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Investigation on microstructure and properties of 0.17% carbon steel with dispersed cementite particles

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ABSTRACT

Using "ultra fast cooling (UFC) + thermo-mechanical treatment (TMT)" process, nanoscale cementite particles were obtained while the matrix varied from "proeutectoid ferrite + degenerated pearlite" to complete lath-like bainitic matrix by controlling the UFC stop temperature. Microstructures were examined by optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Results showed that TMT process promoted cementite precipitation in proeutectoid ferrite, leading to more uniformly distributed cementite particles. The tensile properties and Charpy V-notch (CVN) impact toughness were evaluated. The correlation with the microstructural features is then discussed in details.

1. Introduction

Facing intense competition, steel companies in China are now pushing their limit to reduce the production costs. One feasible and efficient way is to reduce the alloying element while maintain comparable mechanical properties by process optimization. Cementite, as a most economic strengthening phase in steels, has recently attracted wide attentions.

Fu et al. (2007) systematically investigated the type, size distribution and volume fraction of cementite particles in high strength low carbon steels formed during thin slab continuous casting and rolling process (TSCR). These particles (<20 nm) have produced equivalent strengthening contribution as grain refinement. Later on, a comprehensive analysis of nanometer sized cementite in Ti microalloyed high strength weathering steels during TSCR was carried out by using chemical phase analysis, X-ray small-angle scattering and high resolution transmission electron microscopy (Fu et al., 2011). Results showed that the particles (<36 nm) included mainly cementite and TiC and the volume fraction of cementite is 4.4 times of that of TiC, generating stronger strengthening effect than that of TiC. Wang et al. (2013) studied the unique effects of UFC on pseudo-eutectoid transformation behavior in hypoeutectoid steels which contains carbon of 0.04–0.5 wt%. In their work, cementite existed as lamellar plates in 0.04 and 0.5 wt% carbon steels, while complete nanoscale particles were achieved in 0.17 wt% carbon steel. For intermediate bulk carbon content i.e., 0.33 wt%, cementite exhibited mixed morphology including nanoscale particles and lamellar plates. The cementite particles were of 20–30 nm large and contributed ~100 MPa strengthening increment, showing comparative strengthening ability as microalloying carbide.

Except the strengthening effect, cementite will also affect the toughness of steels. For example, traditional furnace tempering of martensite results in cementite particles at martensite lath boundaries. Under slow heating rate, cementite tends to coarsen and becomes potentially detrimental to toughness. In view of this, heat treatment on-line process (HOP) was developed. Hayashi et al. (2008) applied HOP technology for tempering of a low carbon steels with microstructures mainly consisting of martensite. They found out that rapid heating rate of HOP technology brought about uniform refinement and dispersion of cementite, which ensures an excellent combination of strength and toughness. Besides the size of cementite particles, morphology of cementite, which is usually integrated with ferrite matrix as a whole, i.e., pearlite, also affects the toughness of steels. Shanmugam et al. (2006) and Anumolu et al. (2008) studied the correlation between microstructure and impact toughness in polygonal ferrite-pearlite steels. Their results indicated that, when compared with normal lamellar pearlite,

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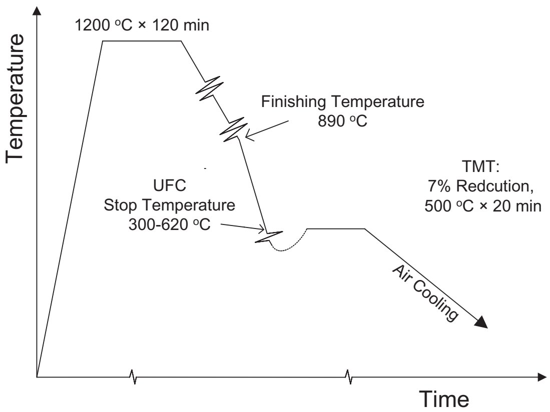

Fig. 1. Experimental procedure for hot rolling.

degenerated pearlite which is composed of ferrite and broken cementite particles is more favorable for improving impact toughness.

In the present work, nanoscale cementite particles were produced by using "UFC + TMT" process in a hypo-eutectoid steel containing 0.17 wt% carbon. Various microstructural matrixes were obtained by controlling the UFC stop temperature. Besides microstructure observation, evaluation of mechanical properties was carried out, including tensile properties and impact toughness. The formation mechanism of cementite particles, correlation of process, microstructure and properties are then discussed in detail.

2. Experimental

A hypo-eutectoid steel with nominal chemical composition of 0.17C-0.2Si-0.7Mn-0.004P-0.001S-0.002N (wt pct.) was produced by vacuum induction melting. The casted ingot was forged into 70 mm thick plate and then supplied for laboratory hot rolling. Using ThermoCalc with tcfe6 database, the A_{e3} temperature was determined to be 1106 K (833 °C).

Experimental procedure for hot rolling is presented in Fig. 1. After homogenization at 1200 °C for 120 min, a two-stage hot rolling was conducted to reduce the thickness of the plate to 7 mm. The reduction ratio for the 1st and 2nd stage rolling was 64% and 72%, respectively. The hot-rolled plate was then subjected to UFC process with cooling stop temperature between 300 and 620 °C. Before the plate was air-cooled to room temperature, a TMT process including 7% single reduction plus subsequent 20 min holding at 500 °C was carried out. For comparison, another hot rolling experiment without TMT process was performed. Detailed process parameters are summarized in Table 1.

Samples for optical metallography were prepared by traditional method including grinding, polishing and etching in 4% nital solution. The microstructure was observed by optical microscope (OM, LEICA DMIRM) and scanning electron microscope (SEM, FEI Quanta600). Transmission electron microscopy (TEM, FEI Tecnai G2 F20) samples were prepared by cutting slices from the samples followed by mechanical grinding to 50 μm using SiC papers. Next, twin-jet electropolishing was carried out to perforation using a mixture of 9% perchloric acid, 91% absolute ethyl alcohol at −40 °C and potential of 30 V. Tensile and Charpy V-Notch (CVN) impact test samples were prepared along the rolling direction. The tensile samples (gage width of 12.5 mm, gage length of 50 mm) were tested at room temperature using an Instron tensile testing machine at a crosshead speed of 3 mm min^{-1}. The CVN samples (5 mm × 10 mm × 55 mm) were prepared with the notch parallel to the thickness direction. The CVN impact tests were conducted on a conventional Charpy-type pendulum impact machine.

In order to study the effect of UFC on toughness, the CVN impact test was also done for an industrially hot rolled and accelerated cooled steel product where the resulting microstructure consists of proeutectoid ferrite and lamellar pearlite. The chemical composition is 0.13C-0.84Mn-0.2Si-0.029Ti-0.017P-0.004S-0.038Al and the plate thickness is 16 mm. It should be mentioned that normal sample size of 10 mm × 10 mm × 55 mm was used in this CVN impact test.

3. Results

3.1. Microstructure

Fig. 2 shows the microstructure of the sample with UFC stop temperature of 620 °C, i.e., UFC process No. 1. The two main constituent phases are proeutectoid ferrite and degenerated pearlite where cementite exists as dispersed, round or rod-like particles (see Fig. 2b). The effect of TMT treatment on microstructure can be identified by comparing UFC process No. 1 with UFC + TMT process No. 2. The UFC stop temperature employed in process No. 2 is 10 °C lower than that in process No. 1, which leads to a marked decrease in proeutectoid polygonal ferrite (see Figs. 2 and 3a). Besides, as contrasted to Fig. 2b, the enlarged image in Fig. 3b shows a large number of extremely fine cementite particles formed in proeutectoid ferrite grain. This was also confirmed by TEM image in Fig. 3c.

For UFC + TMT process No. 3, acicular-shaped ferrite appears as one of the major constituent phases and the fraction of proeutectoid polygonal ferrite is further decreasing (see Fig. 4). This is also observed in the samples subjected to UFC + TMT process Nos. 4 and 5 (see Figs. 5 and 6). A detailed analysis in Fig. 4c shows a heavily dislocated structure in the acicular-shaped ferrite and a great number of cementite particles precipitated on dislocations. When the UFC stop temperature is below 600 °C, bainitic lath structure becomes one of the most important features. TEM images (Figs. 5 and 6c) clearly shows the round, or rod-like cementite particles precipitated in/between bainitic lath. For the lowest UFC stop temperature i.e., 300 °C (Fig. 7), a microstructure of complete lath-like bainitic structure was achieved. Cementite particles are densely and uniformly distributed in the bainitic matrix (see Fig. 7b and c).

The orientation relationship between orthogonal cementite and BCC ferrite was determined by selected area diffraction pattern (SADP) in Fig. 8b. Energy dispersive X-ray analysis (EDS) in Fig. 8c confirmed the rod-like particle circled in Fig. 8a was cementite which contains only Fe and C. Results indicate that cementite bears the following orientation relationship with ferrite, i.e., $(01\text{-}1)_\theta \| (4\text{-}1\text{-}1)\alpha$ and $[011]_\theta \| [122]\,\alpha$.

Table 1
Experimental hot rolling parameters for different processes.

Process type	A	B				
No.	1	2	3	4	5	6
Finishing temperature/°C	890	890	890	890	890	890
UFC stop temperature/°C	620	610	600	580	500	300
TMT	–	7% Reduction, 500 °C × 20 min				