Influence of sudden load changes on the fatigue crack propagation in cold drawn prestressing steel

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Abstract. This paper analyzes the effect produced by sudden load changes on the fatigue of cold drawn prestressing steel wires to be used in prestressed concrete. Fatigue tests were performed on cylindrical samples under load control, using fatigue steps with different stress, and observing the appearance of a transient state in the fatigue crack propagation curve ($\mathrm{d}a/\mathrm{d}N$-ΔK) when the $K_{\max}\Delta K$ product suddenly decreases, a sort of overload retardation effect that allowed the calculation of the plastic zone size. In addition, the fatigue crack growth rate in the Paris regime, $\mathrm{d}a/\mathrm{d}N$, obeys mainly to the parameter ΔK and it is hardly ever affected by $K_{\max}$. The study of the fatigue fracture surface shows: (i) that the micro-roughness of ductile micro-tearing patterns is a function of $K_{\max}$; (ii) the existence, in some tests, of a small zone with fatigue initiation fractography (with a tearing topography surface), related to the decrease of crack tip opening displacement, a phenomenon similar to that of crack initiation and growth from a micro-notch.

Introduction

The phenomenon of fatigue crack propagation involves two driving forces on the crack tip, the stress intensity range ΔK and the maximum stress intensity factor $K_{\max}$ [1-3], the latter parameter showing a great influence. For this reason, there are two values for the propagation threshold, ΔK^* (cyclic damage) and $K^*_{\max}$ (static damage), which are the minimum conditions required for the fracture to advance, depending on the load and environmental history [4-7]. For ductile materials, fatigue driving force is controlled by ΔK, whereas in fragile materials $K_{\max}$ is the relevant parameter [8].

The main reason for the retardation in overload crack advance, as well as the crack tip closure, are the crack branches and the contact between surfaces, of rough fracture, after overload [9]. Thus, a block of compressive overload cycles may cause retardation on the growth rate of the initial crack, due to the oxide-induced closure which generates debris [10]. On the other hand, other authors maintain that every deviation of large crack growth behaviour can be linked to the presence of residual stresses on the material [6]. Overload retardation effect increases with the number of overload cycles until it reaches a maximum value, existing a characteristic distance between overloads which ensures the greatest retardation effect [11]. A tensile overload followed by a compressive overload causes the acceleration of the fatigue crack growth rate for negative values of R ratio [12].

The aim of this paper is to analyze the effect caused by sudden load changes on the fatigue of cold drawn pearlitic steels, using the data obtained from tests with two load steps of different stresses $\sigma_{\max}$ or $\Delta\sigma$, studying the effect of a step's last cycles on the following step's first cycles. For this purpose, the following factors were examined: (i) the cyclic crack growth rate, (ii) the plastic zone size, (iii) the aspect of micro-tearing pattern and (iv) the crack tip opening displacement.

Experimental Procedure

Material analysed. The material used for this research was prestressing steel (commercial product) of eutectoid composition (0.789 %C, 0.681 %Mn, 0.210 %Si, 0.218 %Cr and 0.061 %V) and pearlitic microstructure, resulting from seven steps of cold drawing as well as a thermal relaxation treatment which eliminates residual stresses caused by the cold drawing process. The characteristic mechanical properties of the material are: Young modulus (E = 209 GPa), yield strength (σ_Y = 1480 MPa) and tensile strength (σ_R = 1820 MPa).

Fatigue tests. The test specimens were cylindrical bars of 300 mm of length and 5.1 mm of diameter. Before the fatigue test, a small transversal cut was performed mechanically in the middle part of the specimens, so as to cause the crack initiation at this point. The influence of K_{max} and ΔK on fatigue was studied from the tests where the tensile load was performed on the axial direction, with constant maximum fatigue stress σ_{max} and stress range $\Delta\sigma$ in both steps, but with different values between both steps (changing either one or both parameters). The frequency used was 10 Hz with a sinusoidal wave shape and the maximum stress was always below the material strength yield. Every load step was maintained for a long enough period of time so as to observe crack advance. The designed test types appear sketched on Fig. 1. Tests A and A' present a change in σ_{max}; tests B and B', in $\Delta\sigma$; and tests C and C', in both parameters. For all of them, the changes in load conditions from one step to the following one were sudden. For tests A, B and C the decrease of σ_{max} or of $\Delta\sigma$ was 50% compared to its previous value; whereas for tests A', B' y C' there was an increase of 30% with regards to its previous value, because there is a greater fracture risk for the wire.

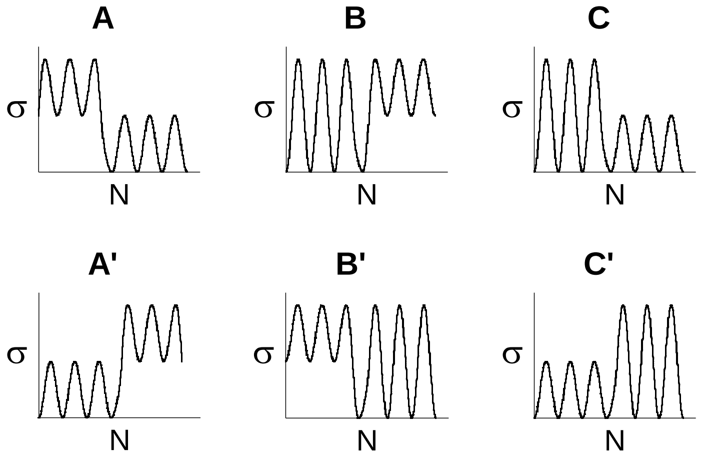

Fig. 1. Tests with sudden load changes.

Fractographic analysis. By means of optical microscopy and scanning electron microscopy the fracture surfaces caused by fatigue were observed in the researched prestressing steel wires for the step changes in the different tests. Several longitudinal cuts were also made on the perpendicular sections to the crack front. After an adequate preparation (grinding, mirror polishing and 5% Nital etching for some seconds), they were also observed using scanning electron microscopy. In all the photographs of the fracture surface and the fracto-materialographic cuts, the fatigue crack advance always occurs from left to right.

Results and Discussion

Microstructure. Figure 2 shows the microstructure of 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 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.

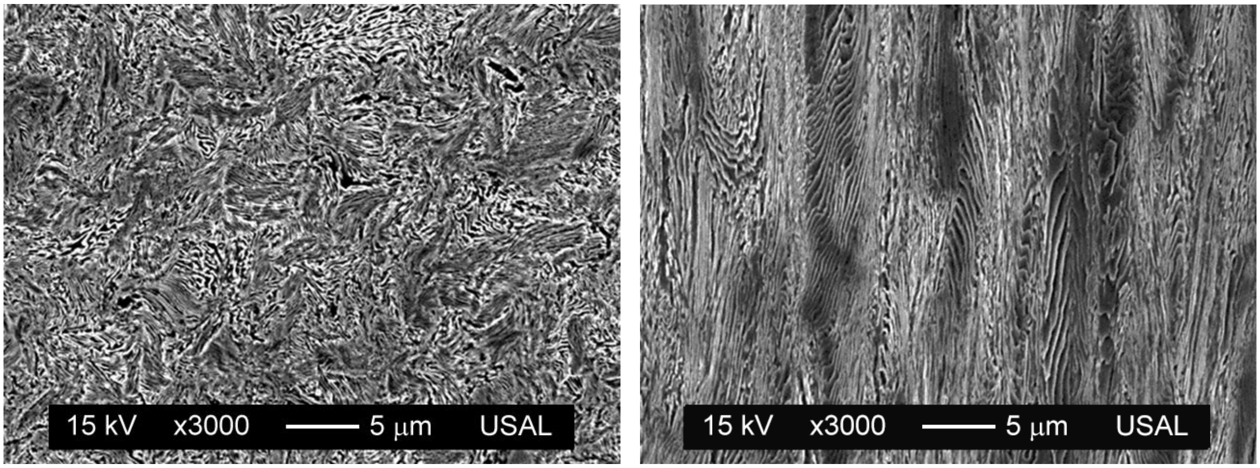

Fig. 2. Microstructure of prestressing steel wire: in the transversal section (left) and the longitudinal section (right).

Cyclic crack growth rate. The fatigue crack propagation curve in the Paris regime, cyclic crack growth rate versus the stress intensity range d*a*/d*N*-Δ*K*, for cold drawn pearlitic steel is shown in Fig. 3. This representation is the same for different values of the *R* ratio [13]; so cyclic crack growth rate depends mainly on the stress intensity range, whereas maximum stress intensity factor during fatigue, $K_{\max}$, is barely relevant. The fit of the Paris curve for prestressing steel show coefficients *C* and *m* de Paris of $4.1 \cdot 10^{-12}$ and 3.3, where the unities are those corresponding for d*a*/d*N* to be in m/cycle and Δ*K* in $\mathrm{MPam}^{1/2}$.

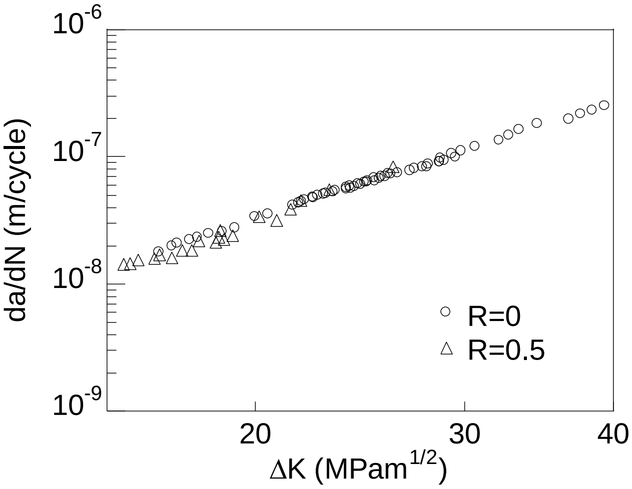

Fig. 3. d*a*/d*N*-Δ*K* curve in the Paris regime.

The effect caused by the sudden load change on the fatigue crack growth curve in the Paris regime is the induction of a transient state in the crack advance, where the propagation rate shows a sort of retardation when the load decreases. Once this zone has been crossed, the corresponding rate to the stationary branch is reestablished [14,15]. This transient state appears on d*a*/d*N*-Δ*K* curve in the shape of branches joining the steady-state regime, as shown in Fig. 4.

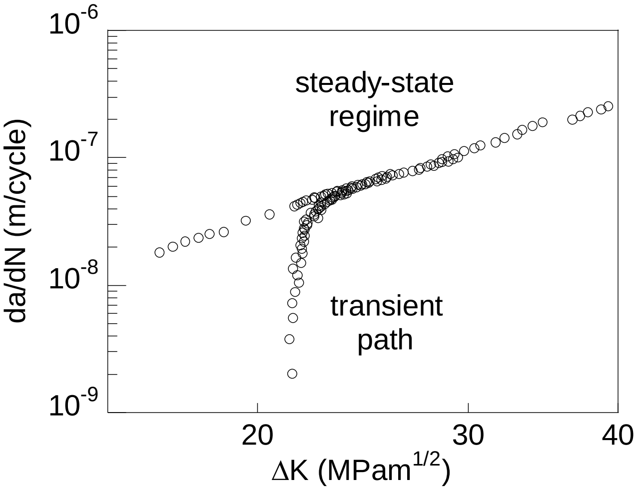

Fig. 4. d*a*/d*N*-Δ*K* curve: steady-state regime + transient path.

Plastic zone size. An experimental estimation was made of the plastic zone size (r_P) at the crack tip during the tests performed on the prestressing steel wires, since it was considered to be the main factor causing the transient state according to an analogue mechanism to that of overload retardation caused by the plastic zone close to the crack tip [16]. The retardation is considered to be produced when the plastic zone created on the crack tip for the last cycles of a step is crossed by the plastic zone, smaller, caused by the initial cycles of the next step. The overload retardation phenomenon is proved to depend on the number of cycles which cause it [11], although it was considered that the last load cycle is the main responsible for this fact. Using the mentioned hypotheses, the expression experimentally obtained for the plastic zone size of cold drawn pearlitic steel is the following,

$$r_\mathrm{p} = 0.14 \frac{K_\mathrm{max} \Delta K}{\left(\frac{\sigma_\mathrm{Y} + \sigma_\mathrm{R}}{2} \right)^2} \qquad (1)$$

where the plastic zone size is directly proportional to the factor $K_\mathrm{max}\Delta K$, which considers both parameters driving the mechanisms of the crack tip [1-3]. Furthermore, its value is inversely proportional to the mean value of the yield strength σ_Y and the tensile strength σ_R of cold drawn pearlitic steel, because this materials present strain hardening. The expression shows a coefficient of 0.14 very close to that of other models [17,18].

Ductile micro-tearing pattern. Figure 5 shows fatigue fracture surfaces in the steels, for the different conditions of load in two steps, after the specimen was separated in two parts by applying an increasing load until fracture. It is observed in them the existence of a semielliptical crack front (corresponding to the sudden step change) on the fatigue surface of all tests (except for B'). The visible crack front can be caused by the fractographic variation to a microscopic level and by the change of the crack tip opening displacement, which occurs with the step change in the tests.

The fatigue surface in pearlitic steel is formed by micro-tearings, mechanism of ductile fracture with evidence of plastic flow which imparts an appearance characteristic to the fatigue process. The way in which the crack propagates in this steel does not show any striations, as it occurs in pure metals and ductile alloys. Micro-tearings in cold drawn pearlitic steel present a smaller size and more curved geometry than those in the hot rolled wire where it comes from, due to the microstructural changes (orientation of the pearlitic lamellae, curling of the lamellae in the transverse section and decrease of its interlamellar spacing, cf. Fig. 2) and to the plastic strain undergone by steel during the drawing process [13].

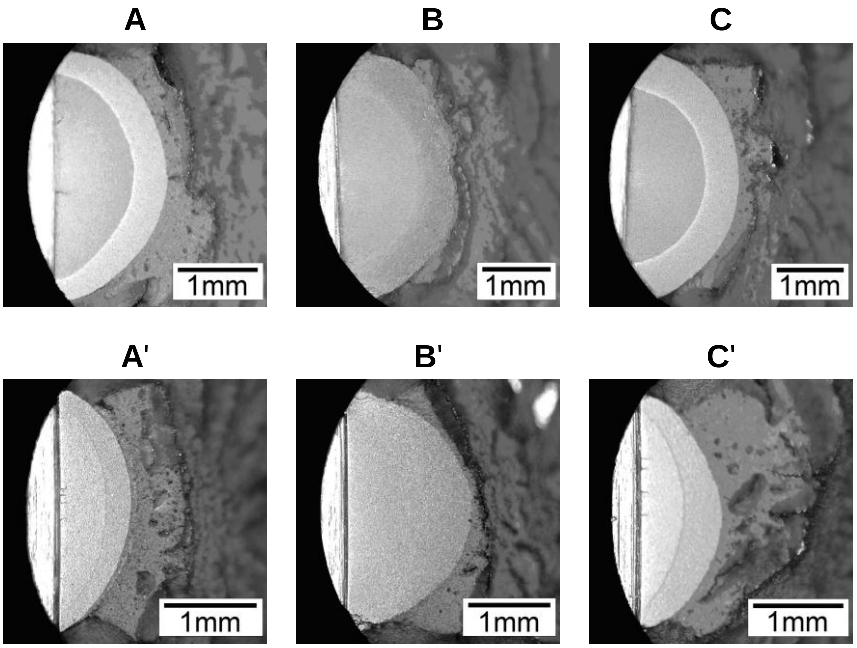

Fig. 5. Fatigue fracture surfaces.

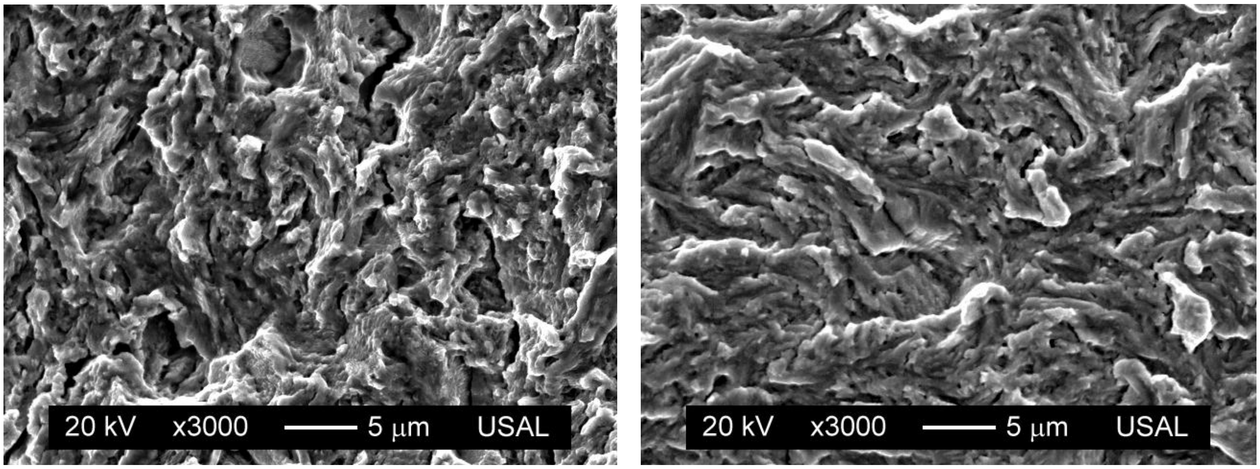

Fig. 6. Fractography test A: $K_{\max}$=54 MPam$^{1/2}$ (left) and $K_{\max}$=27 MPam$^{1/2}$ (right).

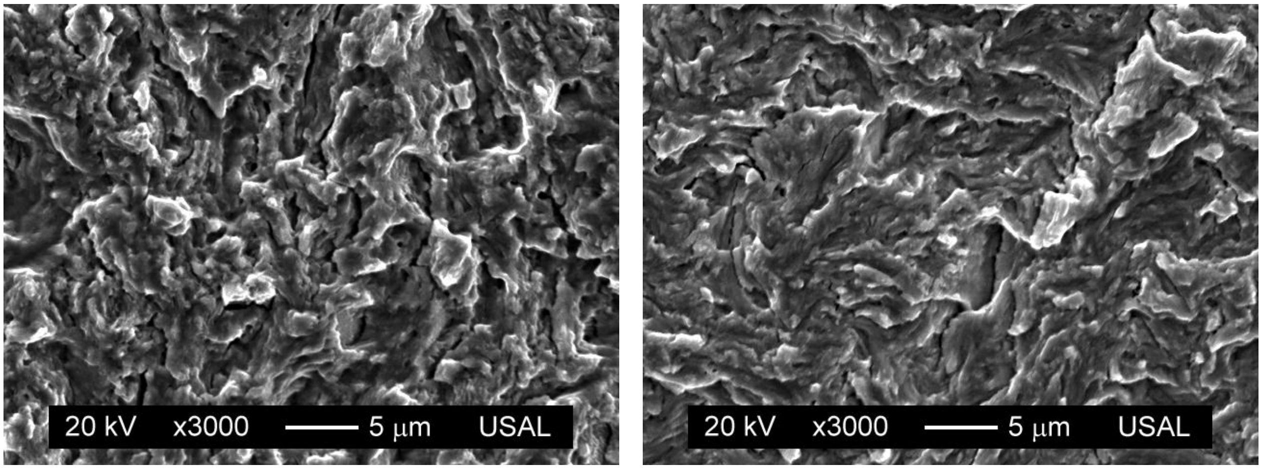

Fig. 7. Fractography test C: $K_{\max}$=40 MPam$^{1/2}$ (left) and $K_{\max}$=20 MPam$^{1/2}$ (right).

Figures 6 and 7 show the ductile micro-tearing patterns for several levels of fatigue intensity. This observation, together with the fact that in tests B and B' (where $K_{\max}$ is constant) there are no fractographic changes in a microscopic level, leads one to think that the micro-tearing shape is mainly determined by the maximum stress intensity factor during fatigue $K_{\max}$, and very scarcely by the stress intensity range ΔK.

For some tests, specifically A and C (Fig. 8), the fracture surface in the step change shows a small zone of approximately 20 μm, with a fatigue initiation topography formed by ductile micro-tearings quite plane and oriented in the main direction of crack advancement, i.e., *tearing topography surface* or *TTS* [19], as shown in Fig. 9.

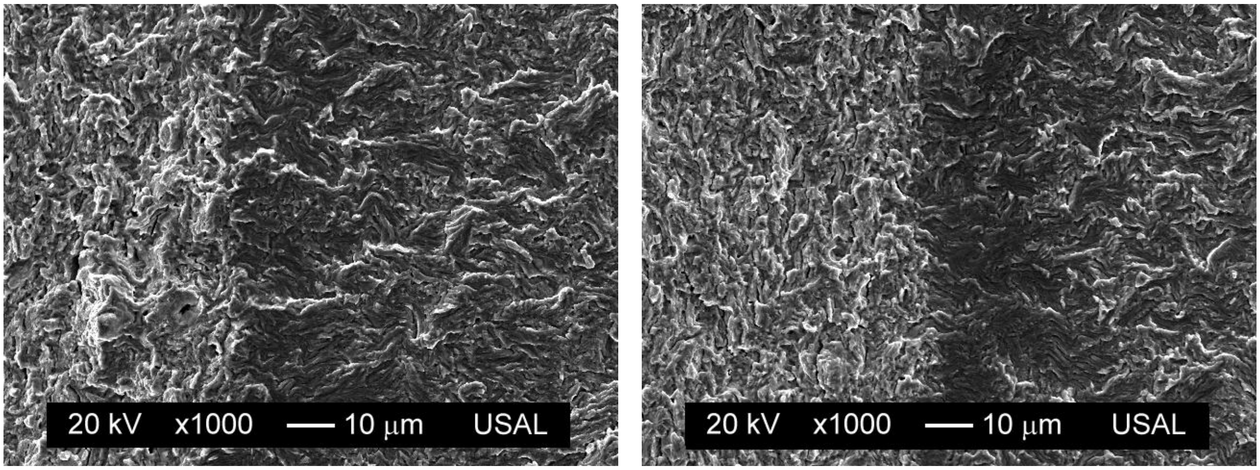

Fig. 8. Fractography: test A (left) and test C (right).

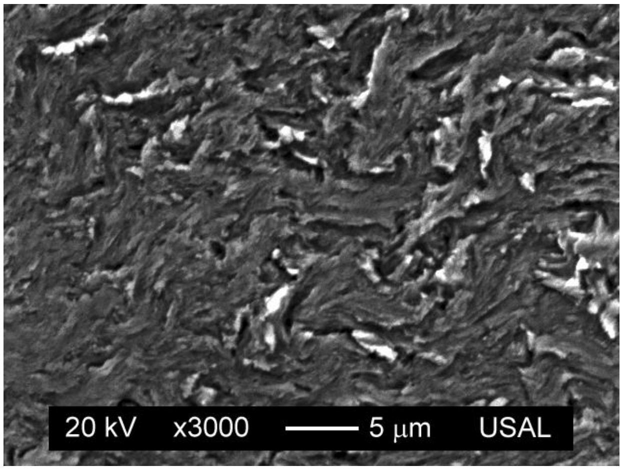

Fig. 9. Fractography tearing topography surface, TTS.

Crack tip opening displacement (CTOD). A possible explanation of this region with initiation fractography is the sudden decrease of the CTOD at the beginning of the second step in several tests, causing a new crack from another one with such a CTOD that it can be considered a micro-notch. Retardation in overload crack advance is controlled, as well as by the plastic zone, by growth micromechanisms close to the threshold [9]. This phenomenon appears intensely in test A, where it was observed that the crack opening variation is very strong when the load step changes (Fig. 10).

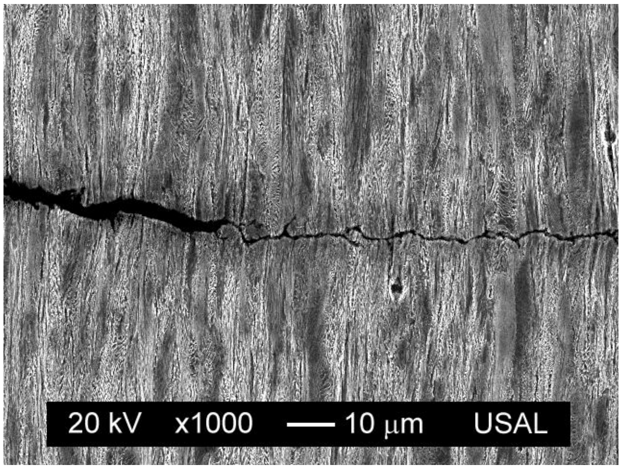

Fig. 10. Longitudinal cut (fracto-materialography) in test A.

The maximum CTOD $\delta_{\max}$, under plane strain, can be calculated with the following expression, where E represents Young modulus and σ_Y the yield strength,

$$\delta_{\max} \approx \frac{K_{\max}^2}{2\sigma_Y E} \qquad (2)$$

and the cyclic CTOD $\Delta\delta_t$ is,

$$\Delta\delta_t \approx \frac{\Delta K^2}{4\sigma_Y E} \qquad (3)$$

With these equations, an estimation was made of the change of the CTOD with the sudden load variation when changing from one step to the following one for the tests types (Fig. 11). It can be observed that in tests A, B' and C the CTOD decreases when the sudden load change occurs, being that this phenomenon is stronger in test A, where this effect was experimentally observed (Fig. 10). On the other hand, in tests A', B and C' there is a greater CTOD after the step change, as their fatigue surface show (Fig. 5).

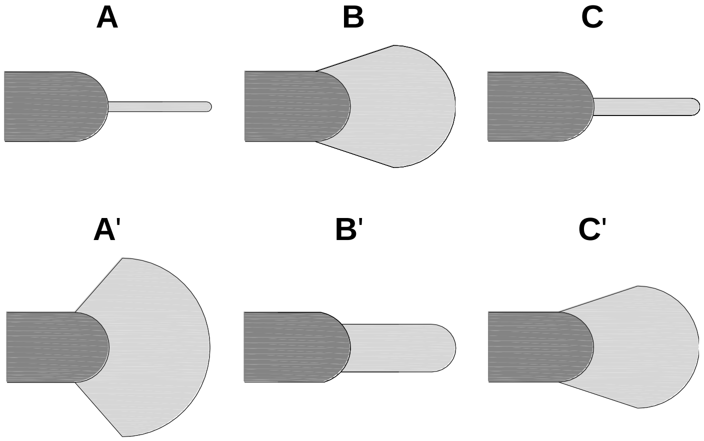

Fig. 11. Crack tip opening displacement (CTOD) for $K_{\min}$.

Conclusions

The following conclusions may be drawn regarding the influence of sudden load changes on the fatigue crack propagation in cold drawn prestressing steel:

- (i) Fatigue crack growth rate in Paris regime, da/dN, obeys mainly to the parameter ΔK and it is hardly ever affected by changes in $K_{\max}$. The sudden decrease in $K_{\max}$ or ΔK causes a transient state in the curve da/dN-ΔK.
- (ii) The plastic zone size depends on the product of both characteristic fatigue parameters, $K_{\max}\Delta K$. Its sudden decrease causes the overload retardation effect, due to the change of the plastic zone size, allowing its calculation.
- (iii) The fatigue crack surface in pearlite presents a ductile micro-tearing pattern, whose appearance and micro-roughness change with $K_{\max}$. On the other hand, ΔK hardly affects the appearance of the fatigue crack surface.
- (iv) The sudden load change sometimes causes a zone whose fractography is that of fatigue initiation, consistent with tearing topography surface or TTS. This is attributed to the sudden decrease of the crack opening, causing a similar phenomenon to that of crack growth from a notch.

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