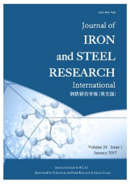
Journal of Iron and Steel Research, International 24 (2017) 67—76

ScienceDirect

Contents lists available at ScienceDirect

Journal of Iron and Steel Research, International

journal homepage: www.chinamet.cn



Dependence of tensile properties on microstructural features of bimodal-sized ferrite/cementite steels

Jiang-li Ning*, Yun-li Feng, Ming-ming Wang, Shen-bai Zheng, Jie Li

College of Metallurgy and Energy, North China University of Science and Technology, Tangshan 063009, Hebei, China

ARTICLE INFO

Key words:
Tensile property
Ferrite/cementite steel
Bimodal-sized structure
Warm rolling
Work hardening rate

ABSTRACT

A medium-carbon steel was processed through different warm rolling techniques, and the microstructural features with bimodal grain size distribution were found to be different. The combination of strength and ductility was ameliorated in the steel processed through warm rolling characterized by biaxial reduction. The enhanced strength is attributed to the densely distributed fine intragranular cementite particles and the small grain size in the coarse grain regions. The enhanced uniform elongation is due to the improved work hardening behavior at the large-strain stage. This work hardening behavior is predominantly ascribed to the finely dispersed intragranular particles. The relatively small grain size with nearly equiaxed shape in the coarse grain regions helps stabilize the uniform deformation to a large strain.

1. Introduction

Reducing the grain size of various materials to submicron- or nano-scale is effective in enhancing the strength of the materials; however, their ductility is usually reduced mainly because of the deterioration in work hardening capability[1-4]. Several strategies, including the introduction of bimodal or multimodal grain structures[5-10] and second-phase particles in the fine grain interiors[1-3,11-13], have been developed to improve the strength-ductility combination of various materials.

The combination of bimodal grain size distribution and nanoscale second-phase particles was recently demonstrated to be an effective method to enhance the balance between strength and ductility in ultrafine-grained (UFG) iron and steels[9,10,14-16]. Several thermomechanical approaches[14-16] have been used to obtain bimodal ferrite grain structures with heterogeneously distributed cementite particles in carbon steels, in which the particles are mainly concentrated in the regions of former martensite[14,15] or pearlite[16]. Bimodal grain structures are readily derived in steels through thermomechanical approaches based on the evolution of different phases[14-16]. Moreover, controlling the features of bimodal structures quantitatively is feasible by controlling the volume fraction, morphology, and distribution of different phases in the initial structures[15].

However, the relationship between mechanical behaviors and bimodal grain structures with heterogeneously distributed second-phase particles is not fully understood mainly because of complicated microstructural features. Conflicting results have been presented in several instances. For example, Azizi-Alizamini et al.[15] reported continuous yielding and a smooth stress-strain curve in tensile tests at room temperature, whereas Wang et al.[14] reported distinct yielding and nearly linear work hardening during tensile deformation. Both of these studies[14,15] conducted cold rolling and subsequent annealing on martensite-ferrite carbon steels and obtained bimodal ferrite structures with heterogeneously distributed carbide precipitates.

The dependence of mechanical properties on the microstructural features of bimodal materials needs to be systematically studied; these microstructural features include grain size difference, ratio between the volume fractions of ultrafine grains and coarse grains, spatial distribution of the different-sized grains (e. g., banded, agglomerated, or random), and aspect ratios of grains (e. g., elongated or equiaxed). In previous investigations[11-13], the homogeneous distribution of cementite particles in UFG fer-

---

* Corresponding author. Assoc. Prof., Ph.D.; Tel.: +86-18633311698.
E-mail address: *ts_njl@sina.com* (*J.L. Ning*).

Received 18 March 2016; Received in revised form 23 May 2016; Accepted 1 June 2016

rite matrices was proven to be effective in improving the work hardening rate, and consequently, the combination of strength and ductility. However, comprehensive research on how cementite particles that are heterogeneously distributed in the bimodal ferrite structure influence tensile properties, particularly the work hardening behavior, is lacking.

The present study provides insights into the relationship between tensile behaviors and various microstructural features in a medium-carbon steel characterized by bimodal ferrite grain structures and heterogeneously distributed cementite particles, which are prepared through different warm rolling (WR) techniques.

2. Experimental

Commercial medium-carbon steel with 0.42% carbon, 0.56% manganese, 0.25% silicon, 0.017% sulfur, and 0.016% phosphorus (in wt. %) was used. The initial microstructure of the as-received bars was ferrite-pearlite (F-P), which was used for WR and subsequent study.

The carbon steel was machined into cuboid-shaped samples with a size of 15 mm×15 mm×100 mm for WR. Two different techniques of WR were applied. The first technique, which is biaxial reduction WR (BA-WR) is illustrated in Fig. 1, led to the biaxial reduction of the sample. After each pass of rolling, the sample was rotated 90° around the longitudinal direction and was subjected to the next pass. The second technique, which is conventional WR (denoted by UA-WR), led to a uniaxial reduction of the sample. The sample was never rotated during this process. WR was conducted at 580 ℃. The samples were quenched in water, reheated to 580 ℃, and held for 30 min between the rolling passes. The reduction ratio for each pass was equivalent in both BA-WR and UA-WR; hence, the total equivalent strain was theoretically equivalent in the two techniques, as shown in Table 1.

The microstructure was characterized through an FEI Quanta FEG 650 field emission scanning electron microscope (SEM). The specimens were mechanically polished and etched with 3 vol. % nital solution. The cementite particle sizes were measured with the Image-Pro Plus 6.0 image analysis software. Characterizations were conducted on two cross sections, which were perpendicular to the transverse direction (TD) and rolling direction (RD) of each warm rolled sample, respectively. These cross sections are denoted as TD and RD sections, respectively.

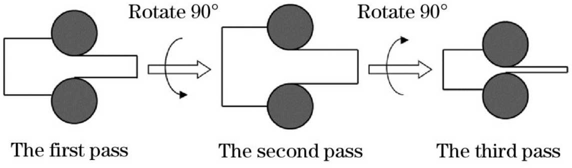


Fig. 1. Schematic of the BA-WR process.

Table 1

Reduction ratio and equivalent strain for each pass of the two warm rolling processes

Number of passes	1	2	3	4	Total
Reduction ratio	0.25	0.21	0.33	0.30	—
Equivalent strain	0.33	0.27	0.45	0.41	1.46

Note: The equivalent strain for each pass is calculated by $\varepsilon=\frac{2}{\sqrt{3}}\ln\left(\frac{t_0}{t}\right)$, where t_0 and t are the thickness before and after each pass of rolling, respectively.

Detailed microstructural characterization was conducted with electron backscattering diffraction (EBSD) technique. EBSD data were collected with the TSL OIM Data Collection software, and the step size for scanning was 0.2 μm. The samples were prepared through mechanical polishing followed by electropolishing. Low-angle boundaries (LABs) or subgrain boundaries were defined as boundaries with misorientation angles between 2° and 15°; high-angle boundaries (HABs) or grain boundaries were defined as boundaries with misorientation angles greater than 15°.

The mechanical properties were examined through uniaxial tensile tests using specimens with thickness of 2.2 mm, width of 6 mm, and gauge length of 32 mm. An Instron-type machine was used for the tests. An extensometer was mounted on each specimen to measure the exact displacement. The tests were performed at room temperature and at an initial strain rate of $5\times10^{-4}\ \mathrm{s}^{-1}$. The tests were repeated three times for each condition to substantiate the reproducibility of the tensile curves.

3. Results

3.1. Microstructural characterization

The steel exhibited distinct microstructural features after applying the different WR techniques. Fig. 2 shows the SEM micrographs of the TD sections of the two WR samples. The samples comprise two regions; one is characterized by colonies of fine subgrains with concentrated cementite particles, whereas the other is characterized by coarse grains that are nearly free of particles. The aspect ratios of the fine subgrain colonies and the coarse grains are very different. The BA-WR sample showed a nearly equiaxed shape (Fig. 2(a)), whereas the UA-WR sample showed a sharply elongated shape (Fig. 2(b)).

The distributions of the cementite particles in the fine subgrain regions of the two samples are shown in Fig. 2(c, d). The two samples exhibited significant differences. The distribution of the particles in the