**Cold drawn pearlitic steel wires for wind turbines structures:**
*In the wake of Miguel de Cervantes and Johann Sebastian Bach*

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**Abstract.** Wind turbines are key elements in the field of renewable energies. They can be considered as engineering evolutions of old-fasion windmills appearing in the master work by Miguel de Cervantes: *Don Quijote de la Mancha*. The main subject of this paper is related to fracture behaviour and structural integrity of cold drawn pearlitic steel wires for wind turbine structures and foundations. At the microscopic level, cold drawing generates progressive slenderizing and orientation of the pearlitic colonies (*first microstructural level*) and increasing orientation and densification of the ferrite/cementite lamellae (*second microstructural level*), thereby inducing anisotropic fracture behaviour and crack path deflection. In addition, the hierarchical structure of cold drawn pearlitic steel wires in two microstructural levels (*colonies and lamellae*) allows a consideration of them as hierarchically structured materials (HSM). Furthermore, an analogy is established in the paper between the microstructural arrangement in cold drawn pearlitic steels and the multi-level structure of Johann Sebastian Bach’s music.

1. **Prologue: In the framework of “Don Quijote de la Mancha” by Miguel de Cervantes**

The high importance of wind energy in the field of the so-called *renewables* (or *clean*) energies is nowadays out of doubt. In this framework, wind energy turbines (Figure 1) are key structures to generate the energy. Although with different purpose, in certain sense they can be considered as engineering evolutions of the old-fashion windmills (Figure 2) appearing in the master work by Miguel de Cervantes Saavedra: “Don Quijote de la Mancha”, whose cover page is reproduced in Figure 3 (“Don Quixote de la Mancha”) in old Spanish, later evolved to modern Spanish, a developed and important language spoken nowadays by almost 550 million of people in the world. Figure 4 shows the Monument devoted to Miguel de Cervantes in the Plaza de España of Madrid, including not only the statue of the writer, but also of their creatures *Don Quijote de la Mancha* and *Sancho Panza*, whose profile is shown in Figure 5.

The main subject of this paper is related to fracture behaviour and structural integrity of cold drawn pearlitic steel wires for wind turbine structures and foundations. Therefore, such a structural steel will be considered as an energy material, since it is of key importance for the foundation (or even for the structure itself when it is made of prestressed concrete) of modern wind turbines. Special attention will be paid to the material-science type relationship between microstructure (including its geometrical arrangement) and macro- and microscopic fracture behavior.
Figure 1. Modern wind energy turbines.

Figure 2. Ancient windmills in Campo de Criptana (Ciudad Real, La Mancha, Spain).

Figure 3. Cover page of “Don Quijote de la Mancha” by Miguel de Cervantes Saavedra.
Figure 4. Cervantes Monument in the Plaza de España (Madrid, Spain), including the statue of Miguel de Cervantes Saavedra and those of Don Quijote de la Mancha and Sancho Panza

Figure 5. Profile view of Don Quijote and Sancho (Cervantes Monument in Madrid).

2. Structural integrity of wind energy turbines

Structural health monitoring of wind turbine system is a critical issue in the development of wind energy [1,2]. In this framework, the two most important technical concerns are related to (i) the correct maintenance of the wind turbine gearbox [3-6], (ii) the structural integrity of the wind tower structure and foundation [7,8].

The author of the present paper has developed investigations in the specific field of damage tolerance of the wind turbine gearbox bearings [5,6], analyzing the phenomenon of hydrogen-assisted rolling-contact fatigue (HA-RCF) in the materials. In addition, his research is mainly concerned with fracture and structural integrity of eutectoid cold drawn prestressing steel wires to be used, e.g., in the main structure [7] and in the foundation or supporting system [8] of wind energy turbines in the case that prestressed concrete is the main structural material.

High-strength cold drawn pearlitic steel wires have extraordinary mechanical properties [9-12], so that they can be considered as high-performance materials (HPM) [9,10], their excellent behaviour being clearly influenced by the microstructural arrangement generated during the manufacture process by progressive (multi-step) cold drawing [10].

This paper offers a materials-science (micro- and macro-) approach to the fracture and structural integrity (in air and aggressive environments) of cold drawn pearlitic steel wires, by establishing a relationship between microstructure and fracture performance and introducing the innovative concept of microstructural integrity.
3. Hierarchical structure of cold drawn pearlitic steel wires

Cold drawn pearlitic steel wires are manufactured progressively in several steps (Figures 6 and 7) to increase the strength by a strain hardening mechanism, at the same time producing a microstructural evolution [13-15], as shown in Figure 8 in the form of slenderizing [16] and orientation [17] of the first microstructural level (parlitic colonies), together with densification [18] and orientation [19] of the second microstructural level (ferrite/cementite lamellae).

![Figure 6. Manufacture of prestressing steel wires by progressive multi-step cold drawing.](image)

Fracture of cementite lamellae or special interlamellar spacing appears in the research by Toribio et al. [20] who identified, denoted and described a new (non-conventional) microstructural unit: the pearlitic pseudocolony (Figure 9), a special pearlitic colony in which the lamellae are not oriented along the wire axis or cold drawing direction, thereby producing an anomalous (extremely high)
pearlitic interlamellar spacing, sometimes associated with breaking (local fracture) and curling of cementite lamellae. These characteristics make them weakest areas or potential fracture initiation units, i.e., places able to produce fracture path deflection.

**Figure 7.** Scheme of the cold drawing process: (a) pass of the steel through the die; (b) progressive (repetitive) cold drawing in six passes; (c) 3D scheme of the whole manufacturing chain.
Figure 8. Microstructures of cold drawn pearlitic steels in longitudinal (left) and transverse (right) sections for steels that have undergone 0, 2, 4 and 6 steps of cold drawing (from top to bottom).
Figure 9. Pearlitic pseudocolonies in heavily cold drawn pearlitic steels after six drawing steps (longitudinal section).

The afore-said microstructural levels produce a hierarchical microstructure in the cold drawn pearlitic steels [16-21]. Therefore they can be regarded as hierarchically-structured materials (HSM) in which the different scales of analysis provide scientific information about the fracture performance in air and aggressive environments.

4. Fracture performance of cold drawn pearlitic steel wires

4.1. Fracture in air
Pearlitic steels with small (or null) degree of cold drawing fail in air (and at room temperature) in a predominantly ductile manner, so that the Miller & Smith micromechanical model of fracture in air by shear cracking in pearlite [22] has been proposed to explain the fracture process in slightly cold drawn pearlitic steel [23], as depicted in Figure 10. The plastic yielding of the tougher (and more ductile) ferrite leads to micro-fracture and yielding of the more brittle cementite lamellae.

Figure 10. Microstructure-based model of fracture for slightly cold drawn pearlitic steel (on the basis of the Miller-Smith model of shear cracking of pearlite with fracture of cementite).
Figure 11 sketches the micromechanics of fracture in the case of heavily cold drawn pearlitic steel; as explained in previous paragraphs, the pseudocolonies represent weakest units promoting fracture and crack deflection appears when the macroscopic fracture path reaches a pearlitic pseudocolony, that itself fails by shear cracking of pearlite if not previously pre-cracked or pre-damaged as a consequence of the manufacture process by cold drawing [23], thus producing curling and micro-fractures.

![Figure 11](image)

**Figure 11.** Microstructure-based model of fracture in the case of heavily cold drawn pearlitic steel (on the basis of the pearlitic pseudocolony as the weakest fracture unit promoting crack deflection).

4.2. Fracture in aggressive environments

The analysis of fracture of progressively cold drawn pearlitic steel was performed in previous research [24-26]. In the following sections the main results are described, with distinction between the two main regimes of environmental cracking.

4.2.1. Hydrogen assisted cracking (HAC)

Figure 12 shows microstructure-based models of fracture in progressively cold drawn pearlitic steels in the case of hydrogen assisted cracking (HAC). Depending on the degree of cold drawing, any of the two mechanisms of hydrogen embrittlement, hydrogen enhanced localized plasticity (HELP) or hydrogen enhanced decohesion (HEDE) could be operative, as described elsewhere [24].

For small or null degree of cold drawing, HELP is predominant, Figure 12(a), linked with shear cracking of pearlite and a micromechanical mode of fracture in the form of tearing topography surface or TTS, i.e., a mechanism with a non negligible degree of plasticity in the pearlitic microstructure, similar to that appearing in the case of fatigue crack propagation with transfer of the material from the crack tip to the flanks of the growing crack. This experimental fact could indicate the important role of plasticity in both fatigue crack propagation and HAC.

For heavily cold drawn pearlitic steels fractured in a hydrogen environment, HEDE is predominant, and in this case the concept of splitting or delamination fracture [26] is applicable. It could be decohesion, delamination or debonding between similar microstructural units, either the pearlitic colonies (the fracture path advancing just along the colony boundaries) or the ferrite/cementite
lamellae, the delamination being through the interface, with a fracture mechanism similar to that of composite materials (as a matter of fact, the cold drawn pearlitic steel is a micro-composite material).

Figure 12. Microstructure-based model of hydrogen assisted cracking (HAC) in progressively cold drawn pearlitic steel.

4.2.2. Localized anodic dissolution (LAD)
Figure 13 shows a microstructure-based model of localized anodic dissolution (LAD) or pure stress corrosion cracking (SCC), cf. [25]. It could be valid for any degree of cold drawing.

Figure 13. Microstructure-based model of localized anodic dissolution (LAD) in progressively cold drawn pearlitic steel

For pearlitic steels with low (or null degree of cold drawing), metal dissolution takes place and produces crack tip blunting (with round tip), cf. Figure 13(a). When the drawing level increases, the
stronger anisotropy favors cornered blunting, cf. Figures 13(b) and 13(c) over round blunting. In the case of heavily cold drawn pearlitic steels, Figures 13(d), 13(e) and 13(f) show the sequence of enhanced dissolution just at the corners, finally producing crack deviation. In the most heavily drawn pearlitic steels, again the concept of splitting or delamination fracture [26] is applicable.

Apart from the described pioneering papers [23-26], dated more one decade ago, studying the relationship between hierarchical microstructure of cold drawn pearlitic steels and their fracture behavior, more recent papers present alternative analyses on the same topic [27-30]. In addition, the author of the present paper has published three very recent reviews [31-33] dealing with structural integrity [31], environmentally assisted cracking [32] and hydrogen effects [33] in progressively cold drawn pearlitic steel wires.

5. Closing remark about the relationship between microstructure and fracture behaviour
Cold drawing in pearlitic steel produces a closely packed and oriented hierarchical microstructure, thereby influencing the fracture behavior in air and aggressive environment which becomes very anisotropic (splitting or delamination) in the case of heavily cold drawn pearlitic steels.

6. Epilogue: An approach to Johann Sebastian Bach
On the basis of the hierarchical microstructure of cold drawn pearlitic steels (two levels of colonies and lamellae), a link can be established with the multi-scale (multi-level or multi-layer) structure of Johann Sebastian Bach’s music. Figure 14 shows the Bach’s image by Elias Gottlob Haussmann, the only authentic portrait of Johann Sebastian Bach (that in which the composer has the canon triplex).

In this framework, one really remarkable example is the Christmas Oratorio composed by six Cantatas (macro-structure), each of them with its own micro-structure (consisting of contrasting sections of recitatives, arias and choruses). Another beautiful evidence of multi-level structure of Bach’s music is given in Figure 15 showing some early bars of the Fugue No 1 in C Major BWV 846 of The Well-Tempered Clavier (Book I). The (macro-) structure of the fugue itself contains (micro-) structure of thematic sections (subject and counter-subject) and connecting passages (episodes or divertimenti), i.e., it is a hierarchical structure like that of cold drawn pearlitic steel wires.


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