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Relationship between microstructure and yield strength for plain carbon steel with ultrafine or fine (ferrite+cementite) structure

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ABSTRACT

Plain carbon steels with different ultrafine or fine-grained ferrite matrix (α)+cementite particle (θ) structures were formed through thermo-mechanical processes. Scanning electron microscopy was used to analyze the initial microstructural parameters, and the dislocation morphology was analyzed by transmission electron microscopy. A relationship between the microstructural parameters and yield strength was established for plain carbon steel with an ultrafine or fine ($\alpha+\theta$) structure. The results indicated that the yield strength of plain carbon steel with an ultrafine or fine ($\alpha+\theta$) structure had a direct relationship with the grain size of the ferrite matrix and the size, volume fraction and location of cementite particles, and the enhancement in yield strength caused by the cementite particles was improved with the increase in carbon content or the particle-refinement.

1. Introduction

The yield strength of single-phase ferritic steel can be significantly improved by grain refinement, but the capability of uniform plastic deformation of the steel is markedly deteriorated [1–3]. For example, the yield strength of IF steel is improved from approximately 150 MPa to approximately 500 MPa but its uniform elongation is decreased from approximately 25% to approximately 1% when its grain size is refined from 4.1 μm to 1.1 μm [2]. Furthermore, a number of studies have confirmed that the introduction of dispersed cementite particles into an ultrafine-grained ferrite matrix, i.e., obtaining plain carbon steel with an ultrafine ($\alpha+\theta$) structure, can considerably enhance the yield strength and the uniform plasticity relative to that of single-phase, ultrafine-grained ferritic steel [4–15]. Furthermore, Zhao et al. [9] showed that the yield strength of plain carbon steel with an ultrafine ($\alpha+\theta$) structure with a similar grain size is clearly increased when the carbon content is increased from 0.05 wt% to 0.6 wt%. These facts imply that the yield strength of plain carbon steel with an ultrafine ($\alpha+\theta$) structure most likely has a relationship with both ferrite grains and cementite particles.

The Hall–Petch relationship is often applied to quantitatively analyze the relationship between yield strength and grain size for polycrystalline metals. Additionally, according to the results of Ohmori et al. [10] and Song et al. [16] regarding the yield strength of low-carbon (0.07–0.3 wt% C) steel with the ($\alpha+\theta$) structure, the average sizes of ferrite grains in the range of 0.2–45 μm are largely consistent with the Hall–Petch relationship. However, the results of Syn et al. [17] suggest that the yield strength of medium-high-carbon (0.4–1.8 wt% C) steel with the ($\alpha+\theta$) structure, with an average size of ferrite grains in the range of 0.5–65 μm, has a relationship not only with the ferrite grain size but also with particle spacing. Therefore, even though the Hall–Petch relationship is applicable to the yield strength of low-carbon steel with an ultrafine or fine ($\alpha+\theta$) structure, it is most likely unsuitable for high-carbon steel with an ultrafine or fine ($\alpha+\theta$) structure. Moreover, although the relationship established by Syn et al. [17] considered the role of the ferrite matrix and cementite particles, the frictional stress (σ_0) was not individually considered. Consequently, it is necessary to establish a reasonable relationship for plain carbon steel with an ultrafine or fine ($\alpha+\theta$) structure, with carbon contents ranging from a low-carbon level to a high-carbon level.

In this study, plain carbon (0.17–0.97 wt% C) steels with different ultrafine or fine ($\alpha+\theta$) structures, in which the average size of ferrite grains ranged from approximately 1 μm to approximately 9 μm and the average size of cementite particles ranged from approximately 0.2 μm to approximately 1.0 μm, were formed using different thermo-mechanical processes [5,18]. The microscopic roles

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of the ferrite matrix and cementite particles during yielding were investigated as the basis for establishing a reasonable quantitative relationship between the microstructural parameters and yield strength for plain carbon steel with an ultrafine or fine ($\alpha+\theta$) structure.

2. Experimental

2.1. Chemical composition

The materials used consist of several plain carbon steels, i.e., low-carbon steel, medium-carbon steel, and high-carbon steel containing eutectoid steel and hypereutectoid steel. The detailed chemical compositions of these steels are shown in Table 1.

2.2. Microstructure preparation

Hot-rolling and cold-rolling were conducted using a two-high reversing mill. Wing-shaped specimens [5] for the hot compression test were machined from a hot-forged and air-cooled ingot. The forging temperature ranged from 1100 °C to 850 °C. The hot compression tests were performed using a Gleeble 1500 thermal simulator.

(a) *Low-carbon steel with different fine ($\alpha+\theta$) structures:* After hot-rolling into sheets with a thickness of 4 mm at a temperature of 1000–1200 °C followed by water quenching, the hot-rolled specimens were cool-rolled to a cumulative reduction of 70% (1.2 mm) at room temperature. Then, the cold rolled specimens were annealed at 650 °C for 1–3 h, as shown in Fig. 1a.
(b) *Medium-carbon steel or eutectoid steel with different fine ($\alpha+\theta$) structures:* After holding at 650 °C for 5 min, wing-shaped specimens were deformed to a strain of 1.61 at 0.1 s^{-1} and air cooled, reheated to 750 °C and held for 5–7 min, and then slowly cooled to 700 or 710 °C and held for 3–20 h, as shown in Fig. 1b.
(c) *High-carbon steel with different ultrafine ($\alpha+\theta$) structures:* After austenitizing at 850–1000 °C for 10 min, the wing-shaped specimens were cooled to 650 °C at a rate of 30 °C/s and then deformed to a strain of 1.61 at 0.01–1 s^{-1}, air cooled to room temperature and subsequently annealed at 650 °C for 0.5–3 h, as shown in Fig. 1c.
(d) *Eutectoid steel with another type of fine ($\alpha+\theta$) structure:* After austenitizing at 850 °C for 10 min, the wing-shaped specimens were cooled to 650 °C at a rate of 30 °C/s and then deformed to a strain of 1.61 at a strain rate of 5–10 s^{-1}, water quenched and subsequently annealed at 650 °C for 30 min, as shown in Fig. 1d.

2.3. Microstructure characterization and tensile test

The microstructure observations were performed using a Zeiss SUPRA55 field-emission scanning electron microscope (SEM). The SEM images were obtained parallel to the direction of compression [5]. Specimens for the SEM analyses were electropolished using the standard method with an electrolyte composed of 20% $HClO_4$+10% glycerol+70% C_2H_5OH under 15 V at room temperature and etched with 4% Nital. The microstructural parameters were measured using Image-Pro Plus 6.0 (produced by Media Cybernetics company, USA) image analysis software applied to the SEM images. Thin foils for transmission electron microscopy (TEM, JEM2010, operated at 200 kV) were prepared by twin-jet electropolishing using a solution composed of 5% $HClO_4$+95% CH_3COOH under 75 V at −20 °C to −30 °C, and the TEM images were obtained parallel to the tensile direction.

Room-temperature (RT) tensile tests were conducted using a Reger 3010 tensile tester at a strain rate of 1×10^{-3} s^{-1} under extensometer-measured strain control. Dog-bone-shaped specimens [5] were cut from the middle of the thermo-mechanical processed specimens with a gage length of 4 mm × 12 mm and a thickness of 1.8 mm for medium-high-carbon steel and with a gage length of 4 mm × 12 mm and a thickness of 1.2 mm for low-carbon steel.

Table 1
Chemical compositions of plain carbon steels (wt%).

Samples	C	Mn	Si	P	S
Low-carbon steel	0.17	0.36	0.090	0.017	0.013
Medium-carbon steel	0.45	0.67	0.28	0.0080	0.0074
Eutectoid steel	0.81	0.28	0.20	0.016	0.014
Hypereutectoid steel	0.97	0.26	0.31	0.0056	0.0040

3. Results

3.1. Microstructures

The typical ultrafine or fine ($\alpha+\theta$) structures of plain carbon steel are shown in Fig. 2. Low-carbon steels with different fine ($\alpha+\theta$) structures were formed using the process illustrated in Fig. 1a, and these steels consisted of a ferrite matrix with an average grain size of approximately 4–8 μm and cementite particles with a mean size of approximately 0.2–0.3 μm, as shown in Fig. 2a. The different fine ($\alpha+\theta$) structures of medium-carbon steel or eutectoid steel were obtained through the process shown in Fig. 1b, and they consisted of a ferrite matrix with an average size of approximately 2–8 μm and cementite particles with an average size of approximately 0.2–1.0 μm, as shown in Fig. 2b and c, respectively. High-carbon steels with different ultrafine ($\alpha+\theta$) structures were obtained via the dynamic transformation of undercooled austenite followed by a short annealing (Fig. 1c) [18], and these steels consisted of an ultrafine-grained ferrite matrix with an average size of approximately 1–2 μm and cementite particles with an average size of approximately 0.3–0.6 μm, as shown in Fig. 2d and e, respectively. Eutectoid steel with another type of fine ($\alpha+\theta$) structure, referred to as EAF, was formed by a process similar to that for the ultrafine ($\alpha+\theta$) structure but using a larger strain rate and water cooling (Fig. 1d) [5], and this steel consisted of a ferrite matrix with an average size of approximately 2 μm and cementite particles with an average size of approximately 0.2–0.3 μm, as shown in Fig. 2f. The sizes of the cementite particles for EAF show a clear bimodal distribution, in which the volume fraction and the average size of intragranular cementite particles are approximately 8–10% and 0.1–0.2 μm, respectively, and that of intergranular cementite particles are approximately 2–4% and 0.4–0.6 μm, respectively. The average size of ferrite grains was larger, but the average size of cementite particles was smaller, in EAFs than that of the ultrafine ($\alpha+\theta$) structures for eutectoid steel.

The characteristic feature of the ultrafine or fine ($\alpha+\theta$) structure is an ultrafine or fine-grained ferrite matrix with dispersed cementite particles, and the cementite particles can be divided into intragranular particles and intergranular particles. Fig. 3 is a schematic diagram based on the work of Syn et al. [17] to illustrate the microstructural parameters of the ultrafine or fine ($\alpha+\theta$) structure. In this study, the microstructural parameters that are considered to play a role in the yield strength can be summarized as follows: the average size of ferrite grains, i.e., D_α; the volume fraction and average size of cementite particles,