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Role of second phase cementite and martensite particles on strength and strain hardening in a plain C-Mn steel

Ming-Chun Zhao [a], Xiao-Fang Huang [a], Andrej Atrens [b,*]

[a] School of Material Science and Engineering, Central South University, Changsha 410083, PR China
[b] The University of Queensland, Division of Materials, Brisbane, Qld 4072, Australia

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ABSTRACT

This work investigated the role of second phase cementite and martensite particles on the strength and the strain-hardening rate in a plain C-Mn steel. The change in microstructure (including the change of the ferrite grain size and the change in the second phase particles from cementite to martensite) contributed to the change in the athermal component of the yield and the tensile strengths but caused little change in the thermal component. Second phase cementite and martensite particles improved the strain-hardening rate. The microstructure consisting of ferrite grains and martensite particles had a high potential for improving uniform elongation due to a high strain hardening rate which restrains the occurrence of necking.

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1. Introduction

Plain C-Mn steels are economical structural materials because they contain no costly alloying elements. For structural applications, steels must meet requirements of strength and ductility. These are often measured using a tensile test. Maximum uniform elongation occurs at the maximum engineering stress when the work hardening in the material can no longer compensate for the decrease in section. This condition in the tensile test is described by the condition of plastic instability:

$$\sigma \geq \frac{d\sigma}{d\varepsilon} \quad (1)$$

where σ is the flow stress, ε is the true strain, and $d\sigma/d\varepsilon$ is the strain-hardening rate [1,2]. A high strain hardening rate leads to a large amount of uniform elongation because a high strain hardening rate delays the onset of the plastic instability. Ashby [3,4] showed that the strain-harden rate depends on the dispersion of hard second phase particles and proposed the concept of strain-hardening design using second phase particles to improve the strength–ductility balance. A recent development is plain C-Mn steels with an ultrafine-grain ferrite/cementite microstructure, hereinafter UGF/C microstructure. This microstructure is produced by heavy hot deformation and is characterized by ultrafine ferrite grains containing fine globular cementite [5–8]. The average ferrite grain size is about a micrometer. The cementite particles are less than 100 nm in diameter. Such plain C-Mn steels with an UGF/C microstructure have been produced with a good combination of strength and some uniform elongation [9,10]. Fine martensite second phase particles should cause strain-hardening even stronger than that caused by the fine cementite particles in the UGF/C steels, because martensite is even harder than cementite. Therefore, plain C-Mn steel, with ultrafine ferrite grains and fine martensite second phase particles, hereinafter called the F/M microstructure, should have an excellent combination of strength and elongation.

Our previous work indicated that annealing the UGF/C microstructure caused progressive coarsening, i.e. submicron-sized ferrite grains gradually coarsened and as did cementite particles through Oswald ripening. These processes increased with increasing annealing temperature [5,6]. When the annealing temperature reached the intercritical annealing temperature, carbon-rich areas formed carbon-rich austenite and these areas transformed into fine martensite particles when the sample was water quenched, and produced a F/M microstructure.

This work investigated the role of second phase cementite and martensite particles on the strength and the strain-hardening rate in a plain C-Mn steel. The aim was to explore the potential to develop plain C-Mn steels with an improved combination of strength and ductility.

2. Experimental procedure

The chemical composition (wt.%) of the plain C-Mn steel was 0.148% C, 0.311% Si, 1.506% Mn, 0.01% Al, 0.002% S, 0.001% P, 0.0012%

* Corresponding author. Tel.: +61 3365 3748; fax: +61 3365 4799.
E-mail address: andrejs.atrens@uq.edu.au (A. Atrens).

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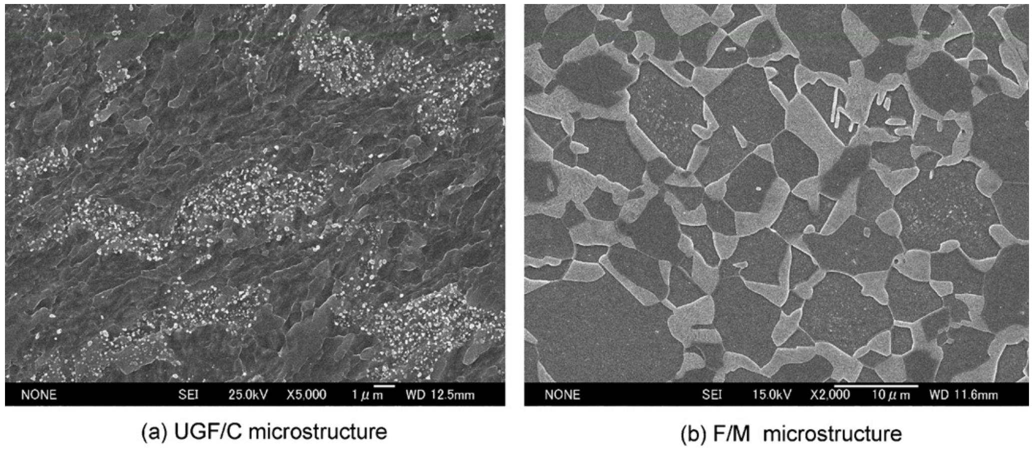

Fig. 1. SEM micrographs of (a) the UGF/C microstructure and (b) the F/M microstructure.

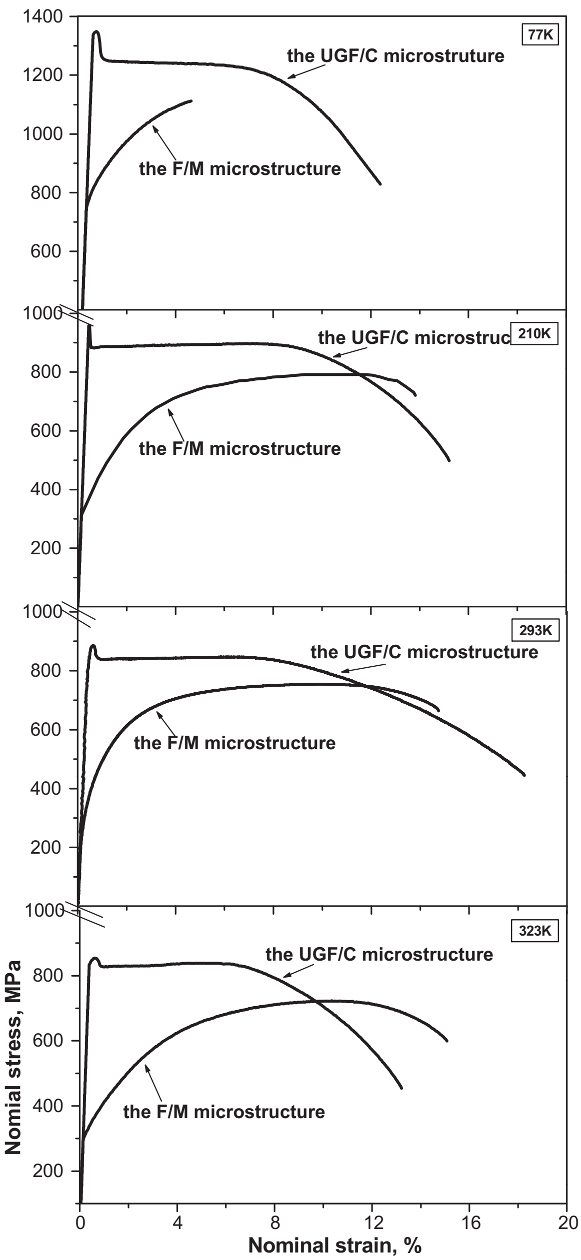

Fig. 2. Nominal stress–strain curves.

N, and 0.0014% O. The ingot was melted in vacuum on a laboratory scale and homogenized for 60 min at 1473 K. To produce the UGF/C microstructure, the ingot was hot forged to 115 mm diameter rods, reheated for 60 min at 1173 K, caliber groove rolled to 79 mm square rods at 1073 K, to 24 mm square rods at 823 K, to 17 mm square rods at 723 K with the total area reduction of approximately 95%, and water quenched. The F/M microstructure was produced by annealing the UGF/C microstructure for 600 min at 993 K and water quenching.

Microstructures were examined in the transverse direction by scanning electron microscopy (SEM) after mechanical grinding, polishing and etching in a 2% nital. Cylindrical tensile test specimens were machined with length parallel to the rod length, with a gauge diameter of 3.5 mm and a gauge length of 25 mm. Tensile tests were performed with a cross-head speed of 0.5 mm/min at 323 K, 293 K (room temperature), 210 K and 77 K. The appearance and fracture surfaces of tensile test specimens were examined using a digital camera and SEM.

3. Results and discussion

Fig. 1 presents the UGF/C and the F/M microstructures. The UGF/C microstructure consisted of a ferrite matrix with ultra-fine grains containing nano-sized globular cementite particles. The average ferrite grain size was less than 1 μm. The ferrite grains were slightly elongated due to the heavy deformation. The cementite particles were less than 100 nm in diameter and were distributed heterogeneously with a local high density. The F/M microstructure consisted of ferrite grains and fine martensite particles. The average ferrite grain size was approximately 10 μm. Martensite particles were distributed along the ferrite grain boundaries. The martensite particle size was a few micrometers. The fine size of the martensite particles was attributed to the original UGF/C microstructure, because areas with a high density of cementite particles in the UGF/C microstructure formed small grains of carbon-rich austenite due to the dissolution of cementite particles, whereas areas with a low density of cementite particles remained ferrite during the inter-critical annealing. The small grains of carbon-rich austenite transformed into fine martensite upon water quenching.

Fig. 2 presents the engineering stress–strain curves for each microstructure. The lower yield stress was used as the yield stress for the UGF/C microstructure, which had a yield-drop. The 0.2% offset stress was used for the F/M microstructure with continuous yielding. The UGF/C microstructure showed discontinuous yielding followed by slight strain hardening with a considerable uniform elongation. This considerable uniform elongation was different to

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