Improved cold-drawn eutectoid steel wires based on residual stress measurement and simulation: Part 2. Optimization of mechanical properties

Knowledge of residual stresses can be used to improve the performance of drawn wires. In this second part, the influence of residual stresses on the mechanical properties (tensile, stress relaxation and stress corrosion tests) is studied

By J.M. Atienza, J. Ruiz-Hervias, M. Elices

Cold-drawn eutectoid steel wires are used in prestressed concrete structures to provide compressive stresses to the concrete. For that purpose, they are loaded up to 60 to 70% of their tensile strength. Although the loading stress is lower than the elastic limit (around 85% of the tensile strength), failure may occur in service conditions due to stress corrosion. Wire failure reduces the load bearing capacity and may lead to catastrophic collapse of the prestressed structure. The risk of these failures can be increased by the presence of tensile residual stresses on the surface of the wires.

Cold-drawing generates considerable residual stresses which, added to the service stresses, may seriously affect the mechanical properties and durability of the wires [1,2]. Until now, the measuring of residual stresses was considered more a scientific problem and even revealing their presence was a challenging task [3].

However, wire manufacturers were aware of the deleterious effect produced by the presence of tensile residual stresses at the surface of the wires after drawing. That is the reason why they consider residual stresses both dangerous and damaging, and hence attempt to reduce their influence by stress relieving treatments. But residual stresses may also have beneficial effects if we are able to obtain the desired profile.

With the advent of powerful experimental techniques for measurement of residual stresses — such as neutron and X-ray diffractometers — and of faster computers to simulate numerically the wire drawing processes, this phenomenon is seen now in a new light. A significant research effort has been undertaken in recent years in order to understand, measure and control the residual stresses in cold-drawn wires [3-5].

In the first part of this paper [3], the advances on the measurement and simulation of residual stresses have been discussed. In this second part, the influence of residual stresses on the mechanical properties required by standards to this kind of wire (tensile, stress relaxation and stress corrosion tests) is reviewed. The control of residual stresses may play an important role in the design of new post-drawing treatments and the optimization of the performance of the wires.

The profile of residual stresses in wires for prestressed concrete

In order to summarize the different possibilities of residual stress profiles in prestressed concrete wires, they have been classified into three groups, shown in Figure 1, based on their residual stress state at the surface, a parameter measurable by X-ray diffraction. It is thought that these three kinds of wires will help us to explain the influence of residual stresses on the mechanical properties:

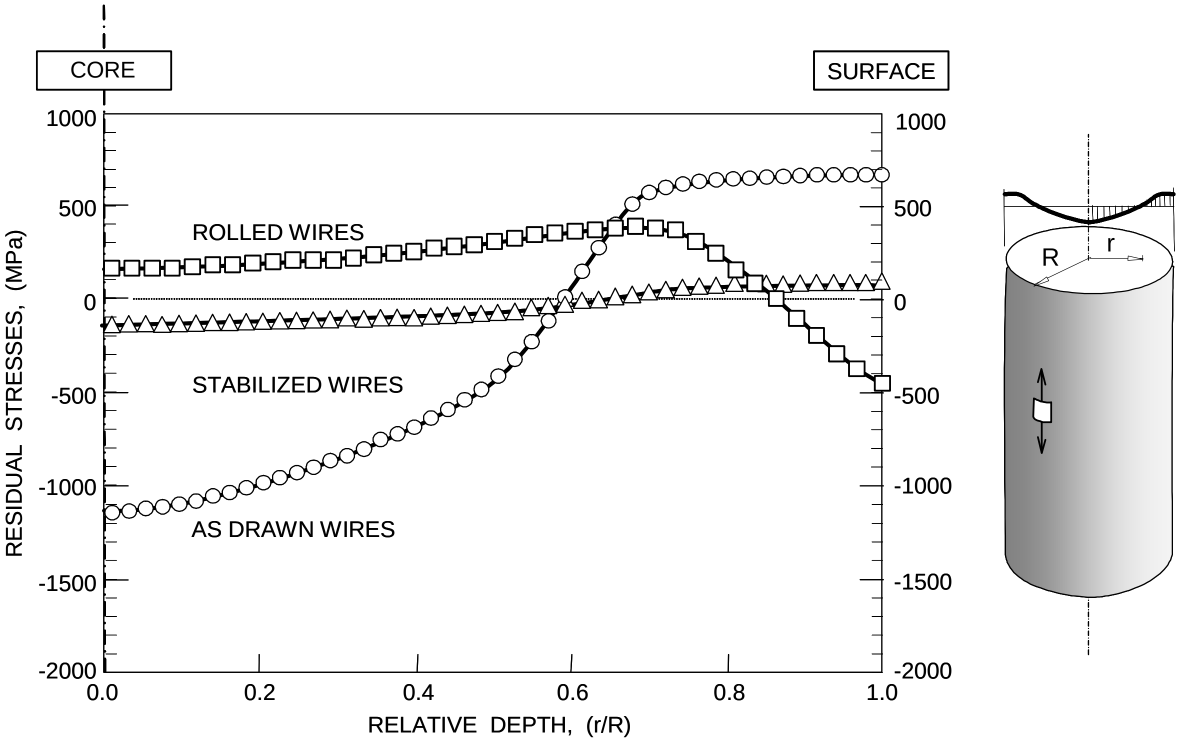

Figure 1. Typical profiles of residual stresses along the wire diameter for as-drawn, stabilized and rolled wires. These results were obtained by the combination of finite element calculations and experimental measurements by conventional X-ray, neutron and synchrotron diffraction techniques [3].

a) As-drawn: Tensile residual stresses at the surface

A profile of residual stresses, with tensile stresses at the surface, is generated in the prestressed concrete wires by the cold-drawing. The term "as-drawn" refers to the wires manufactured by cold-drawing, following a commercial procedure. These wires, without any further treatment after drawing, were considered to have high tensile surface residual stresses.

b) Stabilized: Small residual stresses at the surface

Stabilized wires were obtained by applying a thermomechanical stress relieving treatment to the as-drawn wires. Residual stresses due to cold-drawing are known to be detrimental to the performance of prestressing concrete steel tendons, and different procedures were devised to eliminate or decrease such stresses before delivering steel wires. The actual procedure, called stabilizing, is a thermomechanical treatment based on a combination of heating and stretching the wire. However, the actual parameters of this treatment depend on each producer. The stabilized wires, also called "very low relaxation wires" because of their very good behavior in the stress relaxation test, are the kind currently used in prestressed concrete structures. This treatment is very effective in removing the residual stresses generated by drawing; it can be considered that no residual stresses act on the surface of these wires.

c) Rolled wires: Compressive residual stresses at the surface

The third set, termed “rolled”, can be obtained by rolling the surface (see, for example, [2] for a description of this procedure) that produces a small plastic deformation on the wire surface, analogous to a “massage”. Compressive residual stresses can be induced on the wire surface by this procedure. The effect of this process is similar to the use of a specific last drawing die, yielding a very small reduction of area.

Residual stresses and the tensile test

Residual stresses can alter the shape of the stress-strain curve of the wires obtained in a tensile test [6]. During a tensile test for a wire without residual stresses, the stress distribution is uniform along the cross section (Fig. 2a); initially the stress remains within the elastic regime and finally reaches a yield value and from this point the stress-strain curve is no longer a straight line.

In a tensile test on an as-drawn wire (with residual stresses), the stress distribution is not uniform across the section, as is shown in Fig. 2b. During loading, stress increases and the first yielding appears on the surface where initially there were tensile stresses. This local plastification produces the loss of linearity in the stress-strain curve very early. As load increases, yielding extends towards the interior of the bar (Fig. 2b) and the stress-strain curve starts deviating from a straight line. It should be noted that this may happen with a low level of tensile stresses in the inner part of the bar or even with compressive stresses in that area (Fig. 2b). A similar reasoning can be made regarding the rolled wires, though on this occasion the yield point is reached in the centre of the wire first.

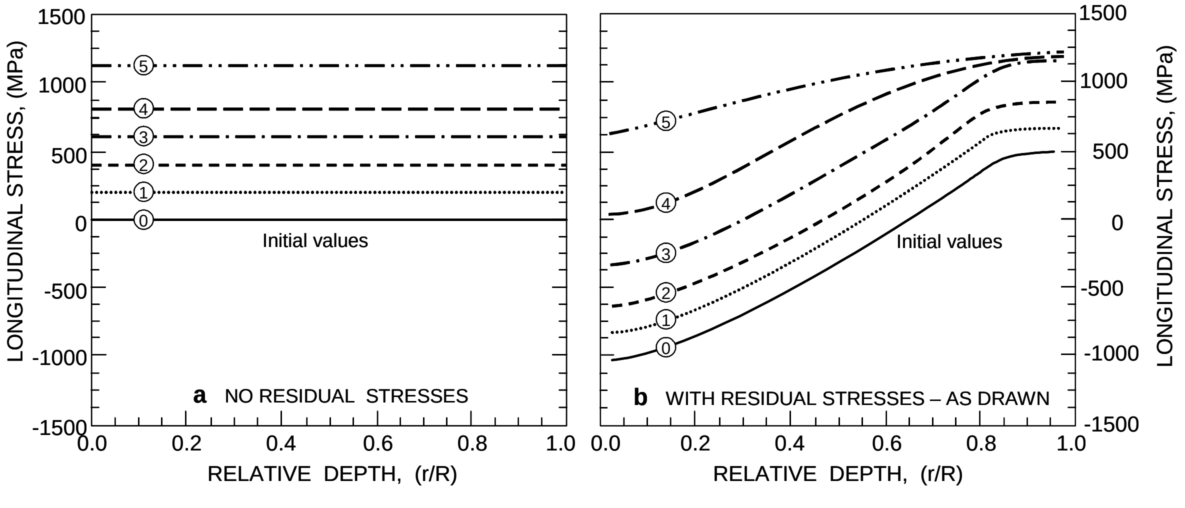

Figure 2. Longitudinal stresses as a function of relative depth during a tensile test of a cold-drawn wire (elastic limit approx 1100 MPa): a.- Wire without residual stresses; b.- Wire with residual stresses due to cold drawing. Stresses in both figures correspond to the same loading steps

The presence of residual stresses is reflected in the shape of the stress-strain curve. In Figure 3 the results of a tensile test for the three kinds of wires are compared. In practical terms, the presence of tensile residual stresses (whether they are tensile or compressive at the surface) decreases the yield stress — usually measured as $\sigma_{0,2}$ — as regards values without residual stresses and have almost no influence in the strength σ_{max}. Therefore, the presence of residual stresses will affect the ratio $\sigma_{0,2}/\ \sigma_{max}$, a figure that appears in most standards for steels for prestressing concrete [7]. More precisely, these standards recommend that $\sigma_{0,2}/\ \sigma_{max}$ should be in between 0.85 and 0.95, with some suggesting optimum values of about 0.90-0.93.

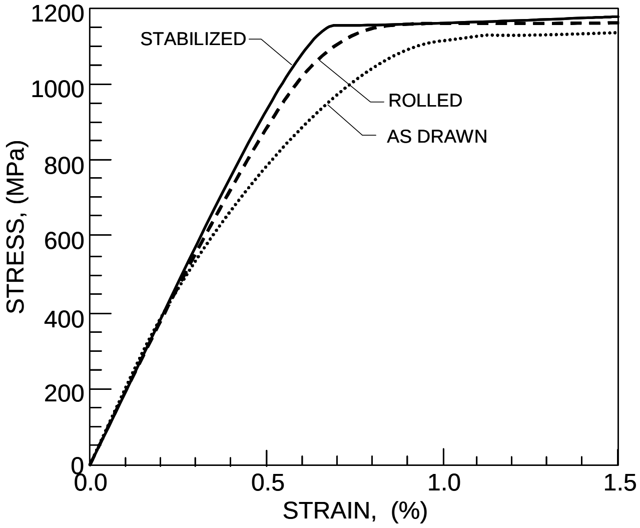

Figure 3. Comparison between the tensile tests of as-drawn, stabilized and rolled wires.

In summary it was found that the presence of residual stresses favors the onset of yielding. The higher the residual stresses, whether it is tensile or compressive at the surface, the lower the yield stress in a tensile test. The ratio $\sigma_{0,2}/\ \sigma_{max}$ decreases with increasing values of residual stresses. Given the deleterious effect of tensile residual stress at the surface on fatigue and stress corrosion [1,2] it was reasonable to put a lower limit to $\sigma_{0,2}/\ \sigma_{max}$. The ratio $\sigma_{0,2}/\ \sigma_{max}$ can be increased by relieving residual stresses, a common procedure after drawing, based on termomechanical treatments.

Residual stresses and the stress relaxation test

Tensile stresses in steel tendons decrease with time, mainly due to *stress relaxation* (*Creep* is the change in strain with time in a material held under constant stress, whereas *stress relaxation* is the loss of stress in a material held at a constant strain). These stress losses in steel tendons are of paramount importance to structural safety because the prestressed compressive load of the concrete is reduced. Design codes place limits for keeping these losses within safe margins [7]. Stress losses are measured according to a standardized test (ASTM E328, ISO15630/3) and the figures should be provided by the manufacturer for the acceptance of the steel tendons; those with a figure of stress losses of less than 2.5% of the initial stress — after 1000 hours, when stressed at 0.70 of the tensile strength — are called “low relaxation” tendons and are the ones used nowadays in prestressing.

The authors have shown that wires with the same composition, microstructure and similar mechanical properties may have very different behavior in the stress relaxation test if they differ in their residual stress profiles [8]. This effect could be explained if the influence of the initial load is taken account.

It is well known that in steel tendons the higher the initial stress the greater the relaxation losses, a fact collected in codes and textbooks [7]. Fig. 4a shows stress relaxation losses after 250 hours in stabilized wires (whose residual stresses are very low or, in practise, almost negligible) loaded at different percentages of the ultimate tensile stress (from 50% to 98%). The losses are small at low values of initial stresses and increase suddenly when these stresses approach the yield stress (approx 85-90% of maximum load). At higher values of initial stress it seems that stress relaxation losses reach a saturation value.

Stress relaxation losses after 250 hours in as-drawn and rolled wires, again loaded at different percentages of their respective ultimate tensile stresses, are shown in Fig. 4b. The behavior of these two types of wire — whose residual stresses are by no means negligible — is quite different from that of stabilized wires (Fig. 4a).

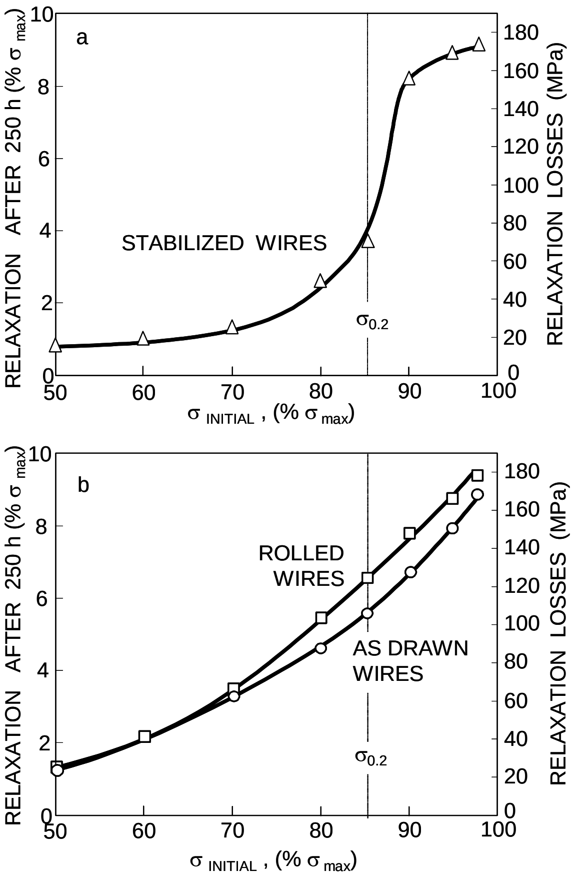

Figure 4. Stress relaxation losses (at 250 hours) as a function of the initial load (both expressed as a percentage of the ultimate tensile stress). a.- Stabilized wires. b.- As-drawn and rolled wires.

The role of residual stresses can be inferred from the following reasoning: The actual stress distribution in the section of the wires during the test is quite different in the three types of wires. In the case of the stabilized wires the stress distribution across the section is almost uniform, so the wire is subjected to the same initial load all over the cross section. In the case of the as-drawn wires, the stress distribution across the section at the beginning of the relaxation test is by no means uniform. Once loaded, the outer regions of the wire are subjected to higher stresses than the inner part, so the stress relaxation in these regions is higher, as can be inferred from Fig. 4a. The stress relaxation losses of the wire are the sum of the losses produced along the whole section. Similar reasoning can explain the experimental results shown in Fig. 4b for the rolled wires.

In the case of the standard test (initial load 70% σ_{max}), the stress relaxation of as-drawn and rolled wires is much higher than that of stabilized ones. The stress distribution across the section at the beginning of the relaxation test is not uniform for these two kinds of wires. The outer regions of as-drawn wires and the inner regions of rolled wires are subjected to higher stresses approaching the yield stress ($\sigma_{0,2}$), so stress relaxation in these regions is very high, as can be inferred from Fig. 4a. On the contrary, the inner regions of as-drawn wires and the outer regions of rolled wires support lower stresses than those in stabilized wires and consequently lower relaxation losses, although these differences are not enough to balance the high stress losses of the outer layers. The overall behavior is that as-drawn and rolled wires exhibit relaxation losses much higher than those of stabilized ones, almost double at 1000 hours (Fig. 5).

Another result, one which merits particular attention, is that at high initial loads the stress relaxation behaviour of the three types of wire becomes similar. At high stresses, the role of residual stresses is concealed because most of the wire section has yielded and the stress gradient across the section becomes smooth, so the stress profiles across the wire sections for stabilized, as-drawn and rolled wires are almost identical. Thus, the advantages of stabilized wires are lost when they are stressed at high loads, greater than $0.80\sigma_{max}$.

In summary; when dealing with stress relaxation losses, the whole section, all layers, is crucial. From this point of view, the best behavior is obtained in wires with small residual stresses (stabilized). The presence of residual stress, regardless of whether they are tensile or compressive at the surface, will increase the stress relaxation losses of the wires.

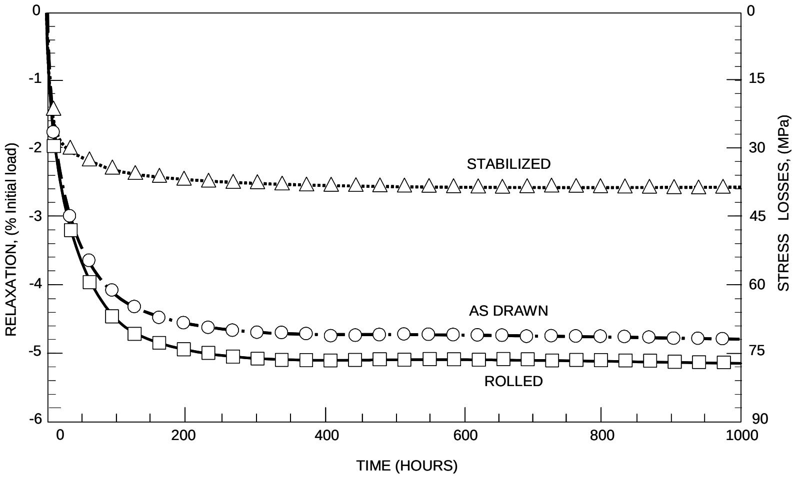

Figure 5. Stress relaxation losses as a function of time in the three types of wire. These tests were performed at 70% of the ultimate tensile load. Stress relaxation losses are measured as a percentage of the initial load.

Residual stresses and the stress corrosion test

Experience has shown that the durability of steel tendons for prestressing concrete is good enough when they are protected by sound and uncracked concrete. However, when steel tendons are not properly protected, cracks may develop under the combined action of stress and an aggressive environment, and grow at stress intensities well below the fracture toughness of the material. Such a phenomenon is known as environmentally assisted cracking or stress corrosion cracking. A significant number of prestressed structures (mainly bridges) located near marine environments have suffered this kind of problem [1]. The former International Federation for Prestressing (*fib*) considers there is a pressing need for the improvement of the durability of prestressed concrete structures in aggressive environments.

The *fib* proposed the ammonium thiocyanate test in 1978 [1,2] to control the susceptibility to environmental cracking, by testing stressed samples exposed to the pertinent aggressive environment and by recording times to fracture. The *fib* test uses an aqueous solution of ammonium thiocyanate (NH_4SCN) in contact with the steel at a constant temperature of 50±1˚C.

Wire failures are influenced by surface defects and by the presence of residual stresses, as was shown by the authors [1,2]. Previous results [1] showed that the surface damage that can trigger fracture in this test should have a depth of 0.1 mm or less. When the specimen is loaded in the stress corrosion test, the actual stress state in the cross section is obtained by adding the constant applied stress to the existing residual stress profile. In the case of the as-drawn wire, the resulting stress at the surface during the corrosion test is higher than the applied stress and it can reach the yield stress even at small applied loads.

In the Figure 6, the times to rupture at different initial loads in the *fib* test of the three types of wires are compared: wires as-drawn (with high surface tensile residual stresses) have the worst behavior, whereas rolled wires (with surface compressive stresses) are the best. The results using an initial load of $80\%\sigma_{max}$, as proposed by standards [7], are shown in Table 1. Generating compressive residual stresses at the surface of the wires is very effective in improving their time to rupture in this kind of test.

In summary, a good correlation was found between residual stresses at the wire surface and times to rupture in the stress corrosion test proposed by the *fib*. Differences in rupture times in prestressing steel wires — with the same microstructure, surface quality and mechanical properties — can be explained by the differences in their residual stress state at the surface. Tensile residual stresses at the surface, added to loading stresses, are dangerous for the material. The stress corrosion behavior could be improved if compressive residual stresses were induced at the wire surface. Decreasing the adverse surface tensile stresses, or even better, changing to compressive stresses, the environmental assisted cracking will be significantly improved.

Table 1. Times to rupture in the *fib* test for the three kinds of wires.

	As-drawn	Stabilized	Rolled
Time to Rupture (h)	2	4	12

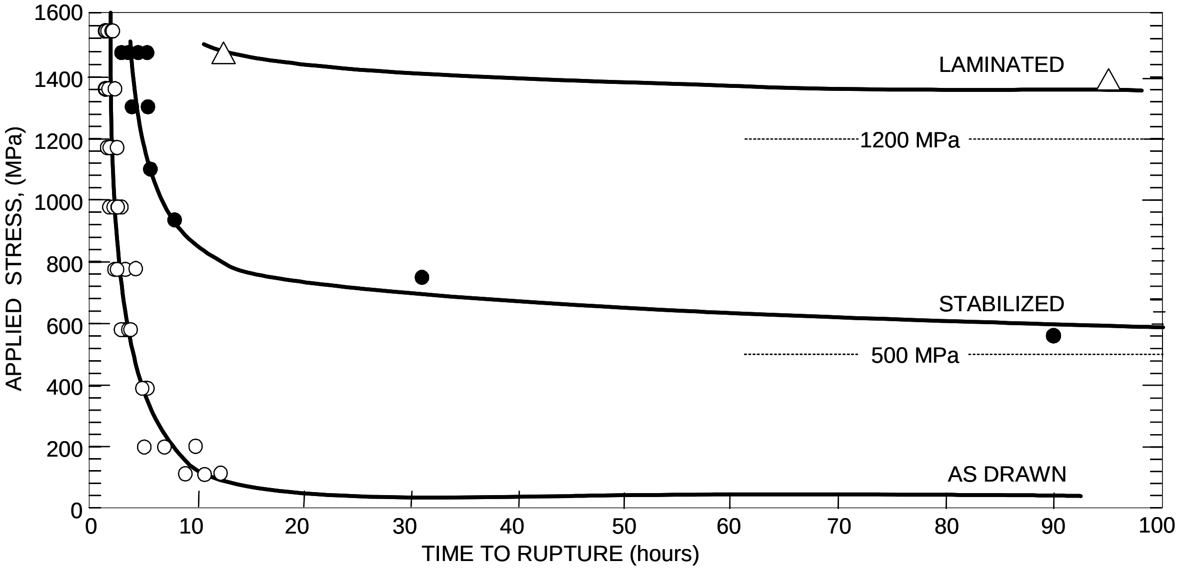

Figure 6. Rupture times, in the NH_4SCN test (*fib* stress corrosion test) at different initial loads, for as-drawn, stabilized and rolled wires [2].

Discussion

Residual stresses have a significant influence on the mechanical behavior of prestressing steel wires and today, even taking into account their limitations, we have powerful tools to face the problem of residual stress characterization. It is expected that residual stress values at the surface of the wires would be required by standards in the future.

Although prestressing steel wires have excellent mechanical properties (high strength and high elastic limit combined with reasonable ductility), the question that still remains is if we are able to improve the performance of these wires in aggressive environments. Results from this work show that the susceptibility to stress corrosion could be improved significantly if compressive residual stresses were induced at the wire surface. In contrast, these treatments may affect the behavior of the wires in the tensile test by reducing the elastic limit and in the stress relaxation test by increasing the stress relaxation losses. Thus, we obtained wires with more durability in aggressive environments, but they could not be considered “very low relaxation” wires.

In other words, we cannot optimize the whole properties at the same time; the results of the stress corrosion test depend, among other parameters, on the surface condition of the wire, while the tensile and the stress relaxation tests depends on what happened throughout the section. It is necessary to choose the adequate treatment depending on the requirements and the actual working conditions of the wires.

In the authors′ opinion, due to the problems of stress corrosion that may appear in prestressed concrete structures built near marine environments, preparation of special purpose wires could be of particular interest, assuming some stress relaxation losses, to assure a better behavior when they are to be used in structures near sea water.

In any case, techniques based on residual stress control seem to be an appropriate tool to design the post-drawing treatments based on quantitative measurements and not only on empirical procedures.

Future challenges

In the previous paragraphs, the effects of residual stresses on the mechanical behavior have been discussed facing only at macrostresses. In a two-phase material such as eutectoid steel, macrostresses could be defined as the average of stresses in a volume that takes over all phases. In other words, the mean stress of all phases together. Macrostresses are what we normally call stress, those with which we have to deal at a macroscopic scale, in most of our engineering applications. However, in a two-phase material the residual stress state can differ from phase-to-phase and neutron or X-ray diffraction methods measure the crystalline phase stresses.

In Figure 7 ferrite and cementite stresses are depicted together with the macrostress profile in an as-drawn eutectoid wire described in the first part of this paper [3,4]. Residual macrostresses are computed by the stress experimentally measured in every phase, weighted with their relative percentage in volume (rule of mixtures, in this case 90% ferrite and 10% cementite). This is a figure of significant interest (to the authors´ knowledge, the first time in which a whole profile of residual stresses has been obtained for both phases). From the macroscopic point of view, this profile shows tensile surface stresses with all the previously mentioned shortcomings. However, from the microscopic point of view, this is a very attractive profile. We should not forget that eutectoid steel could be considered as a composite material, a laminate material of alternating ferrite (matrix-soft phase) and cementite (reinforcing-hard phase) lamellae. In Figure 7 it is shown that the soft phase will be subjected to a previous compressive state, like a prestressing treatment inside the steel wire, which would be beneficial for the performance of the wire.

In Figure 8 appears the evolution of macro and ferrite phase residual stresses with a stress relieving treatment and a surface rolling treatment. Post-drawing treatments are used to relieve residual macrostresses or to obtain compressive macrostresses at the surface. The drawback is that with these treatments, while we are obtaining the desired profile of macrostresses we are losing the beneficial effects of the compressive phase stress in the ferrite. That is the reason why in many cases post-drawing treatments improve the elastic limit but slightly reduce the strength of the material. In essence, we are losing the prestressing effect inside the material.

In our opinion, the future challenge is to develop post-drawing treatments that allow us to obtain the desired profile of residual macrostresses while keeping ferrite in compression. This way would be the most appropriate to optimize the performance of these wires.

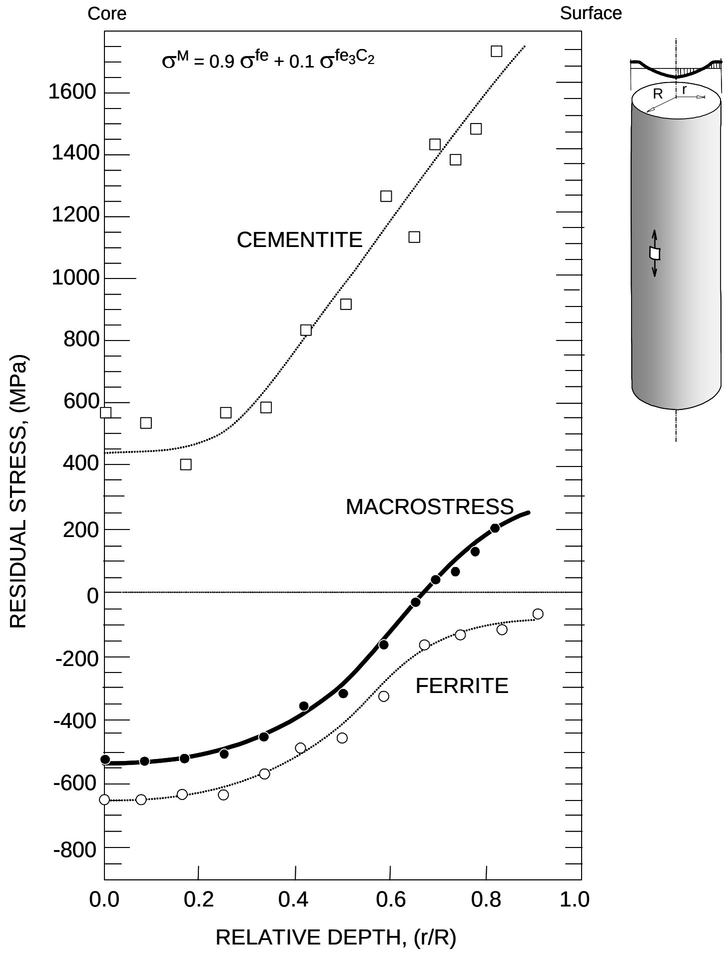

Figure 7. Residual stresses in the ferrite and cementite phases of a pearlitic wire after one drawing pass measured by synchrotron radiation. Macrostress in the pearlitic material was determined by the stress measured in every phase, weighted with their relative percentage (90%-ferrite, 10%-cementite) [3,4].

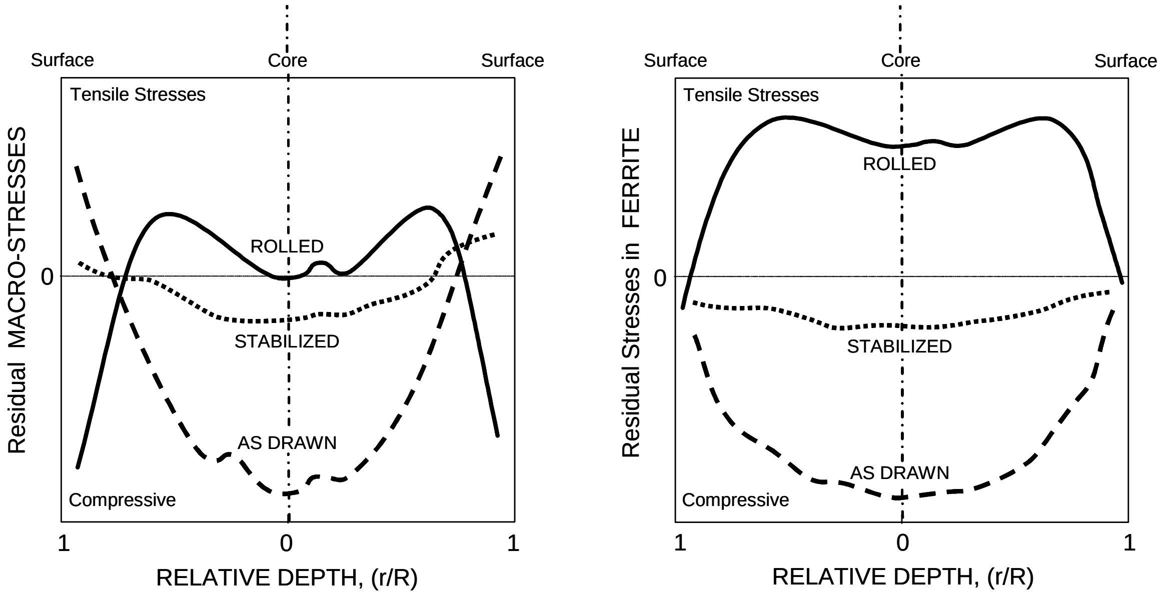

Figure 8. Effect of stabilizing and surface rolling treatments on the profiles of residual macrostresses and residual stresses in ferrite in a cold-drawn eutectoid steel wire.

Acknowledgements

The authors gratefully acknowledge the support of the Spanish Ministry of Fomento, by means of the grant "Durability of prestressed concrete tendons", and the Spanish Ministry of Education, by means of grant FEDER 2FD1997-1513. They are also indebted to Mrs. María Martínez, Mrs. Mar García and Mr. Federico Mompeán for their contribution to the neutron and synchrotron measurements and Mr. Luis Caballero for the stress corrosion tests. Help and useful comments from Mr. Luis del Pozo, from Emesa Trefilerías, and Mr. Javier del Río, from Bekaert, are also acknowledged.

References

1. M. Elices, "Influence of residual stresses in the performance of cold-drawn pearlitic wires," *Journal of Materials Science*, 39(12), pp 3889-3899, 2004.
2. J.M. Atienza, J. Ruiz-Hervias, L. Caballero, and M. Elices. "Residual stresses and stress corrosion in cold drawn eutectoid steel wires". *Wire Journal International*, pp 53-57, june 2007.
3. J.M. Atienza, J. Ruiz-Hervías, M. Elices. "Improved cold-drawn eutectoid steel wires based on residual stress measurement and simulation: Part 1. Residual stress characterization". *Wire Journal International*, march 2008.
4. M.L. Martinez-Perez, F.J. Mompean, J. Ruiz-Hervias, C.R. Borlado, J.M. Atienza, M. García-Hernandez, M. Elices, J. Gil Sevillano, Ru Lin Peng and T. Buslaps, "Residual stress profiling in the ferrite and cementite phases of cold-drawn steel rods by synchrotron X-ray and neutron diffraction". *Acta Materialia*, 52, pp 5303-5313, 2004.
5. J. Ruiz-Hervías, J.M. Atienza, M. Elices and E.C. Oliver, "Optimisation of post-drawing treatments by means of neutron diffraction". *Materials Science and Engineering*, in press 2008.
6. J.M. Atienza, and M. Elices. "Influence of residual stresses in the tensile test of cold drawn wires". *Materials and Structures*, 36, pp 548-552, 2003.
7. CEB-FIP (1990). Model Code 1990, Lausanne, (1991). ASTM-A421 (1991), EHE-UNE 36094 (1994), BS-2691 (1991)
8. J.M. Atienza and M. Elices. "Role of residual stresses in the stress relaxation of prestressed concrete wires". *Journal of Materials in Civil Engineering* 19:8, pp 703-707, 2007.