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Effect of thermo-mechanical treatments on residual stresses measured by neutron diffraction in cold-drawn steel rods

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Abstract

Cold-drawing is employed to fabricate wires and rods, which are mainly used as structural reinforcements in construction as well as in the tyre industry. As a consequence of processing, a residual stress profile is developed. The wires are subjected to post-drawing thermo-mechanical treatments with the aim of improving their durability and stress relaxation behaviour. It is claimed that they do so by reducing the residual stresses produced by cold-drawing, although no conclusive data have been given. In this paper, residual stress profiles are measured by neutron diffraction in two cold-drawn pearlitic steel rods subjected to a true strain 1.7: "as-drawn" and "stabilized" (thermo-mechanical treatment). The results show that the post-drawing treatment is very successful in reducing the residual stresses produced by drawing, especially in the surface region of the rods. This explains the improvement of the stress relaxation and stress corrosion behaviour observed in the "stabilized" samples.

Keywords: Residual stresses; Neutron diffraction; X-ray diffraction (XRD); Pearlitic steels; Drawing

1. Introduction

The wide range of structural applications of eutectoid steel wires and rods derives from their excellent mechanical properties; high strength and elastic limit combined with reasonable ductility [1]. They are used, for example, as structural reinforcements in prestressed concrete and in tyres, and as cables in mining and off-shore petroleum production as well as other applications. The manufacturing process (cold-drawing) consists of reducing the wire section by successive passes through a set of conical dies. Several studies [2–5] have shown that the cold-drawing produces tensile residual stresses (RS) at the wire surface and compressive ones at the center. These stresses are known to influence the mechanical behaviour of the wires [6,7] as well as their durability [8,9]. The wire manufacturers are aware of the problem and use empirical post-drawing treatments with the aim of improving the mechanical properties demanded by the prestressing standards, namely tensile strength and stress relaxation. It is claimed that these treatments (whose details are, in general, protected by the companies) alleviate the RS generated by cold-drawing, but no conclusive data have been provided so far.

A better knowledge of the effect of post-drawing thermo-mechanical treatments on RS would be very beneficial. The mechanical properties and the wire durability could be improved by selecting a post-drawing treatment which produces a suitable RS field in the wire. In addition, the availability of reliable RS experimental data would allow the implementation of finite element codes that take into account RS generated by cold-drawing.

Cold-drawn eutectoid steels are a microcomposite of alternating ferrite (α-Fe) and cementite (CFe_3) lamellae. External load is shared between both phases and despite the low volume fraction of cementite (around 10%), its contribution to the overall mechanical properties of the steel is remarkable [10]. The non-destructive measurement of RS is commonly made using diffraction techniques with either X-rays or neutrons [11]. Laboratory X-ray diffraction is limited to the surface region of the material due to its low penetration (typically several microns in steel). Therefore, when a stress profile is to be determined in an engineering material or component, neutron or high-energy X-rays (synchrotron radiation) are required. If the material is multiphase, as in the case of eutectoid steel, the RS from the

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Nomenclature

d_i	lattice spacing in the i-direction
d_0	stress-free reference lattice spacing
G	shear modulus
K	bulk modulus
$\frac{1}{2}S_2^m$, S_1^m	diffraction elastic constants

Greek letters

$\underline{\underline{\varepsilon}}$	strain tensor
$\underline{\underline{\varepsilon'}}$	deviatoric strain tensor
ε_H	hydrostatic strain
ε_i	principal strain in the i-direction
ε'_i	components of the deviatoric strain tensor
ε_{ij}	components of strain (the subscripts i, j go from 1 to 3)
λ	first Lamé constant
$\underline{\underline{\sigma}}$	stress tensor
$\underline{\underline{\sigma'}}$	deviatoric stress tensor
σ_H	hydrostatic stress

different phases may be analyzed separately, by considering the specific diffraction peaks produced by each phase. The techniques are well established, and discussed in detail for example in [11,12]. However, the measurement of residual stresses in the cementite phase is a difficult task in cold-drawn eutectoid steels due to the poor peak statistics. In addition to the low volume fraction of CFe_3, its orthorhombic structure spreads the scattering intensity into a large number of Bragg reflections.

A number of studies have been carried out to measure residual stresses in the ferrite phase of cold-drawn steels by X-ray diffraction [13–16]. Some authors have also measured residual stresses in cementite by X-ray diffraction [17–19], neutron diffraction [20–23] and high-energy synchrotron radiation [4,24]. Sometimes, residual stresses could not be determined in the lamellar cementite because of the strong peak broadening caused by elastic and plastic strains associated with cold-drawing [24]. On the other hand, cementite stresses are frequently averaged over the whole cross-section of the sample, in an attempt to improve the poor peak statistics. For example, Van Acker et al. [20] obtained ferrite and cementite stress values averaged over the cross-section of thin wires (cold-drawn from 3.25 mm to 1.22 and 0.89 mm) and inferred strain profiles using a layer removal technique and subsequent corrections for stress relaxation.

The main objective of this paper is to study the influence of industrial post-drawing thermo-mechanical treatments on RS in eutectoid steel rods. To this end, textures and detailed residual strain profiles were measured by neutron diffraction in samples of commercial steel rods (5.2 mm diameter) in the "as-drawn" condition and after the post-drawing treatment (know as "stabilizing") to reduce the RS. It was attempted to measure strain profiles and textures in both phases (ferrite and cementite) of the material. However, the low signal coming from the cementite phase precluded strain scanning in this phase, so only average values are reported. The results indicate that the treatment employed is very effective in reducing the RS and that it does not change significantly the fiber texture produced by cold-drawing.

2. Experimental

2.1. Material

Cold-drawn eutectoid steel rods for this research were supplied by EMESA (Arteixo, La Coruña, Spain). The chemical composition of the steel used is 0.815 C, 0.231 Si, 0.642 Mn, 0.012 P, 0.008 S, 0.044 V and 0.221 Cr (mass%). The initial rod for the cold-drawing process (12 mm diameter in our case) is subjected to a multi-step drawing process until the diameter corresponding to the final product (5.2 mm) is reached. In this case, eight passes are employed and an 81% section reduction is achieved. True strain given by drawing reaches 1.7, as calculated by $2\ln(\Phi_0/\Phi_f)$, where Φ_0 and Φ_f are the initial (12 mm) and final (5.2 mm) diameters, respectively. The resulting cold-drawn rod, which is coiled in a reel, will be named T8. After drawing, the rod is given a thermo-mechanical treatment known as "stabilizing" with the aim of reducing the residual stress level, and the final product is obtained (TE sample). As a result of the treatment, where the diameter does not change, the rod is straightened.

Longitudinal and transverse cross-sections were prepared for metallographic analysis. After polishing, samples were etched with Nital 2%. Before SEM observation, a thin Au–Pd film was deposited on the surface of the samples by sputtering. The rod microstructure is fully pearlitic, as corresponds to the eutectoid point (0.8% C). In the micrographs obtained by SEM (Fig. 1), both the initial and the T8 rod are shown. The TE rod is not included because the microstructural features observed by SEM are not changed by the thermo-mechanical treatment. It can be seen that the microstructure is fairly isotropic in the initial rod, with the ferrite/cementite lamellae randomly oriented, as shown in Fig. 1a and b. After drawing, the lamellae are considerably thinner (interlamellar spacing around 100 nm) and mainly aligned in the drawing direction, which coincides with the rod axis, as seen in Fig. 1c and d.

Conventional tensile tests were performed with a universal testing machine to obtain the mechanical properties of the T8 and TE rods. The results are given in Table 1. The elastic limit and the tensile strength are slightly reduced as a consequence of the stabilizing treatment, whereas the elongation is significantly enhanced (5.1% for the TE in comparison with 1.9% for the T8 rod).

Table 1
Mechanical properties (average of three tests) of the "as-drawn" T8 and the "stabilized" TE rods

	T8	TE
E (GPa)	190	205
$R_{p0.2}$ (MPa)	1720	1615
R_m (MPa)	1940	1850
ε_{R_m} (%)	1.9	5.1