Materials Science & Engineering A 632 (2015) 103–109

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Effect of initial microstructure on the work hardening behavior of plain eutectoid steel

H. Rastegari*, A. Kermanpur, A. Najafizadeh

Department of Materials Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran

ARTICLE INFO

Article history:
Received 29 November 2014
Received in revised form
14 February 2015
Accepted 16 February 2015
Available online 6 March 2015

Keywords:
Eutectoid steel
Work hardening behavior
Pearlite spheroidization

ABSTRACT

Work hardening capability and tensile properties of the plain eutectoid steel rods are the key factors in the wire drawing process to fabricate high strength wire rods with a minimum failure. In the present research, the work hardening behavior of eutectoid steel with different initial microstructures of bainite, duplex bainite+pearlite, pearlite, partially spheroidized and spheroidized pearlite was assessed in terms of instantaneous work hardening exponent (n value) and work hardening rate (θ) using room temperature tensile test. The results show an inverse parabolic behavior for variation of instantaneous n value versus true strain, i.e., work hardening exponent initially increases up to a maximum value and then decreases. The bainitic microstructure exhibits the lowest n value, whereas the spheroidized pearlitic one shows the highest. It is shown that the fine pearlitic microstructure containing partially spheroidized regions exhibited the best combination of tensile properties, n value and work hardening rate.

1. Introduction

Plain carbon eutectoid steel wire rods are extensively used for the production of pre-stressed concrete wires used in huge buildings, suspension bridges, large concrete pipes and railroad concrete ties [1–3]. The eutectoid steel wire rods can be industrially fabricated in the following manner. First, the billets undergo hot rolling with a finish temperature of 800–1050 °C. Cooling after hot rolling can be carried out continuously (by air-blasting) or isothermally (by lead or salt bath furnace) [4–6]. The best combination of tensile properties and cold wire drawability is achieved by lead patenting process [7–9]. However, due to some disadvantages such as low safety, environmental pollution, superficial impurities and high investment costs, its application has been limited. On the other hand, continuous cooling procedure (Stelmor method), increases the production rate and does not need extra investment [10–12]. The main objection to this method is non-uniform cooling due to overlapping of rod rings at both sides of the loops on the cooling bed [13,14]. According to the CCT diagram of the eutectoid steel, cooling rate in the range of 25–35 °C/s could make the finest pearlite microstructure [15].

In any cases, the main objective is to achieve the maximum increased strength during cold wire drawing process [16–20]. Hence, initial tensile properties and work hardening behavior of eutectoid steel rods during deformation are the key factors that determine the final mechanical properties. These factors depend on the types of microstructure. The microstructure with the highest work hardening ability and desired tensile properties (UTS_{min}: 1000 MPa, El_{min}: 12% and RA_{min}: 35% [3]) is preferred.

In recent years, numerous investigations have been conducted on the work hardening capability of different alloys [21–23]. Work hardening is usually assessed in terms of either the work hardening rate ($d\sigma/d\varepsilon$) or the strain hardening exponent (n value) experimentally obtained from the true stress–strain (σ–ε) curve of room temperature tensile test. The higher n value is often related to the higher level of strengthening, to retard the localization of deformation and to enhance the uniform elongation under complex stress conditions [24–26]. Therefore, the main issue for developing high performance structural steels is to obtain a higher work hardening exponent [26] according to Hollomon equation [27].

Although work hardening exponent is conventionally supposed to be a constant value, the experimental results indicated that it is changed during the plastic deformation. In earlier investigations, the variation of instantaneous n value versus plastic strain has been taken into account [26,28–30]. However, to the best of the author's knowledge, few works have been reported on the effects of microstructural features on the work hardening behavior of eutectoid steels. Gensamer et al. [31] have shown that the coarse pearlite and bainite microstructures had the minimum and maximum yield ratio,

* Corresponding author. Tel.: +98 9132860582; fax: +98 3133932121.
E-mail address: h.rastegari@ma.iut.ac.ir (H. Rastegari).

http://dx.doi.org/10.1016/j.msea.2015.02.040
0921-5093/

Table 1
Heat treatment conditions applied to the eutectoid steel specimens.

Specimen no.	T_{aus} (°C)	Cooling rate (°C/s)
1	950	Isothermal at 480 °C
2	950	Isothermal at 520 °C
3	950	Isothermal at 560 °C
4	850	7
5	850	26
6	950	7
7	950	26

respectively, which in turn can be reflected by the amount of strain hardening during straining. In the present work, the effects of different initial microstructures including bainite, duplex bainite+pearlite, pearlite with different interlamellar spacing and colony size, partially spheroidized and spheroidized cementite on the work hardening behavior of eutectoid steel were investigated.

2. Materials and experimental procedures

The material used was a commercial eutectoid steel rod with a diameter of 12 mm and the chemical composition (by wt%) of 0.82 C, 0.21 Si, 0.68 Mn, 0.01 P, 0.009 S and 0.003 N (SWRH82B grade – JIS G3506 standard). In order to generate different initial microstructures, samples with 70 mm length were austenitized at 850 and 950 °C followed by isothermal and continuous cooling. Isothermal transformations were carried out in a salt bath furnace for 5 min. Continuous cooling was obtained in the laboratory using a constant velocity blower. Table 1 lists all the temperatures and cooling rates used for the isothermal and continuous decomposition of austenite. It should be noted that the recalescence effect was not taken into account in isothermal experiments.

Microstructures were characterized using optical microscopy and scanning electron microscopy. Picral reagent was used as an etchant. As a standard method, the fineness of a lamellar structure is measured by the true interlamellar spacing, λ_0, defined as the perpendicular distance across two consecutive lamellae [32]. The effects of different microstructures on the work hardening behavior of eutectoid steel rods were analyzed using room temperature tensile tests (computer controlled servo-hydraulic facility-Instron model 8502) at a crosshead rate of 1 mm/min using round specimens of 5 mm in diameter and 25 mm in gage length according to the ASTM-E8 standard [33].

The work hardening rate and exponent values were calculated from the yield to the ultimate tensile strength. The experimental true stress–true strain curves were fitted with Eq. (1), which is the logarithmic form of Hollomon equation ($\sigma = k\varepsilon^n$):

$$\ln \sigma = \ln k + n \ln \varepsilon \tag{1}$$

where k is the strength index. The instantaneous n value and work hardening rate were obtained from experimental curves by the following equation:

$$n|_i = \left.\frac{d \ln \sigma}{d \ln \varepsilon}\right|_i = \left.\frac{\varepsilon\, d\sigma}{\sigma\, d\varepsilon}\right|_i = \frac{\varepsilon_i\,(\sigma|_{i+1} - \sigma|_{i-1})}{\sigma_i\,(\varepsilon|_{i+1} - \varepsilon|_{i-1})} \tag{2}$$

$$\theta|_i = \left.\frac{d\sigma}{d\varepsilon}\right|_i = \frac{\varepsilon_i}{\sigma_i} n_i \tag{3}$$

As can be seen, the differentiation of the true stress–true strain curve is needed in this technique, but the short-range noises may cause such differentiation calculus infeasible. In order to solve this problem, the curves were smoothed by fitting a high-order polynomial (method: LOESS [non-parametric regression]; sampling proportion: 0.1) to remove the irregularities and fluctuations in the experimental curves.

3. Results and discussion

3.1. Microstructures

Fig. 1 shows different microstructures of the eutectoid steel specimens obtained by isothermal and continuous heat treatments. In order to measure the austenite grain size, two specimens were quenched in water from the temperatures of 850 and 950 °C. The results exhibited a smaller austenite grain size of about 18.2 ± 2.1 µm for austeniting at 850 °C, whereas a larger grain size of about 53.6 ± 5.0 µm for austeniting at 950 °C. Austenitization at 950 °C followed by quenching in salt bath furnace with temperatures of 480, 520 and 560 °C resulted in the formation of "bainite" (Fig. 1a), "duplex bainite+pearlite" (Fig. 1b) and "very fine fully pearlitic" microstructures (Fig. 1c). Based on the TTT diagram of the eutectoid steel, temperatures of 480 and 520 °C are lower than that at the nose of the curve (about 530 °C). Thus, it is expected to achieve a fully bainitic microstructure in both conditions. However, a fraction of pearlite (about 38%) was formed at 520 °C at prior austenite grain boundary resulting in a duplex bainitic–pearlitic microstructure (Fig. 1b). Isothermal transformation of austenite at 560 °C resulted in the development of a fully pearlitic microstructure with an interlamellar spacing of about 130 nm and average colony size of 7.3 µm (Fig. 1c). It is clear that interlamellar spacing of pearlite depends on the temperature at which it grows. Indeed, smaller interlamellar spacing can be established as the temperature of transformation is decreased (near the nose temperature) with the result that the degree of undercooling increases with decreasing temperature [31].

Continuous cooling from 950 °C at the rate of 26 °C/s led to precipitation of small amount of proeutectoid ferrite along the prior austenite grain boundaries plus fine pearlite microstructure with an interlamellar spacing of about 165 nm and average colony size of 5.6 µm ("fine pearlite+proeutectoid ferrite": Fig. 1d). Development of proeutectoid ferrite occurs because proeutectoid Fe_3C particles precipitate selectively in the grain boundaries depleting the surrounding regions of carbon. Thus, pearlitic cementite is suppressed and ferrite films are permitted to form [34]. It has been reported that in the fine pearlitic microstructure, thin cementite plates show a noticeable plastic behavior [35]; but, due to nucleation of voids on the ferrite–pearlite interface, pearlite plus proeutectoid ferrite structure provides a weaker cold drawability than the fully pearlitic structure [36]. The initial microstructure of eutectoid rods in as-rolled condition mainly consisted of "relatively coarse pearlite" with an interlamellar spacing of about 290 nm and colony size of about 7.1 µm (Fig. 1e). After austenitizing at 950 °C and slow cooling (7 °C/s), a "coarse pearlite" microstructure was produced with an interlamellar spacing of about 308 nm and colony size of about 16.3 µm (Fig. 1f).

Continuous cooling from 850 °C followed by 26 °C/s, resulting in a "partially spheroidized" microstructure with an interlamellar spacing of about 215 nm and colony size of about 12.4 µm was obtained (Fig. 1g). Finally, "spheroidized microstructure" with average grain size of 310 nm was obtained by short time static annealing at 850 °C and continuous cooling at the rate of 7 °C/s. Occurrence of spheroidization process during slow cooling can be attributed to the small grain size and high grain boundary area resulting in the formation of a very fine pearlitic microstructure just after transformation. It is reported by Caruso et al. [37] that spheroidization is faster in fine pearlite than in coarse pearlite. Hence, the structure is highly susceptible to being globular and is converted to the spheroidized microstructure during next slow cooling [37,38]. It is worth mentioning that the spheroidization is a completely diffusion controlled process; so, the fragmentation of