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APPROXIMATE EVALUATION OF' DIRECTIONAL TOUGHNESS IN COLD DRAWN PEARLITIC STEELS

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ABSTRACT

In this paper, an approximate procedure is proposed to estimate the fracture toughness of heavily drawn pearlitic steels in both longitudinal (wire axis) and transverse (perpendicular) directions, calculating the critical load at the pop-in situation (coincident with crack deflection) and at the catastrophic failure instant (final fracture which takes place at maximum load). The method is based on the experimental fact of anisotropic behaviour in this kind of steel, with crack deviation from the original direction in mode I, the deflection angle being almost 90°, which represents a propagation step aligned to the wire axis or cold drawing direction. After this 90°-step, the crack propagates in a direction close to the original one transverse to the wire axis. These two propagation directions —perpendicular to each other— allow an estimation of the directional fracture toughness in axial and radial directions.

INTRODUCTION

High-strength cold drawn steels are used in civil engineering as structural members in the form of bars, wires, strands, tendons and cables (e.g., high-strength steels for reinforcing and prestressing concrete) which are axially loaded under very severe loads, so that the knowledge **of** their fracture toughness is very important in structural engineering design, construction and maintenance [1].

This paper presents a simple procedure for evaluating the fracture toughness in cold drawn prestressing steel wires on the basis of simple fracture tests in which anisotropic fracture behaviour was detected [2] as a consequence of the microstructural orientation in the wire axis direction produced during the manufacture process by cold drawing [3].

EXPERIMENTAL PROGRAMME

Cold Drawn Materials

A high strength eutectoid steel was used in this work. Different degrees of cold drawing were analyzed, associated with the *final* steps of the manufacturing process to obtain prestressing steel wires. Table 1 gives the chemical composition (common to all the steels) whereas Table 2 shows the nomenclature, diameter and mechanical properties of the steel wires. The number of drawing steps applied to each one is indicated by the digit in its own name, so that only heavily drawn steels were analyzed: A4, A5 and A6 which have undergone respectively 4, 5 and ***6*** steps of cold drawing.

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**
NOMENCLATURE, DIAMETER AND MECHANICAL PROPERTIES OF **THE STEELS**

Steel	A4	/45	A6
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

E: Young's modulus, σ_Y: yield strength, σ_R: ultimate tensile stress (UTS)
P, n: Ramberg-Osgood parameters: $\varepsilon = \sigma/E + (\sigma/P)^n$

Fracture Tests

Cylindrical samples of **30** cm were used by cutting the steel wires. Samples were subjected to axial fatigue to produce a precrack before the fracture test. The precracking programme was designed so that the maximum stress intensity factor at the final stage (just before the fracture test) never exceeded **60%** of the critical stress intensity factor reached at final failure. This condition was checked after the fracture tests to reject those specimens precracked at higher loads. Fig. **1** shows the specimens used in the fracture tests.

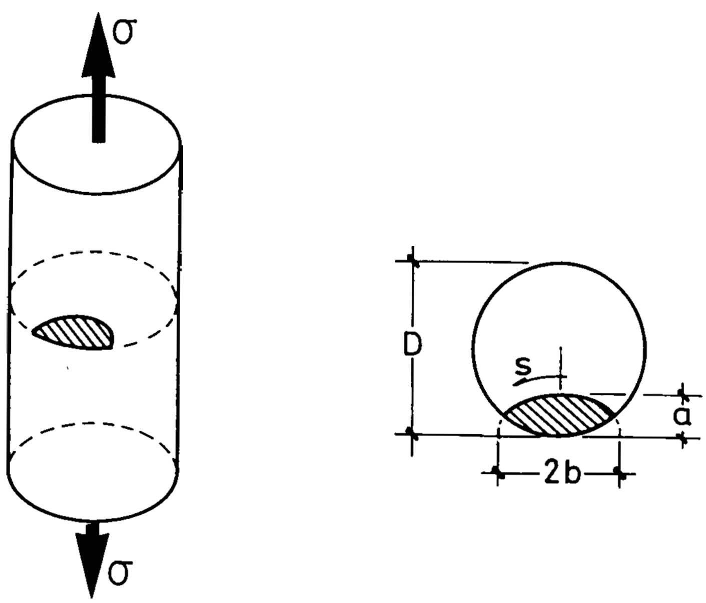


Figure 1: Cracked bars used in the experimental programme.

After fatigue precracking, the cracked rods (shown in Fig. 1) were subjected to monotonic tensile loading up to fracture with a crosshead speed of **3** mm/min. The load applied on the specimen and the relative displacement of two points symmetrically placed in relation to the crack plane were continuously monitored during the test, the first by means of the load cell and the second using an extensometer (whose gage length was **12.5** mm) placed in front of the crack, so as to record the complete load-displacement plot.

Experimental Results

The heavily drawn steels analyzed in this paper (A4 to A6) exhibited anisotropic fracture behaviour with crack deflection and a *propagation step* oriented 90° in relation to the initial propagation direction by fatigue in mode **I.** This 90°-step is quasi-parallel to the wire axis or cold drawing direction, a consequence of the marked microstructural orientation induced by cold drawing **[3].** The fractographic analysis on the fracture samples **[4]** revealed that the predominant micromechanisms of fracture in heavily drawn steels are micro-void coalescence (MVC), i.e., dimpled fracture, with evidence of isolate cleavage (C) facets indicating locally brittle fracture.

Fig. **2** shows a scheme of the fracture profiles and microscopic fracture modes in the three steels analyzed in this paper. There is a first subcritical crack growth in mode **I** by MVC over a very small distance x_S up to the propagation step and finally further growth in a direction close to the initial one **(20-30°** from it). The step gets closer to the fatigue precrack border as the drawing becomes heavier, and in the fully drawn steel (A6) the step is located just at the fatigue precrack border (x_S=0). Fracture surfaces are MVC before the step (when x_S is different from zero) and MVC with some C facets after it.

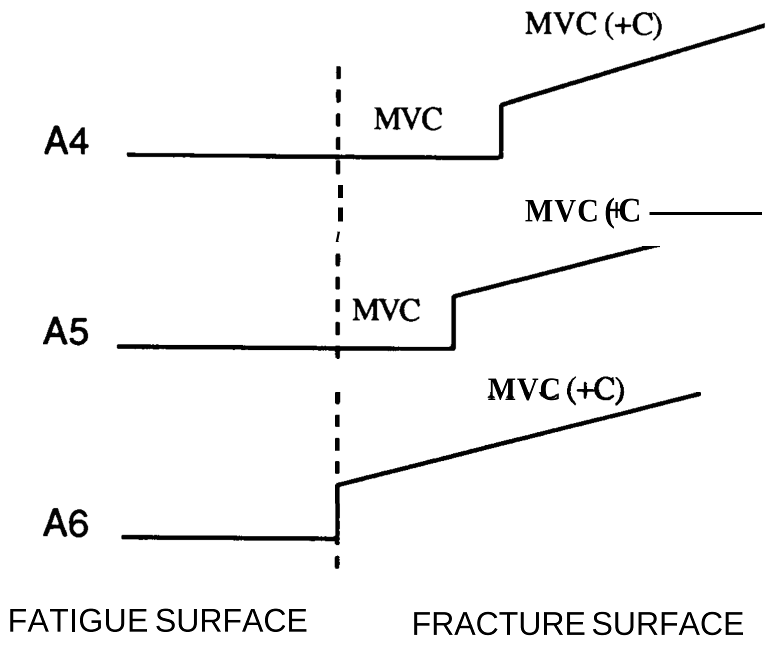


Figure 2: Fracture profiles and microscopic fracture modes.

The load-displacement plots during the fracture tests showed no decrease in load, and this happened with independence of the degree of cold drawing. The appearance of the load-displacement plot in the fracture tests was seen to depend on the strain hardening level. In heavily drawn steels the plot always exhibited a first linear portion (associated with mode I propagation), later a *pop-in* (associated with the 90°-step) and finally a non linear part (associated with the further propagation in a direction close to the initial one in mode **I).** The presence of the 90°-step explains the non linear part of the load-displacement curve: after a *pop-in* associated with the step, the plot becomes curved as a consequence of bending of the cracked sample. This explanation was experimentally checked by performing a fracture test with two extensometers placed symmetrically in relation to the crack plane, one of them in front of the crack mouth and the other one in the opposite position (at the other side of the diameter).

The *pop-in* is not produced by plastic yielding but by a kind of microstructural yielding due to the appearance of the 90°-step as a consequence of the presence of extremely slender pearlitic pseudocolonies [3] created in the steel during manufacture by cold drawing. Such pseudocolonies posses an anomalous (very high) local interlamellar spacing which makes them preferential fracture paths with minimum local toughness. This is consistent with the ideas presented in [5], according to which the *pop-in* in the load-displacement curve is produced by a small amount of abrupt crack extension and could be related to the presence of heterogeneities in the material in the form of large inclusions, carbides or, in the case of the pearlitic steel analyzed in this paper, the afore-said pearlitic pseudocolonies produced by heavy drawing.

Therefore, two characteristic points may be defined in the load-displacement curve: the point of initiation of non-linear behaviour (at a load value F_Y) and the point of final fracture (at the maximum load level F_{max}). The former was associated with a detectable *pop-in* in the load-displacement plot, which marks the beginning of the non-linear behaviour. These two points could be used to define a characteristic load and its corresponding characteristic value of stress intensity factor.

EVALUATION OF FRACTURE TOUGHNESS

Stress Intensity Factor

To evaluate the fracture toughness in the steel wires, an expression is needed of the stress intensity factor (SIF) for the geometry and loading conditions depicted in Fig. 1. In this paper, the following general expression [6] is used:

$$K_I = Y(a/D)\,\sigma\sqrt{\pi a} \tag{1}$$

where σ is the remote axial stress, a the crack depth and Y* (a/D) a dimensionless function given by (cf. [6]):

$$Y(a/D) = [0.473 - 3.286\,(a/D) + 14.797\,(a/D)^2]^{1/2}\,[(a/D) - (a/D)^2]^{-1/4} \tag{2}$$

which was obtained using the finite-element method together with a compliance technique to obtain a global value of the stress intensity factor from the energy release rate.

Fracture Criterion

A fracture criterion on the basis of the energy release rate G will be used to account for the anisotropic behaviour, i.e.:

$$G = G_c \tag{3}$$

In materials with strength anisotropy —as the cold drawn steels considered in this paper— the specific energy for fracture depends on the propagation angle θ in relation to the crack plane in the standard fracture mechanics sense, $G_c(\theta)$, and it can be related to the *directional fracture toughness* $K_{IC}(\theta)$ as follows:

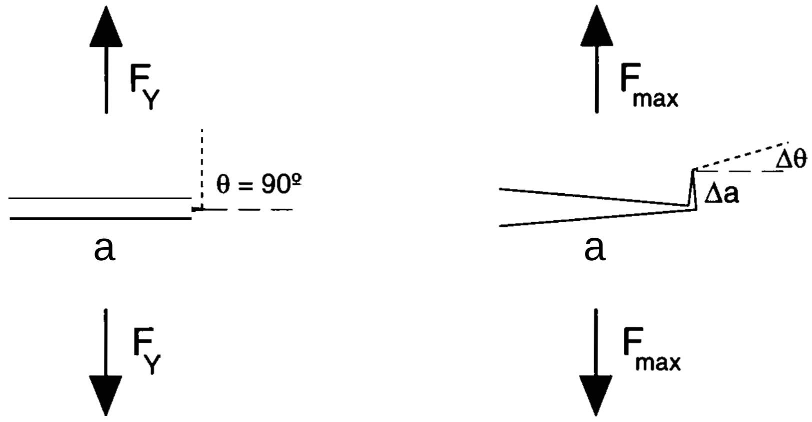
$$G_c(\theta) = \frac{K_{IC}^2(\theta)}{E'} \tag{4}$$

where E'=E in plane stress and $E'=E/(1-\nu^2)$ in plane strain. In addition, and taking into account the propagation step (cf. Fig. 2) oriented 90" in relation to the radial direction (original crack propagation direction in mode I), the relation between the energy release rates in the radial (θ=0°) and axial (θ=90°) directions is [7]:

$$G(90°) = 0.2615\,G(0°) \tag{5}$$

which indicates clearly that the energy release rate for crack deflection is quite lower than the correspondent value for crack propagation in mode I, and thus crack deviation from the mode I direction only happens if the fracture resistance in the axial direction —measured in terms of specific energy for fracture— is low enough.

Fig. 3 shows the relevant fracture instants in the tests: crack deflection at a load level F_Y (associated with the ***pop-in*** and the 90"-step) and final fracture at a load level F_{max} following a direction close to the initial one. These two key fracture instants allow an approximate evaluation of directional toughness in cold drawn steels.



(a) (b)

Figure 3: Relevant fracture instants: (a) initiation of fracture (*pop-in*) with crack deflection at a load level F_Y; (b) final fracture with crack propagation following a direction close to the initial one at a load level F_{max}.

Directional Toughness

The following hypotheses will be used to obtain the approximate value of the directional toughness:

(i) The subcritical crack growth by **MVC** in mode I (before the 90" step, cf. Fig. 2) is neglected, i.e., the crack length for calculating the critical value of the SIF is the fatigue crack length: $a \approx a_{fat}$.

(ii) The ***pop-in*** crack growth is neglected in macroscopic terms, assuming that it represents only the size of a microstructural fracture unit (the pearlitic pseudocolony, cf. [3]), i.e., Aa ≈ 0.

(iii) The final crack propagation path after the 90"-step is assumed to occur following a direction parallel to the initial crack plane in mode I, i.e., the propagation angle in Fig. 3b is neglected: **A8** ≈ 0.

Now, the fracture criterion based on the energy release rate is applied to the fracture instants of Fig. 3a and 3b to obtain the directional fracture toughness of the steels in directions θ=90° (Fig. 3a) and θ=0° (Fig. 3b). With regard to the first, the fracture criterion (3) yields:

$$G\,(a, F_Y, 90°) = G_c\,(90'') \tag{6}$$

and considering the relation (5) between the energy release rates in different directions:

$$0.2615\ G\,(a, F_Y, 0°) = G_c\,(90'') \tag{7}$$

or, in terms of SIF, accounting for **(4)** and considering that in this mode I case $G = \mathbf{K_I}^2/E'$:

$$\sqrt{0.2615}\ \mathbf{K_I}\,(a, F_Y) = K_{IC}\,(90'') \tag{8}$$

which gives the directional toughness in axial (θ=90°) direction.

With regard to the fracture instant associated with maximum load (Fig. 3b), the fracture criterion (3) simply gives, considering hypothesis (iii), i.e., $\Delta\theta \approx 0$:

$$G\,(a, \Delta a, F_{max}, 0°) = G_c\,(0°) \tag{9}$$

In a mixed mode case like this, the energy release rate depends on both K_I and K_{II}, as follows:

$$G = \frac{K_I^2 + K_{II}^2}{E'} \tag{10}$$

where K_I and K_{II} which depend on the following variables:

$$K_I = K_I(a, \Delta a, F_{max}) \tag{11}$$

$$K_{II} = K_{II}(a, \Delta a, F_{max}) \tag{12}$$

and considering now hypothesis (ii), i.e., Aa ≈ 0, then $K_{II} \approx 0$, $K_I = K_I(a, F_{max})$ and $G = K_I^2/E'$. Then the fracture criterion (9) may be expressed in terms of **SIF** as follows:

$$K_I(a, F_{max}) = K_{IC}(0°) \tag{13}$$

which gives the directional toughness in radial (θ=0°) direction.

Fig. **4** shows the results of directional toughness in radial and axial directions. During the last stages of cold drawing (those represented in Fig. **4),** it is seen that there is a certain improvement of fracture toughness with the number of cold drawing steps, specially in axial (90") direction. However, the improvement of fracture toughness with cold drawing is more significant during the first and intermediate stages of drawing, cf. [2].

The directional fracture toughness is between two and three times higher in radial direction (θ=0°) than in axial one (θ=0°). This is a signal of the very high strength anisotropy of heavily drawn steels, which can be explained by considering the markedly oriented pearlitic microstructure, cf. [3], after the manufacture process.

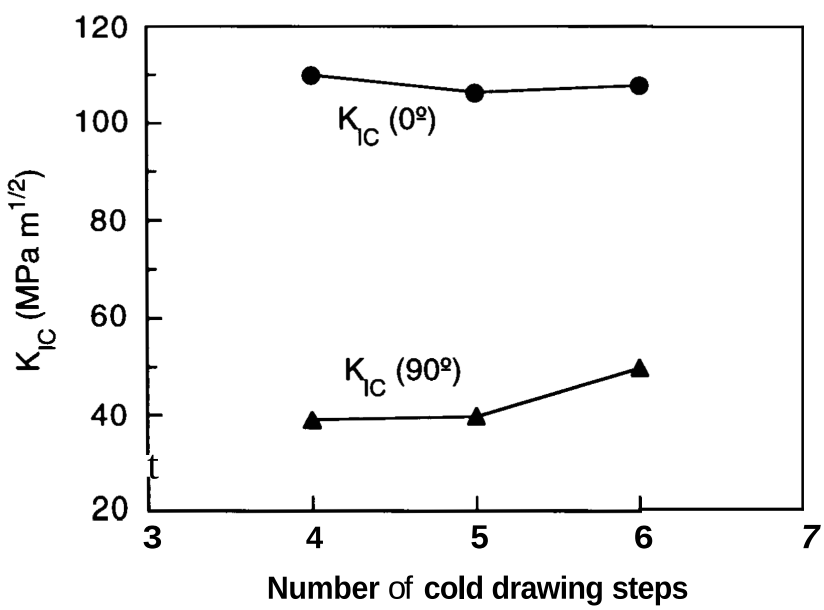


Figure 4: Directional fracture toughness in the cold drawn steels in radial (0°) and axial (90") directions.

CONCLUSION

An approximate procedure was proposed to estimate the directional fracture toughness of heavily drawn pearlitic steels in axial and radial directions, using a fracture criterion based on the energy release rate and some assumptions based on the experimental results. The values of directional toughness are seen to be quite higher in radial than in axial direction, which indicates that heavily drawn steels are very anisotropic from the fracture mechanics viewpoint.

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