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Effect of microstructure on mechanical behavior for eutectoid steel with ultrafine- or fine-grained ferrite+cementite structure

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ABSTRACT

A eutectoid steel with various ultrafine- or fine-grained ferrite matrix (α)+cementite particle (θ) structures was fabricated to explore the effects of the microstructural features on the mechanical behavior of hard particle-strengthened two-phase alloys. The effect of microstructure on the parameters of an analytical model and the mechanical behavior for the eutectoid steel with ultrafine- or fine-grained $\alpha+\theta$ structure were analyzed basing on statistical data and physical metallurgy. The results showed that the rate of dislocation-storage caused by ferrite grain boundaries and cementite particles is approximately a microstructural constant and is proportional to the dislocation mean free path. The larger ferrite grains and the larger volume fraction of intragranular cementite particles are beneficial to obtaining a lower rate of dynamic recovery when ultrafine- or fine-grained $\alpha+\theta$ structures with an equal dislocation mean free path, and the uniform elongation increases with the decrease in the rate of dynamic recovery. Moreover, the ultimate strength is closely related to the effective dislocation mean free path including both roles of the storage and the recovery of dislocations. It is feasible to design a microstructure consisting of ultrafine- or fine-grained ferrite matrix and tiny cementite particles mainly within grain interior to possess an enhanced strength-plasticity synergy for the eutectoid steel.

1. Introduction

It has been well confirmed to improve the mechanical properties by dispersing cementite particles in the ferrite matrix for ultrafine-grained ferritic steels [1–14]. For example, the ultimate strength and the uniform elongation of a single-phase ferritic steel with a grain size of about 0.45 µm can be improved significantly from approximately 580 MPa to 720 MPa and 1–8%, respectively, through introducing the submicron cementite particles with a volume fraction of approximately 2% [6,13], which is attributed to the accumulation of more dislocation density [7]. Although a relationship between the yield strength and microstructural parameters has been further studied from the perspective of microscopic mechanism for steels with ultrafine-grained $\alpha+\theta$ structure [12], the corresponding microstructural relationship for the ultimate strength and the uniform elongation are rarely involved. According to the Considére criterion, $\sigma_u = d\sigma/d\varepsilon$, where σ_u is the true ultimate stress, ε is the true strain and $d\sigma/d\varepsilon$ is the work-hardening rate [7], the enhancement of work-hardening capability is the key factor to increase the uniform elongation of steels with ultrafine-grained $\alpha+\theta$ structure in comparison with single-phase ultrafine-grained ferritic steels [6–14]. Moreover, the ultimate strength can be simply divided into two parts including the yield strength and the stress increment caused by work-hardening, and, thereby, the work-hardening clearly also plays an important role in the ultimate strength. Furthermore, it is necessary to clarify the role of ferrite matrix and cementite particles in the work-hardening to establish a microstructural relationship of the ultimate strength and the uniform elongation for steels with $\alpha+\theta$ structure.

A number of results indicate that the enhancement in the work-hardening capability of steels with ultrafine-grained $\alpha+\theta$ structure, comparing with single-phase ultrafine-grained ferritic steel, is closely related with its lower rate of dynamic recovery or annihilation in addition to the storage of more dislocation density caused by cementite particles [2,10,19,20]. Therefore, the work-hardening behavior in the steels with $\alpha+\theta$ structure consists of two opposite processes, i.e., dynamic hardening and dynamic softening, and is controlled by the evolution of geometrically necessary dislocation (GND) density and statistically stored dislocation (SSD) density, which is well described by the Kocks-Mecking (K-M) model and modified K-M models [15–17]. Moreover, the effect of microstructure on the work-hardening behavior of steels with $\alpha+\theta$ structure can be further understood by establishing the relationship between model parameters and microstructural para-

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meters, and, apparently, it is also beneficial to establish microstructural expressions for the ultimate strength and the uniform elongation. However, there are little works to discuss the effect of microstructure on the parameters of K-M model and modified K-M models.

In our previous work [17], an analytical model based on the K-M model and its modified forms was established to predict the stress partitioning for each phase and the enhancement in the work-hardening of a eutectoid steel with ultrafine- or fine-grained $\alpha+\theta$ structure, which has been verified by using in situ synchrotron-based X-ray diffraction. The analytical model can demonstrate credibly the evolution of GND density and SSD density for the eutectoid steel with ultrafine- or fine-grained $\alpha+\theta$ structure, and, however, it cannot reflect directly the effect of an initial microstructure on the mechanical behavior. In this paper, the eutectoid steel with various ultrafine- or fine-grained $\alpha+\theta$ structures were synthesized by using different thermo-mechanical processings, and the work-hardening behavior was discussed basing on the analytical model. The relationship between model parameters and microstructural parameters were established basing on the role of ferrite matrix and cementite particles in the work-hardening. Furthermore, the relationship between mechanical properties and microstructural parameters were proposed in an attempt to elucidate the effect of microstructure on the ultimate strength and the uniform elongation for the eutectoid steel with $\alpha+\theta$ structure or other hard particle-strengthened two-phase alloys.

2. Experimental

The material studied is a commercial eutectoid steel with a chemical composition of 0.81 C, 0.28 Mn, 0.20 Si, 0.016 P and 0.014 S (mass%). Wing-shaped specimens [4] for a hot-compression test were machined from a hot-forged and air-cooled ingot. The forging temperature ranged from 1100 to 850 °C. The hot-compression tests were performed by using a Gleeble 1500 hot simulator. After austenitizing at 850–950 °C for 10 min, the specimens were cooled at 30 °C/s to 650 °C and deformed to a strain of 1.61 at a strain rate of 0.1 s^{-1}, and then they were air-cooled, and an additional annealing step was performed in a muffle furnace at 650 °C for 0.5–3 h to obtain various ultrafine-grained $\alpha+\theta$ structures [12], referred to as U. After holding at 650 °C for 5 min, the specimens were deformed to a strain of 1.61 at a strain rate of 0.1 s−1 and air cooled, reheated to 750 °C and held for 5–7 min, and then cooled to 700 or 710 °C in the furnace and held for 3–20 h to obtain a group of fine-grained $\alpha+\theta$ structures [12], referred to as F. After austenitizing at 850 °C for 10 min, the 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 to obtain another group of fine-grained $\alpha+\theta$ structures [4,12]. Since the average size of cementite particles in this group of fine-grained $\alpha+\theta$ structures is deep-submicron scale (< 0.3 μm), they are named as fine-grained $\alpha+DS\text{-}\theta$ structure for distinguishing from the microstructure F, referred to as FD, and the microstructural parameter of FD and F will be described in Section 3 in detail.

The microstructure observations were performed by using a Zeiss SUPRA55 field-emission scanning electron microscope (SEM). Specimens for the SEM analyses were electropolished by 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 from the SEM images by using Image-Pro Plus 6.0 (produced by Media Cybernetics company, USA) image analysis software. Thin foils for transmission electron microscopy (TEM, JEM2010, operated at 200 kV) were prepared by using a twin-jet electropolishing in an electrolyte consisting of 5% HClO4 and 95% CH3COOH under 75 V at a temperature range from −20 °C to −30 °C.

Room-temperature (RT) tensile tests were conducted by using a Reger 3010 tensile tester at a strain rate of $1\times10^{-3}\ s^{-1}$. A contact extensometer was used to measure strain in the sample gage upon loading. Dog-bone-shaped specimens [4] were cut from the middle of the thermo-mechanical processed specimens with a gage section of $12\times4\times1.8\ mm^3$.

Table 1
Microstructural parameters and mechanical properties of the eutectoid steel with various ultrafine- or fine-grained $\alpha+\theta$ structures.

Samples	D_α (μm)	f (%)	D_θ (μm)	σ_u (MPa)	ε_u
U1	1.2	12.1	0.32	833	0.112
U2	1.2	12.1	0.28	865	0.106
U3	1.1	12.1	0.27	857	0.104
U4	1.0	12.1	0.27	838	0.101
U5	1.2	12.1	0.37	804	0.108
U6	2.2	12.1	0.35	782	0.126
U7	1.1	12.1	0.34	805	0.115
U8	1.7	12.1	0.34	780	0.131
U9	1.3	12.1	0.39	796	0.115
F1	4.7	12.1	0.87	630	0.153
F2	3.5	12.1	0.62	694	0.147
F3	4.2	12.1	0.92	629	0.166
F4	2.7	12.1	0.81	649	0.148
F5	3.3	12.1	1.08	655	0.157
F6	4.0	12.1	0.88	646	0.160
F7	4.0	12.1	0.89	668	0.154
F8	6.4	12.1	0.93	628	0.156
F9	8.3	12.1	0.73	652	0.173
FD1	1.7	12.1	0.25	973	0.137
FD2	2.1	12.1	0.22	915	0.126
FD3	2.4	12.1	0.29	881	0.133
FD4	2.1	12.1	0.19	906	0.102

3. Results

The microstructural parameters and the mechanical properties of the eutectoid steel with various ultrafine- or fine-grained $\alpha+\theta$ structures, including the average grain size of ferrite matrix (D_α), the volume fraction (f) and the average size (D_θ) of cementite particles, the true ultimate strength (σ_u) and the true uniform elongation (ε_u), are listed in Table 1, and the typical microstructures are shown in Fig. 1a–c. The eutectoid steel with various ultrafine-grained $\alpha+\theta$ structures (U1-9) consisted of a ferrite matrix with $D_\alpha \approx 1\text{–}2$ μm and cementite particles with $D_\theta \approx 0.2\text{–}0.4$ μm, as shown in Fig. 1a (U1). The eutectoid steel with various fine-grained $\alpha+\theta$ structures (F1-9) consisted of a ferrite matrix with $D_\alpha \approx 2\text{–}9$ μm and cementite particles with $D_\theta \approx 0.6\text{–}1.0$ μm, as shown in Fig. 1b (F1). The eutectoid steel with fine-grained $\alpha+DS\text{-}\theta$ structures (FD1-4) were fabricated by using a thermo-mechanical processing basing on the dynamic transformation of undercooled austenite [18], as shown in Fig. 1c (FD1), and the microstructures consisted of a ferrite matrix with $D_\alpha \approx 2$ μm and cementite particles with $D_\theta \approx 0.2\text{–}0.3$ μm. The engineering stress-strain curves and the true stress-strain curves of the eutectoid steel with ultrafine- or fine-grained $\alpha+\theta$ structure (Fig. 1) are exhibited in Figs. 2a and 2b, respectively, and it is evident that the FD1 has better strength-plasticity synergy than that of the others. Fig. 3 shows statistical charts between the true ultimate strength and the uniform elongation for the eutectoid steel with various ultrafine- or fine-grained $\alpha+\theta$ structures, and the data also indicate that the strength-plasticity synergy of FDs is higher than that of the others.

Statistical charts between the inverse square root of D_α and the ultimate strength are shown in Fig. 4a for the eutectoid steel with various ultrafine- or fine-grained $\alpha+\theta$ structures. Fig. 4a exhibits that the ultimate strength of FDs are higher than that of the others under an equal grain size, but the ultimate strength demonstrate no particular relationship with ${D_\alpha}^{1/2}$. Fig. 4b depicts the ultimate strength as a function of the inverse square root of f/D_θ. The ultimate strength are approximately proportional to the $(f/D_\theta)^{1/2}$, which may results from the much higher GND density caused by cementite particles than that caused by ferrite grain boundaries [4]. Figs. 5a and 5b show statistical