Role of Surface Defects in the Initiation of Fatigue Cracks in Pearlitic Steel

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Abstract In this paper, tensile fatigue tests were performed under load control, with constant stress amplitude, on pearlitic steel wires with different cold drawing degree, from the hot rolled bar (not cold drawn at all) to the commercial prestressing steel wire (which has undergone seven cold drawing steps and a stress relieving treatment). Results show that fatigue cracks in pearlitic steels initiate at the wire surface starting from small defects, whose size decreases with the drawing process, as the cross sectional area of the wire does. Some of these defects appear during the drawing process itself. Fatigue cracks created from defects (initiation phase) exhibit a fractographic appearance consisting of ductile microtearing events which can be classified as tearing topography surface or TTS. Such microtearings are more planar in the initiation period than in the propagation phase and exhibit a spacing remarkably lower in the pretressing steel wire than in the hot rolled bar, so that their size decreases with cold drawing as the steel microstructure does.

Keywords Pearlitic steel, Cold drawn steel wire, Initiation of fatigue cracks, Surface defects

1. Introduction

Fatigue life of steel wires depends on their surface state and the existence of defects (such as microcracks, inclusions, etc.) present in the material. In wires made of eutectoid cold drawn steel, the fatigue process initiates in surface defects [1-3], broken martensite layers (due to a overheating during the wire drawing process), longitudinal groves and holes mainly caused by surface inclusions [1]. Many times surface defects are caused by the drawing process itself [4].

Surface defects present in the material before wire drawing can be eliminated by such a mechanical treatment. A scratch on the wire surface can be removed by repeated drawing; however, the flaw remains inside the wire because of the development of an overlap, and it is thus difficult to completely remove the flaw [5]. In corrosion-fatigue the aggressive environment can blunt the surface defects due to material dissolution, increasing the number of cycles required to initiate cracking [6].

The main cause of failure in steel wires is the presence of non-metallic inclusions during wire drawing or service [7]. The existence of non-metallic inclusions in cold drawn pearlitic steel affects its fatigue properties [8] by modifying the local stress state surrounding the inclusions, depending on the size, localization, composition and geometry of the inclusion [9].

This paper studies the defects able to initiate the fatigue phenomenon in pearlitic steel applied in two forms —i.e., as a hot rolled bar and as a commercial prestressing steel wire— by analyzing the effects of cold drawing on such defects and the microstructural arrangement and how these changes affect the fatigue performance of prestressing steel.

2. Experimental Procedure

2.1. Material

The material used was eutectoid pearlitic steel (chemical composition 0.789% C, 0.681% Mn, 0.210% Si, 0.010% P, 0.218% Cr, 0.061% V). It was studied in two forms: firstly, as a hot rolled bar (non cold drawn at all) and, secondly, as a commercial prestressing steel wire which has undergone seven cold drawing steps up to reaching a cumulative plastic strain ε^P=1.6 and a posterior stress-relieving treatment to eliminate, or at least diminish, residual stresses. Steel was supplied in form of wires with circular section, the diameter ranging respectively between 11 and 5 mm for the hot rolled bar and the prestressing steel wire.

Cold drawing produces a clear improvement of conventional mechanical properties (Table 1) obtained from a standard tension test: both the yield strength (σ_Y) and the ultimate tensile strength (UTS, σ_R) increase with cold drawing, while the Young's modulus (E) remains constant and the strain at UTS (ε_R) decreases with it.

Table 1. Mechanical properties of the material in both conditions, i.e. as a hot rolled bar and as a prestressing steel (cold drawn) wire

Steel	E (GPa)	σ_Y (MPa)	σ_R (MPa)	ε_R
Hot rolled bar	202	700	1220	0.078
Prestressing steel wire	209	1480	1820	0.060

Cold drawing also improves the fatigue and fracture behaviour of eutectoid steel. The fracture toughness K_{IC} was obtained by means of fracture test on precracked wires under tensile loading, as described in [10]. The K_{IC} value increases from 53 MPa·m$^{1/2}$ in the hot rolled bar to 137 MPa·m$^{1/2}$ (for θ=0º, fracture toughness in the transverse direction) in the prestressing steel wire, where cold drawing also induces an important strength anisotropy with a directional fracture toughness whose value is dependent on the particular axis of analysis. Values C and m (constants of the Paris law) were obtained by means of tensile fatigue tests, as explained in ref. [11]. The m coefficient in the Paris law (slope of the line) is the same for the two steels and rounds the value 3, whereas the C parameter decreases with cold drawing, changing form $5.3\cdot10^{-12}$ in the hot rolled bar to $4.1\cdot10^{-12}$ in the cold drawn wire (units for C and m are the adequate to measure da/dN in m/cycle and ΔK in MPa·m$^{1/2}$).

2.2. Test Procedure

Wöhler fatigue tests were performed under tensile load control with constant $\Delta\sigma$, sinusoidal wave shape, frequency of 10 Hz, R-ratio R=0 and a maximum stress lower than the yield stress σ_Y (some S-N tests were performed under a stress range of about half the yield strength). The specimens were in the form of 30 cm long bars of circular cross section and the same diameter as the supplied wires. A total number of 20 tests were performed. Fracture surfaces were analyzed by scanning electron microscopy (SEM).

3. Experimental Results

3.1. Microstructure

Figs. 1 and 2 show the microstructure of both steel forms, hot rolled bar and prestressing steel wire, in both transverse and longitudinal section, where the horizontal side of the micrograph corresponds to the radial direction and the vertical side is associated with the axial direction in the longitudinal cut and with the circumferential one in the transverse cut.

Cold drawing produces important microstructural changes in the pearlitic steel [12, 13] in the form of slenderizing of pearlitic colonies, decreases of interlamellar spacing of pearlite and progressive orientation with cold drawing of both colonies and lamellae. Thus, the transverse section (Fig. 1) shows that the lamellae evolve towards a structure with increased packing closeness while at the same time adopting a curved appearance (*curling* phenomenon) from the very beginning of the cold drawing process (very common when drawing metals with bcc structure). With regard to the longitudinal section (Fig. 2), both decrease of interlamellar spacing and lamellar orientation in axial direction are observed.

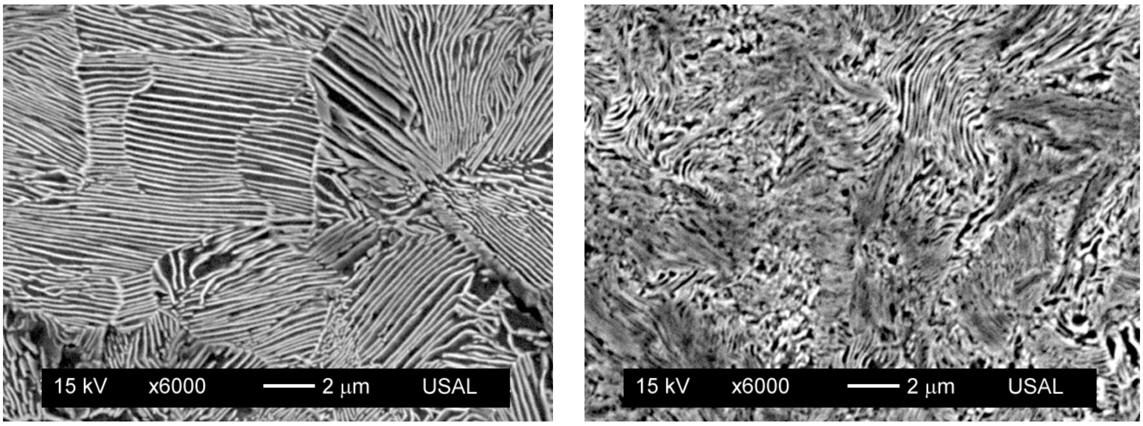

Figure 1. Microstructure in the transverse section: hot rolled bar (left) and prestressing steel wire (right)

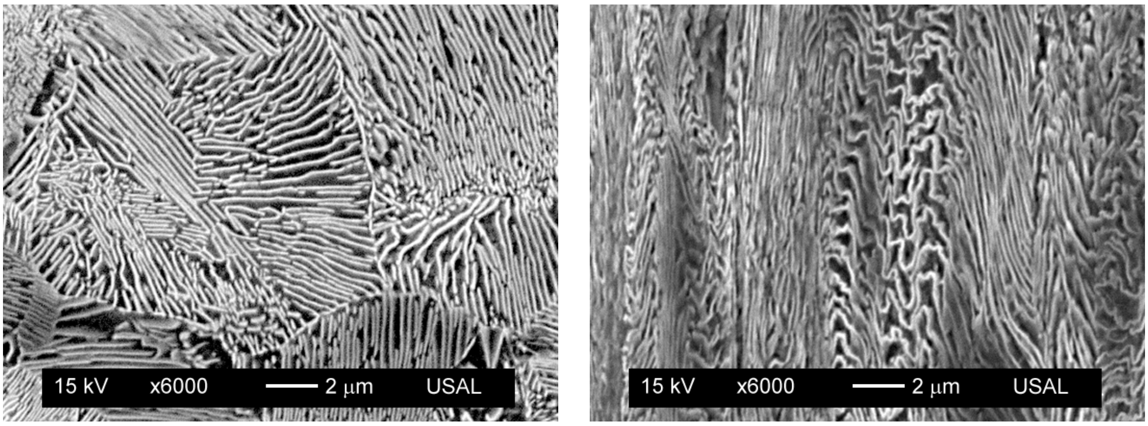

Figure 2. Microstructure in the longitudinal section: hot rolled bar (left) and prestressing steel wire (right). In both micrographs the vertical side is associated with the wire axis or cold drawing direction

3.2. Initiation of Fatigue Cracks from Surface Defects

The surface quality of both commercial products, hot rolled bar and prestressing steel wire, is very different (Fig. 3). While in the first (which comes from a hot rolling process) some material losses and irregularities can be observed on its uneven surface, in the prestressing steel wire (heavily drawn) longitudinal grooves are observed (typical surface features in drawn steel wires [1]), the roughness being higher in the hot rolled bar than in the prestressing steel wire. The defects (pre-existent in the hot rolled bar) change the geometry with the drawing process, their depth decreasing up to the total disappearing in some cases [5]. In addition, the analyzed material (in the two forms as a hot rolled bar or a prestressing steel wire) has frequent inclusions (sulphides, oxides, silicates…), some of which can be found on the wire surface, provoking voids on the material (Fig. 4).

Results show that fatigue cracks in pearlitic steels begin at the wire's surface starting from some of these small defects (Fig. 5). The defect size decreases with the drawing process, as the cross sectional of the wire does. In the hot rolled bar the fatigue initiators are mainly the surface defects with small aspect ratio (material losses at the peripheral zones) while in the prestressing steel wire such initiators are principally the voids created by, probably, the existence of particles near the wire surface (cf. Fig. 5). Depth of maximum surface defects is about 120 μm in the hot rolled bar and about 25 μm in the cold drawn wire. Initiation of fatigue cracks from surface defects is due to the fact that the latter act as stress concentrators.

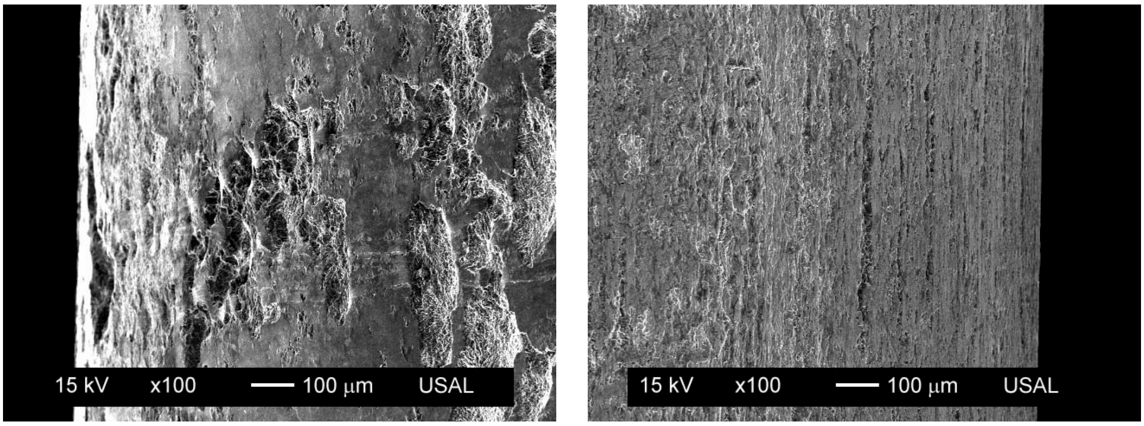

Figure 3. Surface of the material in the two forms: hot rolled bar (left) and prestressing steel wire (right). In both pictures the vertical side is aligned with the wire axis or cold drawing direction

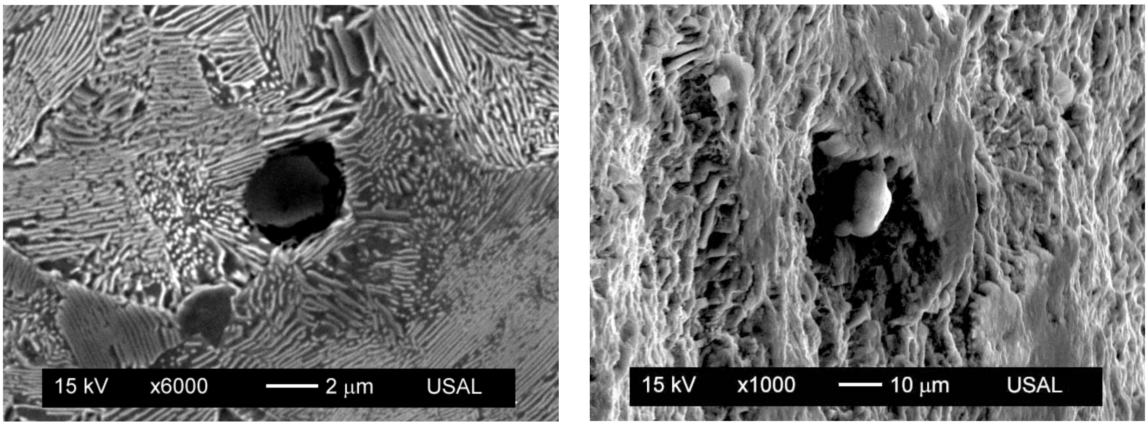

Figure. 4. Inclusions in hot rolled bar: inside the wire (left) and on the wire surface (right). In both pictures the vertical side is aligned with the wire axis or cold drawing direction

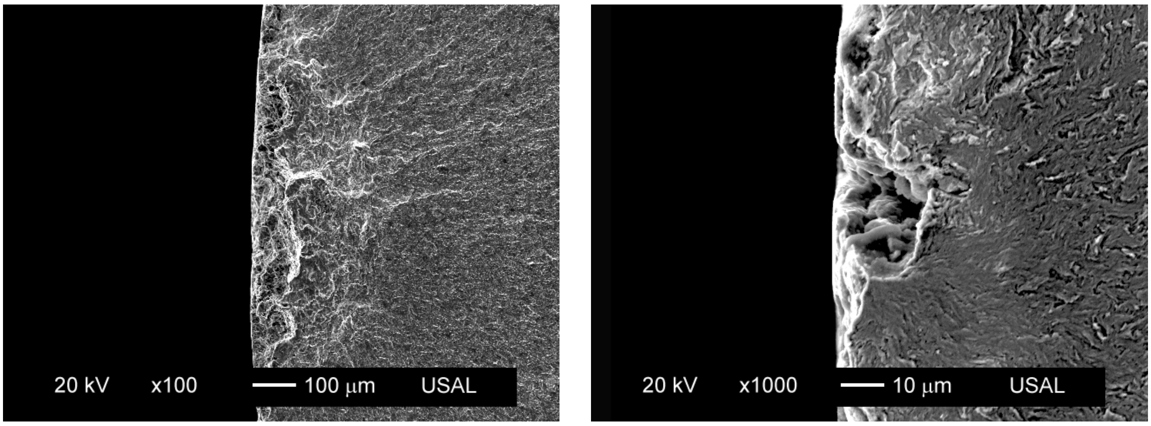

Figure. 5. Initiation of fatigue crack growth from a surface defect: hot rolled bar (left) and prestressing steel wire (right). Both images represent the transverse fatigue fracture surface (circular section perpendicular to the wire axis or cold drawing direction) and crack growth direction takes place from left to right in the fractographs

With regard to fatigue crack initiation from the surface defects in the material supplied as a hot rolled bar and a prestressing steel wire, Fig. 6 shows the same information as Fig. 5 but includes arrows to identify the fatigue crack growth from the aforesaid defect. It is seen that the defect appearance is different in the two material forms. In the hot rolled bar the surface defect looks like an extremely shallow flaw with an approximate aspect ratio of 0.2 whereas the prestressing steel wire such a defect looks like a relatively small circumferential flaw with an approximate aspect ratio equal to the unity. In the matter of the initiation of fatigue crack growth, it is important to say that, apparently, there is no single initiation point over the defect boundary, but instead of it a line (i.e. a set of points can be viewed) defining the emerging fatigue crack front at the early stages of cracking and diverging fatigue propagation lines emanating from the defect: lack of material previously lost during the manufacturing process in the case of the hot rolled bar and voids created by a previous inclusion in the prestressing steel wire.

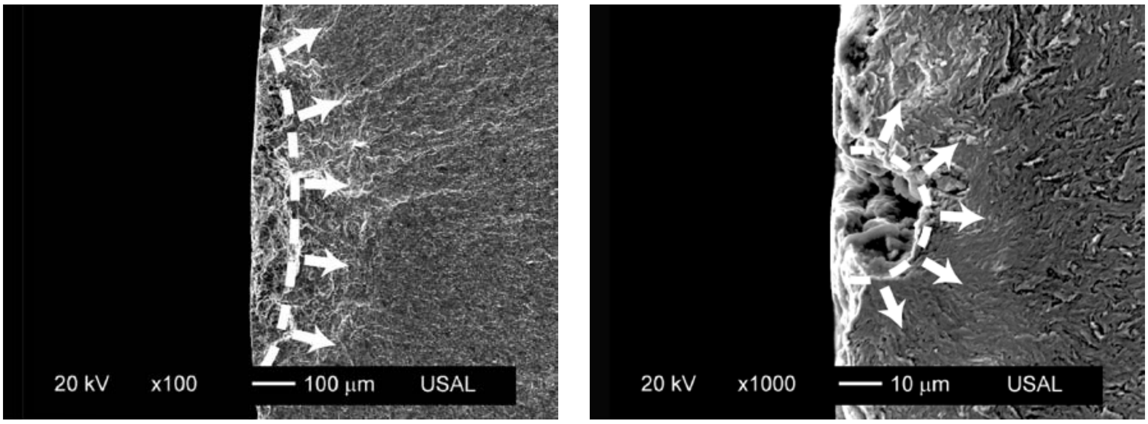

Figure 6. Initiation of fatigue crack growth from a surface defect: hot rolled bar (left) and prestressing steel wire (right), including arrows to identify the fatigue crack growth from defect

In high strength eutectoid steels fatigue crack growth can start from defects caused by the drawing process itself. Fig. 7 shows a surface defect possibly generated by a hard particle in the wire surface during the drawing process, because a longitudinal track, aligned in the drawing direction, appears in the wire surface. A sort of plastic deformation can be observed surrounding the hole (Fig. 7; left) with a very regular geometry. Fig. 7 also includes a magnification (right) of the surface defect (and consequent fatigue crack growth) viewed from different angle, showing the longitudinal scratching marks, an evidences of the pre-damage created by an inclusion (hard particle) during the plastic straining as a consequence of the manufacturing process by cold drawn.

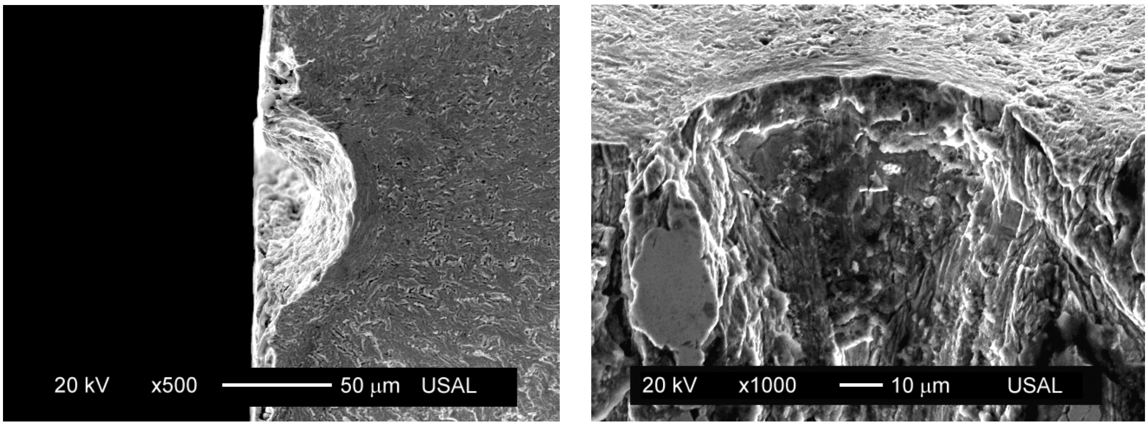

Figure 7. Surface defect caused by cold drawing producing transverse cracking in the prestressing steel wire (left) and magnification of the surface defect (and consequent fatigue crack growth) viewed from different angle (right)

Fatigue cracks created from defects exhibit a fractographic appearance consisting of ductile microtearing events (Fig. 8), which can be classified as *tearing topography surface* or TTS [14]. Such microtearings are less rough in the initiation period (Fig. 8) than in the propagation phase (Fig. 9) and exhibit a spacing remarkably lower in the prestressing steel wire than in the hot rolled bar, so that their size decreases with cold drawing as the steel microstructure does, and a sort of materials science relationship appears between microstructural unit size and fatigue microfracture event. The aforesaid TTS microfracture mode has been associated with hydrogen embrittlement in pearlitic steel [15] and it can be considered a slow propagation mode in hydrogen-assisted fracture processes linked with subcritical cracking at one micrometer per second or less [16].

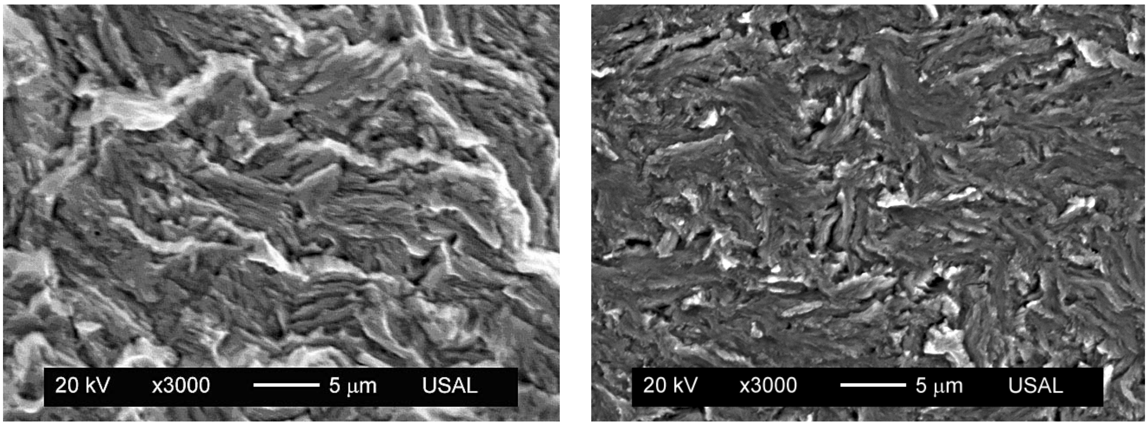

Figure 8. Fractograph corresponding to fatigue initiation phase: hot rolled bar (left) and prestressing steel wire (right). In both images the fatigue crack growth direction is from left to right

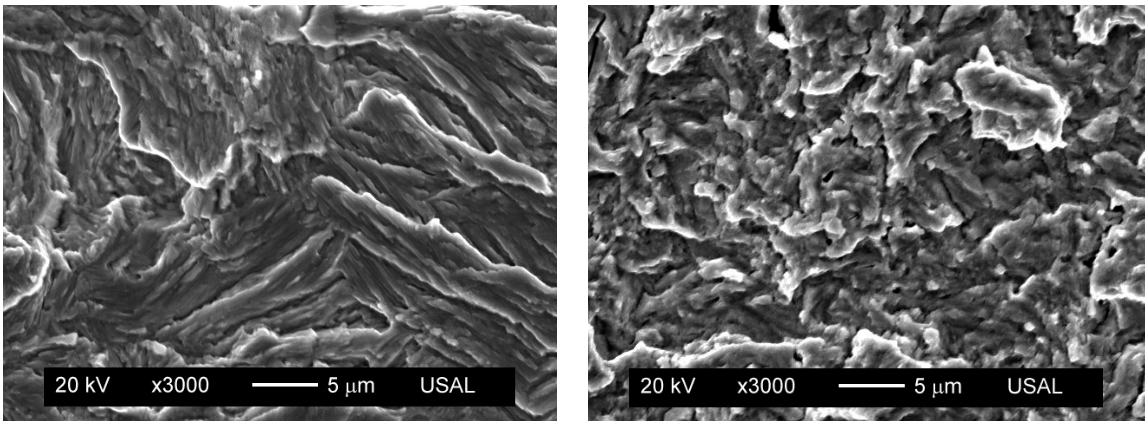

Figure 9. Fractograph corresponding to fatigue propagation phase: hot rolled bar (left) and prestressing steel wire (right). In both images the fatigue crack growth direction is from left to right

4. Simulations

In the Whöler tests, a smooth specimen (samples of the as-supplied wire) was subjected to fatigue loading under constant amplitude, stress level of about half of the yield strength ($\Delta\sigma=\sigma_Y/2$), up to fracture due to initiation and propagation of a fatigue crack reaching its critical value (Fig. 10).

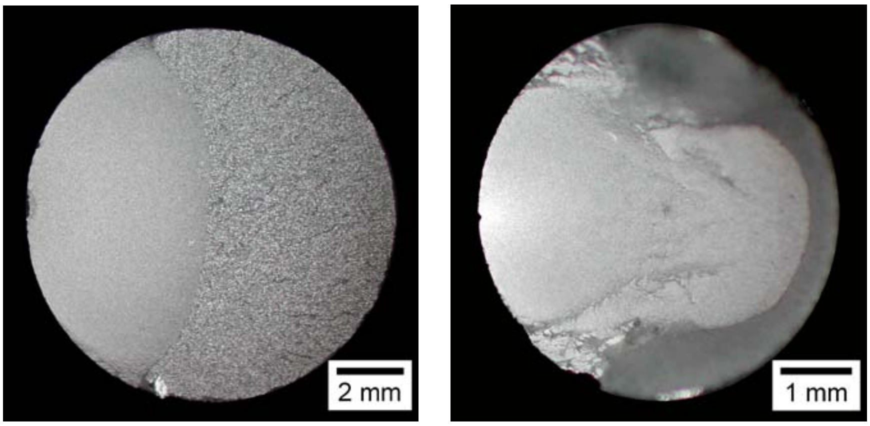

Figure 10. Fracture surface in the specimens after the Whöler tests: hot rolled bar (left) and prestressing steel wire (right). In both images the fatigue crack growth direction is from left to right

Fatigue life N_f was experimentally obtained by means of Whöler tests. The experimental results corresponding to prestressing steel are similar as those previously obtained by Beretta and co-workers [3, 4]. In addition, a numerical estimation was made of the number of cycles needed for crack propagation N_p, on the basis of a simple model previously used by other authors in the scientific literature [17, 18], considering that it follows the Paris law [19],

$$\frac{da}{dN} = C\Delta K^{m} \tag{1}$$

and the stress intensity range ΔK is given by,

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \tag{2}$$

where Y is the dimensionless stress intensity factor (SIF).

The number of cycles for propagation was calculated by following expression derived from the Paris law,

$$N_p = \frac{1}{C\Delta\sigma^{m}\pi^{m/2}}\int_{a_0}^{a_C}\frac{da}{Y^{m}a^{m/2}} \tag{3}$$

where a_0 and a_C are respectively the initial and the final crack sizes, the first associated with the fatigue threshold [2] and the latter with the critical instant of failure (K_{Imax}=K_{IC}, according to the local fracture criterion) and the path followed by the crack during propagation is that plotted in Fig. 11. During its growth, the fatigue crack exhibits an elliptical shape in the Paris regime.

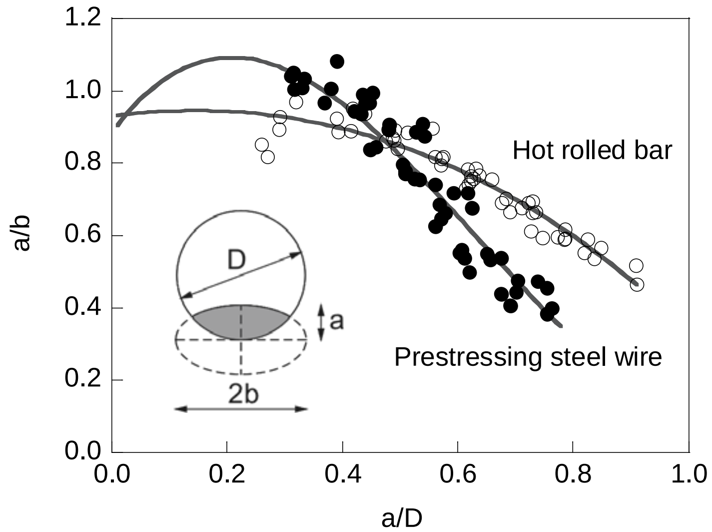

Figure 11. Geometrical changes in the crack front during fatigue crack propagation

The crack front was characterized as an ellipse with semiaxes a (crack depth) and b, its centre been at the wire surface. On the basis of the experimental tests [11] and extrapolating for small crack sizes where the crack front exhibits a quasi-circular appearance (Fig. 12), a relationship was obtained between the relative crack depth (crack depth divided by the diameter, a/D) and the aspect ratio (ratio between the semiaxes of the ellipse, a/b), Fig. 11.

The size effect appearing in the steel samples was taken into account during the propagation phase because it changes the geometric evolution during fatigue. In a previous research work, Shin and Cai [20] observed how when the sample diameter decreases, the fatigue crack growth rate (FCGR) changes at the crack surface when compared with the same value at the crack centre, whereas for higher diameters the FCGR (represented by the Paris law) is the same at the centre and the surface. The aforesaid size effect affects how the crack front evolves (and thus the crack aspect ratio).

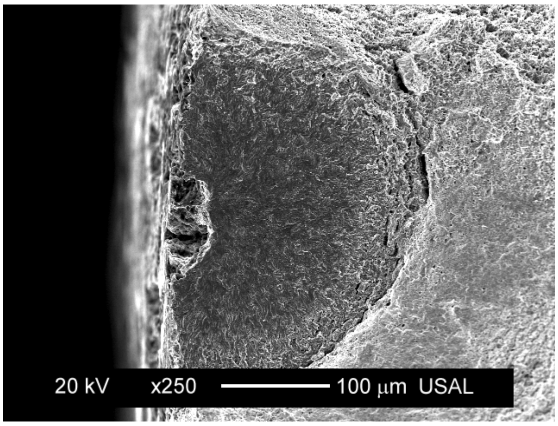

Figure 12. Short crack emanating from a surface defect in the form of void created by a previous inclusion in cold drawn steel. Fatigue crack propagation from left (surface defect) to right

The dimensionless SIF Y employed is that calculated by Astiz [21], for the central point of the crack front by using the finite element method, which depends on the relative crack depth a/D and the aspect ratio a/b through the coefficients C_{ij} (Table 2),

$$Y = \sum_{\substack{i=0 \\ i\neq 1}}^{4} \sum_{j=0}^{3} C_{ij} \left(\frac{a}{D}\right)^{i} \left(\frac{a}{b}\right)^{j} \tag{4}$$

Table 2. Coefficients C_{ij} of Eq. (4) taken from ref. [21]

i	*j=0*	*j=1*	*j=2*	*j=3*
0	1.118	-0.171	-0.339	0.130
2	1.405	5.902	-9.057	3.032
3	3.891	-20.370	23.217	-7.555
4	8.328	21.895	-36.992	12.676

Solution of equation (3) was obtained in incremental form, the convergence being guaranteed by the adequate choice of the crack increment Δa (sufficiently low).

The number of cycles associated with crack initiation N_i can also be estimated as follows [17, 18],

$$N_i = N_f - N_p \tag{5}$$

where the common definition of initiation in reality pertains to both nucleation and propagation of microcracks [22].

Table 3 shows the fatigue life N_f experimentally obtained for a stress range about half of the yield strength of each material. In both the hot rolled bar and the cold drawn wire the life is around 300000 cycles, which indicates that the cold drawing process improves the fatigue performance in a similar way that the increase of material strength. In addition, the main part of the fatigue life (measured as number of cycles) is associated with the propagation phase in the hot rolled bar and with the initiation phase in the cold drawn wire.

Table 3. Fatigue life N_f (experimental, average of five tests), number of cycles for propagation N_p (obtained by simulations) and number of cycles for initiation N_i ($N_i = N_f - N_p$)

Steel	$\Delta\sigma$ (MPa)	N_f (cycles)	N_p (cycles)	N_i (cycles)
Hot rolled bar	347	308200	253700	54500
Prestressing steel wire	790	312910	57655	255255

The prestressing steel wire exhibits a Paris curve below that of the hot rolled bar (lower parameter *C*) [11], thus producing a retardation in fatigue crack propagation with the cold drawing process. In addition the fracture toughness is also higher in the cold drawn wire than in the hot rolled bar [23]. This indicates that cold drawing is beneficial since it improves both the fatigue and the fracture performance by dropping the Paris law [11] and elevating the fracture toughness [10], a clear implication for structural engineers. Moreover, the prestressing steel wire is again the best option on the basis of a clear reduction of the size of the surface defects (acting as crack initiators) and the microstructural changes induced by the drawing process (e.g., orientation of the cementite layers acting as barriers to dislocational movement). Both characteristics, small surface defects and special microstructural arrangement, contribute to a delay of the initiation of fatigue crack growth.

5. Conclusions

The following conclusions may be drawn from the experimental results of fatigue crack growth from surface defects in pearlitic steel:

(i) Fatigue cracks in pearlitic steels are initiated at the wire surface starting from small defects. In the hot rolled bar the fatigue initiators are mainly the surface defects (material losses) while in the prestressing steel wire such initiators are principally the voids created by the existence of particles near the wire's surface.

(ii) Fatigue cracks created from defects exhibit a fractographic appearance consisting of ductile microtearing events which can be classified as *tearing topography surface* or TTS, and exhibit a spacing remarkably lower in the prestressing steel wire than in the hot rolled bar.

(iii) The number of cycles necessary for fatigue crack initiation in the prestressing steel wire is quite higher than that of the hot rolled bar (for $\Delta\sigma=\sigma_Y/2$) and thus changes in surface defects and microstructural arrangement produced by the drawing process considerably improves its fatigue performance.

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References

[1] I. Verpoest, E. Aernoudt, A. Deruyttere, M. de Bondt, The fatigue threshold, surface condition and fatigue limit of steel wire. Int J Fatigue, 7 (1985) 199–214.
[2] J. Llorca, V. Sánchez-Gálvez, Fatigue threshold determination in high strength cold drawn eutectoid steel wires. Eng Fract Mech, 26 (1987) 869–882.
[3] S. Beretta, S. Matteazzi, Short crack propagation in eutectoid steel wires. Int J Fatigue, 18 (1996) 451–456.
[4] S. Beretta, M. Boniardi, Fatigue strength and surface quality of eutectoid steel wires. Int J Fatigue, 21 (1999) 329–335.
[5] T. Shinohara, K. Yoshida, Deformation analysis of surface flaws in stainless steel wire drawing. J Mater Process Technol, 162–163 (2005) 579–584.
[6] N. Singh, V. Sánchez-Gálvez, Effect of $Ca(OH)_2$+NaCl environment corrosion fatigue crack growth in cold drawn eutectoid steel rods. Br Corros J, 26 (1991) 117–121.

[7] M. Yilmaz, Failures during the production and usage of steel wires. J Mater Process Technol, 171 (2006) 232–239.
[8] G.J. Fowler, The influence of non-metallic inclusions on the threshold behavior in fatigue. Mater Sci Eng, 39 (1979) 121–126.
[9] K. Lambrighs, I. Verpoest, B. Verlinden, M. Wevers, Influence of non-metallic inclusions on the fatigue properties of heavily cold drawn steel wires. Procedia Engineering, 2 (2010) 173–181.
[10] B. González, Influencia del proceso de fabricación en el comportamiento plástico y en fractura de aceros de pretensado, PhD Thesis, University of Salamanca, Zamora, Spain, 2007.
[11] J. Toribio, J.C. Matos, B. González, Micro- and macro-approach to the fatigue crack growth in progressively drawn pearlitic steels at different R-ratios. Int J Fatigue, 31 (2009) 2014–2021.
[12] J. Toribio, E. Ovejero, Effect of cumulative cold drawing on the pearlite interlamellar spacing in eutectoid steel. Scripta Mater, 39 (1998) 323–328.
[13] J. Toribio, E. Ovejero, Effect of cold drawing on microstructure and corrosion performance of high-strength steel. Mech Time-Depend Mater, 1 (1998) 307–319.
[14] A.W. Thompson, J.C. Chesnutt, Identification of a fracture mode: the tearing topography surface. Metall Trans A, 10 (1979) 1193–1196.
[15] J.E. Costa, A.W. Thompson, Hydrogen cracking in nominally pearlitic 1045 steel. Metall Trans A, 13 (1982) 1315–1318.
[16] J. Toribio, A.M. Lancha, M. Elices, Characteristics of the new tearing topography surface. Scripta Metall Mater, 25 (1991) 2239–2244.
[17] A. Sonsöz, A.E. Tekkaya, Service life estimation of extrusion dies by numerical simulation of fatigue-crack-growth. Int J Mech Sci, 38 (1996) 527–538.
[18] D.O. Olowokere, D.I. Nwosu, Numerical studies on crack growth in a steel tubular T-joint. Int J Mech Sci, 39 (1997) 859–871.
[19] P.C. Paris, F. Erdogan, A critical analysis of crack propagation laws. J Basic Eng, 85D (1963) 528–534.
[20] C.S. Shin, C.Q. Cai, Fatigue crack propagation properties from small sized rod specimens. Nucl Eng Des, 236 (2006) 2574–2579.
[21] M.A. Astiz, An incompatible singular elastic element for two- and three-dimensional crack problems. Int J Fract, 31 (1986) 105–124.
[22] D.L. McDowell, An engineering model for propagation of small cracks in fatigue. Eng Fract Mech, 56 (1997) 357–377.
[23] J. Toribio, A. Valiente, Failure analysis of cold drawn eutectoid steel wires for prestressed concrete. Eng Fail Anal, 13 (2006) 301–311.