attention was paid to the evolution with cold drawing of the two basic microstructural levels: the *pearlite colonies* (first microstructural level) and the *pearlitic lamellae* (second microstructural level). Sections were prepared from all steel wires and mounted to undergo four grinding stages, from 320 to 1200 grit, and three polishing passes followed by etching in Nital 2%. The pearlite colonies were observed by optical microscopy, whereas scanning electron microscopy was required to resolve the lamellar structure of the pearlite.

With regard to the first microstructural level, Fig. 1 shows the optical micrographs of two different stages of the cold drawing process where an increasing deformation (slenderizing) is observed in the colonies, which determines their angle in relation to the axis. At the same time, a progressive orientation of the colonies in the cold drawing direction (wire axis) can be seen in the longitudinal metallographic sections.

In the matter of the second microstructural level, Fig. 2 shows the scanning electron micrographs of two different stages of the cold drawing process where an increasing closeness of packing is observed in the lamellae, with decrease of the interlamellar spacing. Again a progressive orientation of the pearlitic lamellae in the cold drawing direction (wire axis) can be seen in the longitudinal metallographic sections.

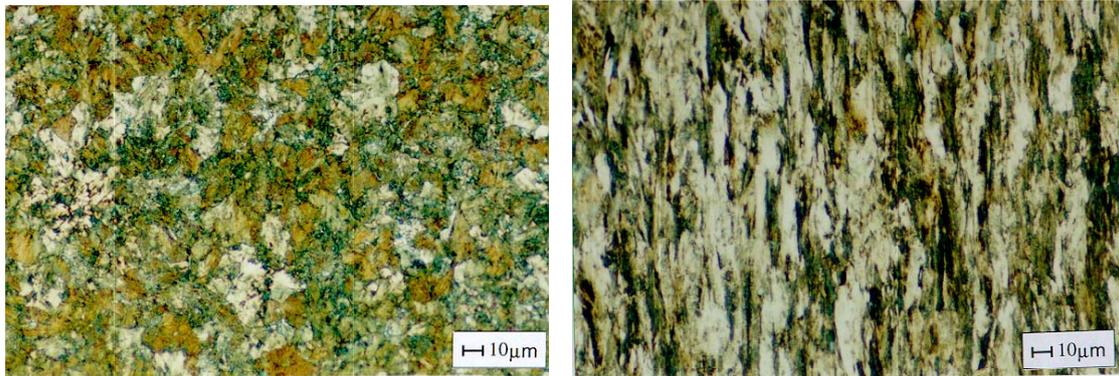


Figure 1. Pearlite colonies (first microstructural level) in steels 0 (left) and 6 (right).

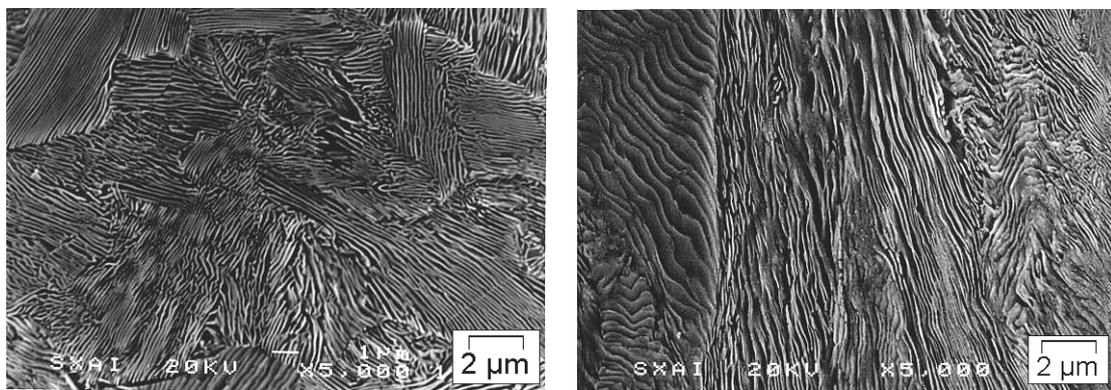


Figure 2. Pearlite lamellae (second microstructural level) in steels 0 (left) and 6 (right).

Therefore, both the pearlite colonies and the pearlitic lamellar microstructure tend to align to a direction quasi-parallel to the wire axis as cold drawing proceeds, thus inducing a progressive *strength anisotropy* in the steel, the degree of anisotropy being an increasing function of the level of cold drawing (or strain hardening) in the steels.

EXPERIMENTAL PROGRAMME

To relate these microstructural results to the macroscopic EAC behaviour, slow strain rate tests were performed on transversely precracked steel wires immersed in aqueous environment and subjected to axial loading. After precracking, samples were placed in a corrosion cell containing aqueous solution of 1g/l $\text{Ca}(\text{OH})_2$ plus 0.1g/l NaCl (pH=12.5). The experimental device consisted of a potentiostat and a three-electrode assembly: metallic sample (working electrode), platinum counter-electrode and saturated calomel electrode (reference). Tests were performed at constant electrochemical potential with the two values of -1200 mV SCE and -600 mV vs SCE, the former associated with the *cathodic regime* of cracking for which the environmental mechanism is *hydrogen assisted cracking* (HAC), and the latter linked with the *anodic regime* of cracking for which the environmental mechanism is *localised anodic dissolution* (LAD), cf. [5,6].

CONSEQUENCES OF COLD DRAWING ON CRACK PATHS

The experimental results showed a fundamental fact in both HAC and LAD: the EAC behaviour becomes more anisotropic as the degree of cold drawing increases, so a transverse crack tends to change its propagation direction to approach that of the wire axis, and thus a mode I growth evolves towards a mixed mode propagation. It may be assumed that the microstructural orientation in drawn steels influences the macroscopic behaviour, so that the EAC resistance is a directional property which depends on the microstructural orientation in relation to the cold drawing direction (*strength anisotropy* with regard to EAC behaviour). This anisotropic EAC behaviour of the drawn steels can be evaluated by means of the *crack path* or *fracture profile* after the EAC tests.

Hydrogen Assisted Cracking (HAC)

Fig. 3 shows the evolution of crack paths with cold drawing under HAC conditions, where a progressive change in the macroscopic topography as the cold drawing increases was observed in all fracture surfaces. Fig. 3a offers a 3D-view of these fracture surfaces, showing that mixed mode crack growth appears from a certain cold drawing level, and is associated with crack deflection which starts just at the tip of the fatigue precrack, i.e., a deviation in the crack growth path, from its initial fatigue crack growth path, appears at the very beginning of the HAC test.

Fig. 3b shows the geometric parameters describing the crack path, whereas the evolution of the fracture profile as the degree of cold drawing increases is given in Fig. 3c. In the first steps of cold drawing (specimens 0 and 1) the crack growth develops in mode I in both fatigue precracking and HAC. In steel 2 there is a slight deflection in the hydrogen-assisted crack, and this deflection is not uniform along the crack front but produces a wavy crack at different levels, and finally follows again the direction perpendicular to the wire axis. The same happens in steel 3, but in this case the deviation angle is higher. For the most heavily drawn steels (4 to 6) 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. In these last stages of cold drawing, not only crack deflection but also crack branching are seen just after the fatigue precrack tip, i.e., there are two pre-damage directions (*crack embryos*), only one of which becomes the final fracture path.

Localised Anodic Dissolution (LAD)

Fig. 4 shows the evolution of crack paths with cold drawing under LAD conditions, where a progressive change in the macroscopic topography as the cold drawing increases was observed in all fracture surfaces. Fig. 4a offers a 3D-view of these fracture surfaces. For the slightly drawn steels (0, 1 and 2), the fracture surfaces were macroscopically plane and oriented perpendicularly to the loading axis. Steel 3 shows a certain angle between the plane of the fatigue precrack and the fracture propagation direction in aggressive environment, evolving from mode I that maintains the crack propagation in the fatigue precracking plane to a mixed mode cracking, the growth direction changing to form an angle with the fatigue plane. In the most heavily drawn steels (4, 5 and 6) the deviation from the fatigue precrack plane was even higher.

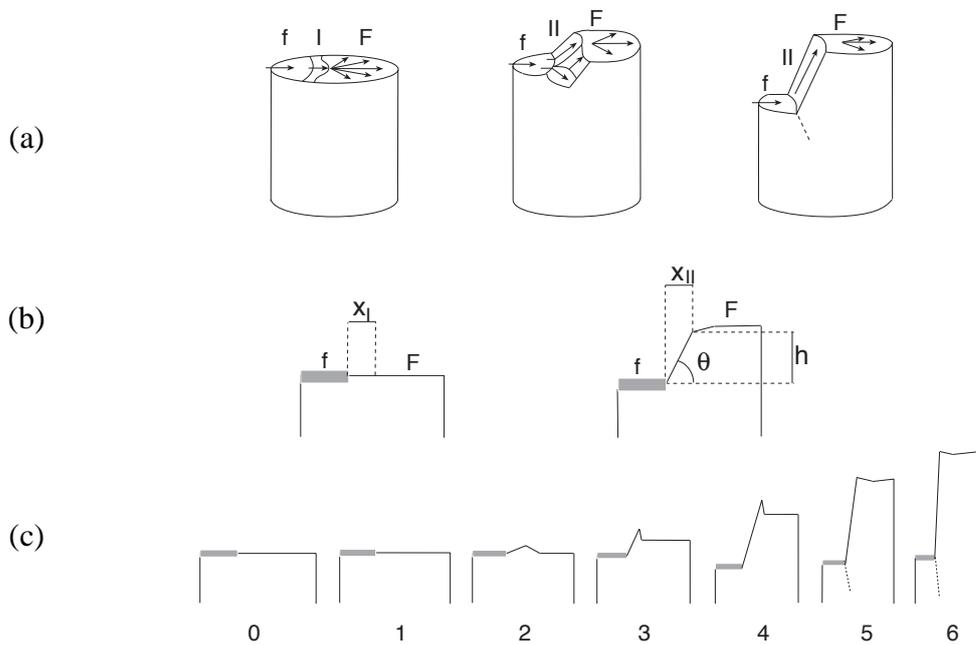


Figure 3. Evolution of crack paths with cold drawing (HAC environmental conditions): (a) general appearance of the fracture surfaces; (b) geometric parameters describing the crack path; (c) evolution of fracture profiles; f: fatigue crack growth; I: mode I cracking; II: mixed mode cracking; F: final fracture by cleavage at the critical situation.

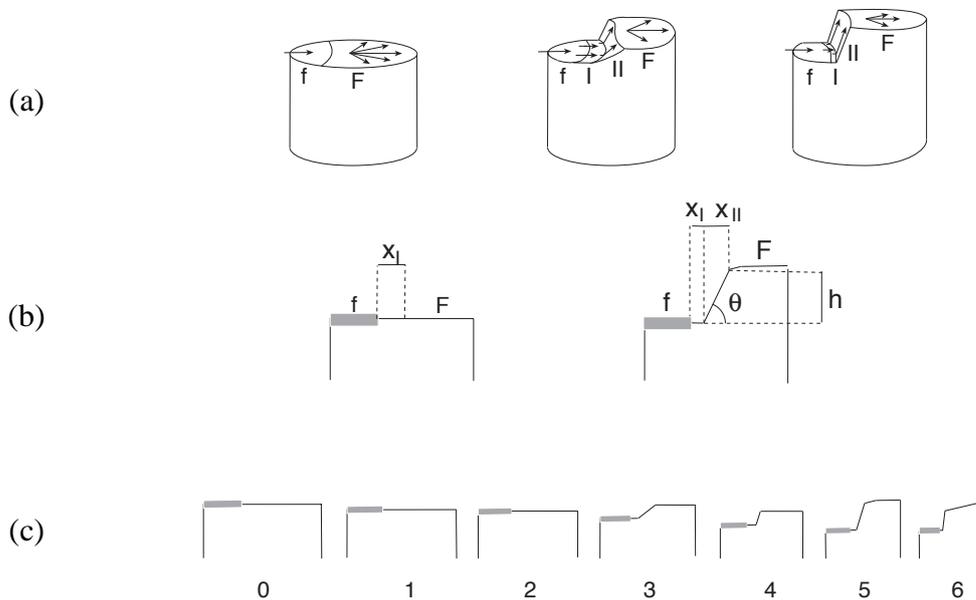


Figure 4. Evolution of crack paths with cold drawing (LAD environmental conditions): (a) general appearance of the fracture surfaces; (b) geometric parameters describing the crack path; (c) evolution of fracture profiles; f: fatigue crack growth; I: mode I cracking; II: mixed mode cracking; F: final fracture by cleavage at the critical situation.

In the steels with intermediate and high levels of cold drawing, the macroscopic crack path presents three characteristic zones (Fig. 4b). After the fatigue precrack there is a first propagation in its own plane (mode I cracking) over a distance x_I ; after this the crack changes its propagation direction and a mixed mode propagation takes place over a distance x_{II} (horizontal projection); finally the crack path follows the original direction up to final fracture. Fig. 4c offers the evolution of the fracture profile of all the steels. In heavily drawn steels (4 to 6), the mode I propagation distance decreases as the cold drawing degree increases, the step appears before and is associated with increasing values of the angle θ and the step height h , i.e., the crack growth path approaches the wire axis or cold drawing direction.

RELATIONSHIP BETWEEN MICROSTRUCTURE AND CRACK PATHS

In this section, a relationship is established between the microstructure of the steels (progressively oriented as a consequence of cold drawing) and the macroscopic crack paths (also evolving with the degree of cold drawing in the steels). Fig. 5a shows a plot of the evolution of the orientation angles of the pearlitic colonies and lamellae with cold drawing (angle α between the transverse axis of the wire and the major axis of the pearlite colony, modelled as an ellipsoid; angle α' between the transverse axis of the wire and the direction marked by the pearlite lamellae in the longitudinal metallographic section). In both cases there is an increasing trend with cold drawing, i.e., the pearlite colonies and lamellae become increasingly aligned in the drawing direction.

Fig. 5b shows the evolution with cold drawing of the macroscopic parameters characteristic of the crack path (fracture profile) in the HAC tests. In the slightly drawn steels the behaviour is isotropic or quasi-isotropic and the macroscopic hydrogen-assisted crack grows in mode I. The steels with an intermediate degree of cold drawing (2 and 3) exhibit a slight crack deflection associated with mixed mode propagation. In the most heavily drawn steels the crack deflection is more pronounced and the mixed mode takes place suddenly after the fatigue precrack, the deviation angle and the step height reaching their maximum values.

Fig. 5c shows the evolution with cold drawing of macroscopic parameters characteristic of the crack path (fracture profile) in the LAD tests. The behaviour is qualitatively similar to that of the HAC tests, i.e., isotropic or quasi-isotropic in the slightly drawn steels and increasingly anisotropic with cold drawing. The important difference is that the material is able to undergo mode I cracking in LAD conditions, even for the heavily drawn steels, although when the crack deflection appears the mode I propagation distance is a decreasing function of the degree of cold drawing (Fig. 5c).

Fig. 5 demonstrates that the progressive microstructural orientation (at the two levels of colonies and lamellae) clearly influences the angle and height of the fracture step (increasing with the degree of cold drawing in both HAC and LAD) and the mode I distance in LAD (decreasing with it for heavily drawn steels). This change in crack propagation direction can be considered as the signal of the microstructurally-induced anisotropy of these materials: from a certain degree of cold drawing the cracks find propagation directions with lower fracture resistance. Thus the macroscopic crack paths in the steels—indicating a progressively anisotropic behaviour with cold drawing—are a consequence of the microstructural evolution towards an oriented arrangement.

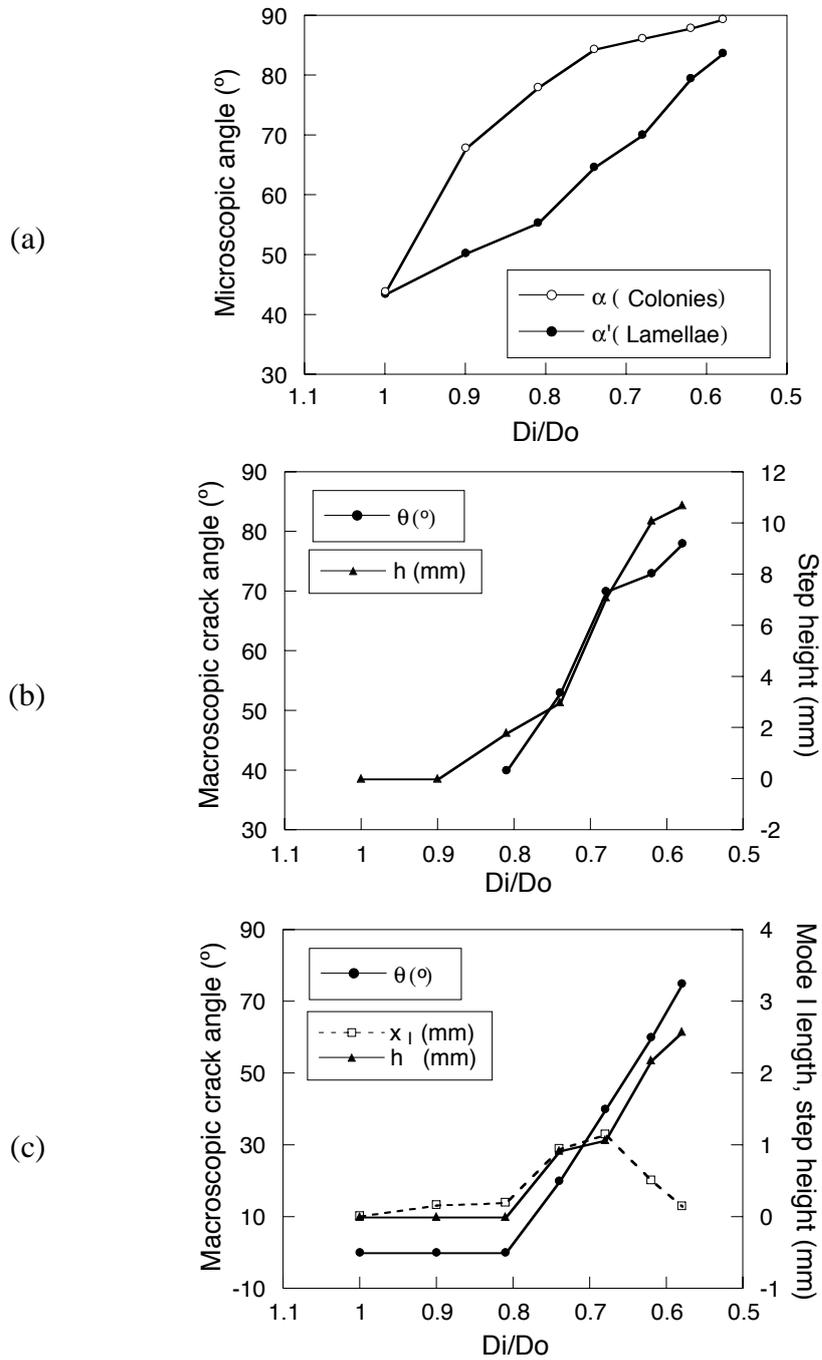


Figure 5. Relationship between the microstructure of the steels and the crack paths: (a) evolution with cold drawing of the orientation angles of colonies and lamellae in the pearlitic microstructure; (b) evolution with cold drawing of the macroscopic crack angle and step height in HAC conditions; (c) evolution with cold drawing of the macroscopic crack angle, step height and mode I propagation distance in LAD conditions; the angles α , α' and θ are measured from the radial direction (transverse to the wire axis).

CONCLUSIONS

The strong plastic deformations produced during manufacture affect the steel microstructure which becomes progressively oriented in the wire axis direction as a direct consequence of cold drawing. This happens at the two basic microstructural levels: the pearlite colony and the pearlitic lamellae. The material possesses thus a composite microstructure.

The afore-said microstructural orientation influences the microscopic and macroscopic aspects of the fracture mode in aggressive environments, showing a general evolution from crack propagation in mode I for slightly drawn steels to mixed mode propagation (with strong mode II component) for heavily drawn steels.

In the two EAC regimes (HAC and LAD) there is a strong correlation between the microstructural orientation angles (at the two levels of the pearlitic colonies and lamellae) and the macroscopic crack deflection angles (representing the macroscopic crack paths), which clearly demonstrates the influence of the oriented microstructure — and thus of the manufacture process by increasing cold drawing— on the macroscopic EAC behaviour of the steel wires.

Acknowledgements

The authors wish to acknowledge the financial support provided by the following Spanish Institutions: Ministry for Science and Technology (MCYT; Grant MAT2002-01831), Ministry for Education and Science (MEC; Grant BIA2005-08965), Ministry for Science and Innovation (MCINN; Grant BIA2008-06810), *Junta de Castilla y León* (JCyL; Grants SA067A05, SA111A07 and SA039A08), and the steel supplied by EMESA TREFILERÍA (La Coruña, Spain).

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