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MECHANISMS OF FRACTURE IN PEARLITIC STEELS WITH DIFFERENT DEGREES OF COLD DRAWING

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ABSTRACT

In this paper the fracture process of steels with different levels of cold drawing is studied. Results demonstrated that progressive drawing affects the fracture behavior, so that heavily drawn steels exhibit anisotropic fracture behavior with a change in crack propagation direction which approaches the wire axis or cold drawing direction. A micromechanical model of fracture is proposed to rationalize the results on the basis of the microstructural evolution in the steels as a consequence of the drawing process which produces a progressive orientation, along the drawing axis, of the two basic microstructural levels: the pearlite colonies and the pearlitic lamellae. In slightly drawn steels, the Miller-Smith model of shear cracking in pearlite seems to be adequate to describe the fracture process. In heavily drawn steels, a fracture propagation step appears, and it may be caused by extremely slender *pearlitic pseudocolonies* aligned in the drawing direction, with very high *local* interlamellar spacing which makes them preferential fracture paths with minimum local resistance.

KEYWORDS

Pearlitic steel, cold drawing degree, fracture micromechanisms, microstructure-based modeling.

INTRODUCTION

Manufacturing of pearlitic steels to obtain prestressing steel wires to be used in prestressed concrete structures consists of cold drawing a hot rolled bar in several passes to increase the yield strength by producing strong plastic deformations in the material. Thus the manufacturing process in the form of increasing cold drawing — with the subsequent progressive plastic deformation— produces important microstructural changes in the steel which could influence its ulterior fracture performance.

Previous research on this topic dealt *only* with the first and last steps of the cold drawing manufacturing process, i.e., the hot rolled bar (base material) and the commercial cold drawn prestressing steel wire (high-strength material to be used in prestressed concrete). Ref [1] presents a general overview, while [2] studies the anisotropic fracture behavior of the fully drawn wire. This paper analyzes the fracture phenomenon in wires of eutectoid pearlitic steel with *intermediate* degrees of cold drawing.

EXPERIMENTAL PROGRAM

Samples from a real manufacturing process were supplied by EMESA TREFILERIA. The manufacture chain was stopped in the course of the process, 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). Thus the *drawing intensity* (or straining level) is treated as the fundamental variable to elucidate the consequences of manufacturing on the posterior fracture behavior. The different steels were named with digits 0 to 6 which indicate the number of cold drawing steps undergone. Table 1 shows the chemical composition common to all steels, and Table 2 includes the diameter (D_i), the yield strength (σ_Y), the ultimate tensile stress (σ_R) and the fracture toughness (K_{IC}), cf [3].

TABLE 1
CHEMICAL COMPOSITION (wt %) 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 REDUCTION AND MECHANICAL PROPERTIES OF THE STEELS

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_Y (GPa)	0.686	1.100	1.157	1.212	1.239	1.271	1.506
σ_R (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

Cold drawing produces changes in the pearlite colony (first microstructural unit) in the form of slenderizing [4] and progressive orientation parallel to the wire axis or cold drawing direction [5]. Drawing also produces changes in the lamellae in the form of decrease of interlamellar spacing [6] and orientation parallel to the wire axis [7]. Figures 1 and 2 (cf.[5,7]) show the pearlitic microstructure of steel 6 at the levels of pearlite colonies and pearlitic lamellae respectively, by means of optical and scanning electron micrographs corresponding to longitudinal metallographic sections of the wires (those sections containing the wire axis). It is seen that the microstructure of steel 6 (prestressing steel heavily cold drawn) is markedly oriented in the direction of the wire axis (or cold drawing direction) which corresponds to the vertical side of the two micrographs.

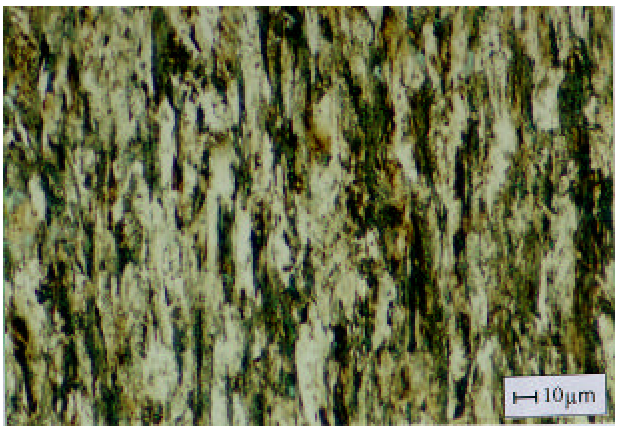


Figure 1: Optical micrograph (steel 6).

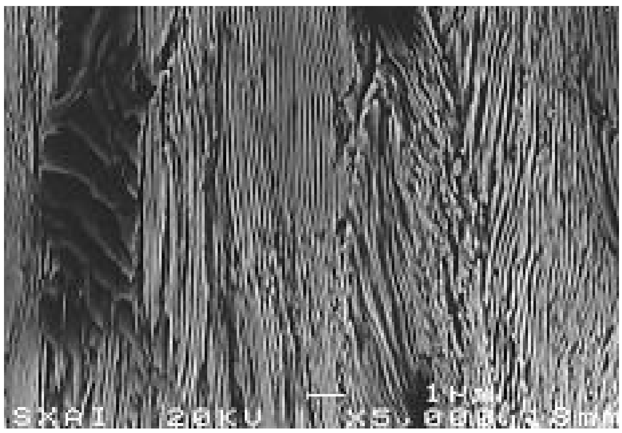


Figure 2: Scanning electron micrograph (steel 6).

In addition, in the most heavily drawn steels there are some exceptional *pearlitic pseudocolonies* (cf. [8]) which are extremely slender, aligned quasi-parallel to the drawing direction and whose *local interlamellar* *spacing* is clearly anomalous —specially high— in comparison with the average (or global) spacing because the cementite plates are not oriented along the wire axis direction so that they are pre-fractured by shear during manufacture, as shown in the left part of Figure 2. The characteristics of these pseudocolonies make them local precursors of micro-cracking, i.e., preferential fracture paths with minimum local fracture resistance [9].

To analyze the fracture mechanisms in the steels with different degrees of cold drawing, two sets of tests were performed: (i) fracture tests on cylindrical precracked samples; (ii) fracture tests on axisymmetric notched specimens with a circumferentially-shaped notch. In the latter case, four notch geometries were used, with the following dimensions: notch A : R/D = 0.03, A/D = 0.10, notch B : R/D = 0.05, A/D = 0.30, notch C : R/D = 0.40, A/D = 0.10, notch D : R/D = 0.40, A/D = 0.30, where A is the notch depth and R the notch radius.

RESULTS

Figure 3 shows the fracture modes in precracked samples. The initial hot rolled material (steel 0) and the slightly drawn steels (steels 1-3) behave isotropically, i.e., cracking develops in mode I following the initial plane of fatigue crack growth (Figure 3a). The most heavily drawn steels (steels 4-6) exhibit a clearly anisotropic fracture behavior in the form of crack deflection after the fatigue precrack with a deviation angle of almost 90º from the initial crack plane and further propagation in a direction close to the initial one (Figure 3b).

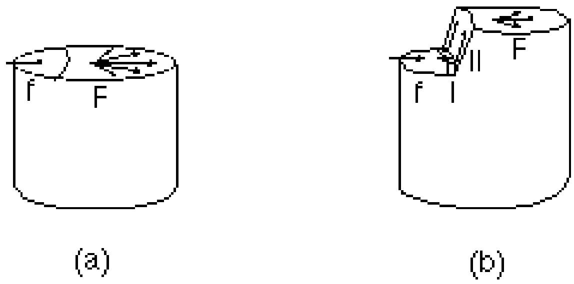


Figure 3: Fracture modes: (a) slightly drawn steels 0-3; (b) heavily drawn steels 4-6; f: fatigue precracking; I: mode I subcritical cracking, II: 90º propagation step; F: final fast fracture.

The fractographic analysis by scanning electron microscopy showed *predominant* appearances from brittle cleavage (C) in the slightly drawn steels (Figure 4: steel 1) to ductile micro-void coalescence (MVC) in the heavily drawn steels (Figure 5: steel 5). The 90º-step appears at a distance x_S from the fatigue precrack tip, and this distance decreases as the cold drawing degree increases, i.e., the step gets closer to the fatigue precrack as the drawing becomes heavier, and in the fully drawn material (steel 6) the step is located just at the fatigue precrack tip (x_S=0). The fibrous appearance of the described step is shown in Figure 6 at two different scales.

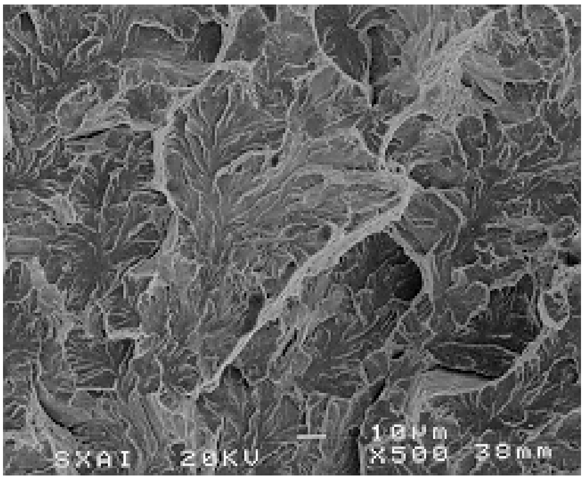


Figure 4: Fracture by cleavage in steel 1.

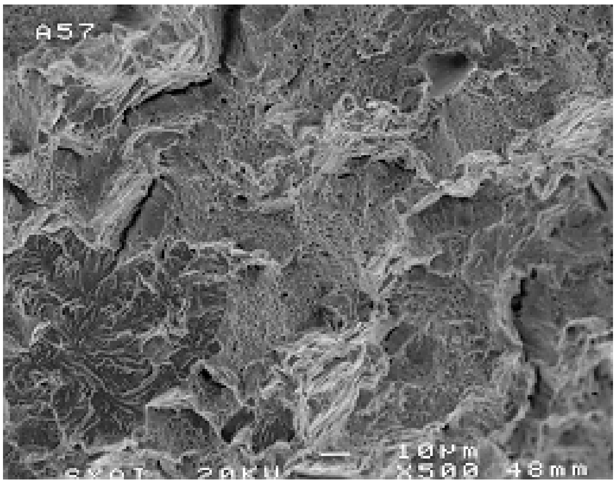


Figure 5: Fracture by MVC in steel 5.

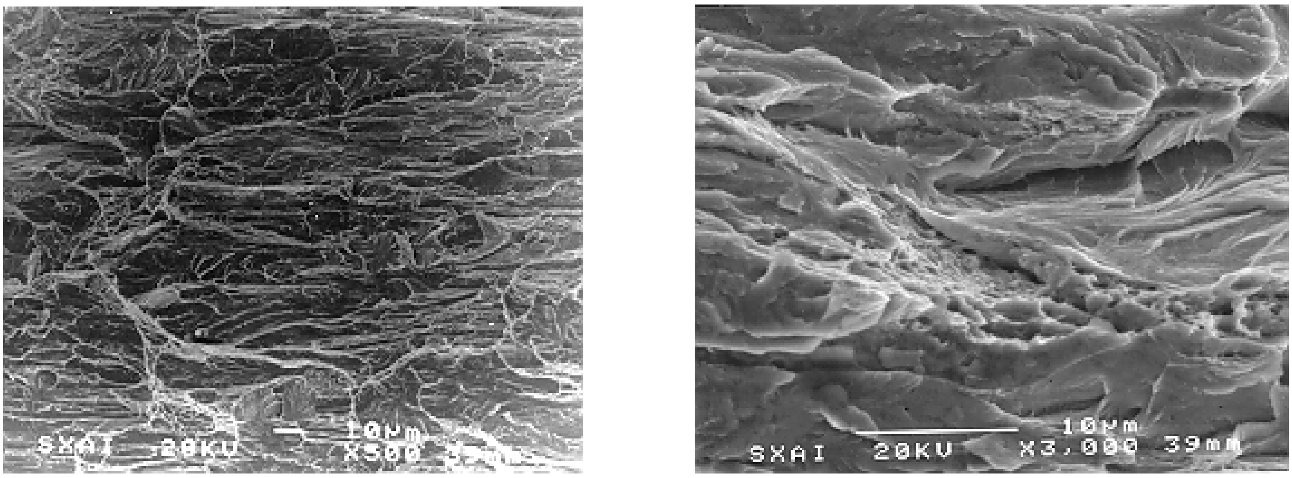
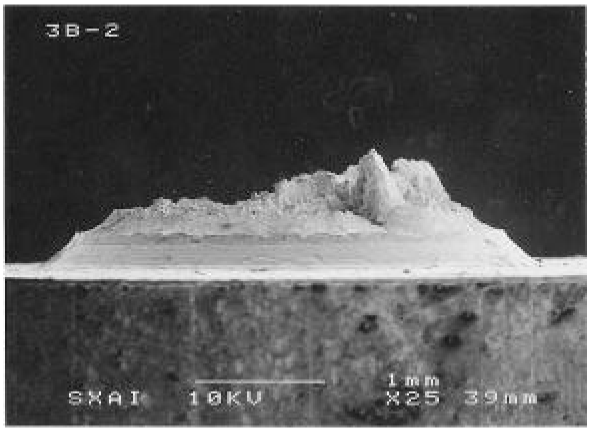


Figure 6: Fractographic appearance of the 90º-step in steel 6, at two different scales

Figure 7 shows two fracture profiles obtained in notched samples (in notch B of maximum stress triaxiality). The fracture profile becomes more stepped as the microstructural orientation in the direction of the wire axis increases as a consequence of cold drawing. This fact explains why specimen 3B (left) exhibits a slightly stepped fracture profile, whereas in the fracture profile of specimen 4B (right) there is a macroscopic step perpendicular to the initial propagation direction transverse to the wire axis. The step is oriented parallel to the wire axis, as in the case of precracked samples of heavily drawn steel.



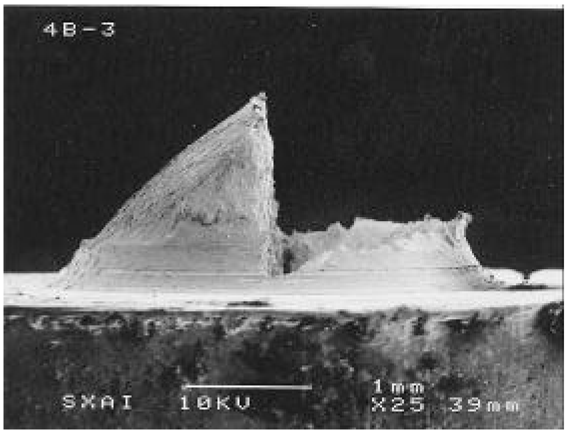


Figure 7: Fracture profile of notch B (maximum depth; minimum radius) and steels 3 (left) and 4 (right).

MICROMECHANICAL MODELLING

Hot Rolled and Slightly Drawn Steels

Since hot rolled and slightly drawn steels exhibit isotropic fracture behavior, a classical micromechanical model for this kind of microstructure allows a rationalization of the fracture behavior. In this framework, the most commonly accepted model is that proposed by Miller and Smith [10] on the basis of a micromechanism of shear cracking in pearlite. It has been used many times in the scientific literature to explain the fracture process in different types of pearlitic microstructures, cf. [11-15].

The model is illustrated in Figure 8 which suggests that micro-cracks are formed by *shear cracking*. First of all, slip takes place in ferrite when the material is stressed. Secondly, due to the stress concentration at the ferrite/cementite interfaces along the ferrite slip plane, the cementite plates become fractured and promote shear. When the shear becomes large enough, there is a final phase of link-up of the holes to form a macroscopic crack which promotes final fracture.

The model by Miller and Smith is able to explain different fracture processes of pearlitic microstructures in air environments (cf. [12]), ranging from ductile MVC to brittle cleavage catastrophic failure. Many times, there is a dimple fracture initiation (ductile region of certain microstructural size) followed by cleavage propagation. The critical size for final fracture depends on the temperature, strain rate and stress triaxiality in the local fracture region [12].

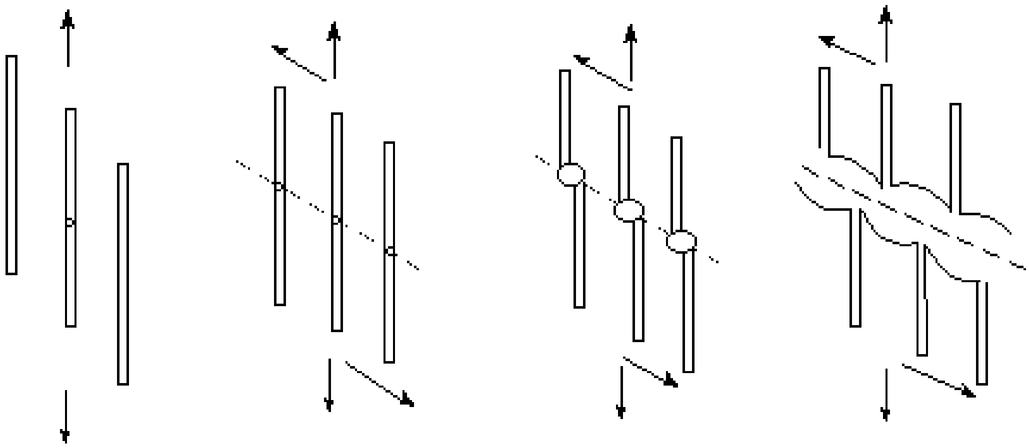


Figure 8: Micromechanical model of fracture by shear cracking in pearlitic microstructures (after Miller and Smith [10]) applicable to fracture in hot rolled and slightly drawn steels.

Heavily Drawn Steels

The anisotropic fracture behavior in heavily drawn steels can be rationalized on the basis of the oriented pearlitic microstructure of the steels. In the metallographic analysis on these steels, some pearlitic pseudocolonies appear aligned to the cold drawing direction and they 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 of *shear cracking* in pearlitic microstructures proposed by Miller and Smith [10].

(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 (mechanical pre-damage)

Thus the pearlitic pseudocolonies act as local micro-crack precursors, and their presence could explain the fracture path in heavily drawn steels (Figure 3b). Figure 9 offers a scheme showing the formation of the 90º-step when the macro-crack (starting from the precrack or from the notch tip) reaches the location of the pearlitic pseudocolony (Figure 9a), and then the pearlitic plates are fractured by a mechanism of shear cracking (shown in Figure 9b) according to the model proposed by Miller and Smith [10].

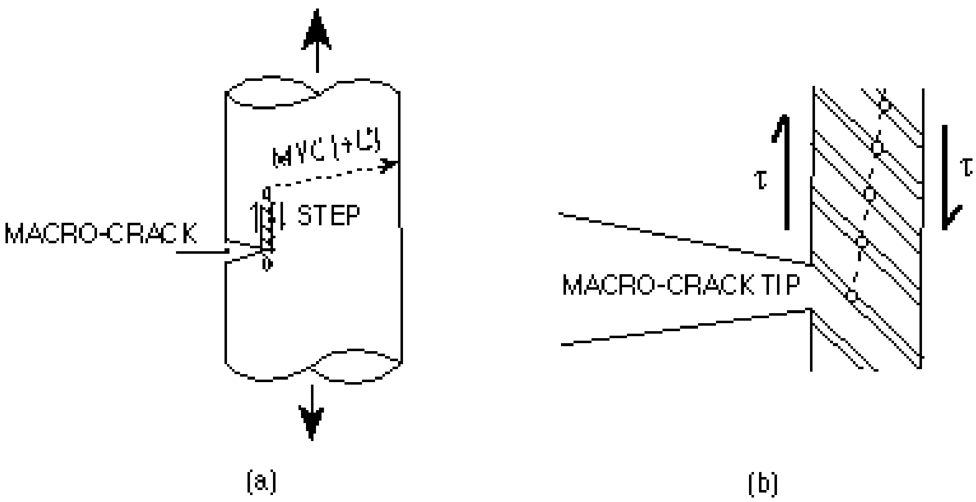


Figure 9: Micromechanics of final fracture in heavily drawn steels: (a) the 90º-step appears when the macro-crack reaches an extremely slender *pearlitic pseudocolony* with anomalous (very high) local interlamellar spacing; (b) the pseudocolony fails very easily by shear cracking of pearlite, according to the model proposed by Miller and Smith [10].

Finally, Figure 10 offers a general sketch of the fracture process in heavily drawn steels, with a first stage of propagation by MVC over a distance x_S up to the appearance of the 90º-step The distance x_S (i.e., the mode I propagation length) is a decreasing function of the drawing degree, a consequence of the frequency of appearance of pseudocolonies which is higher when drawing becomes heavier, i.e., the average distance between these microstructural units is a decreasing function of the level of drawing. The heavier the drawing, the higher the probability of change in crack propagation direction.

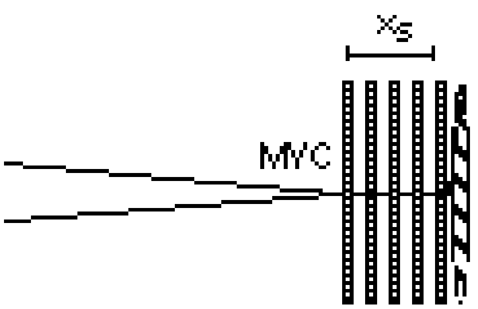


Figure 10: Micromechanical model of initiation and final fracture in heavily drawn steels. The microstructure is assumed to be totally oriented in the cold drawing direction.

CONCLUSIONS

While the fracture behavior of slightly drawn steels is isotropic (mode I propagation), the heavily drawn steels exhibit anisotropy and crack deflection (mixed mode propagation).

In slightly drawn steels, the fracture micromechanism consists of shear cracking in the pearlitic microstructure according to the model proposed by Miller and Smith.

In heavily drawn steels, crack deflection takes place when the macrocrack reaches the position of a pearlitic pseudocolony which represents a local fracture precursor.

Acknowledgements

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