ANISOTROPIC FRACTURE BEHAVIOUR OF EUTECTOID STEELS WITH DIFFERENT DEGREES OF DRAWING

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In this paper the fracture performance of steels with different levels of cold drawing is studied. Results demonstrated that progressive cold drawing affects clearly the fracture performance, i.e., the most heavily drawn steels exhibit anisotropic fracture behaviour with a change in crack propagation direction which approaches the wire axis or cold drawing direction. At the microscopical level, clear changes are observed in the micrographs with appearances from cleavage-like in the slightly drawn steels to predominant micro-void coalescence in the heavily drawn steels. From the engineering point of view, the fracture toughness of the steels increases with cold drawing.

INTRODUCTION

The study of eutectoid prestressing steels has special importance in civil engineering structures where prestressed concrete is widely used (Elices (1)). These steels are manufactured from a previously hot rolled bar with pearlitic microstructure which is heavily cold drawn in several passes to obtain the commercial prestressing steel wire with increased yield strength obtained by a strain-hardening mechanism. Macroscopically, cold drawing produces a progressive reduction in the diameter of the wire by both axial tensile stresses and transverse compressive stresses. Therefore, the final commercial product has undergone strong plastic deformations able to modify drastically its microstructure and to induce progressive anisotropy in the material as a consequence of the important changes at the microstructural level. Thus, although it is clear that cold drawing improves the (traditional) mechanical properties of the steel (i.e., those properties useful for regular service), the microstructural changes during manufacture may produce anisotropic fracture behaviour, as reported previously (Toledano and Toribio (2)).

In this paper the fracture performance of steels with different levels of cold drawing is studied. Thus the *drawing intensity* (or straining level) is treated as the fundamental variable to elucidate the consequences of the manufacturing route on the posterior fracture performance of the material.

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MATERIALS

Samples from a real manufacturing process were supplied by EMESA TREFILERIA (La Coruña, Spain). 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).The chemical composition —common for 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, together with the diameter (D_i) of each wire, the yield strength (σ_{02}) and the ultimate tensile strength (σ_R) showing an expected improvement of (traditional) mechanical properties as the cold drawing proceeds.

TABLE 1– Chemical composition (wt %) of the steel

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 – Nomenclature, diameter and yield strength of the wires

Nomenclature	A0	A1	A2	A3	A4	A5	A6
Diameter 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
σ_R (GPa)	1.175	1.294	1.347	1.509	1.521	1.526	1.762

EXPERIMENTAL PROCEDURE

To analyze the fracture phenomenon in prestressing steels with different degrees of cold drawing, cylindrical samples of 30 cm were used by cutting the steel wires. A starter notch was produced by means of a jewellers file in a plane perpendicular to the wire axis. Samples were subjected to axial fatigue (tensile loading/unloading in the direction of the wire axis) to produce a precrack before the fracture test. Finally, the fatigue precracked rods were subjected to monotonic tensile loading up to fracture with a crosshead speed of 3 mm/min to elucidate the fracture behaviour of the steels and to evaluate the fracture toughness as the critical value of the stress intensity factor K in the cracked bars. To this end, an expression of K for a cylinder with a part-through semi-elliptical transverse crack was used as calculated by Valiente (3) using the finite-element method together with a compliance technique to obtain a global value of the stress intensity factor.

EVOLUTION OF FRACTURE BEHAVIOUR

Macroscopic Analysis

An important experimental fact is observed in the most heavily drawn steels (A4 to A6); it consists of the change in crack propagation direction approaching the wire axis, which represents a deviation angle of almost 90° from that of the propagation throughout the initial plane of the crack (perpendicular to the wire axis). Therefore, the hot rolled bar (which is not cold drawn) and the weakly drawn steels exhibit an isotropic or quasi-isotropic fracture behaviour (it being fully isotropic in the hot rolled bar), whereas the strongly drawn steels exhibit a clearly anisotropic fracture behaviour associated with a deviation angle of almost 90° from the initial crack plane and further propagation in a direction close to the initial one (20-30° from it). The macroscopic fracture mode and the fracture toughness K_{IC} of the steels, measured following the procedure described above, are given in Table 3.

TABLE 3 – Fracture toughness and depth of the ductile region in the steels

Steel	A0	A1	A2	A3	A4	A5	A6
Fracture mode	I	I	I	I	mixed	mixed	mixed
K_{IC} (MPam$^{1/2}$)	63	61	70	74	110	106	107
x_m (μm)	0	0	2.8	32.7	–	–	–
x_s (μm)	–	–	–	–	850	450	0

Microscopic Analysis

To analyze the microscopical modes of fracture, a fractographic analysis by scanning electron microscopy (SEM) was performed on the fracture surfaces of the broken samples. In the first stages of cold drawing (Fig. 1: steels A0 which is not cold drawn and A1) the microscopic fracture mode is cleavage-like. In steels A2 and A3 (Fig. 2) the fracture process initially develops by micro-void coalescence (MVC) and continues by cleavage. Thus a first ductile region of depth x_m is found before the cleavage-like region, as sketched in Fig. 3. The depth of this MVC region was measured and results appear in Table 3. The most heavily drawn steels (A4 to A6) exhibit anisotropic fracture behaviour with a 90°-step, as described above, although certain mode I crack growth appears before the step over a distance x_s (Fig. 4) in which the MVC micro-fracture mode is predominant although the meso-roughness is higher than in the slightly drawn steels. The depth x_s was also measured and the results given in Table 3.

Discussion

The anisotropic fracture behaviour of the most heavily drawn steels is consistent with previous research on prestressing steel (Astiz et al. (4)) and may be explained on the basis of results from metallographic analyses (Toribio et al. (5))

which demonstrate that the microstructure of the steels becomes oriented in the wire axis direction as a consequence of cold drawing, and this happens for the two microstructural levels: the pearlite colony and the pearlite interlamellar spacing.

The macroscopic fracture modes are a function of cold drawing and the clear improvement of fracture toughness in steels A4 to A6 can be attributed to the presence of the mixed mode (associated with the 90°-step). In addition, the level of ductility —measured as the depth of the MVC region x_m— is in principle an increasing function of cold drawing, although this trend is inverted when the mixed mode appears and then the 90°step interrupts the development of the MVC region, so that the 90° step gets closer to the fatigue precrack border (x_s decreases) as the cold drawing degree increases, and in the fully drawn steel (A6) the step is located just at the fatigue precrack border.

The fracture toughness increases with cold drawing, but its evaluation is strictly valid (characteristic of the material independent of the particular geometry) if the fracture process develops in mode I. When the mixed mode appears, an "apparent" toughness —which is not a material property— can be measured and it is only valid for the precracked wire geometry and useful for engineering design when this structural element is used.

CONCLUSION

A relationship was found between the drawing intensity and the fracture behaviour of the steels at both the microscopic and the macroscopic levels. When the cold drawing degree increases there is an associated increase of the level of ductility, the mixed mode ratio and the "apparent" fracture toughness.

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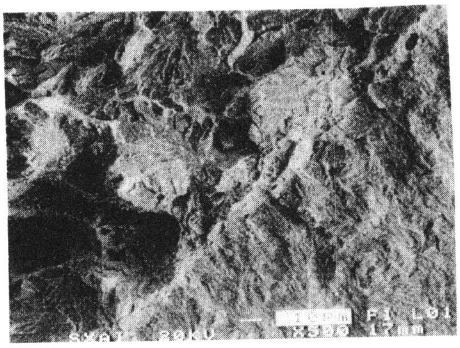

Figure 1. Microscopic fracture mode in the two first stages of cold drawing (steels A0 and A1). The crack propagates from the bottom to the top.

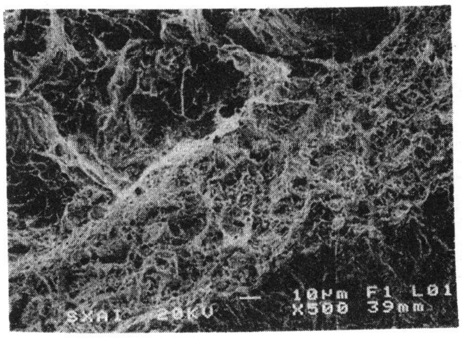

Figure 2. Microscopic fracture mode in steels A2 and A3.

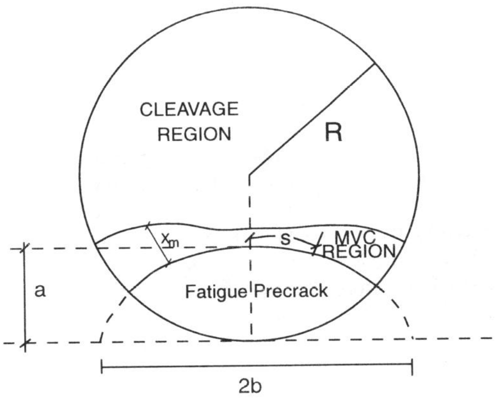

Figure 3. Sketch of crack propagation in steels A2 and A3.

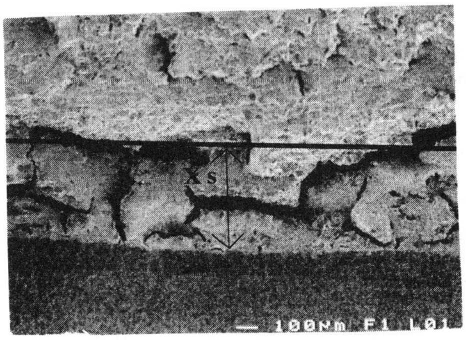

Figure 4. Fracture propagation in steels A4 and A5 (heavily drawn).