Effect of Pearlite Lamellar Orientation on Deformation of Cold-Drawn Pearlite Steel Wire (Postprint)

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Date: 2023-03-19T00:00:00+00:00

Abstract

The effects of pearlite lamellae orientation on the deformation behavior and mechanical properties of pearlite steel wire during cold drawing deformation were investigated using TEM, SEM, and nanoindentation. The results show that: for pearlite lamellae with a smaller angle to the drawing axis, through rotation of pearlite colonies, the lamellae become reoriented parallel to the drawing axis, preferentially forming a ferrite <110> fiber texture; dislocations in ferrite evolve from single slip to multiple slip, and finally to single slip on the same slip system, with a relatively uniform distribution, while cementite and ferrite maintain coordinated deformation. For pearlite lamellae with a larger angle to the drawing axis, they become reoriented to near-parallel to the drawing axis through bending, cementite undergoes fracture and fragmentation, dislocation cells form in ferrite, causing difficulty in subsequent deformation and slow lamellae thinning. After drawing deformation, straight pearlite exhibits higher microhardness than bent pearlite, indicating that pearlite lamellae nearly parallel to the drawing axis have a higher work hardening rate, which is beneficial for deformation strengthening.

Full Text

Effect of Pearlitic Lamella Orientation on Deformation of Pearlite Steel Wire During Cold Drawing

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Supported by National Natural Science Foundation of China (Nos.51371050 and 51301038), Fund of Transformation of Scientific and Technological Achievements from Jiangsu Province (No.BA2014088) and Fund of Prospective Study and Research from Jiangsu Province (No.BY2014127-03)

Manuscript received 2014-11-14, in revised form 2015-04-02

Abstract

Cold-drawn pearlitic steel wires with ultra-high strength have important applications in automobile tires, spring ropes, and bridge cables. Numerous investigations have focused on the hardening mechanisms of pearlitic steel wire, covering microstructural evolution, texture development, and dislocation behavior. In this work, the effects of pearlitic lamella orientation on the mechanical properties and deformation behavior of pearlite steel wire during cold drawing were investigated using transmission electron microscopy (TEM), scanning electron microscopy (SEM), and nano-indentation. The experimental results showed that pearlitic lamellae having a low angle with the drawing direction would be turned parallel to the drawing direction through a combined rotating process of pearlite colonies. The $< 110 >$ fiber texture in the ferrite phase formed first, and the distribution of dislocations in ferrite was almost uniform, with coordinated deformation between cementite and ferrite. Pearlitic lamellae having a large angle with the drawing direction would be bent and turned to approach parallel to the drawing direction. It was difficult for the bent pearlite to deform because of the fragmentation of cementite and formation of dislocation cells in ferrite. After the cold drawing process, the micro-hardness of straight pearlite was higher than that of bent pearlite, indicating that pearlitic lamellae having a low angle with the drawing direction have a higher work-hardening rate during drawing.

Keywords pearlitic steel wire, cold drawing, pearlitic lamella orientation, plastic deformation

Cold-drawn pearlitic steel wires are widely used in critical applications such as radial tires and bridge cables due to their high strength while maintaining adequate toughness [1-4]. The high strength of pearlitic steel wire is achieved through cold drawing deformation. Currently, the highest commercial grade of fine cutting steel wire has reached 3800 MPa, and with increasing demand for cutting hard materials and advances in materials processing technology, higher strength pearlite steel wires are under development. Reportedly [5], laboratory-prepared pearlite steel wire samples have achieved strengths up to 7 GPa.

The excellent mechanical properties of pearlitic steel wire are closely related to its deformed microstructure. During cold drawing, pearlite lamellae gradually transform from an equiaxed structure to a fibrous structure aligned along the axial direction. The average ferrite/cementite lamella spacing gradually decreases [6], with the thinning rate proportional to the reduction in wire diameter. This refined lamellar structure contributes to grain boundary strengthening. The dislocation density in ferrite increases dramatically and forms a $< 110 >$ fiber texture, further strengthening the material [7-9]. During deformation, cementite gradually becomes amorphous and even partially dissolves, which also contributes to the high strength of pearlite steel wire [10-13]. In fact, obtaining well-performing pearlite steel wire is closely related to the entire cold drawing process [14-17]. Due to its lamellar structure characteristics, pearlite exhibits anisotropy during cold drawing, and pearlite colonies with different lamella orientations show vastly different deformation behaviors. Researchers [1,14-16] have preliminarily analyzed the morphologies of deformed pearlite with different lamella orientations, but systematic studies on how lamella orientation affects microstructural evolution are lacking. It remains unclear whether lamella orientation influences the work hardening process of pearlite. The relationship between these phenomena and the morphology of differently oriented pearlite lamellae after deformation is not yet understood.

This work investigates cold-drawn pearlite steel wires with different strain levels, comparing the effects of lamella orientation on microstructural evolution, crystallographic orientation, and mechanical properties during cold drawing, and discusses the influence of lamella orientation on pearlite deformation.

Experimental Methods

The experimental material was SWRS82B high-carbon steel rod with a diameter of 12 mm. Its chemical composition (mass fraction, %) was: C 0.83, Si 0.3, Mn 0.71, Cr 0.19, V 0.07, S 0.003, Fe balance. After pickling and phosphating [19], the high-carbon steel rod was cold drawn through multiple passes to 3.4 mm. The total true strain e was calculated as $e = \ln(A_0/A)$, where A_0 is the original cross-sectional area and A is the cross-sectional area after deformation, giving $e = 2.5$. The average pass reduction was 14%.

Longitudinal section samples were cut from wires with different strain levels using wire electrical discharge machining. After mechanical grinding and polishing, the samples were etched with 4% nitric acid alcohol solution and observed using a Sirion-400 field emission scanning electron microscope (SEM). Mechanically polished samples were stress-relief polished using silica gel and tested using a Micro Materials System 1 nano-mechanical testing system to obtain microhardness values of different microstructures. The loading and unloading rate was 0.6 mN/s, maximum load was 15 mN, hold time was 5 s, and 49 indents were made at a temperature of 25 °C. Longitudinal section samples approximately 300 m thick were mechanically thinned to 100 m, then electropolished using a twin-jet polisher to prepare TEM samples. A JEM 2100F transmission electron microscope (TEM) equipped with a scanning transmission electron microscopy (STEM) detector was used to analyze the deformed microstructure of pearlite. The drawing axis was determined based on the overall preferred orientation of the lamellae, and the crystallographic orientation of ferrite was analyzed using selected area electron diffraction patterns along the ferrite zone axis.

Results

2.1 Microstructural Evolution [Figure 1: see original paper] shows SEM images of longitudinal sections of pearlitic steel wire at different strain levels. The undeformed pearlite exhibited an equiaxed morphology with randomly oriented lamellae approximately 120 nm thick. At a strain of 0.7, two typical morphologies were observed: In region A, the pearlite lamellae had a small angle with the drawing axis and were uniformly elongated and thinned; in region B, the lamellae deviated significantly from the drawing axis and were bent toward the drawing direction, with severe distortion and twisting at the bend locations. When the strain increased to 1.7, most pearlite lamellae became completely parallel to the drawing axis and had clearly thinned, but some pearlite microstructures remained bent and twisted. In region C of [Figure 1: see original paper]c, the bent pearlite lamellae showed non-uniform deformation, obvious distortion, and significantly different thickness compared to adjacent straight pearlite. Researchers [1,16,24] generally believe that the lamella spacing in such bent pearlite microstructures is greater than that in straight pearlite. At a strain of 2.5, the pearlite microstructure had essentially become fibrous, with some fragmented Fe_3C particles present, as shown in region D of [Figure 1: see original paper]d.

During the drawing deformation process, different angles between pearlite lamella orientation and drawing axis led to distinctly different deformed morphologies. Based on the angle between lamella orientation and drawing axis, three typical cases can be distinguished: (1) Lamellae oriented parallel to the drawing axis deform by elongation and thinning; (2) When the angle between lamellae and drawing axis is less than 30°, pearlite colonies can rotate to adjust lamella orientation before elongating and thinning [20]; (3) When the angle exceeds 30°, pearlite microstructures must adjust lamella orientation through non-uniform shear deformation involving cementite bending and fracture to accommodate deformation.

2.2 Lamellae with Small Angle to Drawing Axis [Figure 2: see original paper] shows STEM images of pearlite with lamellae parallel to the drawing axis at different strain levels. Throughout the deformation process, pearlite microstructures with lamellae nearly parallel to the drawing axis remained straight, with uniform dislocation density and no obvious distorted regions. After small deformation at a strain of 0.25, dislocation lines in the pearlite were long and straight, indicating single-slip stage behavior. When the strain increased to 0.5, the $< 101 >$ direction in ferrite, lamella orientation, and drawing axis were all approximately parallel, and the $< 110 >$ fiber texture in ferrite had already formed first in this type of microstructure. At a strain of 1.1, the lamellae had clearly thinned to approximately 60 nm, and dislocations in ferrite had transitioned to multiple-slip stage, with significantly increased density—short and dense, with some dislocations entangled. At a strain of 1.7, the pearlite lamella thickness was about 40 nm, and cementite contrast had significantly decreased, which is related to the amorphous and nanocrystalline structure of cementite after deformation [9,13]. Further analysis of the diffraction patterns and morphology revealed that the $< 110 >$ orientation of ferrite, lamella orientation, and drawing axis were highly coincident, with dislocations existing in a mutually parallel arrangement perpendicular to the axis. At this stage, ferrite dislocations in individual lamellae were generated and multiplied through the $110 < 110 >$ slip system.

2.3 Lamellae with Large Angle to Drawing Axis [Figure 3: see original paper] shows STEM images of pearlite with lamellae significantly deviated from the drawing axis at different strain levels. After small deformation at a strain of 0.25, pearlite lamellae were bent and broken along the axis, forming a kink band morphology. The bent cementite lamellae were fractured, and high-density dislocations existed in ferrite, while regions outside the kink band showed no obvious deformation. When the strain increased to 0.5, the deformation inhomogeneity of the bent pearlite microstructure intensified, with pearlite lamellae bending toward both sides of the kink band, cementite fracturing, and high-density dislocations in ferrite gradually evolving into dislocation cell and wall structures. At a strain of 1.1, the angle between lamellae in the kink band and the drawing axis had decreased, the fractured cementite had lost continuity, and high-density dislocations were concentrated in ferrite within the kink band, forming wall-like structures that divided individual lamellae into two parts—one side with high dislocation density and the other with significantly fewer dislocations. From the [012] zone axis electron diffraction pattern in [Figure 3: see original paper]c, the $< 121 >$ direction of ferrite was parallel to the lamella orientation, while the $< 321 >$ direction was parallel to the drawing axis, indicating that the $< 110 >$ orientation of ferrite was not parallel to the drawing axis, meaning the $< 110 >$ fiber texture had not yet formed. After deformation to a strain of 1.7, the lamella orientation had become nearly parallel to the drawing axis, with bent and twisted cementite and fractured cementite appearing as short rods, while ferrite formed several dislocation cell structures. At this point, the original lamellar structure of pearlite had been severely damaged, and the ferrite/cementite two-phase structure had lost its characteristic features for coordinated deformation. Throughout the entire deformation process, microstructures with large angles between lamella orientation and drawing axis exhibited completely different characteristics: lamellae approached the drawing axis through bending deformation, the bent and fractured microstructure lost its lamellar characteristics, cementite fractured and fragmented, ferrite formed dislocation cell structures, making subsequent deformation difficult, lamella thinning slow, and $< 110 >$ fiber texture formation in ferrite challenging.

2.4 Micro-zone Nano-mechanical Properties Nano-indentation was used to measure the micro-zone hardness of pearlite with different lamella orientations at a strain of 1.1. After deformation, microstructures with lamellae nearly parallel to the drawing axis showed straight and elongated lamellae ([Figure 4: see original paper]a), accounting for approximately 65% of total test points, with an average hardness of 4.7 GPa. Microstructures with lamellae significantly deviated from the axis showed a bent morphology ([Figure 4: see original paper]b), accounting for about 35% of the total, with an average hardness of 4.1 GPa. These results demonstrate that pearlite microstructures with lamellae nearly parallel to the drawing axis have higher hardness than those with lamellae deviating from the axis, indicating that lamellae parallel to the drawing axis are beneficial for work hardening of pearlite, while large deviation angles reduce the work-hardening rate. Based on [Figure 2: see original paper] and [Figure 3: see original paper], bent microstructures exhibit non-uniform dislocation distribution in ferrite, and structures such as dislocation walls and cells make deformation difficult and create stress concentration zones, with numerous regions of low deformation extent existing within the microstructure. These lower-strength regions reduce the overall mechanical properties of the bent microstructure.

Discussion

During cold drawing, pearlitic steel wire is subjected to axial tensile stress and radial compressive stress. Because the lamellar ferrite/cementite structure of pearlite has different deformation capabilities along and perpendicular to the lamella direction, lamella orientation plays a crucial role in the deformation process. Researchers [1,15,24] have proposed that based on the angle between pearlite lamellae and the drawing axis, two cases can be distinguished: (1) When the angle is less than 30°, small local deformations cause rapid rotation of pearlite lamellae to become parallel to the drawing axis. Meanwhile, at relatively small strains ([Figure 2: see original paper]b), the stable $< 110 >$ orientation of ferrite was already parallel to the drawing axis. This may be because when lamella orientation is close to the drawing axis, the crystallographic orientation of ferrite becomes the key factor affecting microstructural deformation. Pearlite colonies not only reduce deformation resistance by adjusting lamella orientation but also align the $< 110 >$ orientation of ferrite in pearlite close to the drawing axis, reducing the number of slip systems required for deformation and further decreasing deformation resistance. This also explains why, compared with other microstructures, pearlite rapidly forms a $< 110 >$ fiber texture during cold drawing [21-23]: during cold drawing deformation, pearlite forms the $< 110 >$

fiber texture not only through dislocation slip in ferrite but also through rotation of pearlite colonies that quickly aligns the $< 110 >$ orientation of ferrite with the drawing axis, causing the $< 110 >$ texture intensity to increase rapidly at strains below 1.5 and then slowly saturate. With both lamella orientation and ferrite $< 110 >$ orientation parallel to the drawing axis, pearlite experiences minimum deformation resistance, and ferrite only needs to activate the fewest slip systems to complete thinning deformation, thereby rapidly and uniformly strengthening the entire microstructure. Notably, at large strains, pearlite lamella spacing has thinned to below 50 nm, and dislocations in ferrite appear in a mutually parallel arrangement ([Figure 2: see original paper]d), with dislocation density lower than at a strain of 1.1. In samples with a strain of 2.5, as shown in [Figure 5: see original paper], this parallel dislocation arrangement becomes more pronounced, and researchers [25] suggest that the strengthening mechanism of ferrite may have changed at this stage.

(2) When the angle between lamella orientation and drawing axis exceeds 30°, pearlite colonies cannot accommodate deformation through small-angle rotation. Under compressive stress, the hard and brittle cementite can only rapidly reduce its angle with the drawing axis through bending and fracture [16], thereby decreasing deformation resistance. This bent and fractured microstructure forms kink bands, where cementite gradually fractures and fragments, and ferrite forms high-density dislocation cell structures. These features cause pearlite to lose the mechanical characteristics of a lamellar structure, resulting in slow lamella deformation and difficult orientation adjustment, so that even at large strains, lamellae still maintain a certain angle with the drawing axis ([Figure 1: see original paper]c). When lamella orientation is not parallel to the drawing axis, the stress state during pearlite deformation is more complex, and the stress on ferrite differs significantly from the ideal state of axial tension and radial compression. Although there is no evidence that ferrite activates slip systems other than $110 < 111 >$, the complex stress state makes it difficult for ferrite in bent microstructures to adjust to the $< 110 >$ orientation ([Figure 3: see original paper]c). Under these conditions, ferrite must activate more slip systems to accommodate deformation, inevitably leading to dislocation entanglement and wall structures that hinder further work hardening. Moreover, cementite fracture and fragmentation in kink bands and high-density dislocations in ferrite create stress concentrations, generating defects such as vacancies and affecting microstructural thermal stability. Research [13] has shown that cementite in kink bands spheroidizes first during heat treatment, reducing the mechanical strength and torsional performance of the wire.

The hardness data from nano-indentation tests for microstructures with different lamella orientations show that microstructures with lamellae parallel to the drawing axis have higher strength after deformation than those with deviated lamellae, indicating that lamella orientation close to the drawing axis is beneficial for work hardening, while large deviation angles reduce the work-hardening effectiveness.

Conclusions

(1) When the angle between pearlite lamella orientation and drawing axis is small, pearlite colonies can rapidly adjust orientation through rotation during cold drawing, aligning lamellae parallel to the drawing axis and first forming the $< 110 >$ fiber texture. Dislocation multiplication in ferrite transitions from single slip to multiple slip and finally back to single slip on the same slip system, with overall dislocation density gradually increasing and remaining uniform. Cementite maintains coordinated deformation with ferrite.

(2) When the angle between pearlite lamella orientation and drawing axis is large, pearlite lamellae approach the drawing axis through bending deformation during cold drawing. The bent and fractured microstructure loses its lamellar characteristics, with cementite fracturing and fragmenting and ferrite forming dislocation cell structures, making subsequent deformation difficult, lamella thinning slow, and $< 110 >$ fiber texture formation challenging.

(3) During cold drawing deformation, pearlite lamella orientation close to the drawing axis is beneficial for deformation strengthening, while pearlite lamellae with large angles to the drawing axis exhibit relatively lower work-hardening rates.

[Figure 5: see original paper] STEM image of pearlitic steel wire with true strain of 2.5

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