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Fatigue and fracture paths in cold drawn pearlitic steel

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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.

1. 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 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 0° to an angle of 90° (measured in relation to the wire axis) in prestressing steel wire (commercial product which has undergone

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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 90° 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.

2. Experimental procedure

2.1. Materials

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

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).

2.2. 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) with magnification factors of 1000×.

2.3. 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% and 30% from one to another step. Fracture tests were performed in the specimens previously pre-cracked by fatigue (up to crack depths between a quarter and a half of the wire diameter), 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 examinate 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 with magnification factors of 1000×.

All photographs and micrographs related to the fatigue and fracture surfaces, together with their metallographic sections, are shown in such a manner that the crack growth is always from left to right.

3. Results and discussion

3.1. 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.

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