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Stress evolution of cold-drawn pearlitic steel wire subjected to uniaxial tension

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Abstract

The aim of this paper is to investigate the effect of uniaxial tension on the residual stress of cold-drawn pearlitic steel wire through X-ray diffraction in combination with layer removal technique. It is found that an extra 0.9% plastic strain is introduced to the steel wire due to the uniaxial tension using a universal electronic tensile machine. The XRD results indicate that uniaxial tension after drawing has dominate influence on the decrease of surface tensile residual stress and the corresponding stress gradient in the drawn wires.

Keywords: Cold drawing; Pearlitic steel; Residual stress; Uniaxial tension; X-ray diffraction

1. Introduction

Progressively cold-drawn pearlitic steel wire is of great practical importance and is widely used as structural materials when very high strength and acceptable level of stabilized toughness are required, such as suspension cables, tyre cord, engineering springs, etc. The mechanical properties of cold-drawn pearlitic steel wire (typically a microcomposite of alternating ferrite (α-Fe) and cementite (Fe_3C) lamellae) are mainly controlled by the microstructure developing during cold drawing and, to some extent, by the residual stresses arising as a consequence of the inhomogeneous plastic deformation during processing [1].

Residual stress distribution in cold-drawn wires has been explored in great detail by using direct investigation techniques such as neutron diffraction (ND) and high-energy synchrotron radiation X-ray diffraction (SR-XRD). The experiment results on the residual stress distributions of pearlitic steel wire indicate that the surface of wire after drawing is subjected to considerable tensile residual stresses, while the centre port is under compression [2–6]. Also, finite element method (FEM) analysis reveals that drawing process generates a similar residual stress state with significant longitudinal tensile stress at the surface of rods [7]. From an application point of view, such high tensile stress on the surface is undesirable and has proved to be detrimental to the performance of cold-drawn wire. It has been extensively documented [5–10] that surface tensile stress may have a dominate impact on the mechanical properties of steel wires by reducing the elastic limit, and increasing the losses in the stress relaxation test and shortening the service life in stress corrosion cracking and fatigue. Therefore, many post-drawing treatments have been devised to eliminate or decrease the residual stress in steel wires [11,12], of which two procedures are mostly utilized [13]. One is purely mechanical treatment—consisting in a further drawing with a very small area reduction (about 1%); the other is thermomechanical treatment based on a combination of heating and stretching the wire (commonly termed as stabilizing). The procedures change the residual stress distribution and suppress the surface stress in pearlitic steel wires, which is beneficial to yield improved mechanical properties.

Recently, an alternative solution for reducing residual stress in cold-drawing rod, namely uniaxial tension after drawing, has been proposed and optimized [9], where the use of an extra finishing die or intricate die geometry is no more needed. The application of a slight axial tension to the bar or wire after drawing is all that requires, and by adjusting the magnitude of the tension it is possible to control the residual stresses in the final product. The procedure helps to decrease the surface tensile stress and to flatten the stress

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distribution in median carbon steel rods (see Ref. [9]). Nevertheless, there are rarely researches dealing with the effect of uniaxial tension on the stress distribution of pearlitic steel wire.

The objective of this study is to illustrate the influence of uniaxial tension after drawing on the stress distribution in the pearlitic steel wire, in which X-ray diffraction together with layer removal technique are utilized. As the axial residual stress is the largest stress tensor amongst all the stress components, which has dominate influence on the mechanical properties of wires, we hereby make focus on the residual stress in the axial direction.

2. Experimental procedures

2.1. Materials and wire drawing process

The initial rods (before drawing) used for this research are hot rolled pearlitic steel with the microstructure of alternating ferrite and cementite lamellae, resulting from a sequence of thermotreatment through Stemol-cool line. The composition in weight percent (wt%) of the rods is 0.82% C, 0.76% Mn, 0.23% Si, 0.007% S, 0.01% P and balance Fe. The pearlite colonies are randomly oriented and exhibit a fine interlamellar spacing of about 150 nm. The steel wires with diameter of 5.12 mm are manufactured by eight passes cold drawing (total strain is 1.86) through conical die.

To modify the residual stress of cold-drawn wire, the drawn wire is subjected to uniaxial tension using a CMT5105 universal electronic tensile machine. Firstly, the cold-drawn wire (150 mm gauge) is subjected to uniaxial tension at a low strain rate of 2 mm/min. Secondly, the wire is slowly unloaded after material exceeds the yielding point, and finally a certain plastic strain is introduced to the wire. The whole procedure is performed at ambient atmosphere to avoid possible calorific effect. It should be emphasized that the additional plastic strain is calculated after wire is unloaded, and in this research only the residual stress of the cold-drawn wire with additional plastic strain of 0.9% is evaluated due to the shortage of specimen.

2.2. X-ray stress measurements by XSTRESS 3000

Stress measurement has been performed on the surface of the as-drawn pearlitic steel wire and those subjected to a uniaxial tension process, employing classical $\sin^2\psi$ method of XRD. The principle of the method is that the interplanar lattice spacing of $\{h\,k\,l\}$ plane can be calculated using Bragg's law by measuring the 2θ angle at which the reflection occurs, the longitudinal strain along the direction (L_3 direction in Fig. 1) of the scattering vector—the bisector between incident and diffracted beam, may therefore be obtained by

$$(\varepsilon'_{33})_{\varphi\psi} = \frac{d_{\psi\varphi} - d_0}{d_0}, \tag{1}$$

where ε'_{33} is the longitudinal strain along the L_3 direction, $d_{\psi\varphi}$ and d_0, respectively are the interplanar spacings for studied $\{h\,k\,l\}$ plane with a normal direction defined by ψ and φ angles, and the unstressed lattice spacing.

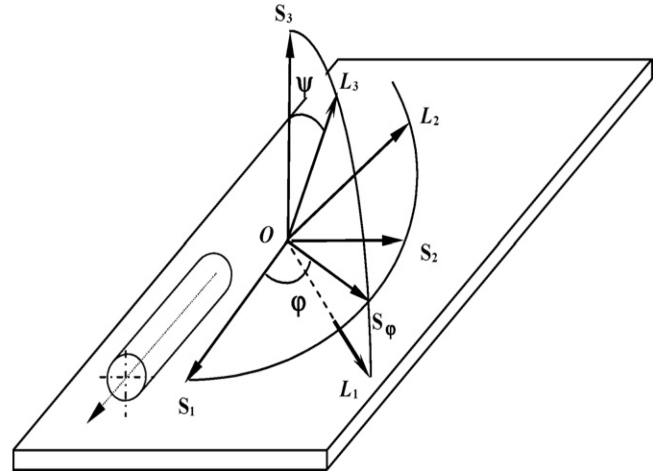

Fig. 1. Definition of the angles ψ, φ, laboratory coordinate system L_i and sample reference system, S_i.

Assuming that the stress tensor at the surface of wire is biaxial (i.e., the stress components in the direction of the surface normal S_3 are negligible), the stress component along the S_φ direction σ_φ is in relation to ε'_{33} as follows (see Fig. 1):

$$(\varepsilon'_{33})_{\varphi\psi} = \frac{1+\mu}{E}\sigma_\varphi \sin^2\psi - \frac{\mu}{E}(\sigma_{11}+\sigma_{22}). \tag{2}$$

Therefore, σ_φ may be obtained directly from the slope of a least-squares line fitted to experimental data measured at various ψ, if the elastic constants E and v are known.

In this study, measurements are conducted by a portable XSTRESS 3000 stress analyzer with a microcollimator of 1 mm, operated at 30 kV and 6.7 mA with Cr Kα radiation (2.29 Å). The diffractometer is used in Ω mode with the $\sin^2\psi$ method, the explosion time (40 s) of MOS detector and ψ oscillation techniques ($\Delta\psi$ of 5°) are utilized to ensure the accuracy. (2 1 1) diffraction with a Bragg diffraction at $2\theta = 156.4°$ for α-Fe is studied to plot the interplanar spacing amongst $\sin^2\psi$ in both positive and negative ranges. Apart from the obvious velocity merit of stress measurement with respect to conventional X-ray diffractometer, the chief significance of the XSTRESS 3000 is its possibility of stress measurement of the practical workpiece with large dimension or complex geometry. All the movements are performed by the goniometer that includes the X-ray source and detectors; so it allows one to operate measurements to large sample without having to cut them into small pieces.

Notice that the X-ray small penetration depth in engineering materials limits its applicability to depth resolved residual stress determination, layer removal technique [4] is therefore utilized to derive the stress profiles across the whole section of wire, where the etching solution with ratio of 12% H_2O_2 and 1% HF, balance H_2O is used.