Influence of Torsion Deformation on Textures of Cold Drawing Pearlitic Steel Wires

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Abstract The influence of torsion deformation on textures of cold drawing pearlitic steel wires was investigated by twisting the wires to different number of revolutions. Macro-texture (over the entire wire cross section) associated with torsion deformation was investigated by X-ray diffraction, while micro-texture (near the wire surface) was characterized by EBSD. The results show that the $\langle 110 \rangle$ macro-texture increases at the beginning of torsion and then decreases with increasing of torsion strain, while the $\langle 110 \rangle$ micro-texture decreases linearly with increasing of torsion strain. The relationships between the $\langle 110 \rangle$ fiber texture and the microhardness of the wires are also discussed.

KEY WORDS: Pearlite; Cold drawing; Torsion; Texture

1 Introduction

The extensive application of cold drawing pearlitic steel wires, such as rail steel, spring steel and bridge cable wires, fully justifies their excellent properties such as high strength, desirable ductility and good formability. Pearlite interlamellar spacing has been confirmed to be the major microstructural parameter that controls the strength of pearlitic microstructures by Embury and Fisher [1], Langford [2], Zelin [3] and Zhang et al. [4]. The strong correlation of the strength with pearlite interlamellar

spacing has led to processing to microalloying and processing approaches to produce pearlite microstructures with fine spacing. Microalloying with chromium and vanadium is the main method to obtain fine and homogeneous lamellar spacing distribution in thick wire rod [5–8]. Processing approaches include optimizing pearlite transformation process conditions [9, 10] and introducing deformation [2]. Cold drawing is considered as the major advantage of the deformational processing approaches to refine the pearlite interlamellar spacing [1, 4]. Damage evolution and optimizing drawing parameters in multi-pass wire drawing process have been studied extensively using experimental or theoretical methods [11, 12].

The existing researches of the cold drawing pearlitic steels mainly focus on the microstructure, texture and mechanical properties of the wires during drawing process. However, torsional ductility is particularly important when the drawn wire is subject to further plastic deformation during manufacturing, such as stranding tire cords or coiling springs [13]. The drawn wires may suffer external stress, such as torsional load or shock load, even without stranding or coiling. For instance, the cable wires of suspension might suffer torsional deformation during coiling process for transportation and uncoiling process for cable

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preparation. Recently, we investigated the influence of torsional load on the microstructures and properties of the drawing wires through twisting the wires to different number of revolutions. Unexpectedly, it is discovered that the tensile strength is extremely sensitive to the torsional load. The results show that the pre-torsion deformation can vary the pearlite interlamellar spacing and the dislocation density in the ferrite lamellae, which directly influences the tensile strength and the microhardness of the pearlitic wires. It is suggested that for the cold drawing pearlitic wires for manufacturing suspension bridge cables, torsional deformation should be avoided during coiling process for transportation or uncoiling process for cable preparation [14].

It is well known that the cold drawing wire also has a strong $\langle 110 \rangle$ fiber texture of the ferrite matrix [3, 15, 16]. Such fiber texture begins to take shape at the initial stage of drawing (with a drawing strain of 0.63) and develops gradually with increasing drawing strain [17]. The formation of the deformation bands in the drawing pearlitic steel wires promotes the development of the fiber texture during wire drawing [18]. The present work mainly focuses on the influence of the torsion deformation on development of the $\langle 110 \rangle$ fiber texture. In order to understand the influencing behavior of the strain gradient of torsion on the evolution of the fiber texture, both macro-texture across the whole longitudinal section of the sample and micro-texture on the sample surface are investigated by X-ray diffraction (XRD) and electron backscatter diffraction (EBSD), respectively. The relationships between the $\langle 110 \rangle$ fiber texture and the microhardness of the drawing wires are also discussed.

2 Materials and Experimental Procedures

Commercial hot galvanized steel wires (thickness of the galvanized zinc layer is about 40 μm) with the chemical composition of Fe-0.84C-0.19Si-0.72Mn-0.04Cr in wt% for manufacturing bridge cables were selected as the original material in this study. The as-received wire with diameter of 7.0 mm has a yield strength of 1634 MPa and the mean pearlite interlamellar spacing of 70 nm approximately.

Torsion was conducted by a unidirectional torsion machine in which the wire remained stationary at one end and could rotate with center axis at the other end. The as-received wires were twisted to 1, 3, 9 and 20 revolutions, respectively (named wire 1, wire 3, wire 9 and wire 20, respectively, usually the as-received wires can sustain at least 25 revolutions before fracture). The rotation speed was 30 r/min, and the gauge length of the wire for the torsion deformation was 70 mm. More details about the experimental procedure of torsion were shown in Ref. [14].

The information of the samples in detail is listed in Table 1. Torsion deformation of cold drawing pearlitic wires and strain curves of wires after torsion are shown in Fig. 1a, b, respectively [14].

The macro-texture of the samples was measured by XRD (Rigaku D/max-2500) with $\text{CuK}\alpha$ radiation. As shown in Fig. 2, the macro-texture measurements were performed at a longitudinally neutral cross section of the drawn wires. The Schulz back reflection technique was used to record (110), (200) and (211) incomplete pole figures of the ferrite phase of the wire samples [15]. The intensity of the pole figures was corrected for defocusing and absorption with a standard powder sample of commercial-purity ferrite. As shown in Fig. 2, the micro-texture was determined by EBSD (Oxford Instrument, HKL, NordlysF detector) equipped in a field emission gun scanning electron microscope (FEG-SEM, FEI Nano Nova400) from the surface layer. The specimens for EBSD examination were grinded using silicon carbide papers from No. 120 to No. 800 and polished with 9 and 3 μm of water-based diamond suspensions on napless clothes and followed by vibratory polishing (0.06 μm colloidal silica suspension for about 1.5 h). The orientation imaging microscopy analysis was performed with the HKL Channel 5. TEM observations were performed on a ZEISS LIBRA 200 FETEM at 200 kV (see details about sample preparation in Ref. [14]). Additionally, the microhardness (Vickers) was determined with a load of 200 g with the holding time of 10 s.

3 Results and Discussion

3.1 Macro-Texture over the Entire Wire Cross Section

Figure 3 shows the XRD inverse pole figures (IPFs) of the original wire and the torsional wires. As shown in Fig. 3a, the original wire has a strong $\langle 110 \rangle$ fiber texture with $\langle 110 \rangle$ direction of the ferrite matrix paralleling to the wire axis (w). From Fig. 3b–e, it is clearly observed that the wires still have the characteristics of the $\langle 110 \rangle$ fiber texture after the torsion deformation with different number of revolutions. Through the comparative analysis of the IPFs, it can be found out that the wire 3 has the strongest $\langle 110 \rangle$ fiber texture (see Fig. 3c) and the wire 20 has the weakest one. It indicates that the $\langle 110 \rangle$ fiber texture is enhanced at the beginning of torsion and then gradually reduced with increasing number of the torsion revolutions.

As shown in Fig. 4, orientation density analyses of the wire samples based on XRD are also conducted here for quantitative analysis of the macro-texture. As shown in Fig. 4a, in contrast to the roll texture of the ferrite/pearlite steels (usually have one or two strong peaks [19]), the drawing wires have a somewhat uniformly shaped α -fiber

Table 1 Information of the torsion deformed wire samples

Sample	Drawing strain	Preset revolutions	Actual revolutions	Shear strain γ^a	Equivalent strain ε_{VM}^a
Wire 1	1.31	1	0.8	0.05	0.03
Wire 3	1.31	3	2.5	0.15	0.08
Wire 9	1.31	9	7.5	0.44	0.25
Wire 20	1.31	20	17.5	1.02	0.60

^a γ and ε_{VM} are calculated at the surface layer of the wire samples, see details of the calculation process in Ref. [14]

Fig. 1 Torsion deformation of cold drawing pearlitic wires **a** and strain curves of wires after torsion **b**. The figures were recreated based on Ref. [14]

Fig. 2 Schematic representations of the specimens for the macro-texture testing (XRD) and micro-texture testing analyses. θ means shear direction. T means transaction of the specimen

which is defined by the Euler angles ($\phi_1 = 0^\circ$, $0 \leq \Phi \leq 90^\circ$, $\phi_2 = 45^\circ$). There are strong orientations between $\{001\}\langle 110 \rangle$ and $\{112\}\langle 110 \rangle$, but from overall perspective, the contents of the main α -fiber components $\{001\}\langle 110 \rangle$, $\{112\}\langle 110 \rangle$, and $\{111\}\langle 110 \rangle$ are similar. From Fig. 4a, it can be seen that the wire 1 and wire 3 have same $\{001\}\langle 110 \rangle$ contents, but the $\{112\}\langle 110 \rangle$ and $\{111\}\langle 110 \rangle$ components of both wire 1 and wire 3 are stronger than that of the original wire. The $\{001\}\langle 110 \rangle$, $\{112\}\langle 110 \rangle$, and $\{111\}\langle 110 \rangle$ components of the wire 9 and wire 20 are much weaker than that of other samples.

The γ -fiber ($60 \leq \phi_1 \leq 90^\circ$, $\Phi = 55^\circ$, $\phi_2 = 45^\circ$) also clearly shows that the wire 3 has the strongest $\{111\}\langle 110 \rangle$ components among all the samples (see Fig. 4b). It indicates that with increasing number of torsion revolutions, the $\langle 110 \rangle$ fiber texture of the wires increases firstly at low strain state and then decreases at high strain state.

It is well known that $\langle 110 \rangle$ parallel to the drawing direction is the hardest orientation in body-centered cubic (bcc) metals and the $\langle 110 \rangle$ fiber texture becomes prevailing under tensile or drawing strain. The development of the $\langle 110 \rangle$ fiber texture of the pearlitic steel is directly related to the plane strain of drawing deformation [2, 17, 20, 21]. Obviously, the introduction of shear strain provided by torsion changes the original strain path, which will influence the content of the $\langle 110 \rangle$ fiber texture. However, the torsion deformation is not a simple reduction in the fiber texture. It is because that the shear strain also can rotate hard alignment cementite and release stress concentrations which are considered as resistances of the growth of the fiber texture during cold drawing process [18]. The change of the cementite alignment and the stress release may cause some ferrite lamellae rotate to the $\langle 110 \rangle$ direction at low strain state and enhance the fiber texture. Therefore, the wire 3 has the strongest $\langle 110 \rangle$ fiber texture (see Figs. 3c, 4). With increasing number of torsion revolutions, the shear strain begins to cause the ferrite matrix slip along the shear direction, which reduces the content of the $\langle 110 \rangle$ fiber texture (see Fig. 3d, e).

Fig. 3 IPFs (in wire axis direction, w) determined by XRD showing macro-textures of the pre-torsion deformed wires: **a** original wire; **b** wire 1; **c** wire 3; **d** wire 9; **e** wire 20

Fig. 4 Orientation density analyses of the pre-torsion deformed wires based on XRD: **a** along α -fiber; **b** along γ -fiber

3.2 Micro-Texture near the Wire Surface

Although the wires still have the characteristics of the $\langle 110 \rangle$ fiber macro-texture after torsion deformation with different number of revolutions, due to the existence of strain gradient in the torsion deformed wires, the micro-texture of the drawn wires was characterized emphatically from the near surface layer (see the EBSD locations in Fig. 2). The micro-texture on the surface of the wire specimens was characterized by EBSD. Inverse pole figure coloring with the wire axis direction is conducted here for displaying the evolution of the $\langle 110 \rangle$ fiber texture with increasing of torsion strain.

Figure 5 displays EBSD maps and IPFs of the wire samples at different shear strain levels between 0.05 and

1.02. It can be seen that the ferrite grains are elongated and oriented at a certain angle to the shear direction (θ). As shown in Fig. 5a, the ferrite grains (f) within the wire 1 are mainly paralleling to the wire axis (w), and the $\langle 110 \rangle$ fiber texture is very strong. From Fig. 5a–d, it can be seen that the ferrite matrix is gradually rotating to θ with increasing number of torsion revolutions. Meanwhile, the $\langle 110 \rangle$ fiber texture is gradually reduced. The wire 20 sample even has a random texture (see Fig. 5d), which indicates that the $\langle 110 \rangle$ fiber texture formed by drawing is gradually reduced by the shear strain. Statistical analysis of the micro-texture shows that both the main α -fiber components $\{001\}\langle 110 \rangle$, $\{112\}\langle 110 \rangle$, and $\{111\}\langle 110 \rangle$ and the γ -fiber $\{111\}\langle 110 \rangle$ decrease linearly with increasing of torsion strain.

Fig. 5 EBSD IPF coloring maps and IPFs of the pre-torsion deformed wires: **a** wire 1; **b** wire 3; **c** wire 9; **d** wire 20

Table 2 Ideal shear textures in bcc system [23, 24]

Shear components	Miller indices
D	$\{1\bar{2}0\}\langle 111 \rangle$
E	$\{1\bar{1}0\}\langle 111 \rangle$
F	$\{110\}\langle 001 \rangle$

It has been reported that the heterogeneous deformation occurs during torsion of the drawn wires, in which the macro-deformation is realized both by the rigid body rotation and the plastic deformation in the elongated grains, which leads to the special texture evolution in the torsional drawn wires [22]. The stable $\{110\}\langle 110 \rangle$ and $\{110\}\langle 112 \rangle$

texture components have been observed during the torsion process in the drawn-annealing-torsion ferrite wires and pearlite wires [22]. Thus, for torsion deformation, shear texture should be discussed. Shear texture is represented by specifying the plane parallel to the shear plane $\{hkl\}$ and the shear direction $\langle uvw \rangle$ [23]. The shear plane is normal to the torsion axis, and the shear direction is the tangential direction to the shear plane. The Miller indices of the ideal shear textures in bcc system are shown in Table 2 [23, 24]. Figure 6a displays the locations of the ideal shear texture components in the $\{001\}$ pole figure. It can be seen that no typical shear textures are observed with increasing of torsion strain (Fig. 6b–d.). Figure 7 displays the shear texture components by the EBSD reconstruction micrographs. As shown in Fig. 7a, there are a few of D texture and E texture

Fig. 6 {001} pole figures showing the important shear textures: **a** location of the ideal shear components; **b** wire 1; **c** wire 3; **d** wire 9; **e** wire 20

Fig. 7 EBSD micrographs showing the evolution of the shear texture components with increasing of torsion strain: **a** wire 1; **b** wire 3; **c** wire 9; **d** wire 20

Fig. 8 TEM bright field micrographs observed from the longitudinal section showing microstructures at the surface layer: **a** wire 1; **b** wire 20

within the wire 1 sample and almost no F component to be observed. Both the E and F textures decrease with increasing of torsion strain. The F component is only observed significantly in the wire 20 sample (see Fig. 7d). Although the wire 20 sample has a random texture and no typical shear textures are observed in macroscopic view (as shown in Fig. 6d), it can be speculated that the torsional wire may display the D shear texture feature if it continues to suffer torsional strain.

The micro-texture of $\langle 110 \rangle$ fiber near the wire surface decreases linearly with increasing of torsion strain, while the macro-texture of $\langle 110 \rangle$ fiber over the entire wire cross section increases firstly and then decreases with increasing of torsion strain. Such differences can be explained in terms of the macroscopic gradients in shear of the torsion deformation. There is a linear strain gradient from the wire axis to the wire surface. The shear strain in the surface layer is much higher than that of in the center layer. As discussed above, low torsional shear strain can cause some ferrite lamellae to rotate to the $\langle 110 \rangle$ direction and enhance the fiber texture through rotating the hard alignment cementite and releasing the stress concentration; high shear strain breaks the plane strain state of drawing and cause the ferrite matrix slip along the shear direction, which reduces the content of the $\langle 110 \rangle$ fiber texture. For the micro-texture determined on the wire surface, the shear strains are relatively high in the wire 1 and wire 3 samples and cause the ferrite matrix slip along the shear direction directly. Therefore, the $\langle 110 \rangle$ micro-texture in the surface layer decreases linearly with increasing of torsion strain.

3.3 Relationships Between Texture and Microhardness

As the previous discussion, the $\langle 110 \rangle$ fiber texture is gradually reduced with increasing number of torsion revolutions. However, hardening behavior during the

microhardness test is clearly observed in the torsional wires. The microhardnesses in the surface layer of the torsion deformed wires with increasing number of revolutions are as follows: original (472 ± 9) HV, wire 1 (476 ± 15) HV, wire 3 (491 ± 9) HV, wire 9 (503 ± 10) HV and wire 20 (515 ± 11) HV. The error bars represent the standard deviation of the hardness data (each microhardness value was the mean of 10 indentations which were placed along the wire axis direction). It indicates that the microhardness of the drawn wires is not affected by the reduction in the fiber texture content. An explanation to such hardening phenomena is that the microhardness of the drawn pearlitic wires mainly depended on the pearlite interlamellar spacing and the dislocation density [4]. For the torsional deformed wires, they have same pearlite interlamellar spacing (equal to that of the original wire, 70 nm), and the main difference is that they have different dislocation densities. Figure 8 illustrates typical TEM bright field micrographs observed from the surface layers of the wire 1 and wire 20 samples. Obviously, more tangled dislocations are observed in the wire 20 sample. It indicates that the dislocation density increases with increasing number of torsion revolutions. It is well known that with the dislocation density increasing the phenomenon of pile-up occurs more easier, which results in the increase of microhardness or strength [4, 25]. The microhardness on the center layer shows a different evolving process, which has been discussed in Ref. [14].

Additionally, it has been demonstrated that the drawing limit is closely related to the critical drawing strain of delamination generation, and the delamination is caused by the $\{110\}\langle 110 \rangle$ texture formed during drawing [26]. Reducing the texture development is considered as one method of deeply drawing for producing fine wires. Therefore, we consider that introducing torsion deformation into the traditional drawing processes may be another

effective method to reduce the texture development and improve the drawing limit.

4 Conclusions

- (1) The correlation between macro-texture intensity development and torsion strains is nonlinear. The $\langle 110 \rangle$ fiber texture is enhanced at the beginning of the torsion and then gradually reduced with increasing of torsion strain.
- (2) The correlation between micro-texture intensity development and torsion strains is linear. The $\langle 110 \rangle$ fiber texture decreases linearly with increasing of torsion strain. However, the microhardness of the drawing wires is not affected by the reduction in the fiber texture content.
- (3) Introducing torsion deformation into the traditional drawing processes may be an effective method to reduce the texture development and improve the drawing limit.

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