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# Deformation of cementite in cold drawn pearlitic steel wire

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ABSTRACT

Nanostructural evolution of cementite lamellae in pearlitic steel wires subjected to cold drawing remains elusive, making it difficult to understand the origin of remarkable ductility in cementite. Using high-resolution transmission electron microscopy (HRTEM), the mechanisms underlying the inelastic deformation of cementite in pearlitic steel wires were examined and elucidated. Deformation of cementite in drawing should be included in two mechanisms: (1) Dislocation mechanism: deformation in low strain pearlite should rely on the movement of dislocation. Flat-crystal cementite was broken up into several different orientation cementite particles. (2) Grain rotation mechanism: the deformation mechanism should be by the rotation of cementite particles. Cementite still keeps lamellar shape, but it was divided into a multilayer structure: central nano-crystal and outermost amorphous cementite.

## 1. Introduction

High-strength steel wires have been widely used in automobiles, suspension bridge building and mining industry. They are routinely produced by subjecting hot-rolled steel rods to cold drawing, a controlled severe plastic deformation process. To increase the strength of steel wires for weight reduction and safety-critical applications such as passenger transportation, the structural evolution of pearlite, the major microconstituent in wire-making steels, during cold drawing has been a subject of extensive investigation over the past several decades [1–8]. Pearlite consists of alternating layers of ferrite and cementite oriented essentially in the same direction. Mechanically, ferrite is soft and can deform plastically to a great extent through dislocation motion. By contrast, cementite is hard and prone to brittle failure [4]. Although cementite phase represents only approximately one-ninth of the total volume in pearlite, its presence is critical to the strength and ductility of cold drawn wires [1–3]. Post-mortem evidence has emerged and shown that cementite lamellae in pearlite exhibits remarkable ductile behavior during cold drawing [5–8]. It raises an intriguing question: how can cementite layers be rapidly deformed by cold drawing to large strains without brittle failure? It appears that fine pearlitic structure favors the plastic deformation of cementite lamellae when subjected to high hydrostatic compression induced by cold drawing. Several studies [5–7] have examined the plastic deformation of cementite in pearlite, from which operative slip systems were proposed. In addition, cementite lamellae were found to decompose under heavy cold drawing [8–11], or assume a spherical shape when heated up to 400 °C [12]. Even so, a complete picture of the structural change of cementite lamellae in pearlitic steel wires in response to the increase of mechanical strain during cold drawing remains elusive. Such a lack of understanding and research has hindered the construction of authentic mechanical models that could be used to understand the origin of ultrahigh strength in pearlitic steel wires. The present study endeavors to elucidate the nanostructural evolution of cementite lamellae in cold drawn pearlitic steel wires. Based upon that, the deformation mechanism of cementite was revealed under different drawing strains, from which a fresh insight into the remarkable ductility of cementite lamellae was gained.

## 2. Experimental procedure

Pearlitic steel wires were produced by Sha-steel Group Company, P. R. China, and used in this work. To prepare these wires, hot-rolled steel rods (12 mm in diameter) that contain 0.83% C, 0.29% Si, 0.38% Mn and 0.23% Cr were used. After pickling and phosphating [13], the rods were drawn successively to a diameter of 3.3 mm, with a total reduction of 92.4% (i.e., $\varepsilon = 2.6$). The average reduction per pass was about 14%.

The microstructure of the wires was characterized using JEM 2000EX transmission electron microscope (TEM).

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## 3. Results and discussion

Fig. 1a is the cross-sectional image of a thin cementite lamella in pearlitic steel rods ($\varepsilon=0$) obtained at a very high magnification. It has a thickness of ~15 nm and exhibits a highly ordered lattice structure. Micro-diffraction pattern of cementite is also presented in the lower right corner of Fig. 1a, confirming that the plate-like cementite is a single crystal. Fig. 1b shows the diffraction pattern of the interface between cementite and ferrite layers generated by using the fast Fourier transformation (FFT) method. The splitting electron diffraction spots are also displayed along the cementite [100] and ferrite $[\overline{3}1\overline{1}]$ zone axes. Notably, the lattice fringes of $(001)_{\text{cementite}}$ and $(010)_{\text{cementite}}$ are almost parallel to those of $(21\overline{5})_{\text{ferrite}}$ and $(141)_{\text{ferrite}}$, respectively, suggesting that the relative orientation of the ferrite and cementite components follows the Pitsch–Petch relationship [14]. Fig. 1c is the Fourier filtered lattice image obtained from FFT diffraction spots of $(001)_{\text{cementite}}$ and $(21\overline{5})_{\text{ferrite}}$ after inverse FFT (IFFT). No lattice mismatch is visible in cementite, while a few mismatches appear in ferrite. The interface of cementite and ferrite is flat, with one mismatch occurring every 20 to 30 $(001)_{\text{cementite}}$ crystal planes. The existence of flat, coherent interface between cementite and ferrite is significant, which makes it possible for dislocations formed in ferrite to glide through the interface into cementite with little resistance.

Fig. 2a shows a layered ferrite/cementite configuration within pearlitic steel wires produced by cold drawing at a low strain ($\varepsilon=0.5$). The FFT diffraction pattern of a selected region in cementite is also presented in the lower right corner of this figure. Different from the pattern obtained from the nondeformed samples (Fig. 1a), multiple sets of diffraction spots arise in this situation, suggesting that the single crystalline cementite has deformed and transformed into a polycrystal. The higher resolution crystal structure of alternating layers of cementite and ferrite is presented in Fig. 2b. The atomic arrangement of cementite is highly ordered, and only a small number of lattice misfittings occurred. The flat interface between cementite and ferrite, however, appears to become uneven in some locations, wherein the dislocations in ferrite move through the interface into cementite. These dislocations, after entering a cementite lamella, would divide it into small domains of slightly different orientations.

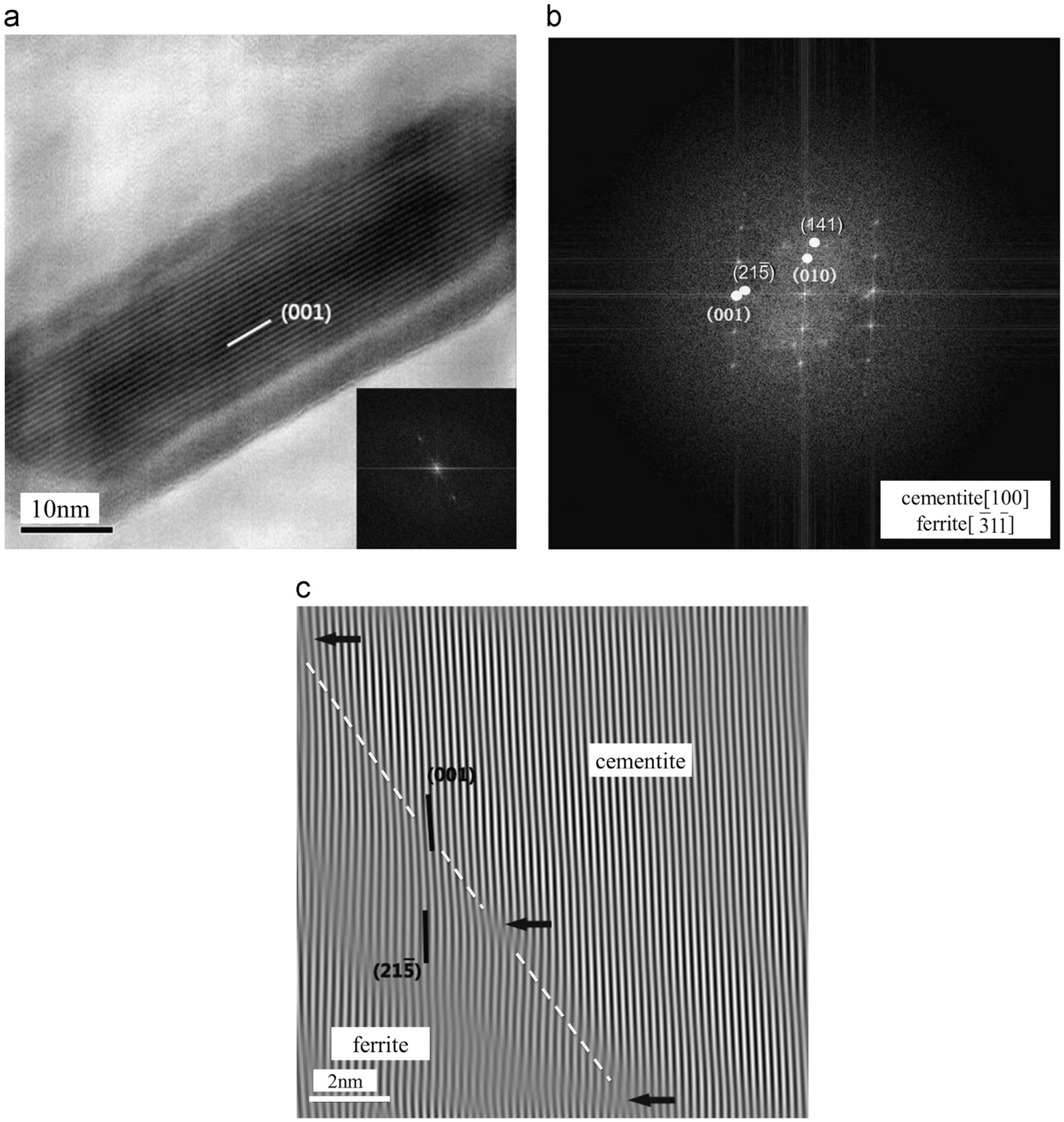

**Fig. 1.** HRTEM micrographs of cementite structure in pearlitic steel rod ($\varepsilon=0$). (a) Cross-section of cementite lamella; (b) FFT pattern of interface between cementite and ferrite; and (c) IFFT image of interface between cementite and ferrite layers.