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Procedia Structural Integrity 2 (2016) 2330–2337

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Fatigue cracking in high-strength cold-drawn pearlitic steel wires for anchorage in rocks

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Abstract

This paper analyzes the fatigue crack path in two pearlitic steels with very different microstructural arrangement: a hot rolled pearlitic steel bar and a commercial high-strength cold drawn prestressing steel wire frequently used for anchorage in rocks. In both materials, fatigue cracks are mostly transcollonial and tend to fracture pearlitic lamellae, so that many different micro-phenomena appear such as non-uniform crack opening displacement, micro-discontinuities, branchings, bifurcations and frequent local deflections, all of them creating a sort of microstructural roughness with regard to the fatigue crack path which is different in hot rolled bar and in the cold drawn wire.

Keywords: Pearlite; cold drawing; fatigue crack path; micro-roughness

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1. Introduction

In recent years, the study of the phenomenon of fatigue crack growth in engineering materials is usually performed by using two-parameters approaches, as shown in the papers by Sadananda and Vasudevan (2004), Stoychev and Kujawski (2005) and Zhang et al. (2005). The fundamental base of such approaches is the use of two driving forces as parameters governing the evolution of the crack under cyclic loading, e.g., ΔK and K_{max}, or ΔK and R. Research carried out by Kujawski (2001) shows that, in the case of ductile materials, the crack driving force for fatigue is dominated by the stress intensity factor (SIF) range ΔK, whereas in the case of brittle materials it is governed by the maximum SIF K_{max}. The concept of an effective SIF K_{eff} is discussed by Marci and Khotsyanovskii (1995) assuming the idea of fatigue crack closure proposed by Elber (1970).

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10.1016/j.prostr.2016.06.292

The crack path under fatigue (cyclic) loading depends on microstructural features of the material. In the case of ferritic-pearlitic steels, Walther and Eifler (2004) showed that the crack advances along the ferritic seam through the grain boundaries. In steel with pearlite uniformly distributed in ferrite, the fatigue cracking path is more tortuous than in those with isolated distribution, with larger angle deflections appearing during the crack advance as suggested by Korda et al. (2006a). In eutectoid steel with fully pearlitic microstructure, the crack tends to break the ferrite/cementite lamellae. In this case the kind of fatigue fracture surface can be classified as transcollonial fracture according to Toribio et al. (2009).

The study by Korda et al. (2006b) in banded ferritic-pearlitic steels indicates that the bands of pearlite (oriented in preferential directions) provoke a decrease of the fatigue crack growth rate, since they produce a more tortuous crack path, with more frequent and more angled deflections and branchings. The tortuous fatigue crack path frequently produces a crack interlock and the crack branching reduces the local crack tip driving forces for its propagation.

The orientation of ferrite/cementite lamellae in fully pearlitic steels produces a retardation in the fatigue crack growth rate, a phenomenon studied by Wetscher et al. (2007) and Toribio et al. (2009). The reason for this particular behaviour is the fact that cementite lamellae behave as serious obstacles for dislocation movement and therefore for crack propagation. In the framework of the fracture mechanics approach, Kitagawa et al. (1975) suggested that the non-linear crack configuration should be taken into account. In addition, variations in crack deflection features influence considerably the fatigue crack propagation rates and threshold SIF range as discussed by Suresh (1983) and Carpinteri et al. (2008).

This paper presents a fracto-materialographic analysis of the fatigue crack growth in two pearlitic steels with very different degrees of microstructural orientation (quite distinct orientation micro-angles in relation to the wire axis), in order to ascertain the fatigue crack path as a function of the specific micro-arrangement of the ferrite and cementite lamellae.

2. Experimental method

The material used in the present paper was a pearlitic steel with eutectoid chemical composition shown in Table 1. It was presented in two forms: the hot rolled bar (not cold drawn at all) and the prestressing steel wire (obtained after seven cold drawing steps and a stress-relieving treatment).

Table 1. Chemical composition.

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

The cold drawing process (up to cumulative plastic strain $\varepsilon^P = 1.57$) produces a clear improvement of the material strength in the form of increase of both yield strength and ultimate tensile strength UTS, while the Young's modulus remains approximately the same (Table 2).

Table 2. Mechanical properties.

Materials	Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)
Hot rolled bar	202	700	1220
Cold drawn wire	209	1480	1820

The fatigue tests consisted of applying a cyclic tensile load on cylindrical samples taken from the bar and the wire (as received, 11.0 mm for the hot rolled bar and 5.1 mm for the cold drawn wire). A sinusoidal wave was used with a frequency of 10 Hz and R-ratio = 0. The maximum stress applied during the tests was always lower than the yield strength of the material.

The fatigue fracture surfaces and the longitudinal cuts on the cracked specimens, after its metallographic preparation and being etched with 4% Nital to reveal microstructure, were examined by scanning electron microscopy (SEM). In all pictures, the crack propagation occurred from left to right.

3. Experimental results

3.1. Microstructural analysis

Fig. 1 shows a scheme of the cuts associated with the materialographic analysis. The horizontal axis of the micrograph corresponds to the radial direction in the wire, while the vertical axis of the micrograph is linked with the hoop cylindrical coordinate in the transverse section of the wire and associated with the axial cylindrical coordinate in the longitudinal section of the wire. The microstructure of both materials (hot rolled bar and cold drawn wire) appears in Fig. 2 in their respective transverse and longitudinal sections.

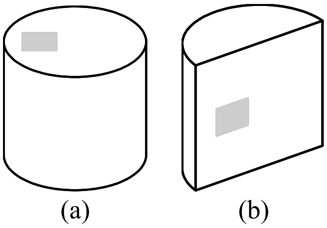


Fig. 1. Micrograph on the: (a) transverse section; (b) longitudinal section.

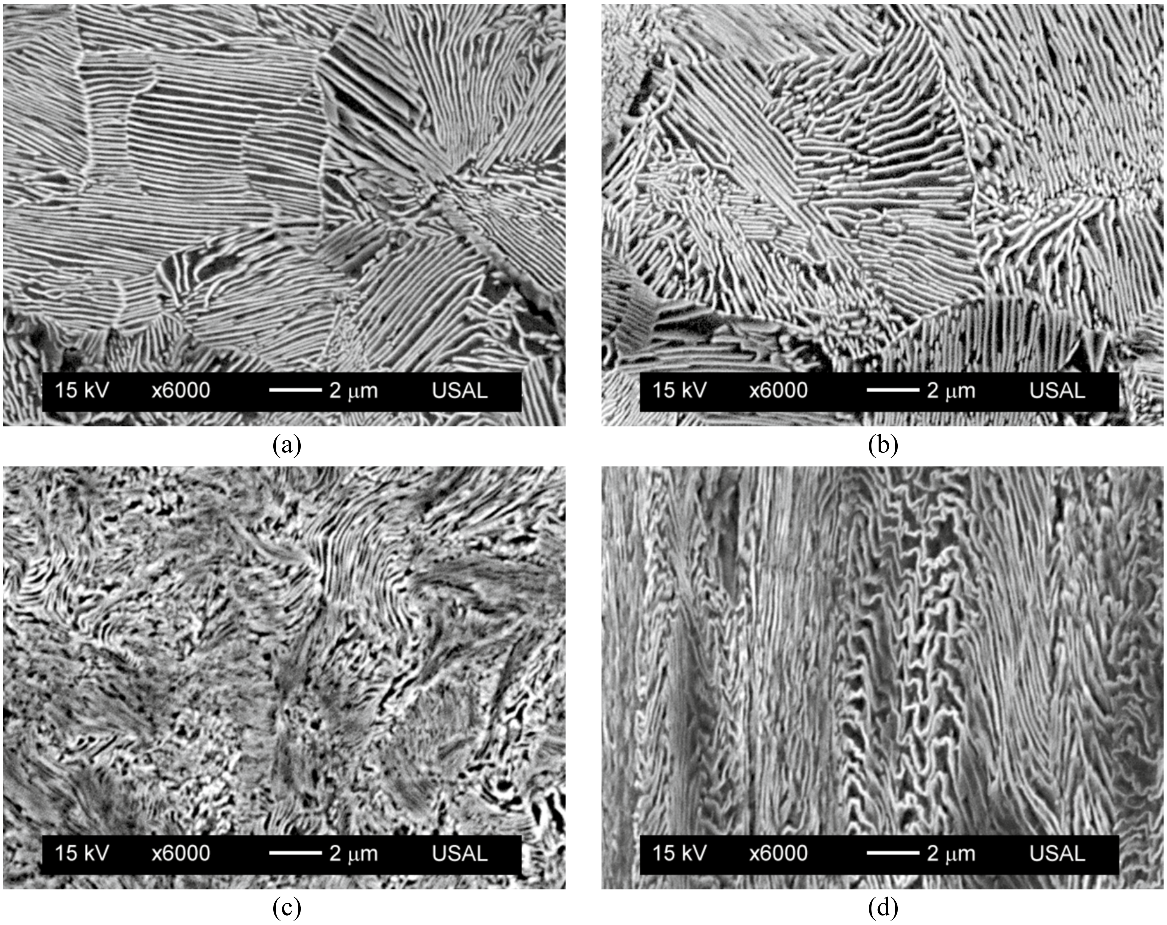


Fig. 2. Microstructure of steel: (a) hot rolled bar in transverse section; (b) hot rolled bar in longitudinal section; (c) cold drawn wire in transverse section; (d) cold drawn wire in longitudinal section.

Cold drawing induces key microstructural changes in the steel at the two basic microstructural levels. As described by Toribio and Ovejero (1997, 1998c) the colonies become progressively enlarged and oriented in axial direction with cold drawing. With regard to the lamellae, Toribio and Ovejero (1998a, 1998b) showed that the interlamellar spacing decreases with cold drawing and at the same time the axial orientation increases.

3.2. Fractographic analysis

Fig. 3 shows a scheme of the micrograph on the fatigue fracture surface. The horizontal axis of the micrograph corresponds to the radial direction, while the vertical axis is linked with the hoop cylindrical coordinate. The fatigue surface exhibits ductile micro-tearing patterns (Fig. 4) corresponding to highly-localized plastic strains.

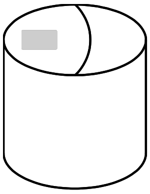


Fig. 3. Micrograph on the fatigue fracture surface.

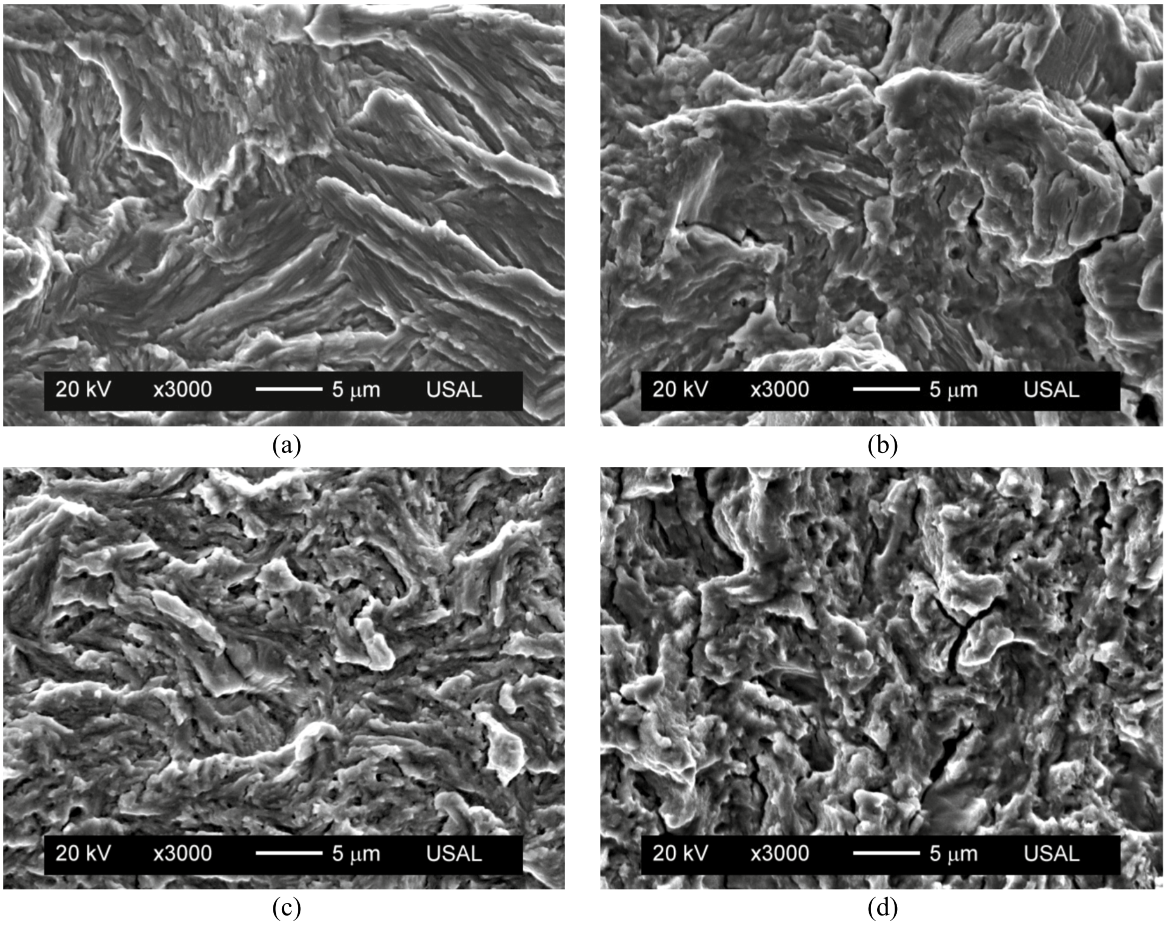


Fig. 4. Fractographic analysis: (a) hot rolled bar, $\Delta K = 23$ MPam$^{1/2}$; (b) hot rolled bar, $\Delta K = 46$ MPam$^{1/2}$; (c) cold drawn wire, $\Delta K = 27$ MPam$^{1/2}$; (d) cold drawn wire, $\Delta K = 54$ MPam$^{1/2}$.

In the drawn steel the ductile micro-tears are smaller and with curvier geometry than in the hot rolled bar (Fig. 4), due to the microstructural changes (mostly in the wire's cross section) produced by the high plastic strain undergone by the heavily drawn steel. An increase of the SIF range ΔK also promotes this phenomenon in both steels.

3.3. Fracto-metallographic analysis

Fig. 5 shows a scheme of the cut associated with the fracto-materialographic analysis. The horizontal axis of the micrograph corresponds to the radial direction in the wire, while the vertical axis of the micrograph is linked with the axial cylindrical coordinate in the longitudinal section of the wire. Fig. 6 includes various longitudinal cuts of the crack path caused by fatigue in the steels studied.

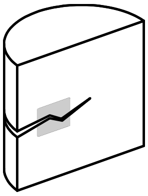
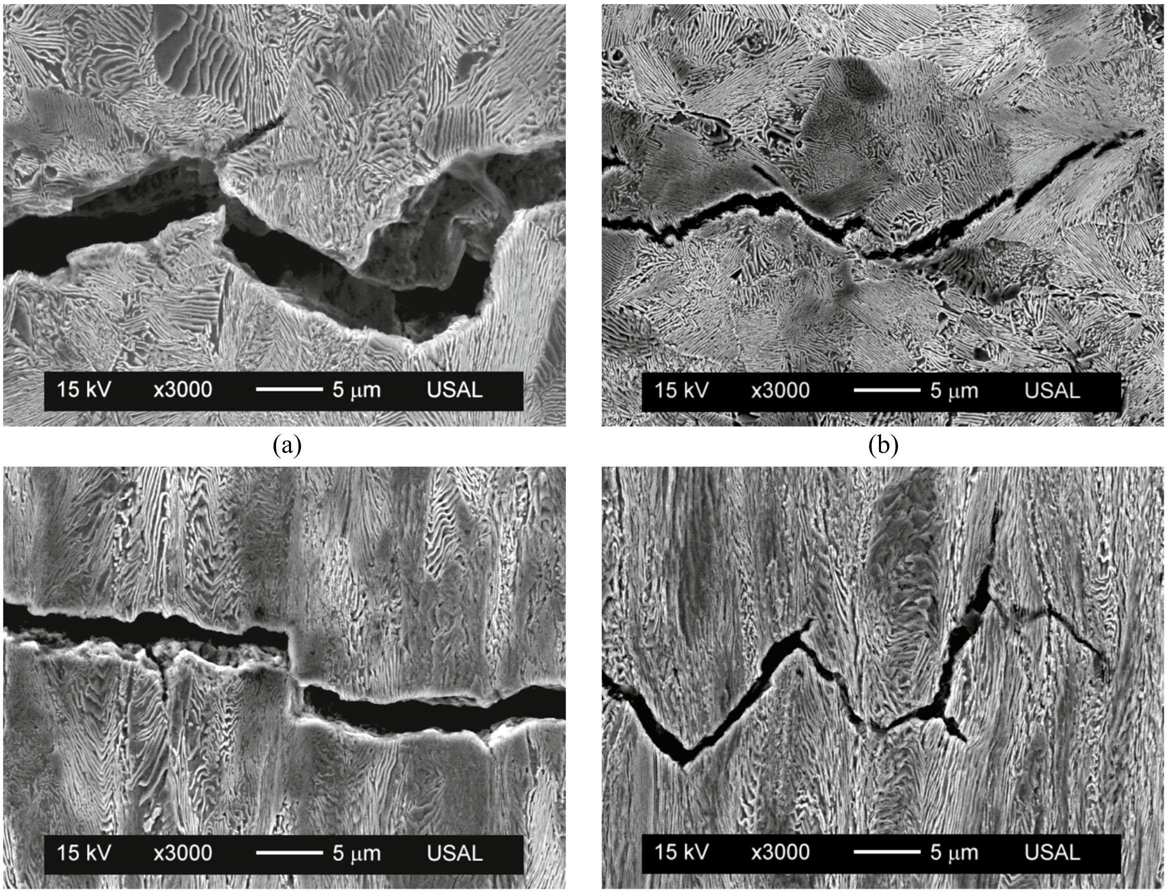


Fig. 5. Micrograph on the longitudinal cut.



(a) (b)

(c) (d)

Fig. 6. Fractometalographic analysis: (a) hot rolled bar, intermediate zone of crack; (b) hot rolled bar, crack tip; (c) cold drawn wire, intermediate zone of crack; (d) cold drawn wire, crack tip.

Fatigue fracture in both steels essentially develops by breaking the lamellae inside the colonies, i.e., it can be classified as *translamellar* and *transcollonial* (breaking the ferrite/cementite lamellae and crossing the colonies), showing very localized plastic damage. Fatigue cracking takes place in a very tortuous manner, with frequent deflections (many micro-deviations from the main direction of macro-crack advance in mode I) and certain evidence of branches and bifurcations.

The afore-said collection of events determines the existence of a local propagation regime with a very marked mode mixity that promotes *locally multiaxial* fatigue crack propagation. The described phenomena, consisting of recurrent deviations from the main crack propagation path, provokes an increase of surface micro-roughness and, therefore, a decrease of the driving force for fatigue, thus slowing down the fatigue crack advance, in agreement with the papers by Korda et al. (2006a, 2006b).

The fatigue cracks exhibit continuous changes in the matter of crack opening displacement (COD), although its magnitude usually drops from the crack mouth to the crack tip. Furthermore, in some zones the crack presents local micro-discontinuities during its growth. An analysis of the mixed mode crack propagation (mode I + mode II) at the finest microscopic level shows some sections in which interlocking can be observed, as described by Mutoh et al. (2007). The common result of this phenomenon is a very small COD that can even end up with the contact of both fatigue fracture surfaces in some specific localized areas.

3.4. Roughness of the fatigue fracture path

After applying several regimes of SIFs during fatigue crack growth, an analysis can be performed of the profiles developed by the fatigue crack in the longitudinal sections of the specimen. The profile length ratio λ (ratio of the actual length of the crack increment, L, to the length of its transverse projection, L_0) was calculated, $\lambda = L/L_0$. Experimental results (Fig. 7) indicate that λ rises with both the degree of cold drawing (a consequence of the manufacture technique by cold drawing that promotes microstructural changes in the material) and the SIF range ΔK (inducing plastic damage in the heavily stresses areas located near the crack tip).

The variable λ described above is a measure of the roughness (asperity) of the fatigue fracture path, i.e., it includes the *deflection angle* of the local branches, partial deviations, micro-deflections, cracking embryos, etc. (during the main propagation path). In the matter of the two parameters governing the fatigue crack growth, both the SIF range ΔK and the R-ratio influence the aspect of the fatigue fracture surface. The rise of any of these (SIF range ΔK and R-ratio) produces the typical micro-tearing features and creates a more tortuous fractographic mode as described in a previous paper by Toribio et al. (2009).

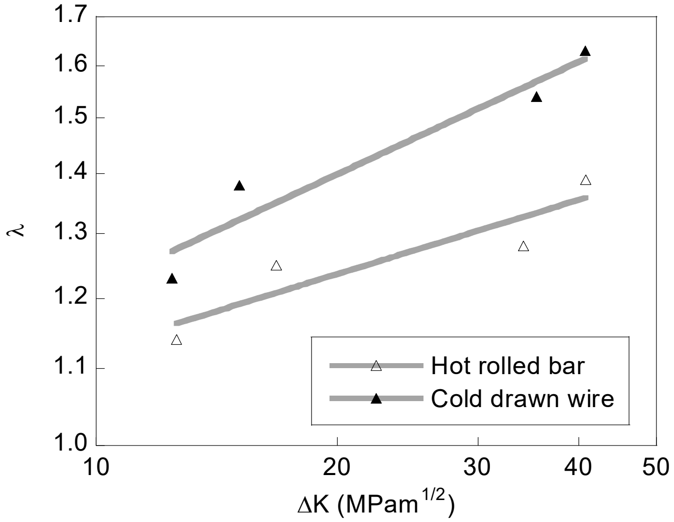


Fig. 7. Profile length ratio, λ, *vs.* stress intensity factor range, ΔK, for the hot rolled bar and the cold drawn wire.

4. Conclusions

On the basis of the fracto-metallographic analysis of fatigue cracking in cold drawn pearlitic steel, the following conclusions can be drawn:

(i) Fatigue cracking in pearlitic steel takes place as a consequence of *micro-plastic tearing*. The cold drawn wire exhibits a pattern resembling micro-tearing, these events being of lower size and more curved aspect than those associated with the hot rolled bar.

(ii) Fatigue cracks are *trans-colonial and trans-lamellar* in both steels. As a matter of fact, fatigue crack propagation can be classified as tortuous, with certain quantity of micro-discontinuities, branchings (frequently bifurcations also appear) as well as local deflections.

(iii) Fatigue fracture in the cold drawn pearlitic wire exhibits an appearance consisting of micro-roughness. The total fractured surface is greater than in the hot rolled bar (base material). The increase of the stress intensity factor (SIF) range, ΔK, also produces higher micro-roughness in the fracture surface.

Acknowledgements

The authors wish to acknowledge the financial support provided by the following Spanish Institutions: Ministry for Science and Technology (MICYT; Grant MAT2002-01831), Ministry for Education and Science (MEC; Grant BIA2005-08965), Ministry for Science and Innovation (MICINN; Grant BIA2008-06810), Ministry for Economy and Competitiveness (MINECO; Grant BIA2011-27870), Junta de Castilla y León (JCyL; Grants SA067A05, SA111A07 and SA039A08) and the Spanish University Foundation “Memoria de D. Samuel Solórzano Barruso” (Grant 2016/00017/001).

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