Crack paths in cold drawn pearlitic steel subjected to fatigue and fracture

J. Toribio, B. González and J.C. Matos

Department of Materials Engineering, University of Salamanca
E.P.S., Campus Viriato, Avda. Requejo 33, 49022 Zamora, Spain
Tel: (34-980) 54 50 00; Fax: (34-980) 54 50 02, E-mail: toribio@usal.es

ABSTRACT. *This paper analyses the influence of microstructural anisotropy of a progressively drawn pearlitic steel (orientation of pearlitic lamellae in the drawing direction) on the microscopic and macroscopic evolution of cracking paths produced by fatigue and fracture. The fatigue crack path is always contained in the transverse section of the wires, i.e., the subcritical propagation develops under a global mode I, so that the main crack path is associated with mode I and some very local deflections take place to produce a roughness in the fatigue crack path depending on the drawing level. The fracture crack path evolves from a global mode I propagation following the transverse plane in slightly drawn steels (including the hot rolled bar that is not cold drawn at all) to a global mixed-mode propagation associated with crack deflection in intermediate and heavily drawn steels (the latter with a strong mode II component), the deviation angle being an increasing function of the drawing degree in the steel.*

INTRODUCTION

Cold drawing in eutectoid steels produces microstructural changes that can affect their mechanical behaviour. In particular, cold drawing is the responsible for the decrease of interlamellar spacing and the progressive orientation of pearlitic lamellae in the drawing direction [1-5]. In addition, heavy drawing generates curling of pearlitic lamellae [6].

In pearlitic steels, fatigue crack growth paths tend to cross the pearlite colonies and break the ferrite/cementite lamellae, exhibiting frequent local deflections, branchings and bifurcations [7]. When pearlite is uniformly distributed in ferrite, the fatigue crack path is more tortuous than in purely ferritic microstructures, and many deflections appear in the crack path. In addition, pearlite inhibits the development of plastic deformation in the vicinity of the crack tip, thereby contributing to the improvement of fatigue resistance due to the increase of plastic constraint in that area [8]. In ferritic-pearlitic steels, banded pearlite (oriented in preferential directions) lowers the fatigue crack growth rate and raises the fatigue propagation threshold K_{th} in relation to the same steel with non oriented pearlite, and the reason is the higher roughness of the cracking path in oriented pearlite, where crack branching lowers the crack driving force and produces interblocking and a sort of retardation effect in the fatigue crack growth rate

[9-10]. In fully pearlitic steels after cold drawing, markedly oriented pearlite contributes to the interblocking effect and, consequently, the fatigue crack growth rate decreases with such an orientation [11-12].

Fracture tests under bending loading on steels before and after cold drawing allowed the calculation on the directional toughness in the steel (on the basis of an energy release rate concept). Such a directional toughness is constant with the angle in the case of the hot rolled steel (isotropic material) which is not cold drawn at all, but it increases from an angle of 0º to an angle of 90º (measured in relation to the wire axis) in prestressing steel wire (commercial product which has undergone several drawing steps) [13]. As a matter of fact, heavily drawn steels exhibit strength anisotropy associated with a fracture crack path with crack deflection and mixed-mode propagation approaching the wire axis or drawing direction [14]. In these steels the longitudinal fracture toughness (associated with longitudinal fracture by delamination) is quite lower than the corresponding toughness value in transverse direction (associated with transverse fracture by breaking the strongest links) [15,16]. At a microscopical level, while in the hot rolled bar the fracture takes place by cleavage, in slightly drawn steels micro-void coalescence (MVC) fracture appears, followed by cleavage. Heavily drawn steels exhibit a fracture crack path with crack deflection at an angle of about 90º followed by a mixed propagation by micro-voids and cleavage [14].

The aim of the present paper is to analyse the evolution of the crack path in progressively drawn pearlitic steels under fatigue and fracture. To this end, fatigue and fracture tests were performed in cylindrical bars, examining the fracture surface at the microscopic and the macroscopic levels to determine the micromechanics of failure, the fracture modes and the crack paths.

EXPERIMENTAL PROCEDURE

Materials

The materials used in this work were cold drawn steels with the same eutectoid composition, as shown in Table 1.

Table 1. Chemical composition (wt%) of the steels.

% C	% Mn	% Si	% P	% S	% Al	% Cr	% V
0.789	0.681	0.210	0.010	0.008	0.003	0.218	0.061

Eight degrees of cold drawing were analysed, from the hot rolled steel (E0 that is not cold drawn at all) to a commercial prestressing steel wire (E7, heavily drawn steel that has undergone seven steps of cold drawing), apart from the six intermediate degrees of drawing. The steels were named with a letter E (indicating the common chemical composition) and a digit (indicating the number of cold drawing steps undergone). The drawing degree was characterised by the cumulative plastic strain in each steel.

Microstructural Analysis

Longitudinal and transverse samples were cut in the steels, polished and mounted to undergo several grinding stages, and different polishing passes followed by etching in Nital 4% to reveal the pearlitic microstructure of the steels. Later, samples were examined by means of a scanning electron microscope (SEM).

Fatigue and Fracture Tests

The specimens for the fatigue and fracture tests were samples in the form of circular rods taken directly from the wires (from 11.0 mm to 5.1 mm diameter) and a length of 30 cm, in which a mechanical notch was produced to initiate fatigue cracking.

Fatigue tests were performed at room temperature, step by step under load control, the load being constant in a step and decreasing from one to another step. Samples were subjected to tensile cyclic loading with an R factor equal to zero, and a frequency of 10 Hz. The maximum load in the first loading stage corresponded to a value of about half the yield strength and was reduced between 20-30% from one to another step. Fracture tests were performed in the specimens previously precracked by fatigue, using a displacement rate of 3 mm/min and tension loading.

Fatigue and fracture test were interrupted and a fracto-metallographic analysis was performed on the cracked samples by cutting along a plane perpendicular to the crack front in order to exanimate in detail the fatigue crack path immersed in the steel microstructure. To this end, after grinding and polishing, samples were etched with 4% Nital during several seconds and later observed by scanning electron microscopy (SEM) with magnification factors of 1000x.

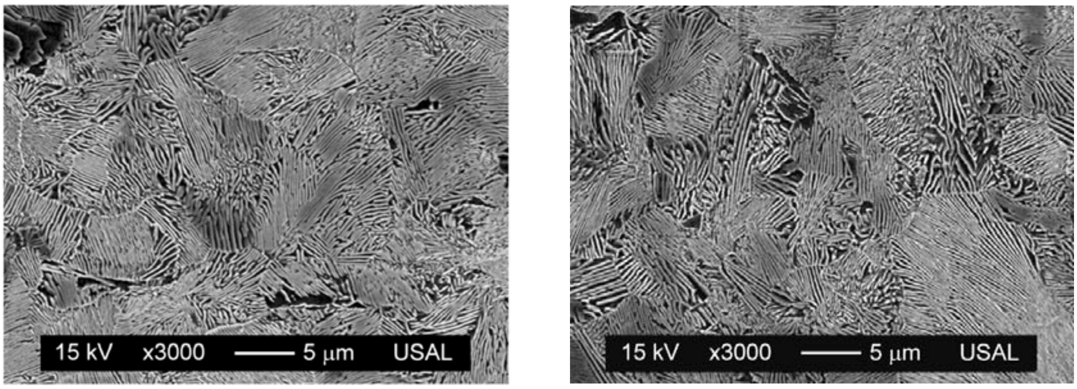
RESULTS AND DISCUSSION

Microstructural Analysis

Pearlite is composed by alternate lamellae of ferrite and cementite forming colonies or sets of ferrite and cementite sharing a common orientation (different from that of the lamellae in the neighbourhood colonies). Figs. 1 and 2 show the changing appearance of both microstructural units (the pearlite colonies and lamellae) in both longitudinal and transverse sections.

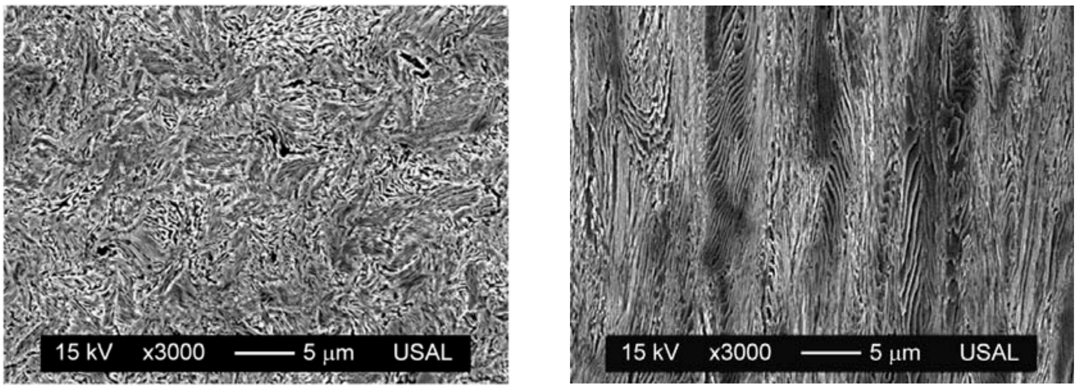
The pearlitic colonies become more slender with the cold drawing process, in agreement with previous research [17]. With regard to the lamellae, the general trend is a decrease of interlamellar spacing and a progressive orientation in the drawing direction (wire axis), also consistent with previous research [4,5]. In addition, the lamellae become curved in the transverse section as the drawing degree increases (*curling* effect).

The average value of the orientation angle (β) of the pearlitic lamellae in relation to the wire axis or drawing direction was measured in the metallographic sections, and the value for each steel is given in Table 2. Such a microstructural orientation angle is a measure of the intrinsic anisotropy of each steel as a function of the number of drawing steps undergone by it during manufacture.



(a) (b)

Figure 1. Scanning electron micrograph showing the microstructure of steel 0
(hot rolled bar that; not cold drawn at all):
transverse section (a) and longitudinal section (b).



(a) (b)

Figure 2. Scanning electron micrograph showing the microstructure of steel 7
(prestressing steel wire that has undergone seven steps of cold drawing):
transverse section (a) and longitudinal section (b).

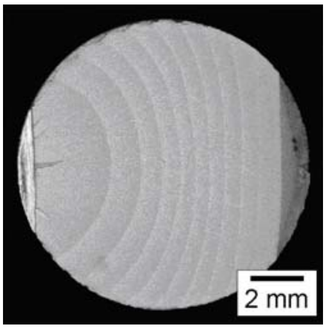
Table 2. Angle of the pearlitic lamellae in relation to the wire axis or drawing direction.

Steel	E0	E1	E2	E3	E4	E5	E6	E7
ε^{P}	0	0.22	0.42	0.59	0.77	0.97	1.13	1.57
β (º)	47	42	36	31	28	23	19	14

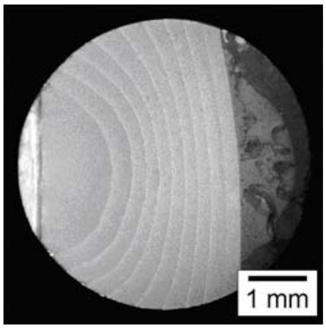
Fatigue Crack Path

The macroscopic fatigue crack path was always contained in the transverse section of the wire, i.e., fatigue crack growth develops in mode I in spite of the markedly oriented microstructure in the progressively drawn steels.

Fatigue cracking in the transverse section can be modelled using semielliptical shapes to reproduce the evolving crack front, cf. Fig. 3, so that preferential cracking paths can be detected [18], and thus the crack aspect ratio is a function of the relative crack depth and of the considered steel (Fig. 4).



(a)



(b)

Figure 3. Fatigue crack front shapes for the hot rolled bar E0 (a) and the prestressing steel wire E7 (b).

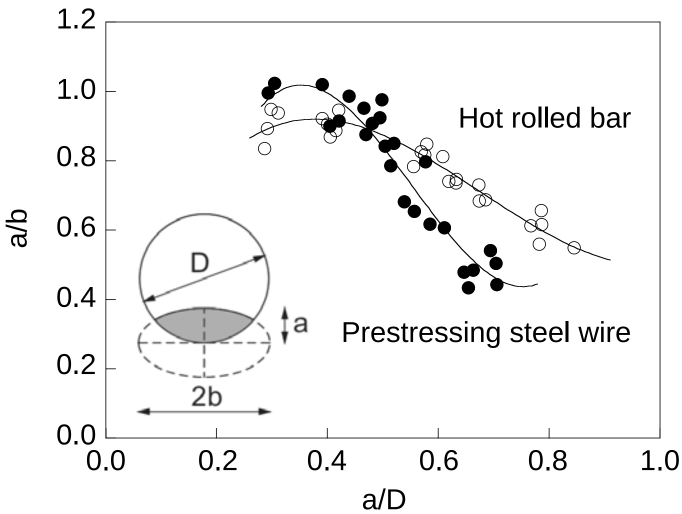
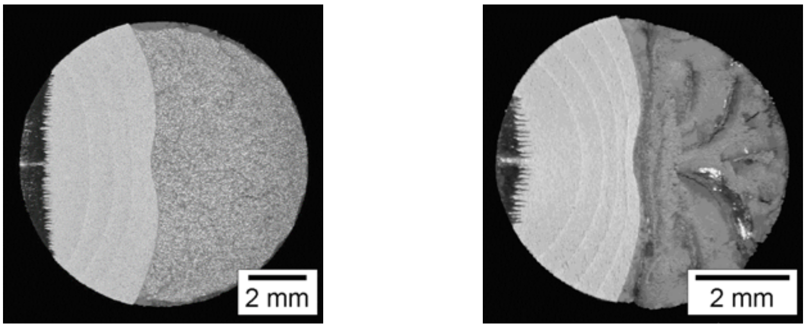


Figure 4. Fatigue crack paths for the hot rolled bar E0 and the prestressing steel wire E7.

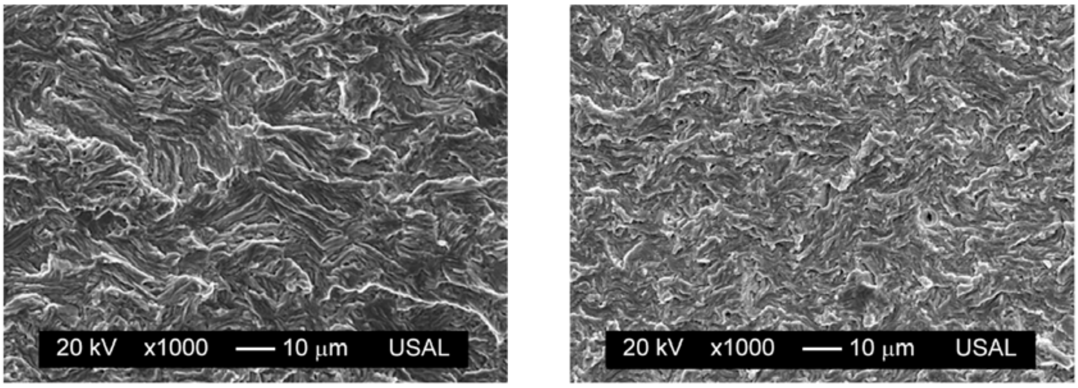
Steels with intermediate degree of drawing exhibit a retardation of fatigue crack growth in the central area of the wire section (Fig. 5) due to the presence of compressive residual stresses in that area and tensile ones in the vicinity of the wire surface. As a matter of fact, the cold drawing process generates an axisymmetric residual stress profile, so that such internal stresses affect the crack growth under cyclic loading. Such a residual stress distribution does not appear neither in steel E0 (hot rolled bar which is not cold drawn at all) nor in steel E7 (prestressing steel wire that has undergone seven drawing steps and a posterior stress-relieving treatment to eliminate residual stresses).



(a) (b)

Figure 5. Fatigue crack front shapes in steels with an intermediate degree of cold drawing: E1 (a) and E6 (b).

At a microscopic level, the fractographic appearance of the fatigue surface in pearlitic steels shows evidence of microplastic tearing events and subcritical crack advance by very localised plastic strain accumulation (Fig. 6). The fatigue process could be associated to a successive movement of dislocations ending at the ferrite-cementite interfaces and promoting fracture by shear cracking, similarly to the mechanism proposed by Miller and Smith [19].



(a) (b)

Figure 6. Fractographic analysis of the fatigue surface in the hot rolled bar E0 (a) and the prestressing steel wire E7 (b).

Fatigue cracks paths are trans-colonial and tend to fracture pearlitic lamellae. Fatigue crack propagation is tortuous, with micro-discontinuities, branchings, bifurcations and local deflections, thereby creating microstructural roughness, and even exhibiting non-uniform crack opening displacement values (Fig. 7). These phenomena confirm the existence of a cracking path evolution under a local mixed mode in the vicinity of the crack tip.

The differences between the fractographic appearance of the hot rolled bar and the prestressing steel wire are due to the microstructural changes and the plastic strain suffered by the steel during cold drawing. In the prestressing steel wire the micro-tearing events are smaller and more curved than in the hot rolled (Fig. 6), consistent with what happens with the microstructure in the transverse section (cf. Figs. 1 and 2). The cracking path in prestressing steel shows a higher microstructural roughness (and therefore a greater net fractured area) than the respective zone in the hot rolled bar (Fig.7).

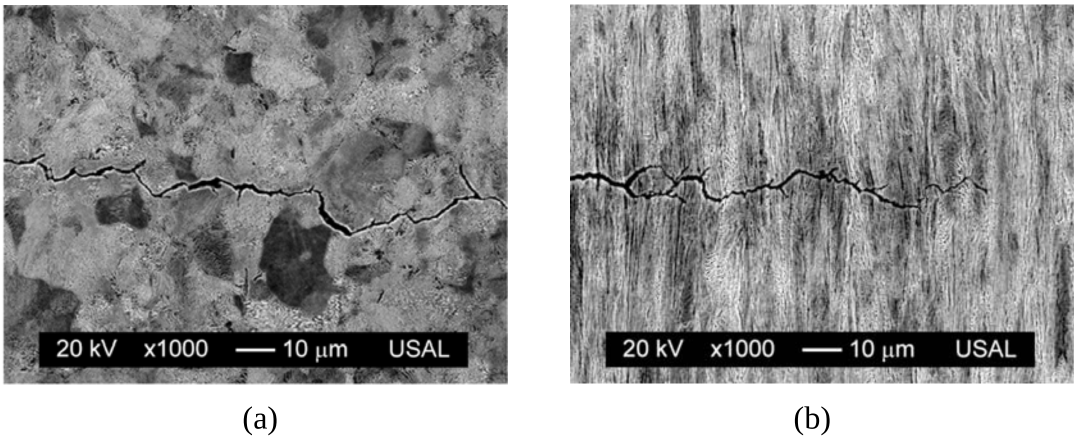


Figure 7. Fracto-metallographic analysis of the fatigue crack paths in the hot rolled bar E0 (a) and the prestressing steel wire E7 (b).

Fracture Crack Path

The photographs of the fracture surface obtained after the fracture tests on cylindrical samples precracked by fatigue are shown in Fig. 8. In this figure, fracture propagates from left to right: mechanical notch, fatigue surface and fracture surface.

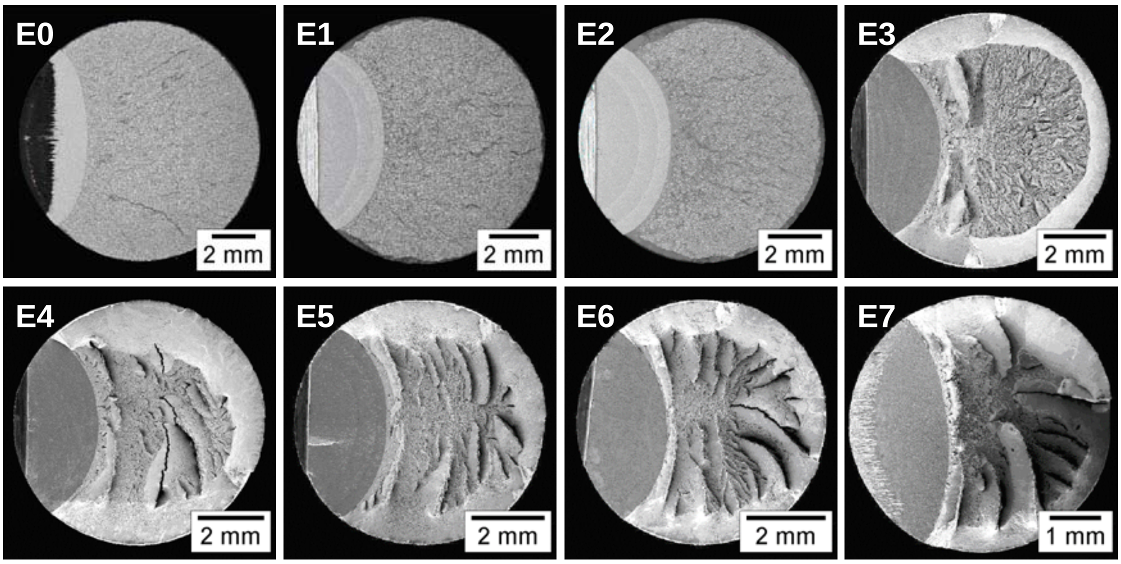


Figure 8. Fracture surface in the eight steels, from E0 to E7 (left to right and up to down). In all pictures fracture propagates from left to right.

The fracture micromechanism changes with the level of plastic deformation (cold drawing degree) in the different steels. At the macroscopic level, fracture is isotropic (contained in the transverse plane) in the hot rolled bar and slightly drawn steels, whereas it is clearly anisotropic (associated with a main deflection in the crack path and frequent micro-deflections) in the case of heavily drawn steels.

To characterise the main deflection angle in the fracture crack path, a fractographic analysis of the crack path profile was performed by cutting and polishing the sample in a plane perpendicular to the crack front (Fig. 9). The anisotropic behaviour becomes more intense as the drawing level increases. In heavily drawn steels, the fracture profile exhibits (after the fatigue precracking) a small step with a small vertical wall. After this step, the fracture crack path develops in such a way that the slope increase with the level of drawing (up to 45º approximately). The angles are given in Fig. 10.

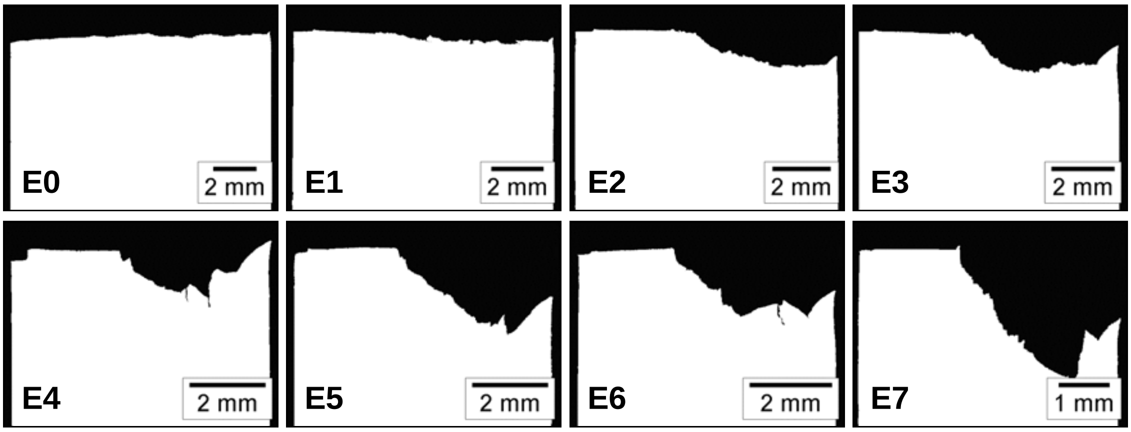


Figure 9. Fracture crack paths in the progressively drawn steels (from E0 to E7).

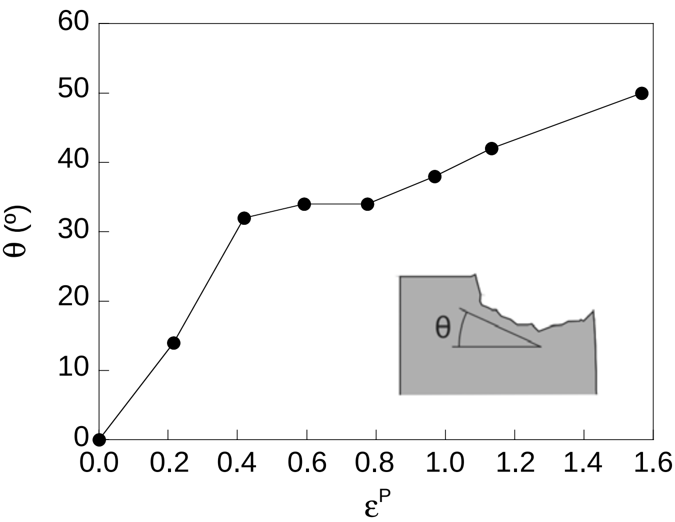


Figure 10. Crack deflection angle in the progressively drawn steels.

The microstructural changes in the steels are associated with changes in the fracture micromechanisms. The hot rolled bar E0 fails in brittle manner by cleavage (Fig. 11), with almost no plastic strain and typical river patterns indicating the crack advance. Fracture initiates at a small area of micro-void coalescence (MVC) next to the fatigue pre-crack (fracture process zone or FPZ) and it ends with shear lips at an angle of 45º with a fracture mode by MVC (external ring). Then the predominant fracture process in the hot rolled bar is by cleavage (brittle) which initiates and ends in a ductile manner.

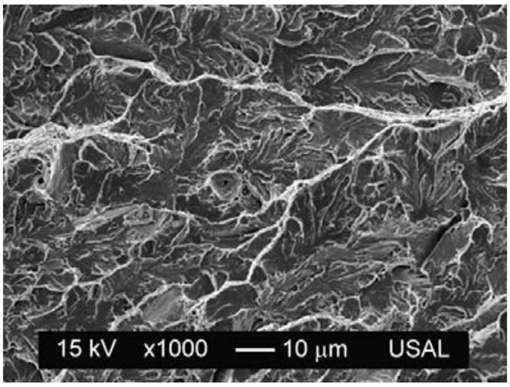


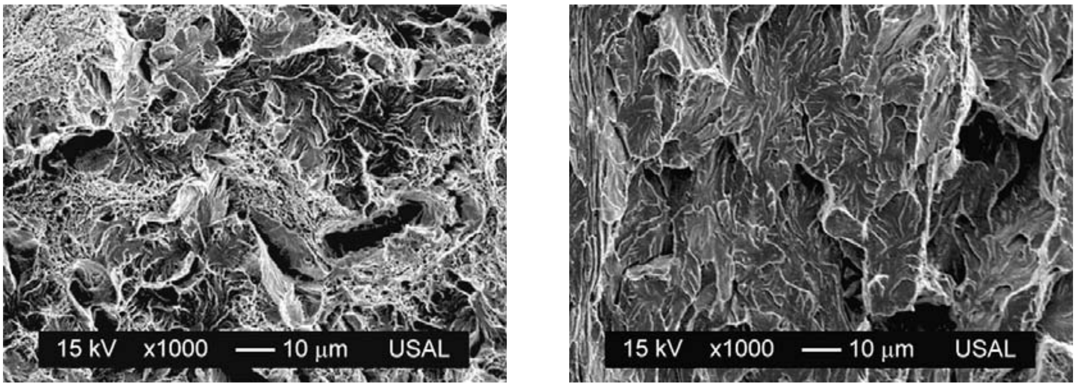
Figure 11. Main fracture surface by cleavage in the hot rolled steel (E0).

In slightly drawn steels the same fracture micromechanisms take place, but the FPZ and the external ring (both formed by MVC) increase with the level of drawing. In addition, some local MVC areas appear in the main fracture area by cleavage in the internal section of the cross sectional area of the wires.

In steels with an intermediate degree of drawing (E3, Fig. 12), and in heavily drawn steels (E7, Fig. 13) fracture initiates just at the FPZ by MVC (just after the fatigue precrack), followed by a vertical cracking path formed by oriented and enlarged cleavage facets (at certain distance from the fatigue precrack) and later by an inclined cracking path formed by a mixture of MVC and cleavage topographies with radial cracking emanating from the centre of the cross sectional area of the wire. This main region contains vertical walls formed by enlarged cleavage and inclined zones by MVC. The final fracture area (external circular ring) is formed by shear lips inclined 45º and a fracture micromechanism by MVC.

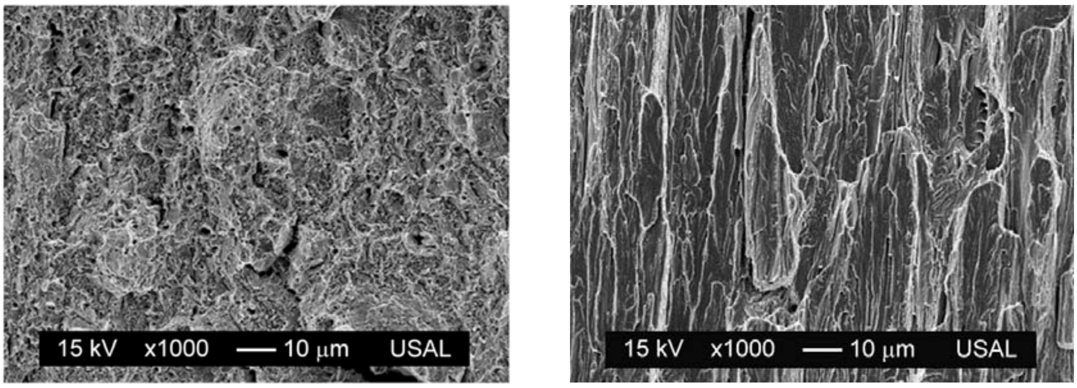
The *horizontal* (or transverse) projection of the internal fracture area is constituted by MVC and cleavage, the size of the cleavage area diminishing with the degree of cold drawing (or cumulative plastic strain level) in the progressively drawn steels in such a manner that it practically disappears in the most heavily drawn steels. In this latter case only isolated cleavage units are detected, so that the predominant fracture area develops by MVC and therefore the initial FPZ and the following inner fracture area are difficult to distinguish.

The *vertical* (or longitudinal) projection consists of the afore-described enlarged and oriented cleavage in the form of vertical walls, the degree of enlargement (slenderising) being an increasing function of the level of drawing (or cumulative plastic strain) in the steels (as in the case pearlitic colonies). The percentage of area of vertical walls (in relation to the whole fracture surface area) also increases with the drawing level.



(a) (b)

Figure 12. Horizontal (a) and vertical (b) fracture surface in a steel with an intermediate degree of drawing (E3).



(a) (b)

Figure 13. Horizontal (a) and vertical (b) fracture surface in the most heavily drawn steel (E7).

Therefore, both the *ductility* (evaluated as a percentage of MVC fracture over the pure cleavage micromechanism) and the *anisotropy* (probability of crack deflection in the fracture path) increase with the level of cold drawing in the different steels, a consequence of the oriented microstructure in the drawn steels. However, in the matter of a property such as the ductility, and precisely as a consequence of the anisotropy of the drawn steel, one must distinguish between the *transverse ductility* (in the horizontal direction) and the *longitudinal brittleness* (in the vertical direction). The idea about increasing ductility with the level of drawing refers to that measured in the transverse direction (the key one in evaluating the fracture resistance of the wires), whereas in the longitudinal direction the behaviour remains brittle, although the area of oriented and enlarged cleavage increases in the most heavily drawn steels, so that the oriented microstructure of these steels produces more crack deflection (because of longitudinal weakness), and such a deflection (with the associated enlarged and oriented cleavage topography) is a sign of anisotropy in the cold drawn steels..

CONCLUSIONS

The cold drawing process produces microstructural anisotropy in the form of orientation of the pearlitic lamellae in the drawing direction and decrease of interlamellar spacing. This phenomenon has direct consequences on the fatigue and fracture behaviour of the steels, as well as on the crack paths.

The *fatigue crack path* is always contained in the transverse section of the wires, i.e., the subcritical propagation develops under a global mode I, so that the main crack path is associated with mode I and some very local deflections take place to produce a roughness in the fatigue crack path depending on the drawing level. The fatigue micromechanism consists of ductile microtearing events with very localised plastic strain, the microtearing patterns becoming more curved as the drawing level increases. With regard to the shape of the crack front, it can be assumed to be semielliptical, with a sort of retardation effect in the central area in the case of steels with an intermediate degree of drawing (*gull* effect), a consequence of the presence of compressive residual stresses in that area (accompanied by tensile ones at the wire surface).

The *fracture crack path* evolves from a global mode I propagation following the transverse plane in slightly drawn steels (including the hot rolled bar that is not cold drawn at all) to a global mixed-mode propagation associated with crack deflection in intermediate and heavily drawn steels (the latter with a strong mode II component), the deviation angle being an increasing function of the drawing degree in the steel. Such an evolution from mode I (slightly drawn steels) to mixed-mode propagation (heavily drawn steels) is associated with a change in the fracture micromechanisms from purely brittle cleavage in slightly drawn steels to the more ductile micro-void coalescence (MVC) fracture micromechanism appearing in the main fracture area in heavily drawn steels that exhibit also oriented and enlarged cleavage mode in the deflection crack path in vertical (drawing) direction. As a summary, both the *ductility* and the *anisotropy* (probability of crack deflection in the fracture path) increase with the level of cold drawing in the different steels, a consequence of the oriented microstructure in the drawn steels which can be observed at the two levels of pearlitic colonies and lamellae.

Therefore the microstructural anisotropy of the steels (consequence of the drawing process) creates a change in the fracture crack path with crack deflection in the most heavily drawn steels. Nevertheless, the fatigue crack path remains globally in mode I, even in the most heavily drawn steels. In this latter case the microstructural orientation produces only an increase of micro-roughness in the fatigue crack path.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support provided by the following Spanish Institutions: Ministry for Science and Technology (MCYT; Grant MAT2002-01831), Ministry for Education and Science (MEC; Grant BIA2005-08965), Ministry for Science and Innovation (MCINN; Grant BIA2008-06810), *Junta de Castilla y León* (JCyL; Grants SA067A05, SA111A07 and SA039A08), and the steel supplied by TREFILERÍAS QUIJANO (Cantabria, Spain).

REFERENCES

1. Embury, J.D., Fisher, R.M. (1966) *Acta Metall.* **14**, 147-159.
2. Langford, G. (1977) *Metall. Trans.* **8A**, 861-875.
3. Dollar, M., Bernstein, I.M., Thompson, A.W. (1988) *Acta Metall.* **36**, 311-320.
4. Toribio, J., Ovejero, E. (1998) *Scripta Mater.* **39**, 323-328.
5. Toribio, J., Ovejero, E. (1998) *Mech. Time-Dependent. Mater.* **1**, 307-319.
6. Gil Sevillano, J., Aernoudt, E. (1987) *Mater. Sci. Eng.* **86,** 35-51.
7. Toribio, J., Matos, J.C., González, B. (2009) *Int. J. Fatigue*, In Press.
8. Korda, A.A., Mutoh, Y., Miyashita, Y., Sadasue, T. (2006) *Mater. Sci. Eng. A* **428**, 262-269.
9. Korda, A.A., Mutoh, Y., Miyashita, Y., Sadasue, T., Mannan, S.L. (2006) *Scripta Mater.* **54**, 1835-1840.
10. Mutoh, Y., Korda, A.A., Miyashita, Y., Sadasue, T. (2007) *Mater. Sci. Eng. A* **468-470**, 114-119.
11. Toribio, J., Toledano, M. (1999). In: *Proceedings of the Seventh International Fatigue Congress (Fatigue '99)*, pp. 2455-2460, Wu, X.R., Wang, Z.G. (Eds.), Higher Education Press, China.
12. Wetscher, F., Stock, R., Pippan, R. (2007) *Mater. Sci. Eng. A* **445-446**, 237-243.
13. Astiz, M.A., Valiente, A., Elices, M., Bui, H.D. (1984). In: *Life assessment of dynamically loaded materials and structures (ECF5)*, pp. 385-396, Faria, L. (Ed.), EMAS, West Midlands.
14. Toribio, J. (2004) *Eng. Fract. Mech.* **71**, 769-777.
15. Toribio, J., Valiente, A. (2004) *Mater. Lett.* **58**, 3514-3517.
16. Toribio, J., Valiente, A. (2006) *Eng. Fail. Anal.* **13**, 301-311.
17. Toribio, J., Ovejero, E. (1997) *Mater. Sci. Eng. A* **234-236**, 579-582.
18. Toribio, J., González, B., Matos, J.C. (2007) *Mater. Sci. Eng. A* **468-470**, 267-272.
19. Miller, L.E., Smith, G.C. (1970) *J. Iron Steel Inst.* **208**, 998-1005.