Developing Very Fine Nanopearlitic Structure in a High Carbon Steel Wire before Drawing

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Abstract

The effects of steel wire patenting process parameters on very fine interlamellar spacing in the pearlitic steel wire were investigated and the optimized condition of the process was achieved. In this work, the initial nanopearlitic structure was obtained in a 0.72 wt% carbon steel wire before the wire drawing process. The results were the minimum interlamellar spacing of 35 nm and maximum ultimate strength of 1960 MPa for austenitizing at 910 ˚C and isothermally transforming to pearlite at 510 ˚C.

Keywords: Nanopearlitic structure, High carbon steel wire, Interlamellar spacing, Austenitizing.

1. Introduction

High carbon steel wires with a pearlitic structure are used extensively in related industries particularly in tire cord applications. It is well known that pearlitic structure is formed via a heat treatment process which is called patenting, a term attributed to the original British patent of James Horsfall[1]. Patenting is normally conducted as a continuous process and typically includes the steps of heating the alloy to a temperature within the range of 900˚C to 1150˚C and subsequently cooling down at a rapid rate to a lower temperature within the range of 720˚C to 450˚C[2]. The former step is applied to form austenite and the latter changes the crystal structure of austenite to pearlite.

The mechanical behavior of pearlitic steels is controlled largely by the microstructure developed during patenting and wire drawing. The important microstructural feature, which is most readily measured is interlamellar spacing (S). A Hall-Petch type relationship offered by Embury and Fisher[3] proposes an estimation of the strength of eutectoid steel wires as a function of interlamellar spacing and wire drawing strain:

$$\sigma = \sigma_0 + [k/ (2S_0)^{0.5}] \exp (\varepsilon/4) \quad (1)$$

where σ_0 is the friction stress, k is the Hall-Petch parameter, S_0 is the initial interlamellar spacing and ε is the true drawing strain. According to equation (1), the strength of pearlitic steels increases with the increase of drawing strain and Hall-Petch parameter and the decrease of initial interlamellar spacing. Many works have been focused on the investigation of these parameters[4-8].

Nam et al.[7] indicated that the increase of carbon content in pearlitic steels increases Hall-Petch parameter whereas Pourladian research[9] demonstrated that increasing carbon content and drawing strain reduce the fracture toughness of steel. Also Yang et al.[8] indicated as carbon content and drawing strain increase, the fatigue resistance and torsional ductility of the steel wires will be decreased. Nonetheless, a reduction in the initial interlamellar spacing can lead to increase in strength and toughness simultaneously. Therefore a structure with minimum initial interlamellar spacing would be very useful.

Although in several works on high carbon steels, the strength has been related to the interlamellar spacing after heavy cold drawing using an equation of Hall-Petch type, such a relationship has not been explicitly obtained to understanding the relationship between the initial microstructure and mechanical properties especially in fine scale microstructures. In addition, a few investigations have done for obtaining nanopearlitic structures without severe plastic deformation. Fine pearlitic structure is a suitable initial microstructure prior to drawing high carbon steel wires. Refining the initial interlamellar spacing increases the tensile strength and hardening rate during wire drawing. To achieve the minimum initial interlamellar spacing, the patenting condition must be optimized. The interlamellar spacing is a sensitive parameter which increases as transformation temperature increases. Mehl et al.[10] demonstrated that the interlamellar spacing decreased as the degree of undercooling, ΔT, below the eutectoid temperature increased. First time Zener[11] in a theoretical analysis calculated the interlamellar spacing of pearlite as a function of undercooling.

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The aim of this study is to refine the initial interlamellar spacing and to investigate the effect of interlamellar spacing on the mechanical properties of 0.72% C hypo-eutectoid steel. In this regard, the sensitivity of S_0 on patenting parameters has been investigated and as a result, a nanopearlitic structure with very fine interlamellar spacing is introduced.

2. Experimental procedure

A hypo-eutectoid steel wire with actual composition of 0.72%C, 0.24%Si, 0.47%Mn and 0.015%P (in wt%) was used. Specimens with 1.8 mm in diameter were annealed at different temperatures ranging from 910˚C to 990˚C for 5 min and subsequently were quenched for pearlitic transformation in a molten lead bath with different temperatures ranging from 510˚C to 570˚C.

The specimens were ground and polished in the usual way. To reveal the microstructure of heat treated wires by scanning electron microscope (SEM) and atomic force microscope (AFM), Nital 2% etching solution was used.

In order to measure the interlamellar spacing, the image analysis system of AFM was used. In this method which has been proposed by Buono et al.[12)], after selecting an image of pearlite colony, a test line running perpendicularly to the alternating lamella was applied over the image. Then image analysis system provided a topographic profile of microstructure along the test line. According to this profile, the average distance between the center of adjacent cementite or ferrite lamellae or a group of any number of lamellae was measured.

Mechanical properties were measured through tensile test. Tensile tests were carried out using an Instron Universal Testing Machin with special jaws to prevent stress concentration and early wire breakage adjacent to the jaws.

3. Results and Discussion
3.1. Microstructure

After austenitizing and subsequent quenching in the molten lead bath, the structure of wire was transformed to the pearlite. A typical pearlitic structure of specimens is shown in Figure 1.

The effect of undercooling on the lamellar spacing of pearlite is shown in Figure 2 in comparison with reported data from the literature. As can be seen, interlamellar spacing values are decreased when the transformation temperature is decreased. This is attributed to increase in ΔT and available driving force for the transformation. Also with decreasing temperature, the slower diffusivity reduces the diffusion depth and consequently reduces the pearlite lamellar spacing which has also been pointed in previous works[16)].

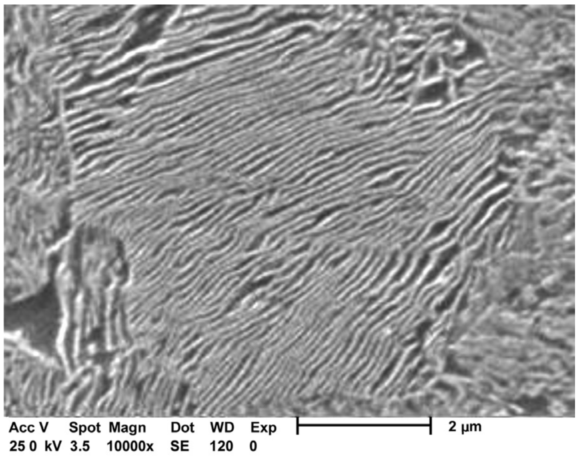

Fig. 1. SEM image of pearlitic microstructure in the patented steel wire with 0.72% C.

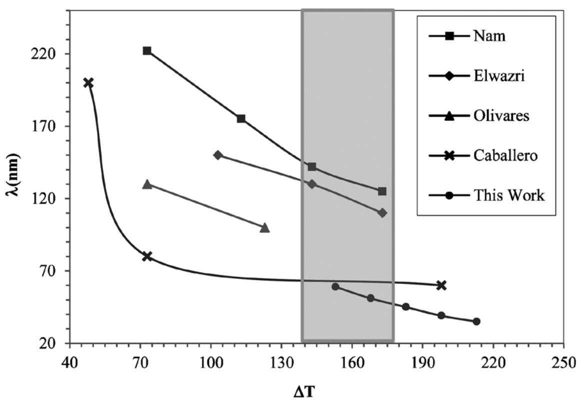

Fig. 2. Interlamellar spacing vs. undercooling in different studies.

Similar trends have been illustrated in the literature[6,7,13-15)] for high carbon steels, but typically these data show higher lamellar spacing than that of hypo-eutectoid steel studied here. The observed non-coincidences are due to the difference in degree of under cooling which is higher in this work. It is interesting to note that in some cases with same undercoolings, the lamellar spacing is lower than others likewise. It may be related to smaller initial austenite grain size or pearlitic colony size that is resulted from lower austenitizing temperature[17)]. Elwazri et al.[6)] indicated that interlamellar spacing was decreased with decrease in initial austenite grain size. This influence of austenite grain size on the pearlite lamellar spacing has been reasoned previously on the basis of total grain boundary area which decreases with increasing grain size on the account of a reduction in the sites for nucleation of ferrite and cementite phases[18)]. On the other hand, in this work the content of carbon was lower whereas according to the previous studies, the increase of carbon content can reduce the initial interlamellar spacing[7)].

As explained above, the lamellar spacing was decreased to a minimum distance of 35 nm with increasing ΔT due to austenitizing at 910 ˚C and subsequently isothermal transformation at 510 ˚C. The developed nanopearlitic structure is shown in Figure 3.

3.2. Strength

In prior studies, strengthening of pearlitic wires has been considered as the additive effect of more than one microstructural mechanism[5,19,20]. Strengthening from initial interlamellar spacing refinement is shown in Figure 4, approximately follows a relation of the Hall-Petch type in agreement with previous works[5,6] that they have generally focused on the lamellar spacing after wire drawing. According to Figure 4, compared to Elwazri et al.[6], the steel used in present work shows higher strength due to finer initial interlamellar spacing and smaller pearlite colony size. Previous studies[6] have indicated a strong dependency of strength on the interlamellar spacing and a possible, although small, dependency on the pearlite colony size.

As can be seen, hardening rate (the slope of line) is increased as the initial interlamellar spacing decreases. The value of 16.7 KNm^{-3} for hardening rate in this work is much higher than Elwazri et al.[6] investigation (8.6 KNm^{-3}). This result indicates that the refinement of initial interlamellar spacing increases strength and hardening rate significantly. Also fine initial interlamellar spacing can promote more homogeneous strain distribution during the subsequent wire drawing; hence, it can lead to an improvement in the ductility.

4. Conclusions

1. The sensitivity of initial interlamellar spacing to the austenitizing and pearlitic transformation temperatures in 0.72 wt% carbon steel were investigated and process parameters were optimized.

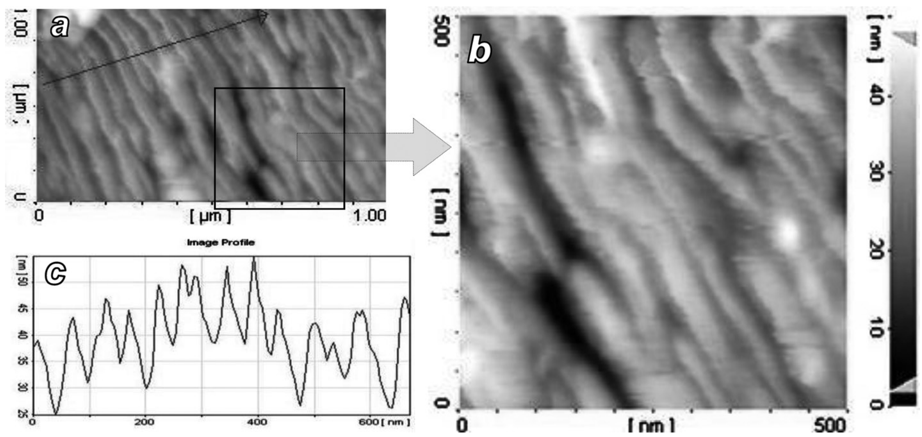

Fig. 3. (a) AFM image of developed nanopearlitic structure along with test line applied in perpendicular direction to the lamellae at a pearlite colony, (b) its higher magnification and (c) the topographic profile of pearlitic microstructure, corresponding to the region crossed by the test line.

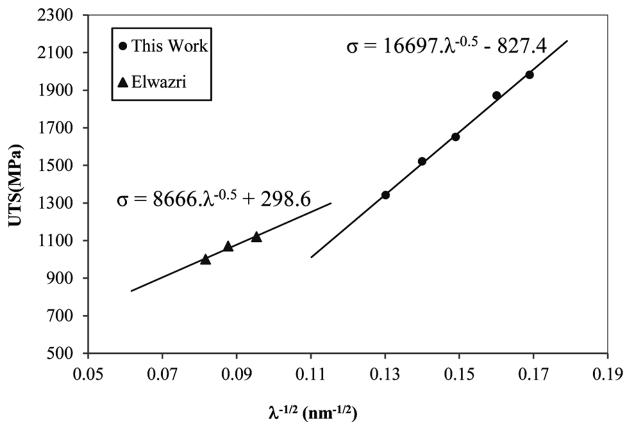

Fig. 4. Ultimate tensile strength vs. the inverse square root of the pearlite interlamellar spacing.

2. Initial interlamellar spacing was observed to decrease with decreasing austenitizing temperature and increasing the degree of under cooling below the eutectoid temperature due to smaller prior austenite grain size and, further driving force and minimum growth rate, respectively.
3. Using lower austenitizing temperature (910˚C) and low transformation temperature (510˚C) revealed simultaneously finest pearlitic structure with 35 nm interlamellar spacing.
4. The strength of pearlitic structure was observed to be linearly dependent on initial interlamellar spacing as a Hall-Petch type equation which was influenced by the interaction of strengthening methods such as the manipulation of transformation temperature, the minimizing initial austenite grain size and pearlite colony size.

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