ANALYSIS OF A SPECIAL CLEAVAGE RELATED TO ANISOTROPIC FRACTURE IN HEAVILY DRAWN STEELS

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Abstract. This work studies the anisotropic fracture behavior of cold drawn prestressing steels which exhibit *exfoliation fracture* consisting of *oriented and enlarged cleavage*, its orientation being parallel to the wire axis or cold drawing direction, and with river patterns detectable in such a direction. Using a computer-assisted image analysis technique, a geometric relationship was found between this *special* cleavage and the *conventional* cleavage topography, which indicates that the fracture micromechanisms in both cases are also similar and allows a definition of the *critical fracture unit* in the drawn material as the pearlite colony more than the prior austenite grain. Thus the slender pearlitic colonies become the new microstructural fracture units and determine the size of the enlarged cleavage facets characteristic of the exfoliation fracture in notched samples of heavily drawn steels.

Resumen. Este artículo estudia el comportamiento anisótropo en fractura de aceros de pretensado que exhiben *fractura por exfoliación* consistente en *clivaje orientado y alargado*, con orientación paralela al eje del alambre o dirección de trefilado, y con claras figuras fluviales detectables en dicha dirección. Utilizando una técnica de análisis de imagen asistida por ordenador, se ha encontrado una relación geométrica entre este clivaje *especial* y la topografía de clivaje *convencional*, lo que indica que el micromecanismo de fractura es similar en ambos casos y permite la definición de la *unidad crítica de fractura* en el material trefilado como la colonia de perlita más que el grano austenítico previo. Así pues, las colonias deformadas se convierten en las nuevas unidades microestructurales de fractura y determinan el tamaño de las facetas alargadas de clivaje características de la fractura por exfoliación en muestras entalladas de acero fuertemente trefilado.

1. INTRODUCTION

Cold drawing is used to produce high-strength steel wires for prestressed concrete in civil engineering construction. This manufacturing technique affects the steel microstructure [1-2], thus leading to crack deflection and anisotropic fracture behavior in air atmosphere and aggressive environments [3-6].

This report deals with the strength anisotropy of cold drawn steels and studies, by means of computer-assisted image analysis techniques, a special mode of fracture (called *exfoliation fracture* throughout this paper) in notched samples of heavily drawn steels supplied from commercial stock.

2. EXPERIMENTAL PROGRAMME

Samples from a real industrial process were used. The manufacturing chain was stopped, and samples of five intermediate stages were extracted, apart from the original material or base product (hot rolled bar: not cold drawn at all) and the final commercial product (prestressing steel wire: heavily cold drawn).

The chemical composition —common to the seven steels— is given in Table 1. The name of each steel indicates the number of cold drawing steps which has undergone, as given in Table 2 for the most heavily drawn steels (from 4 to 6, the only analyzed in this paper), together with the diameter of each wire and the mechanical properties of the materials.

Fig. 1 shows the microstructure of steel 5 which has undergone five steps of cold drawing during the manufacture process. The two basic microstructural levels of pearlite colonies and pearlitic lamellar microstructure (ferrite/cementite) are oriented quasi-parallel to the direction of cold drawing (wire axis).

Fracture tests under tension loading were performed on axisymmetric notched samples with a circumferentially-shaped notch. Four notch geometries (cf. Fig. 2) 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.

Table 1. Chemical composition of the steels.

C	Mn	Si	P	S	Al	Cr	V
0.80	0.69	0.23	0.012	0.009	0.004	0.265	0.06

Table 2. Nomenclature, diameter and mechanical properties of the steels (measured in a standard tension test using smooth specimens).

Steel	4	5	6
D_i (mm)	8.15	7.50	7.00
D_i/D_0	0.68	0.62	0.58
E (GPa)	196.7	202.4	198.8
σ_Y (GPa)	1.239	1.271	1.506
σ_R (GPa)	1.521	1.526	1.762
P (GPa)	2.50	2.74	2.34
n	8.69	7.98	11.49

D_i: diameter of each steel wire after cold drawing
D_0: initial diameter before cold drawing (12 mm)
E: Young's modulus
σ_Y: yield strength
σ_R: ultimate tensile stress (UTS)
P, n: Ramberg-Osgood parameters: $\varepsilon = \sigma/E + (\sigma/P)^n$

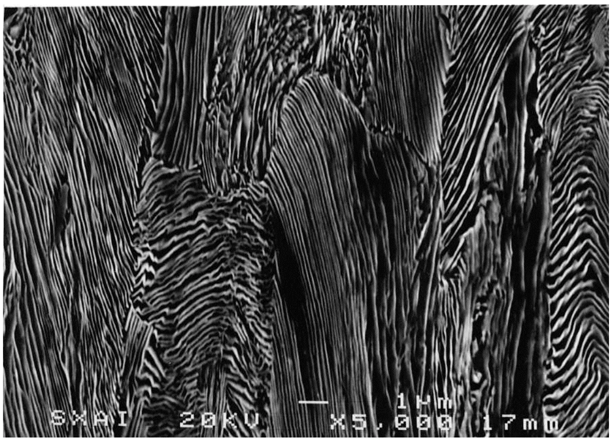


Fig. 1. Microstructure of steel 5. Cold drawing direction parallel to the vertical side of the micrograph.

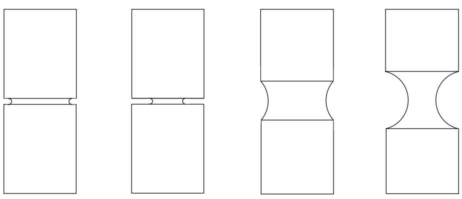
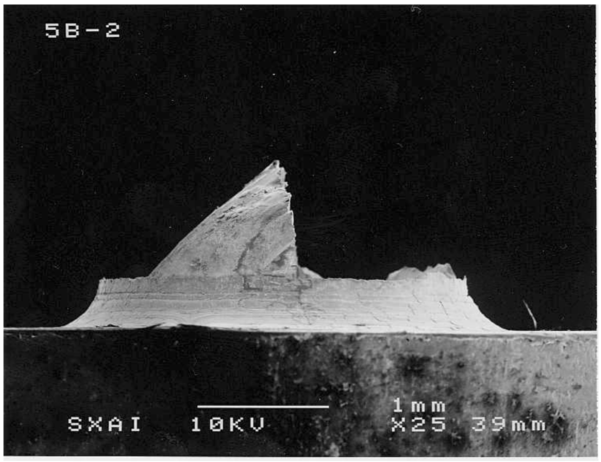


Fig. 2. Notched samples used in the experiments.

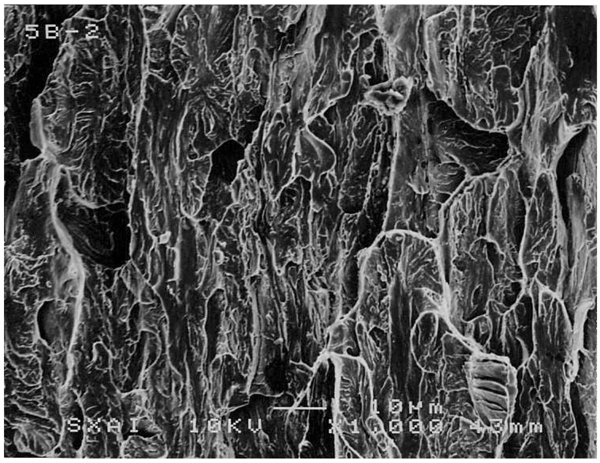
3. EXPERIMENTAL RESULTS

A significant result related to the notched samples of heavily drawn steels was the anisotropic fracture behavior exhibiting a propagation step oriented quasi-parallel to the wire axis or cold drawing direction (*exfoliation fracture*) whose macroscopic and microscopic aspect is given in Fig. 3 for specimen 5B.

The anisotropic fracture behavior described above may be explained on the basis of the very markedly oriented microstructural arrangement shown in Fig. 1 for a steel which has suffered five steps of cold drawing, and causes a special microscopic fracture mode in the step, as discussed in the next paragraph.



(a)



(b)

Fig. 3. Fractographic results of specimen 5B (steel 5 with five stages of cold drawing and notch geometry B of maximum stress triaxiality): view of fracture profile (a) and fractographic appearance of the vertical propagation step (b).

The fractographic appearance of the micrograph shown in Fig. 3b resembles cleavage-like fracture. However, it is not conventional cleavage, but a sort of *oriented and* *enlarged cleavage*, its orientation being parallel to the wire axis or cold drawing direction, and with river patterns which are detectable in such a direction.

This result is common to all heavily drawn wires (steels 4 to 6) with notched geometries with enough constraint (geometries A, B and C). This paper analyzes only the geometry B which exhibits the highest level of stress triaxiality, i.e., the maximum constraint, and thus brittle fracture is promoted in the material.

4. DISCUSSION

Given the cleavage-like aspect of Fig. 3b, now the question arises about whether or not a geometric relationship does exist between this *special* cleavage and the *conventional* cleavage topography. To check this possibility, a computer-assisted image analysis technique was used to transform the fractographs.

The technique was a *virtual* deformation of the photographs of the fracture steps in notched samples of different steels (but the same notch geometry) to check if one fractographic mode of a given degree of cold drawing could be obtained by computer deformation of that of a lower degree of cold drawing.

The computer-assisted virtual deformation of the fractographs was chosen with the same magnitude as the real cumulative plastic strain applied of each steel wire during real cold drawing. It was calculated on the basis of the volume conservation hypothesis of the mathematical theory of plasticity.

The described procedure may be viewed as a *virtual drawing* of the fractographs associated with the propagation steps as if the real drawing during the manufacture process and the anisotropic fracture behavior could be commuted. This operation can be applied to any drawn steel (exhibiting step) to yield a more heavily drawn one.

Fig. 4 shows the *virtual* fractograph of the propagation step in sample 5B (notched geometry B of maximum stress triaxiality and steel 5 which has undergone five stages of drawing). It was obtained by computer enlargement –in the drawing direction– of the *real* fractograph of the step in sample 3B (steel 3, geometry B of maximum stress triaxiality).

The comparison between Figs. 3b (real fractograph) and 4 (virtual fractograph) demonstrate their similarity, which indicates that the fracture micromechanisms in both cases (specimens 3B and 5B) are also similar and they are related to the cleavage fractographic mode with river patterns and cleavage facets.

In the case of conventional cleavage taking place in pearlitic eutectoid steel, the cleavage facet size is a strong function of the prior austenite grain size, although it is always somewhat less [7]. This size is the zone in which the adjoining pearlite colonies of the grain share a common crystallographic orientation of ferrite. It represents the *critical fracture unit* and determines the intrinsic toughness in an isotropic pearlitic material.

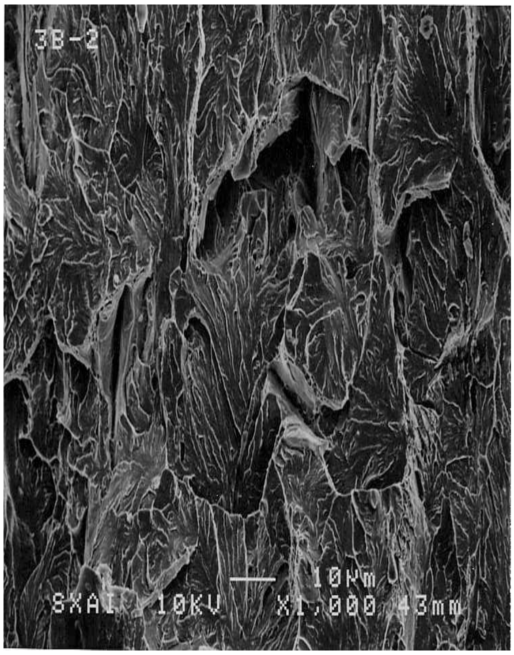


Fig. 4. *Virtual* fractograph of the propagation step in sample 5B (steel 5, geometry B), obtained by computer enlargement (in the cold drawing direction) of the *real* fractograph of the step in sample 3B (steel 3, geometry B of maximum stress triaxiality).

5. CONCLUSIONS

For anisotropic materials such as the cold drawn steels analyzed in this paper, there is a orientation of all microstructural units (and particularly of the pearlitic colonies) in the direction of cold drawing and therefore ferrite lamellae change their orientation during cold drawing (as a part of a colony and a set of ferrite/cementite plates which *do* orientate in the cold drawing direction (axis of the prestressing steel wire).

Then the *new* critical fracture unit in the drawn material would be the pearlite colony more than the prior austenite grain, because different pearlite colonies in the same grain follow distinct orientations paths along the manufacturing route. Thus the slender pearlitic colonies become the new microstructural fracture units and determine the size of the enlarged cleavage facets characteristic of the exfoliation fracture in notched samples of heavily drawn steels.

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