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Cold Drawn Eutectoid Pearlitic Steel Wires as High Performance Materials in Structural Engineering

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Abstract: This paper reviews the fracture performance in air and aggressive environment (stress corrosion cracking) of eutectoid prestressing steel wires with different levels of cold drawing. In air environment, a micromechanical model of fracture is proposed to rationalize the results on the basis of the microstructure of the steels after drawing and the model of Miller & Smith of fracture of pearlitic microstructure by *shear cracking* of the cementite lamellae. In hydrogen assisted cracking (HAC), a microstructure-based model is proposed on the basis of the Miller & Smith model and the mechanism of *hydrogen enhanced decohesion* or, more properly, *hydrogen enhanced delamination* (or *debonding*) between similar microstructural units (colonies or lamellae). In aggressive environments promoting localised anodic dissolution (LAD), the micromechanical model is based on the phenomenon of crack tip blunting and the preferential dissolution of ferrite which favours cornered crack tip shape over smooth crack tip profile.

keyword: Cold drawing, High-strength steel, Pearlitic microstructure, High performance materials, Structural engineering, Fracture behaviour, Stress corrosion cracking, Hydrogen embrittlement.

1 Introduction

Cold drawn eutectoid pearlitic steel wires for prestressed concrete can be considered as high performance materials in structural engineering because: (i) they have an extremely high tensile strength, greater than conventional materials, only limited by cleavage fracture (*cleavage limited strength*) and therefore they can more easily resist a range of external stimuli in the form of mechanical loading or chemical attack (Gil-Sevillano, 1986); (ii) they react in a non-conventional manner due to their inherent *strength anisotropy* induced by the manufacturing process in the form of heavy drawing (Toribio, Ovejero and Toledano, 1997; Toribio and Ovejero, 1999a; Toribio and Ovejero, 1998a); (iii) they really behave as *micro-composites* from the mechanical point of view, so that their oriented lamellar microstructure influences their fracture behaviour and a materials science link can be established between the micro- and the macro-levels (Toribio, 2004; Toribio and Ovejero, 2001a; Toribio and Ovejero, 2001b).

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2 Experimental Procedure

The materials used were high strength pearlitic steels whose chemical composition was eutectoid (0.80 % C, 0.69 % Mn, 0.23 % Si, 0.012 % P, 0.009 % S, 0.265 % Cr, 0.060 % V, 0.004 % Al) and with different levels of cold drawing. Metallographic techniques (Samuels, 1992; Vander Voort, 1984) were used to reveal the fine pearlitic microstructure of the steels. Fig.1 shows, in the most heavily drawn steel, micrographs of the longitudinal section at the two basic microstructural levels of pearlitic colonies and lamellae, both being markedly oriented in a direction quasi-parallel to the wire axis or cold drawing direction, cf. (Langford, 1970; Embury and Fisher, 1966; Toribio and Ovejero, 1997, 1998b, 1998c, 1998d).

3 Materials Behaviour in Air Environment

3.1 Fracture Tests

To analyze the fracture mechanisms in the steels with different degrees of cold drawing, cylindrical precracked samples were taken from the steel wires, with different fatigue precrack depth. Samples were subjected to axial fatigue and the crack depth was continuously monitored by a method based on the compliance of the sample. Later, the fatigue precracked rods were subjected to monotonic tensile loading up to final fracture of the whole specimen, to evaluate the fracture behaviour of the pearlitic steels with different degrees of cold drawing, as well as the evolution of crack shape, i.e., the cracking

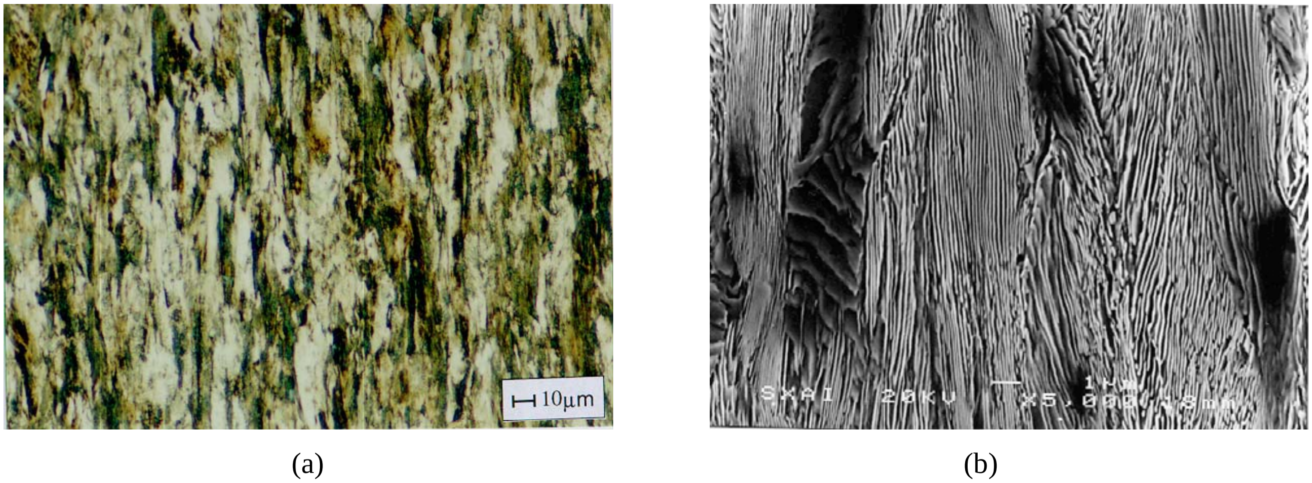

Figure 1 : Micrographs of the longitudinal metallographic section in the most heavily drawn steel showing the pearlite colonies (a) and the pearlitic lamellae (b), both microstructural levels oriented after cold drawing (the vertical side represents the wire axis or cold drawing direction).

profile in the case of anisotropic fracture behaviour (cf. Toribio (2004) for details).

3.2 Experimental Results

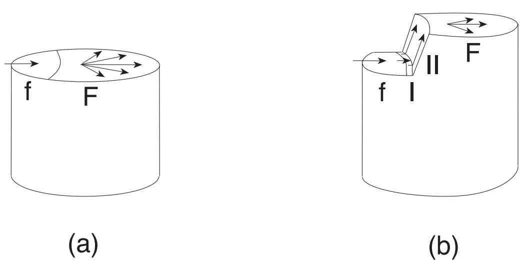

Figure 2 : Fracture behaviour of the different steels: (a) fracture modes in slightly drawn steels; (b) fracture modes in heavily drawn steels; f: fatigue precrack; I: mode I propagation; II: 90^o step producing mixed mode fracture; F: final fracture.

Fig. 2 shows the fracture modes after the tests. The initial hot rolled material and the slightly drawn steels behave isotropically, i.e., cracking develops in mode I following the initial plane of fatigue crack propagation (Fig. 2a). The most heavily drawn steels exhibit a clearly anisotropic fracture behaviour in the form of crack deflection after the fatigue precrack (and some mode I propagation in certain cases) with a deviation angle of almost 90^o from the initial crack plane and further propagation in a direction close to the initial one (Fig. 2b).

3.3 Micromechanical Modelling (Hot Rolled and Slightly Drawn Steels)

Since hot rolled and slightly drawn steels exhibit isotropic fracture behaviour as a consequence of their more or less randomly oriented pearlitic lamellae and colonies, a classical micromechanical model for this kind of microstructure allows a rationalization of the fracture behaviour. In this framework, the most commonly accepted model is that proposed by Miller and Smith (1970) on the basis of a micromechanism of shear cracking in pearlite.

The model is illustrated in Fig. 3. It suggests that microcracks are formed by *shear cracking*. First of all, slip takes place in ferrite when the material is stressed. Then, due to the stress concentration at the ferrite/cementite interfaces along the ferrite slip plane, the cementite plates become fractured and promote shear. When the shear becomes large enough, there is a final phase of link-up of the holes to form a macroscopic crack.

3.4 Micromechanical Modelling (Heavily Drawn Steels)

The anisotropic fracture behaviour in heavily drawn steels can be rationalized on the basis of the oriented pearlitic microstructure of the steels (see Fig. 1). In the metallographic analysis on these steels, some pearlitic pseudocolonies appear aligned to the cold drawing direction and they are potential fracture sites for two reasons:

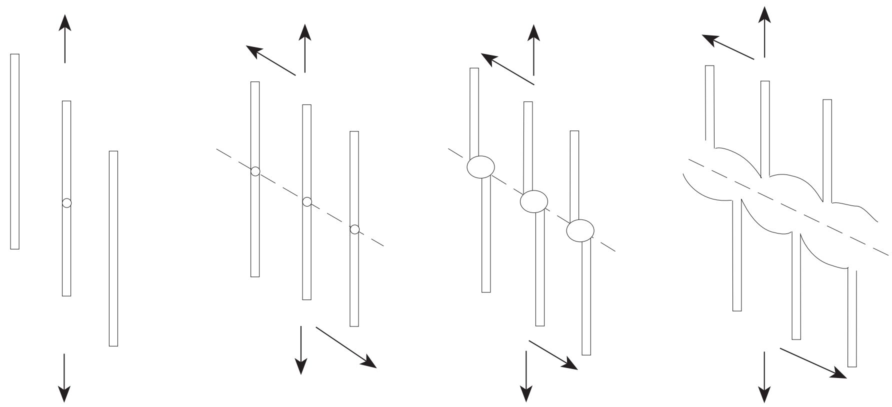

Figure 3 : Micromechanical model of fracture by shear cracking in pearlitic microstructures (after Miller and Smith (1970)) applicable to fracture in hot rolled and slightly drawn steels. The cementite lamellae are fractured by shear deformation of the ferrite plates. Externally applied stress (vertical direction) and microstructure-induced shear strain are drawn.

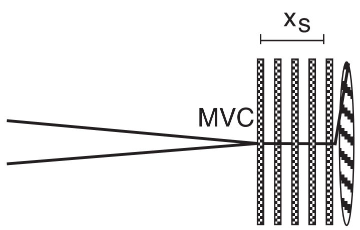

Figure 4 : Micromechanical model of initiation and final fracture in heavily drawn steels. The microstructure is assumed to be totally oriented in the cold drawing direction; x_S: mode I propagation produced by micro-void coalescence (MVC).

(i) the very high local interlamellar spacing which makes them weaker or potentially fracturable by shear cracking of pearlitic plates according to the mechanism of *shear cracking* in pearlitic microstructures proposed by Miller and Smith (1970).

(ii) the presence of some microcracks and defects consisting of plates prefractured in the pseudocolony during the manufacturing process (cold drawing) as a consequence of the very high stresses applied on the wire (mechanical pre-damage).

Thus the pearlitic pseudocolonies act as local microcrack precursors, and their presence could explain the fracture path in heavily drawn steels (Fig. 2b). Fig. 4 offers a general sketch of the fracture process in heavily drawn steels, with a first stage of propagation over a distance x_S up to the appearance of the 90^o-step. The distance x_S (i.e., the mode I propagation length) is a decreasing function of the drawing degree, a consequence of the frequency of appearance of pseudocolonies which is higher when drawing becomes heavier, i.e., the average distance between these microstructural units is a decreasing function of the level of drawing. The heavier the drawing, the higher the probability of change in crack propagation direction.

4 Materials Behaviour under HAC Conditions

4.1 Hydrogen Embrittlement Tests

Hydrogen embrittlement experiments were carried out in the form of slow strain rate tests on precracked steel wires. Samples were precracked by axial fatigue in the normal laboratory air environment to produce a transverse precrack. After precracking, samples were introduced in a corrosion cell containing aqueous solution of 1g/l $Ca(OH)_2$ plus 0.1g/l NaCl (pH=12.5) to reproduce the alkaline working conditions of prestressing steel surrounded by concrete. The experimental device consisted of a potentiostat and a three-electrode assembly (metallic sample or working electrode, platinum counter-electrode and saturated calomel electrode as the reference one). Tests were conducted under potentiostatic control at a constant potential of –1200 mV vs SCE at which the stress corrosion mechanism is HAC (cf. Toribio and Ovejero (2001a) for details).

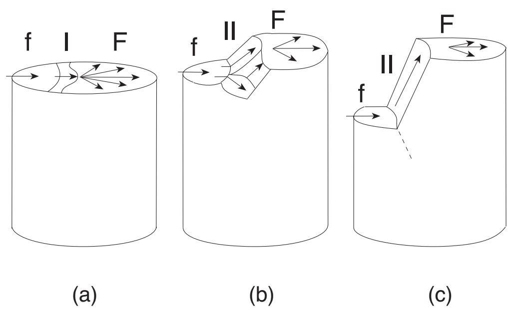

Figure 5 : Fracture surfaces produced by HAC in steels with different degree of cold drawing: (a) null or slight drawing; (b) intermediate drawing; (c) heavy drawing; f: fatigue crack growth; I: mode I propagation; II: mixed mode propagation; F: final fracture.

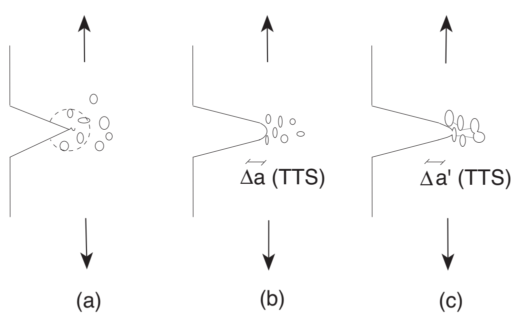

Figure 6 : Micromechanical model of HAC in hot rolled and slightly drawn steels: the mechanism is the so called *tearing topography surface* or TTS (Thompson and Chesnutt, 1979; Costa and Thompson, 1982) with very closely spaced nucleation of voids or defects.

4.2 Experimental Results

A progressive change in the macroscopic topography as the cold drawing increases was observed in all fracture surfaces. Fig. 5 gives a 3D-view of these fracture surfaces, showing that mixed mode crack growth appears from a certain cold drawing level, with *early* crack deflection which starts just at the tip of the fatigue precrack, i.e., at the very beginning of the hydrogen embrittlement test. In the first steps of drawing the crack grows in mode I in both fatigue precracking and hydrogen-assisted cracking (Fig. 5a). In steels with an intermediate degree of drawing there is a slight deflection in the hydrogen-assisted crack, and this deflection is not uniform along the crack front but has a wavy shape (Fig. 5b). For the most heavily drawn specimens (including the commercial prestressing steel wire) the crack deflection takes place suddenly after the fatigue precrack and the deviation angle is even higher and more or less uniform along the whole crack front (Fig. 5c).

This behaviour may be explained on the basis of the oriented microstructure of the material with regard to pearlite colonies and lamellae (cf. Toribio and Ovejero (1997, 1998b, 1998c, 1998d)): as the drawing becomes heavier, the cracks find easier propagation directions with lower fracture resistance. Thus the macroscopic HAC behaviour of the different steels (progressively anisotropic with cold drawing) is a direct consequence of the microstructural changes undergone during manufacture.

4.3 Micromechanical Modelling (Hot Rolled and Slightly Drawn Steels)

A microstructure-based modelling of the HAC phenomenon is proposed to rationalize the experimental results as a function of the degree of cold drawing. In hot rolled and slightly drawn steels, the micromechanism of fracture by HAC is the so called *tearing topography surface* or TTS (Thompson and Chesnutt, 1979; Costa and Thompson, 1982). This non-conventional microscopic fracture mode is undoubtedly associated with the hydrogen-assisted micro-damage process in pearlitic steels and it consists of a very closely spaced nucleation of voids or defects, as sketched in Fig. 6.

4.4 Micromechanical Modelling (Steels with and Intermediate Degree of Cold Drawing)

When the degree of drawing increases, the behaviour becomes anisotropic (cf. Fig. 5b) and a micromechanical model able to account for the different degrees of cold drawing is required. It is based on two models proposed previously: (i) the model by Miller and Smith of fracture of pearlitic microstructure by *shear cracking* (SC) of the cementite lamellae (Miller and Smith, 1970); (ii) the mechanism of *hydrogen enhanced decohesion* (HEDE), a term coined by Gerberich , Marsh, Hoehn, Venkataraman and Huang (1993) to describe a kind of microscopic fracture mode promoted by hydrogen. For the case of a pearlitic microstructure it would be *hydrogen enhanced delamination* (or *debonding*) between two similar microstructural units (colonies or lamellae).

Fig. 7 illustrates the two operative micromechanisms in cold drawn pearlitic steels with an intermediate degree of drawing. In Fig. 7a, it is seen that hydrogen penetration could be easier along the path opened by SC

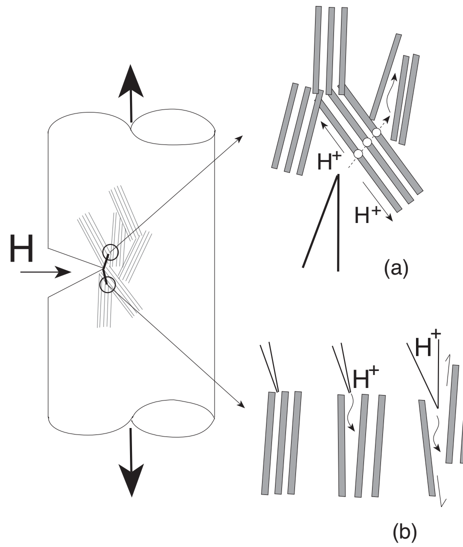

Figure 7 : Micromechanical model of HAC in steels with an intermediate degree of drawing: (a) hydrogen diffusion in the pearlitic microstructure and penetration along the path opened by a Miller-Smith mechanism of shear cracking (SC); (b) fracture by hydrogen enhanced delamination or debonding (HEDE).

of the cementite lamellae. Fig. 7b shows the mechanism of fracture by HEDE. Both could be operative in different regions of the material near the crack tip region. As a consequence of the progressive microstructural orientation induced in the material by the cold drawing manufacturing method, the micromechanism of fracture evolves form predominant SC and hydrogen penetration in slightly drawn steels to predominant HEDE in heavily drawn steels, as described in the following section.

4.5 Micromechanical Modelling (Heavily Drawn Steels)

The importance of the described micromechanism of HEDE in the fracture process by HAC of heavily drawn steels steel is even higher because of the lamellar structure of the steel (markedly oriented) which produces anisotropy regarding fracture and hydrogen diffusion, so that hydrogen diffuses mainly in the direction of the plates ($D_{//} >> D_{\perp}$ in Fig. 8a) and can weaken the bonds or interfaces between the ferrite and the cementite lamellae (which are the weakest links even before the hydrogen presence) thus contributing to the hydrogen-induced fracture by delamination (or debonding) between two similar microstructural units, i.e., at the ferrite-cementite interface or at the pearlitic colony boundaries, as sketched in Fig. 8b.

5 Materials Behaviour under LAD Conditions

5.1 Stress Corrosion Tests

The stress corrosion cracking experiments were slow strain rate tests on precracked wires. The experimental procedure is identical to that described in the previous sections of this paper, but in the tests analyzed in this section the electrochemical potential was –600 mV vs. SCE at which the environmental mechanism is LAD (cf. Toribio and Ovejero (2001b) for details).

5.2 Experimental Results

The progressively drawn steels exhibited a stress corrosion behaviour depending on the degree of cold drawing, as shown in Fig. 9. The behaviour becomes more anisotropic (with mixed mode propagation) as the cold drawing degree increases. For hot rolled and slightly drawn steels, the fracture surfaces were oriented perpendicularly to the loading axis (Fig. 9a). Steels with an intermediate degree of drawing show a certain angle between the planes of the fatigue precrack and the fracture propagation in aggressive environment (Fig. 9b). In the most heavily drawn steels the deviation from the fatigue precrack plane was even higher in the mixed mode propagation by LAD (Fig. 9c).

As in the case of HAC, the explanation of this behaviour lies in the oriented microstructure of the material in the matter of pearlite colonies and lamellae (cf. Toribio and Ovejero (1997, 1998b, 1998c, 1998d)): from a certain degree of cold drawing the cracks find easier propagation directions with lower fracture resistance. Again the macroscopic fracture behaviour of the steels (progressively anisotropic with cold drawing) depends on the microstructural evolution.

5.3 Micromechanical Modelling (Hot Rolled and Slightly Drawn Steels)

In order to rationalize the results, the role of crack tip blunting should be considered as far as this effect influences the development of the LAD proceeding in a coupled way, since anodic dissolution changes the crack shape and thus the crack tip radius, whereas crack tip

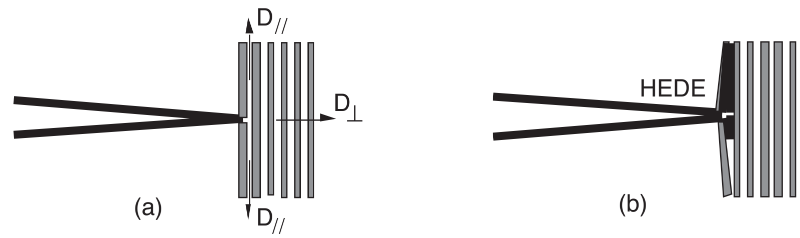

Figure 8 : Micromechanical model of HAC in heavily drawn steels: (a) hydrogen diffusion in longitudinal and transverse directions; (b) fracture by hydrogen enhanced delamination or debonding (HEDE). The microstructure is assumed to be totally oriented in the cold drawing direction.

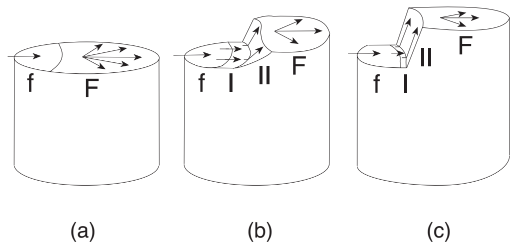

Figure 9 : Fracture surfaces produced by LAD in steels with different degree of cold drawing: (a) null or slight drawing; (b) intermediate drawing; (c) heavy drawing; f: fatigue crack growth, I: mode I propagation; II: mixed mode propagation; F: final fracture.

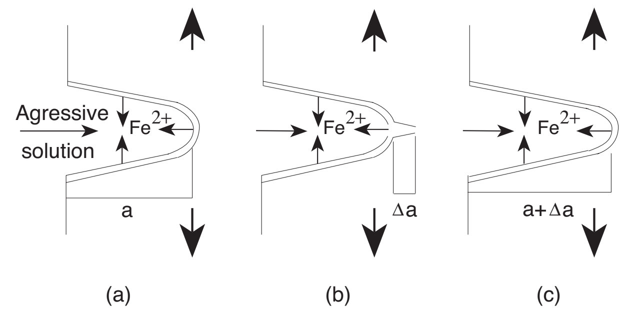

Figure 10 : Micromechanical model of LAD in hot rolled and slightly drawn steels: (a) initial stage, (b) dissolution, film rupture and crack advance, (c) new loop of dissolution.

blunting can affect the resistance of the material to anodic dissolution.

Crack tip blunting influences the fracture behaviour of high strength steels in air (Ritchie and Horn, 1978), with different crack tip shapes ranging from smooth blunting to cornered blunting. In LAD, crack tip blunting may be associated with material dissolution near the tip, and the crack tip radius has shown to be a key parameter for determining the threshold stress intensity factor for stress corrosion cracking K_{ISCC} (Chu, Hsiao and Li, 1979; Ray and Rao, 1993).

In the steels under consideration, Toribio and Ovejero (1999b) discussed the role of crack tip blunting in LAD behaviour. In slightly drawn steels the crack tip radius increases with the degree of cold drawing as a consequence of the blunting effect produced by dissolution. In heavily drawn steels blunting also increases with the degree of drawing, but the trend is interrupted by crack branching and mixed mode propagation.

On the basis of the previous considerations, Fig. 10 shows a micromechanical model of LAD in hot rolled and slightly drawn steels, where dissolution, film rupture and crack advance are repeated in subsequent loops (or cycles) which lead to a certain subcritical crack growth rate accompanied by crack tip blunting as a consequence of the dissolution process itself.

5.4 *Micromechanical Modelling (Steels with an Intermediate Degree of Cold Drawing)*

The micromechanical model of LAD for these anisotropic steels is shown in Fig. 11. In these intermediate steels, crack tip blunting is enhanced by the oriented microstructure of the drawn material (specially at the ferrite/cementite interface) and it can block the film-induced cleavage mechanism which otherwise would be operative (e.g. in the hot rolled material). The crack branching (macroscopic) angle is closely related to the microscopic angle of orientation of pearlitic colonies and lamellae (cf. Toribio and Ovejero (1997, 1998b, 1998c, 1998d)).

The preferential dissolution of ferrite could influence the

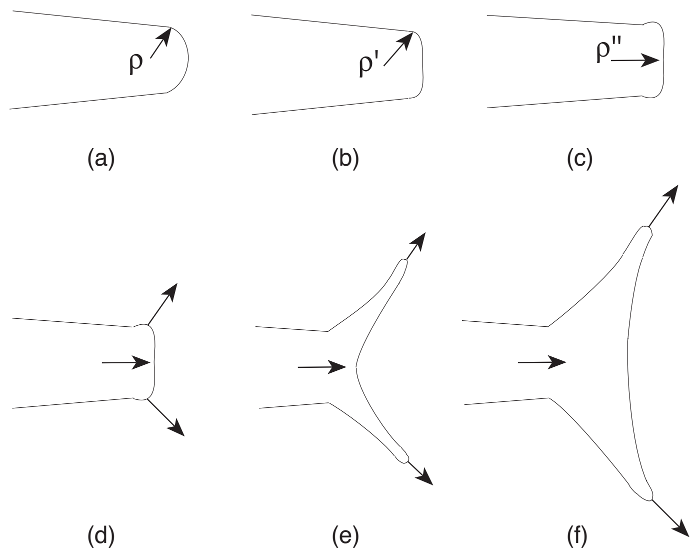

Figure 11 : Micromechanical model of LAD which produces crack tip blunting in steels with an intermediate degree of drawing. The figure shows the evolution from smooth blunting (a) to cornered blunting (c) which favours crack tip branching, cf. (d) to (f).

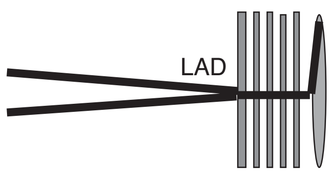

Figure 12 : Micromechanical model of LAD in heavily drawn steels, showing chemical crack advance by dissolution and mechanical crack deflection when the macrocrack reaches a pearlitic pseudocolony. The microstructure is assumed to be totally oriented in the cold drawing direction.

magnitude of crack tip blunting and the blunting mode itself by favouring cornered crack tip shape (by preferential dissolution) over smooth crack tip profile, thus increasing the effective crack tip radius (*blunting effect*) This effect could be so high that would be able to produce crack tip branching, and this fact takes place if the steel is sufficiently anisotropic (cf. heavily drawn steels).

5.5 Micromechanical Modelling (Heavily Drawn Steels)

The mechanism of LAD in these steels could be as explained in Fig. 12: dissolution is produced in mode I along a distance x_{LAD} by chemical attack. The crack continues in mode I and only deviates when it reaches a defect (pre-damage) in the material: an extremely slender *pearlitic pseudocolony* (cf. Toribio, Ovejero and Toledano, 1997) with anomalous (very high) local interlamellar spacing which makes it a preferential fracture locus with minimum resistance to cracking. When this happens, final fracture takes place for purely mechanical reasons, and the pseudocolony fails by breaking the cementite lamellae (very spaced), as in the case of fracture of similar steels in air (cf. Toribio (2004)), according to the model of shear cracking in pearlite proposed by Miller and Smith (1970).

6 Conclusions

In air, heavily drawn steels exhibit anisotropic fracture behaviour. A micromechanical model of fracture is proposed to rationalize the results on the basis of the microstructure of the steels after drawing. In slightly drawn steels, the Miller-Smith model of shear cracking in pearlite may be adequate to describe the fracture process. In heavily drawn steels, a fracture propagation step appears, and it may be caused by extremely slender *pearlitic pseudocolonies* aligned in the drawing direction, with anomalous (very high) *local* interlamellar spacing which makes them preferential fracture paths with minimum local resistance.

In aggressive environments promoting hydrogen assisted cracking (HAC), a microstructure-based modelling is proposed on the basis of two micromechanical models proposed previously: (i) the model of Miller & Smith of fracture of pearlitic microstructure by *shear cracking* (SC) of the cementite lamellae; (ii) the mechanism of *hydrogen enhanced decohesion* (HEDE), a term coined by Gerberich to describe a kind of microscopic fracture mode promoted by hydrogen. In pearlitic microstructures it would be *hydrogen enhanced delamination* (or *debonding*) between two similar microstructural units (colonies or lamellae).

In aggressive environments promoting localised anodic dissolution (LAD), the micromechanical model is based on preferential dissolution of ferrite and progressive microstructural orientation by cold drawing of the two microstructural levels of the pearlite colonies and lamellae, which could influence the magnitude of crack tip blunting and the blunting mode itself by favouring cornered crack tip shape (by preferential dissolution) over smooth crack tip profile, thus increasing the effective crack tip radius (*blunting effect*) and the value of the critical stress intensity factor at the instant of catastrophic failure of the cracked specimens.

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