ANISOTROPIC FRACTURE BEHAVIOUR OF PROGRESSIVELY DRAWN PEARLITIC STEELS

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Abstract. In this paper the fracture performance of axisymmetric notched samples taken from prestressing steels with different levels of cold drawing is studied. To this end, a real manufacture chain was stopped in the course of the process, and samples of all intermediate stages were extracted. Thus the drawing intensity or straining level (represented by the *yield strength*) is treated as the fundamental variable to elucidate the consequences of the manufacturing route on the posterior fracture performance of the material. In addition, since samples with very different notch geometry are considered, the effect of *stress triaxiality* on fracture performance can also be analysed. The anisotropic fracture behaviour of the steels with high level of strain hardening is rationalized on the basis of the markedly oriented pearlitic microstructure of the drawn steels which influences the operative micromechanism of fracture in this case.

Resumen. En este artículo se estudia el comportamiento en fractura de muestras axisimétricas entalladas extraídas de aceros de pretensado con diferentes niveles de endurecimiento por deformación. Con este fin, se detuvo una cadena real de fabricación y se extrajeron muestras de los estadios intermedios. De este modo la intensidad del trefilado o nivel de endurecimiento por deformación (representado por el límite elástico) se trata como la variable fundamental para elucidar las consecuencias del proceso de fabricación sobre el comportamiento posterior en fractura del material. Además, puesto que se utilizan muestras con muy diferentes geometrías de entalla, puede estudiarse el efecto de la triaxialidad tensional sobre la fractura. El comportamiento anisótropo de aceros de pretensado con distinto grado de endurecimiento por deformación puede racionalizarse sobre la base de la microestructura marcadamente orientada en el acero fuertemente trefilado, lo cual condiciona el micromecanismo de fractura operativo en este caso.

1. INTRODUCTION

One of the major concerns in civil engineering construction and maintenance of prestressed concrete structures is the fracture performance of prestressing steel wires which are the fundamental components in the afore-said composite material (prestressed concrete), since these wires suffer the highest levels of stress and may be damaged by the combined action of both mechanical and environmental agents [1].

Manufacture process of prestressing steel wires consist of cold drawing in several passes an eutectoid pearlitic steel bar which was previously produced by hot rolling. From the micromechanical point of view, it is known that the drawing process influences the microstructure of the material [2,3] in the form of progressive trend towards a closer packing [4,5] and a more oriented arrangement [6,7] so that the pearlitic colonies and lamellae become quasi-parallel to the wire axis or drawing direction in the most heavily drawn steels.

At the macroscopic level, prestressing steel wires (heavily drawn) exhibit anisotropic fracture behaviour in air [8,9] and in aggressive environments promoting stress corrosion cracking in several forms [9-11]. A materials science link was established between the microstructure of the cold drawn steels —progressively oriented by manufacture— and the macroscopic fracture behaviour —increasingly anisotropic— in air [12] and corrosive environment [13,14].

This paper combines the effects of a high level of strain hardening produced by cold drawing in the steels (with its associated microstructural consequences) and the presence of stress raises such as notches of very different geometries which generate a triaxial stress state in their vicinity (*mechanical constraint* in the fracture process zone) and, what could be even more important in this research, produce a *geometric constraint* which forces the fracture path to maintain its own propagation plane, thereby establishing a competition between the material

anisotropy which tends to produce deflection of the cracking surface and the geometric constraint which obliges the fracture process to develop in mode I in spite of the inherent strength anisotropy of the material induced by microstructural orientation.

2. EXPERIMENTAL PROGRAMME

The materials were high-strength steels with different degrees of cold drawing. They were obtained from a real manufacturing process by stopping the production chain and taking samples from the intermediate stages. The different steels were named with digits 0 to 6 which indicate the number of cold drawing steps undergone, so steel 0 is the hot rolled bar (base material) and steel 6 is the prestressing steel wire (final commercial product) which has suffered six cold drawing steps.

Table 1 shows the chemical composition common to all steels, and Table 2 includes the diameter (D_i), the cold drawing degree (D_i/D_0), the yield strength (σ_{02}), the ultimate tensile stress (UTS) and the fracture toughness (K_{IC}) of the different steel wires. The K_{IC}-value given in Table 2 represents the critical stress intensity factor as a measure of failure resistance in each steel wire, but it is an actual fracture toughness only in the slightly drawn steels behaving isotropically. In heavily drawn steels (4 to 6) it is obtained *as if* the crack developed in mode I.

Table 1 – Chemical composition of the steels

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 – Diameter (D_i), cold drawing degree (D_i/D_0), yield strength (σ_{02}), ultimate tensile stress (UTS) and fracture toughness (K_{IC}) of the different steel wires.

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
D_i/D_0	1	0.90	0.81	0.74	0.68	0.62	0.58
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
K_{IC} ($MPam^{1/2}$)	60.1	61.2	70.0	74.4	110.1	106.5	107.9

Metallographic techniques were used to reveal the pearlitic microstructure of the steels at the two basic microstructural levels of pearlitic colonies and lamellae. Both microstructural units are seen to become progressively oriented tending to a direction parallel or quasi-parallel to the wire axis or cold drawing direction in the most heavily drawn material (steel 6).

Fracture tests under tension loading were performed on axisymmetric notched samples with a circumferentially-shaped notch. Four notch geometries were used with each material, in order to achieve very different stress states in the vicinity of the notch tip and thus very distinct *constraint* situations, thus allowing an analysis of the influence of such factors on the micromechanical fracture processes. The dimensions of the specimens named A, B, C and D throughout this paper:

Geometry A : R/D = 0.03, A/D = 0.10
Geometry B : R/D = 0.05, A/D = 0.30
Geometry C : R/D = 0.40, A/D = 0.10
Geometry D : R/D = 0.40, A/D = 0.30

where R is the notch radius, A the notch depth and D the external diameter of the axisymmetric specimen.

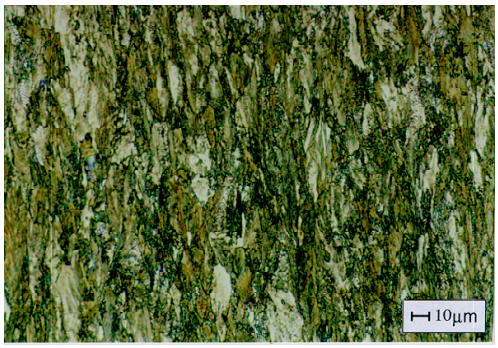
Three fracture tests were performed for each material and geometry (thus a total number of 84 tests were performed: seven materials, four notched geometries and three tests of each) recording continuously the load and the relative displacement between two points distant 25 mm. All the tests were performed under displacement control, so as to allow a complete recording of the load-displacement plot up to final failure.

3. FRACTOGRAPHIC ANALYSIS

In this section, a *macro*-fractographic analysis is performed of the shape of the fracture path depending on the kind of microstructural arrangement produced by the cold drawing process. The study is performed at the macro-level to correlate —in the sense of materials science— the microstructure of heavily drawn steels and their macroscopic fracture behaviourr.

Figs. 1 to 5 show the fracture profiles of notched samples of steels 4 and 6 (i.e., heavily drawn steels) with the geometries A, B and C, together with the pearlitic microstructure of the steels (cf. [4-7]) at the two levels of pearlitic colonies (first microstructural level) and lamellae (second microstructural level), and finally the fractographic appearance of the fracture propagation step parallel to the wire axis or cold drawing direction. A clear anisotropic fracture behaviour is observed in these heavily drawn steels in the form of fracture propagation deflection at an angle of about 90º in relation to the initial fracture propagation. Thus a fracture propagation step appears in a direction parallel to the wire axis of cold drawing direction as a consequence of the oriented microstructure of heavily drawn steels at the two basic microstructural levels of colonies and lamellae.

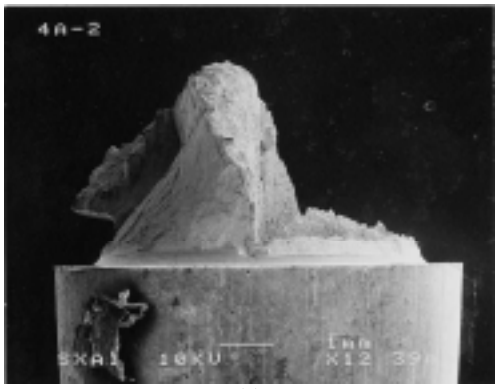
Geometry D does not appear because in this case of minimum triaxiality no clear evidence of anisotropic fracture behaviour in the form of *global* fracture step is detected, but only some *local* deflections which do not become a macroscopic propagation step oriented in the direction of wire axis. Such local deflections are only embryos of anisotropic behaviour.



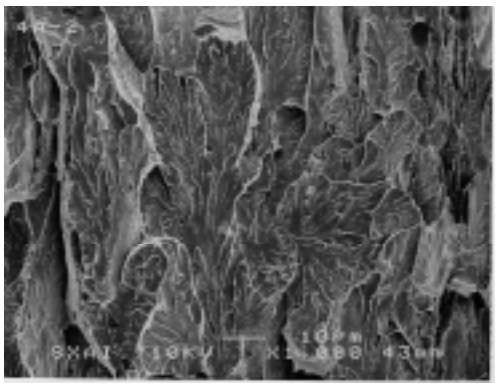
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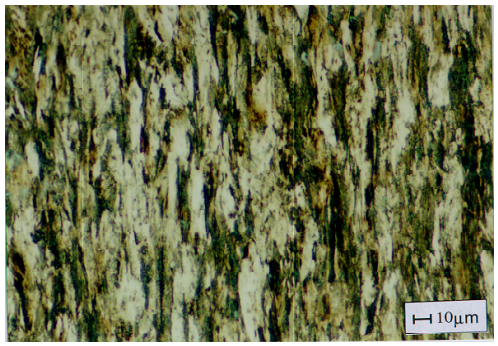


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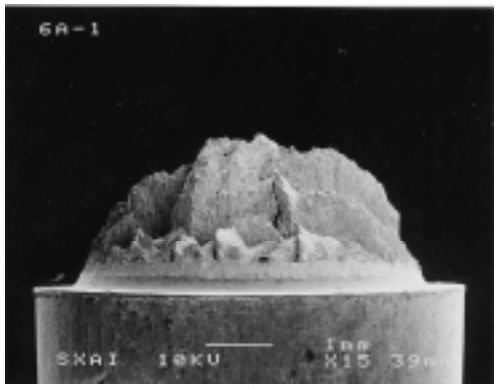
Fig. 1 – Specimen 4A: (a): pearlite colonies; (b) pearlite lamellae; (c) view of the fracture profile; (d) scanning electron micrograph of the fracture propagation step parallel to the wire axis or cold drawing direction.



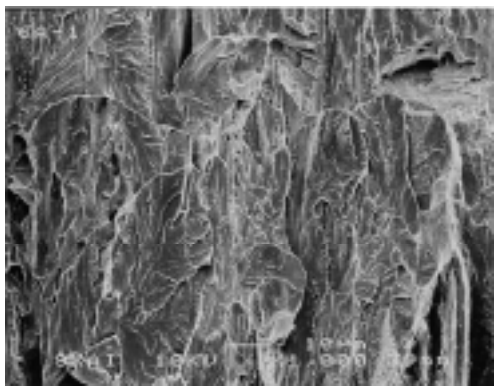
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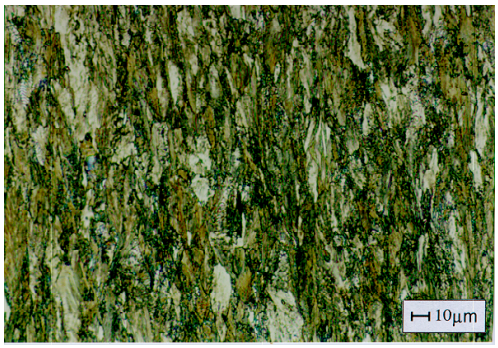


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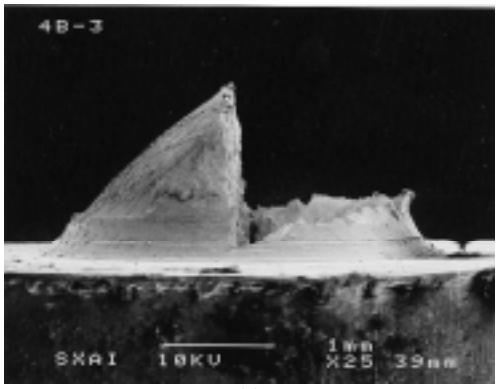
Fig. 2 – Specimen 6A: (a): pearlite colonies; (b) pearlite lamellae; (c) view of the fracture profile; (d) scanning electron micrograph of the fracture propagation step parallel to the wire axis or cold drawing direction.



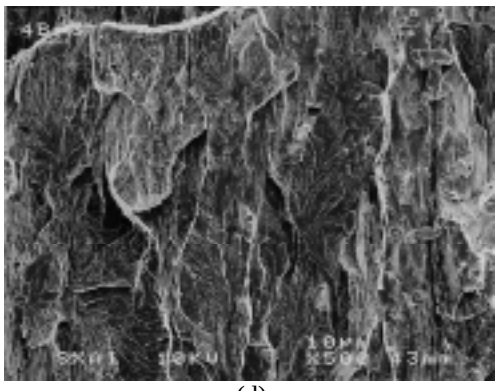
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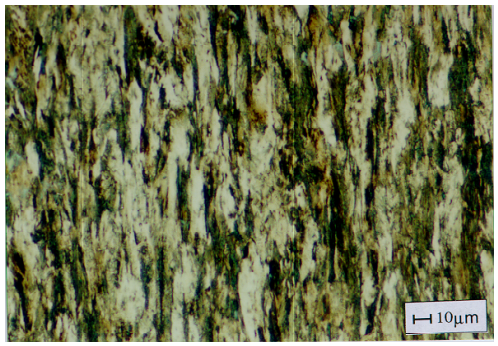


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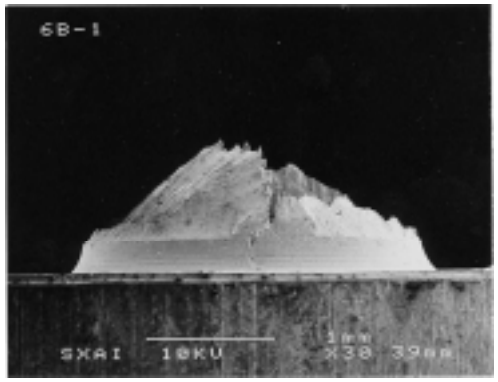
Fig. 3 – Specimen 4B: (a): pearlite colonies; (b) pearlite lamellae; (c) view of the fracture profile; (d) scanning electron micrograph of the fracture propagation step parallel to the wire axis or cold drawing direction.



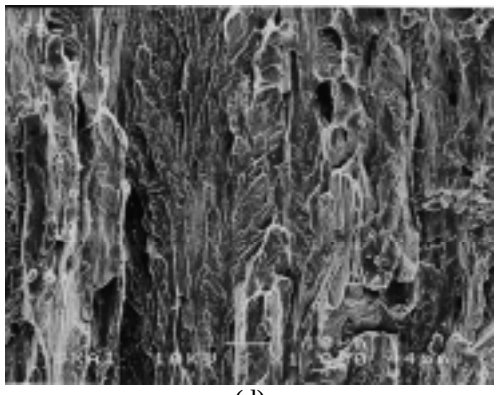
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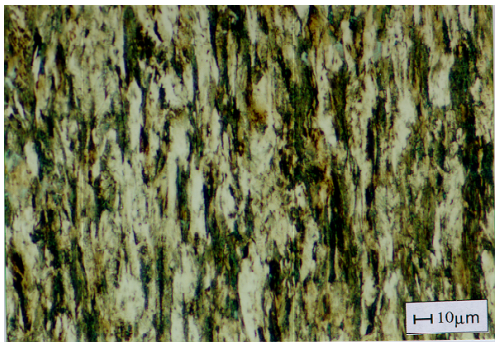


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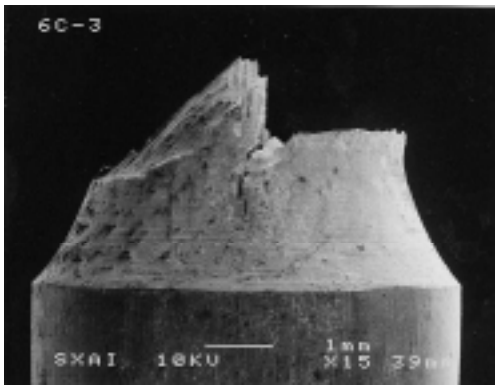
Fig. 4 – Specimen 6B: (a): pearlite colonies; (b) pearlite lamellae; (c) view of the fracture profile; (d) scanning electron micrograph of the fracture propagation step parallel to the wire axis or cold drawing direction.



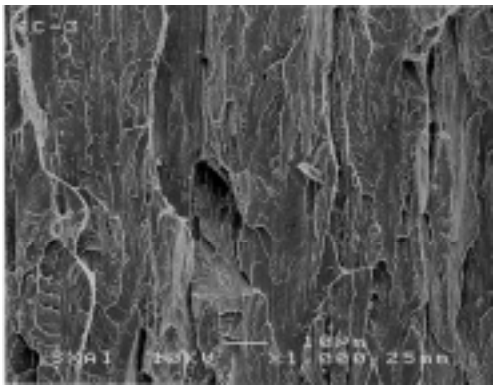
(a)



(b)



(c)



(d)

Fig. 5 – Specimen 6C: (a): pearlite colonies; (b) pearlite lamellae; (c) view of the fracture profile; (d) scanning electron micrograph of the fracture propagation step parallel to the wire axis or cold drawing direction.

Therefore, the afore said fracture propagation step (cf. Figs. 1c to 5c) is a signal of the strength anisotropy induced in heavily drawn steels as a consequence of the microstructural orientation (Figs. 1a to 5a; Figs. 1b to 5b) produced by the manufacturing process consisting of cold drawing. This fact produces fracture propagation deflection and *local* mixed mode crack growth with a strong component of mode II due to the deflection angle which is close to 90º.

In spite of the 90º propagation steps which appear in heavily drawn steels, these produce only a very stepped fracture surface but not a macroscopic *global* crack deflection due to the fact that the axisymmetric notch act as a geometric constraint which makes the fracture surface follow the external circumferential ring.

The fractographic appearance of the fracture propagation step parallel to the wire axis or cold drawing direction is given in Figs. 1d to 5d. It can be described as a kind of cleavage-like topography (with the typical river patterns which mark the propagation direction from bottom to top in the micrographs). It is not, however, conventional cleavage but a sort of *deformed and oriented cleavage*, where both the deformation and orientation are quasi-parallel to the axis of the wires.

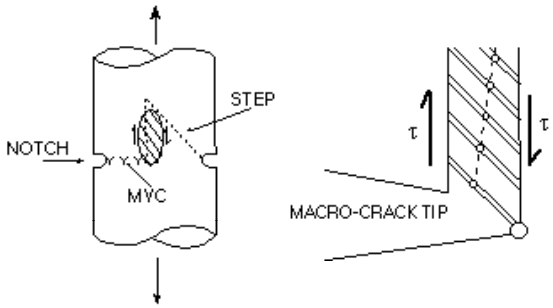
This special fractographic mode consisting of deformed and oriented cleavage indicates that: (i) the fracture propagation step is a typical unstable and fast fracture mode; (ii) such a step is a very directional mode oriented in the wire axis direction. The described characteristics are a logical consequence of the microstructural origin of the step.

4. MICROMECHANICAL MODELLING

In this section a micromechanical modelling of the anisotropic fracture behaviour in heavily drawn steels is offered, as shown in Fig. 6. It is based in the special microstructure of these materials. Fig. 6a shows a metallographic longitudinal section of the most heavily drawn material (steel 6). Apart from the standard pearlitic colonies shown in previous sections (oriented in the cold drawing direction), an exceptional *pearlitic pseudocolony* can be observed in certain areas of heavily drawn steels. This pseudocolony is extremely slender, aligned quasi-parallel to the wire axis, and has a specially high *local interlamellar spacing* due to the fact that the cementite plates are not oriented along the wire axis direction and in some cases are pre-fractured by shear during the manufacturing process. This characteristics makes it a preferential fracture path with minimum local resistance. Thus the pseudocolonies act as local fracture precursors, and their presence could explain the 90º step observed in heavily drawn steels. Fig. 6b offers a schematics showing the formation of the 90º-step when the initial fracture propagation path reaches the location of the pearlitic pseudocolony, and then the pearlitic plates are fractured by a mechanism of shear cracking (shown in Fig. 6c) according to the model proposed by Miller and Smith [15].



(a)



(b) (c)

Fig. 6 – Microstructural bases on anisotropic fracture bahaviour: (a) pearlitic pseudocolony; (b) formation of the 90º step, (c) fracture by shear cracking of pearlite in the pseudocolony, according to the model proposed by Miller and Smith in [15].

5. CONCLUSIONS

The manufacturing process by cold drawing in high-strength perlitic steels produces very important microstructural changes at the two levels of pearlitic colonies and lamellae which become progressively oriented in a direction quasi-parallel to the wire axis or cold drawing direction, thus resulting in a very markedly directional microstructure which influence the fracture behaviour of the materials.

From the materials science viewpoint, there is a clear relationship between the microstructural orientation (in the wire axis direction) produced by cold drawing and the appearance of the fracture profile which becomes more stepped as the degree of cold drawing increases, it being macroscopically flat in slightly drawn steels and very irregular (with 90º steps) in heavily drawn steels.

A micromechanical modelling is proposed of the anisotropic fracture behaviour of heavily drawn steels. The model is based on a metallographic evidence: the presence of some pearlitic pseudocolonies (in certain areas of the material) acting as weakest links or fracture precursors as a consequence of their very high local interlamellar spacing which makes them fail by a mechanism of shear cracking.

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