Materials Science and Engineering A 547 (2012) 51–54

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Revealing microstructural and mechanical characteristics of cold-drawn pearlitic steel wires undergoing simulated galvanization treatment

Feng Fang[a,*], Xian-jun Hu[a,b], Shao-hui Chen[b], Zong-han Xie[c], Jian-qing Jiang[a]

[a] School of Materials Science and Engineering, Southeast University, Nanjing 211189, China
[b] Jiangsu Sha-Steel Group, Zhangjiagang City, Jiangsu Province 215625, China
[c] School of Engineering, Edith Cowen University, Joondalup, WA 6027, Australia

ARTICLE INFO

Article history:
Received 1 June 2011
Received in revised form 1 February 2012
Accepted 10 March 2012
Available online 29 March 2012

Keywords:
Pearlitic steel wire
Cold-drawing
Annealing
Cementite
Spheroidization

ABSTRACT

Spheroidization of lamellar cementite often occurs in cold-drawn pearlitic steel wires during galvanizing treatment, leading to the degradation of mechanical properties. Therefore, it is important to understand effects of galvanization process on microstructure and mechanical properties of cold-drawn wires. In this paper, cold-drawn steel wires were fabricated by cold drawing pearlitic steel rods from 13 mm to 6.9 mm in diameter. Thermal annealing at 450 °C was used to simulate galvanizing treatment of steel wires. Tensile strength, elongation and torsion laps of steel rods and wires with, and without, annealing treatment were determined. Microstructure was observed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). In addition, differential scanning calorimetry (DSC) was used to probe the spheroidization temperature of cementite. Experimental results showed that tensile strength of wires increased from 1780 MPa to 1940 MPa for annealing <5 min, and then decreased. Tensile strength became constant for annealing >10 min. Elongation of wires decreased for annealing <2.5 min, and then recovered slightly. It approached a constant value for annealing >5 min. Tensile strength and elongation of wires were both influenced by the strain age hardening and static recovery processes. Notably, torsion laps of wires hardly changed when annealing time was less than 2.5 min, and then decreased rapidly. Its value became constant when the hold time is greater than 10 min. Lamellar cementite began to spheroidize at annealing >2.5 min, starting at the boundary of pearlitic grains, and moving inward. A broad exothermic peak was found at temperatures between 380 °C and 480 °C, resulting primarily from the spheroidization of lamellar cementite, which is responsible for the degradation of torsion property of cold-drawn wires.

1. Introduction

Cold drawing process can significantly enhance the tensile strength of steel. Through it, high strength steel wires are manufactured and used in the construction of suspension bridges [1,2]. To combat corrosion damage during service, hot dip galvanizing at about 450 °C is typically applied in the manufacturing of wires. As expected, the microstructure and mechanical properties of steel wires change considerably during the galvanizing process [3,4]. Therefore, to develop high strength steel wires with excellent corrosion resistance, it is necessary to understand the effect of the hot dip galvanizing process upon the microstructure and mechanical characteristics of steel wires.

Partial dissolution of cementite has recently been identified in heavily deformed pearlitic steels [4–9]. Various mechanisms that control cementite dissolution have been proposed, such as cementite decomposition due to the increase of its interfacial free energy [4] and segregation of carbon atoms around dislocations [5–7]. Notably, all these processes involve movement of the carbon atoms through the interface between ferrite and cementite. Therefore, the decomposition of lamellar cementite might resume during the galvanization process, in which lamellar cementite may also spheroidize to minimize surface energy [3]. Consequently, the mechanical properties are affected.

Thermal annealing is often used to explore the effect of galvanizing treatment on the microstructure and mechanical properties of cold-drawn steel wires [10–14]. For example, the shape of cementite in cold drawn pearlite wires was studied at different annealing temperatures, and strain age mechanism was revealed [10]. Lee et al. [11] studied the effect of annealing temperatures and hold time on the delamination of wires during torsion tests. Languillaume et al. [12,13] investigated the effect of annealing temperature on the microstructure and strength of wires. Effects of annealing treatment on the spheroidization behavior of cementite in medium carbon steels following continuous shear drawing was also addressed [14]. A fundamental understanding of the relationship

* Corresponding author at: School of Materials Science and Engineering, Southeast University, JiangNing District, Nanjing, China. Tel.: +86 25 52090630; fax: +86 25 52090634.
E-mail address: fangfeng@seu.edu.cn (F. Fang).

0921-5093/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.msea.2012.03.075

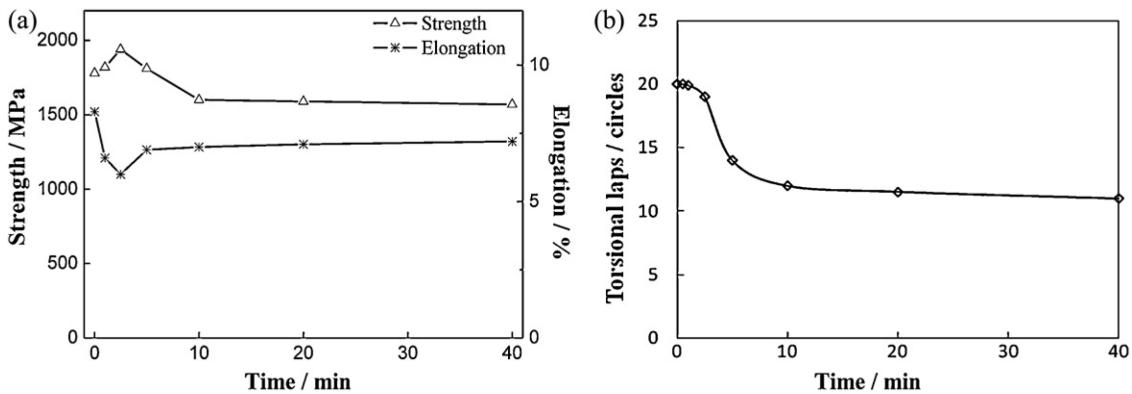

Fig. 1. Mechanical properties of cold drawn pearlitic steel wire after being held for different time at 450 °C: (a) tensile strength and elongation; (b) torsional laps.

between the microstructure and mechanical properties (especially torsional property, an important design parameter for steel wires used in the construction of suspension bridges) during the hot dip galvanizing treatment is still lacking.

In the present work, effects of annealing time at 450 °C on mechanical properties and microstructure of cold-drawn pearlitic steel wires were investigated. In particular, a direct link between torsional property and the spheroidization of lamellar cementite was established.

2. Experimental procedure

Pearlitic steel used in this work were supplied by Sha-steel Group Company in the form of Stelmor-cooled rods. Their chemical compositions are shown in Table 1. After pickling and phosphating [15], hot-rolled rods (13 mm in diameter) were successively drawn to a diameter of 6.9 mm with a total reduction of 72% (ε = 1.27). The average reduction per pass was about 14%.

The annealing treatment of the cold drawn steel wires was used to simulate the galvanizing process. It was carried out in nitrogen atmosphere at about 450 °C at different hold times of 30 s, 1 min, 2.5 min, 5 min, 10 min, 20 min and 40 min.

Tensile strength of wires was determined by tensile tests at room temperature using a CMT5105 type universal testing machine, operating at a constant speed of 2 mm/min. The elongation of wires was measured during tensile tests by an extensometer attached to the testing machine. The tensile tests were performed according to the Chinese national standard GB/T228-2002. The torsion laps of wire samples (sample's length is about 100 times its' diameter) were measured at a rate of one lap per minute by using CTT500 type torsion testing machine. The torsion tests were conducted in accordance with the Chinese national standard GB/T10128-1998. Microstructure of wires was characterized using a scanning electron microscope (SEM, FEI Siron-400) and transmission electron microscope (TEM, JEM 2000EX).

Thermal analysis was undertaken using STA449 F3 differential scanning calorimetry (DSC) (NETZSCH-Gerätebau GmbH, Germany) at heating rate 20 °C/min in a flowing Ar atmosphere [16]. Following the DSC analysis, the microstructure of samples was observed by SEM to correlate new microstructural features with the endothermic or exothermic peaks.

Table 1
Chemical composition of steel wires used in this work.

C	Mn	Si	Cr	V	S	P
0.82	0.76	0.23	0.26	0.04	0.005	0.010

3. Results and discussion

3.1. Mechanical properties

The change of tensile strength with the annealing hold time, presented in Fig. 1a, can be described according to the slope of the curve. Initially, the tensile strength of wires increases from 1780 MPa to 1940 MPa with increasing hold time and reaches maximum strength when the hold time is 2.5 min, while the elongation decreases from 8% to 6%. Such age hardening behavior may result from the diffusion and dislocation pinning of dissolved carbon atoms in lamellar ferrite [17]. With increasing hold time, the tensile strength of the wires decreases, then it reaches a plateau (about 1600 MPa) for hold time >10 min, while the elongation of wires increases, then it plateaus (about 7%) for hold time >5 min. Such age softening behavior occurs, presumably due to the spheroidization of lamellar cementite and the occurrence of recovery of ferrite, and it would be examined in the following section.

Fig. 1b shows the relationship between torsion lap of steel wires and annealing hold time at 450 °C. The torsion lap of steel wires is found to changes very little for hold time <2.5 min. As the hold time increases, it decreases rapidly from about 19 to 12 circles and levels off at about 11circles when the hold time exceeds 10 min.

3.2. Evolution of microstructure

Fig. 2 shows the microstructures obtained from the longitudinal section of pearlite steel rods, cold drawn wires, cold-drawn wires annealed at 450 °C for 2.5 min and for 10 min, respectively. As shown in Fig. 2a, the pearlitic steel rod has a two-phased, lamellar structure composed of alternating layers of (bright) ferrite and (dark) cementite layers with the interlamellar spacing about 100 nm; cementite forms a straight interface with ferrite, in which dislocation density is low. Fig. 2b shows the deformed microstructures of as-drawn wires. The interlamellar spacing of pearlite is reduced to about 25–30 nm, apparently due to the drawing process. One can also note the very high density of extinction contours inside the ferrite lamellae, indicative of the high level of dislocation density. Short hold time (under 1 min) at 450 °C does not result in any observable change in the microstructure of cold drawn wires (not shown here). However, when the annealing time increases to 2.5 min, marked changes in the microstructure of wires occur. While a majority of the deformed lamellar cementite still maintains its straight shape, those near the boundary of pearlitic grains starts to spheroidize, as shown in Fig. 2c. At the same time, extinction contours inside the ferrite lamellae are found to fade out, which means the recovery of ferrite happened [11,12]. The spheroidization of lamellar cementite is easily observed inside pearlite grains in Fig. 2d, indicating that a large amount of lamellar