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Effect of ultra-fast cooling on microstructure and mechanical properties in a plain low carbon steel

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Abstract

In order to explore the ways to obtain excellent mechanical properties in steels with simple compositions, a plain low carbon steel was subjected to ultra-fast cooling precisely combined with laminar cooling (UFC + LC model) and only laminar cooling (LC model) respectively after the same controlled rolling, and the microstructural characteristics as well as corresponding mechanical properties were investigated. The results show that under LC model, the microstructure is composed of coarse proeutectoid ferrite and pearlite, whereas UFC + LC model leads to the appearances of a certain amount of fine sheaf-like bainitic ferrite and acicular ferrite besides plenty of fine proeutectoid ferrite and scarce degenerate pearlite. Bainitic ferrite and acicular ferrite contain plenty of grain boundaries with misorientations of 2–7°, which further refines the microstructure associated with strength under UFC + LC model. Compared with LC model, UFC + LC model increases yield strength from 271 to 365 MPa because of grain refinement and dislocation strengthening effects. In the meantime, the steel treated by UFC + LC model exhibits lower ductile-brittle transition temperature of –59.3 °C compared with that of –44.5 °C of the steel subjected to only LC model as a consequence of microstructural refinement.

Key words: ultra-fast cooling, laminar cooling, plain low carbon steel, microstructural characteristics, mechanical properties

1. Introduction

Controlled cooling after hot rolling is an important part of thermo-mechanical controlled processing (TMCP). Under given chemical compositions and TMCP condition, desired metallurgical structure and mechanical properties can be achieved by controlling the cooling process. Increasing trends to both enhance steel quality and reduce product cost result in higher requirements on TMCP, especially controlled cooling technology, which should possess the capabilities of quick and accurate cooling of hot-rolled steel. However, conventional accelerated cooling technologies, such as laminar cooling (LC), are difficult to meet the above requirements due to low cooling capability, which impels the appearance of advanced cooling technology, namely ultra-fast cooling (UFC).

UFC technology possesses much higher cooling capability and accurate temperature control [1, 2], which has important significance for controlling microstructures and mechanical properties of steels. Some researchers investigated the morphologies of secondary carbide and pearlite in high carbon chromium bearing steel [3], volume fraction and morphology of retained austenite in hot-rolled C-Si-Mn TRIP steel [4], precipitation behaviour of nanoscale cementite in hypoeutectoid steels [5] and size of martensite/austenite constituent in high performance bridge steel [6] respectively under UFC, and corresponding mechanical properties. The results indicate that UFC greatly improves the microstructure morphologies, and enhances mechanical properties.

Compared with above mentioned steels, plain low carbon steels (195–275 MPa grade) have simple compositions but widespread application. Except for a very small amount of Mn and Si, plain low carbon

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steels do not contain any other alloy elements which can raise hardenability of austenite, such as Ni, Cr, Mo. So austenite is apt to recrystallize during conventional accelerated cooling after hot rolling, and usually transforms into coarse proeutectoid ferrite and pearlite with low strength [7]. However, because of very large cooling rate provided by UFC technology, it is possible to control the transformation behaviour of supercooled austenite and transformation products of plain low carbon steels by applying UFC technology, thereby desired mechanical properties can be also obtained even under simple compositions.

In present study, a plain low carbon steel (235 MPa grade) was treated by UFC combined with LC and only LC respectively after the same controlled rolling. By comparison analyses, effects of UFC on microstructural characteristics and mechanical properties were investigated. Above works aim at exploring the ways to achieve high mechanical performances in steels with simple compositions by UFC technology to reduce production cost and save precious resources.

2. Material and experimental procedures

Plain low carbon steel (235 MPa grade) used in the present investigation has a chemical composition (wt.%) of Fe-0.14C-0.27Si-0.52Mn-0.019S-0.023P. A two-stage (i.e., austenite recrystallization and non-recrystallization regions) controlled rolling experiment was performed on a pilot rolling mill with twin rolls of 450 mm in diameter, and TMCP schedule and process parameters are shown in Fig. 1. The slab billets with section size of $140 \times 140\,\mathrm{mm}^2$ (cross dimensions) were reheated to 1200 ℃, held for 1.5 h in a resistance-heated furnace, and hot-rolled into 14 mm thick plates in seven passes during two-stage controlled rolling process. After hot rolling, steel plates were immediately cooled according to UFC + LC and LC models respectively to 450 ℃, followed by air-cooling to ambient temperature. In UFC + LC model, experimental steel was initially cooled by UFC with cooling rate of $80\,℃\,\mathrm{s}^{-1}$ to 650 ℃, then cooled by LC with cooling rate of $15\,℃\,\mathrm{s}^{-1}$. For LC model, experimental steel was cooled only by LC with cooling rate of $15\,℃\,\mathrm{s}^{-1}$. Accordingly, two kinds of steels marked as A and B respectively were developed.

Charpy V-notch specimens with dimensions of $10 \times 10 \times 55\,\mathrm{mm}^3$ were machined from the steel plates in the transverse-longitudinal orientation in accordance to the ASTM E23-2002a Standard [8], and impact tests were conducted over a temperature range of –196 to 20 ℃. The regression analyses for values of absorbed energy *vs* test temperatures were performed using a hyperbolic tangent curve fitting method [9], and the ductile-brittle transition temperatures (DBTTs), at which absorbed impact energy is the average value of upper shelf energy (USE) and lower shelf energy (LSE) [10], were determined. Tensile tests at room temperature were carried out using an Instron-8500 Digital Control tensile testing machine on cylindrical tensile specimens with a gauge diameter of 6 mm and gauge length of 30 mm fabricated in the transverse direction of rolled plates following ASTM E8M-2004 Standard [11].

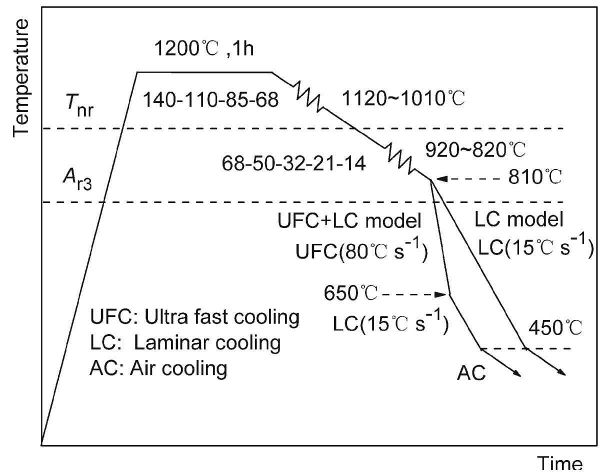

Fig. 1. Schematic diagram of experimental programme and process parameters.

The samples were cut from the plates, and transverse section planes for steel plates were prepared for optical microscope (OM), transmission electron microscope (TEM) and electron back-scatter diffraction (EBSD) analyses. After mechanically polished, the samples for OM analysis were etched with 4 % nital solution, and the metallographic microstructures were observed using a Leica DMIRM image analyser. More detailed microstructural characteristics were examined by TEM analysis. The thin foils for TEM were prepared by mechanical thinning from 300 to 80 μm, along with twin-jet electropolishing in an electrolyte of 8 % perchloric acid and 92 % ethanol at the temperature of –30 ℃, and examined on a JEM2000EX TEM at an accelerating voltage of 200 kV. In order to quantitatively study the information associated with microstructural characteristics, EBSD analyses were carried out on an FEI Quanta 600 SEM equipped with EDAX-TSL orientation-imaging microscope system with a step size of 0.2 μm. EBSD specimens were electrochemically polished with a solution of 80 % ethanol, 12 % distilled water and 8 % perchloric acid (vol.%) at a polishing voltage of 35 V.

3. Results

Figure 2 presents microstructural morphologies of A and B steels, which suggests that microstructure for

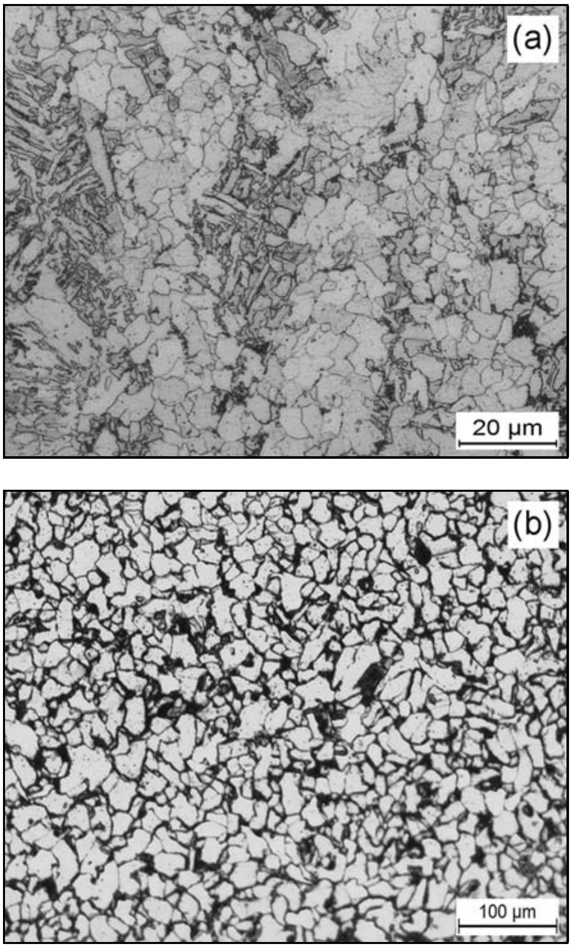

Fig. 2. OM morphologies of A steel (a) and B steel (b).

A steel is dominated by fine proeutectoid ferrite (PF) accompanied by a certain amount of fine sheaf-like bainitic ferrite (BF), acicular ferrite (AF) with interwoven non-parallel microstructural morphology and scarce pearlite (P), whereas B steel is characterized by a common microstructure of coarse PF and P.

The detailed microstructural characteristics of A steel were investigated by TEM analysis, as shown in Fig. 3. It is clearly visible that, compared with PF, BF and AF usually contain high density tangled dislocations. Moreover, it can be found from Fig. 3c that cementite basically appears as slight discrete film with random distribution besides a small amount of parallel cementite laths aligned in certain orientation, suggesting that pearlite degenerates seriously under UFC.

In order to accurately acquire the information associated with microstructural characteristics, for example, boundary structure and effective grain size, EBSD technique was used to quantitatively characterize the microstructures under different cooling conditions, and analysis results are shown in Figs. 4–6, respectively. Figure 4 shows image-quality maps superposed by grain boundaries with different misorientations, indicating that plenty of low angle grain boundaries (LAGBs) with misorientations of 2–15° appear in BF and AF (in A steel), whereas PF (in A and B steels) contains scarce LAGBs.

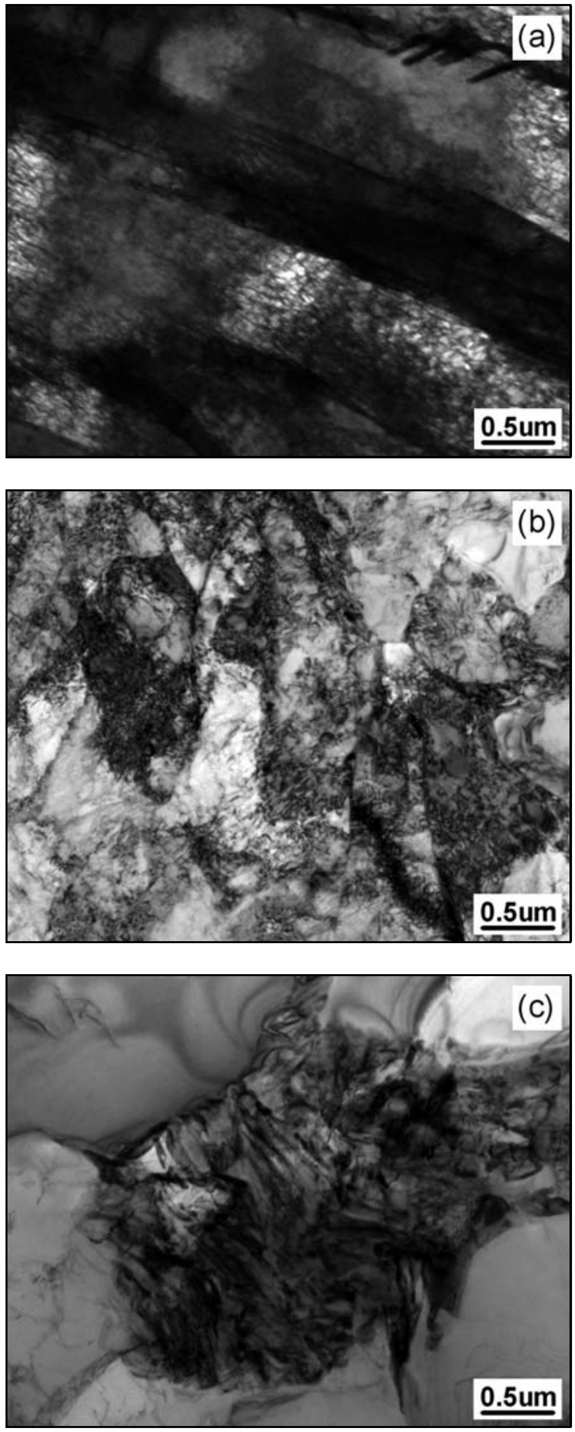

Fig. 3. TEM morphologies of A steel showing BF (a), AF (b) and PF and P (c).

Quantitative analysis results for distributions of grain boundary misorientation are shown in Fig. 5. It can be seen that the misorientation of LAGBs in

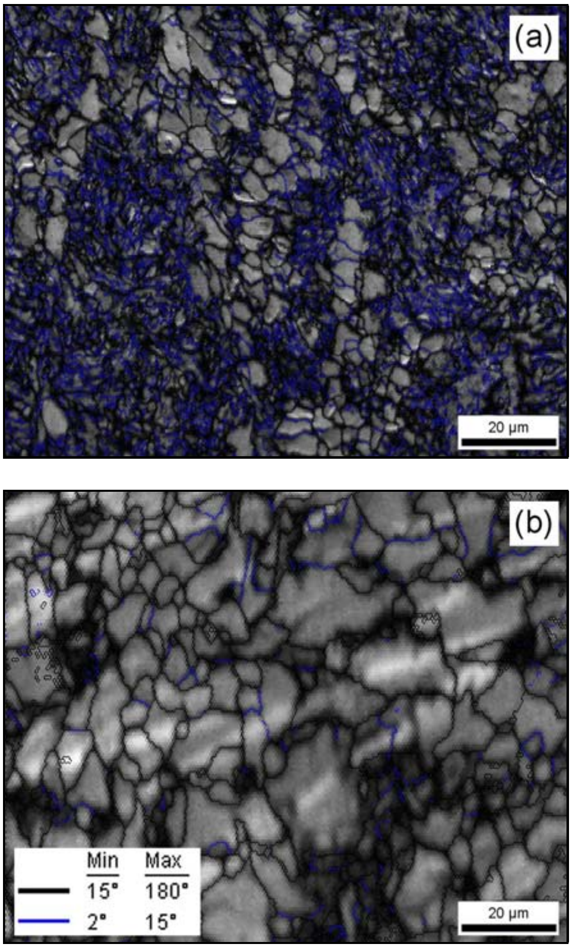

Fig. 4. Image-quality maps of A steel (a) and B steel (b).

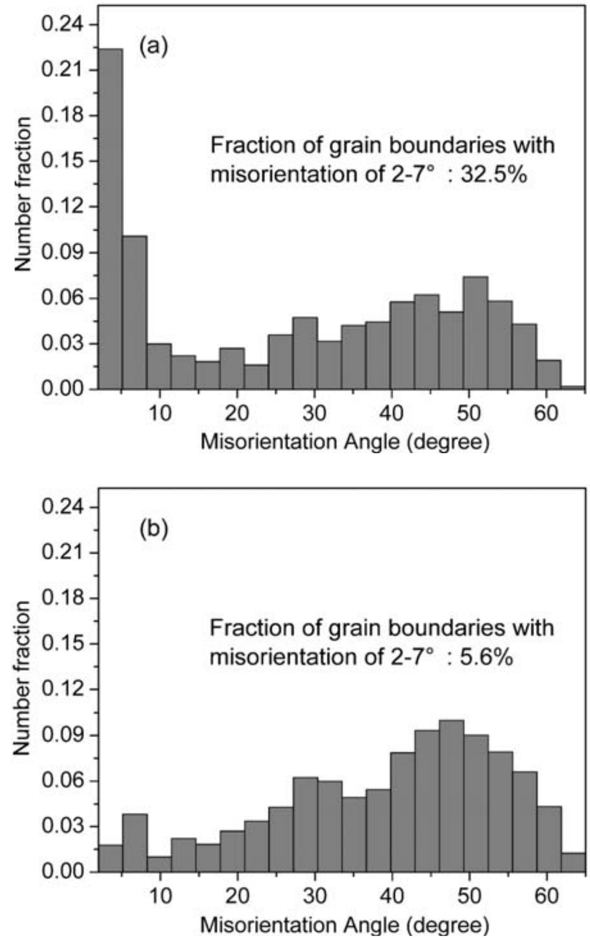

Fig. 5. Distributions of grain boundary misorientation of A steel (a) and B steel (b).

the microstructure for A steel is mainly distributed between 2–7°, and fraction of grain boundaries with misorientation of 2–7° for A steel is significantly higher than that for B steel.

In general, high angle grain boundaries with misorientation of 15° or more are used to act as a crystallographic domain parameter showing effective grain size (EGS) which is microstructural unit controlling low-temperature toughness [12]. Figure 6 shows the misorientation maps at tolerance angle of 15°, indicating EGS of A and B steels. It can be found that overall EGS of A steel is obviously smaller than that of B steel. Based on EBSD quantitative analysis, the values for EGS of A and B steels were determined to be 5.62 and 12.37 μm, respectively.

Stress-strain curves obtained by tensile test are presented in Fig. 7. The values of yield and tensile strength for A steel are 365 and 492 MPa, respectively, whereas those for B steel are 271 and 412 MPa, respectively, indicating that plain low carbon steel can be strengthened by UFC.

Figure 8 shows the absorbed impact energy-test temperature relation obtained by regression analysis, from which DBTTs were determined to be –59.3 ℃ for A steel, and –44.5 ℃ for B steel, respectively, indicating that low-temperature toughness of the former is superior to that of the latter.

4. Discussion

Based on the above comparison analyses, it can be seen that UFC can greatly affect microstructural morphologies and mechanical properties of plain low carbon steel. Very high cooling rate provided by UFC can inhibit recrystallization behaviour of deformed austenite, resulting in that austenite is still in the hardening state in the course of UFC immediately after hot rolling [13]. Consequently, high density of crystal defects formed by accumulated strain in non--recrystallization region, such as dislocations, deformed bands to serve as nucleation sites for ferrite during following transformation are retained within austenite, which greatly refines the microstructure [14, 15]. Hence, plain low carbon steel exhibits fine microstructural characteristics under UFC.

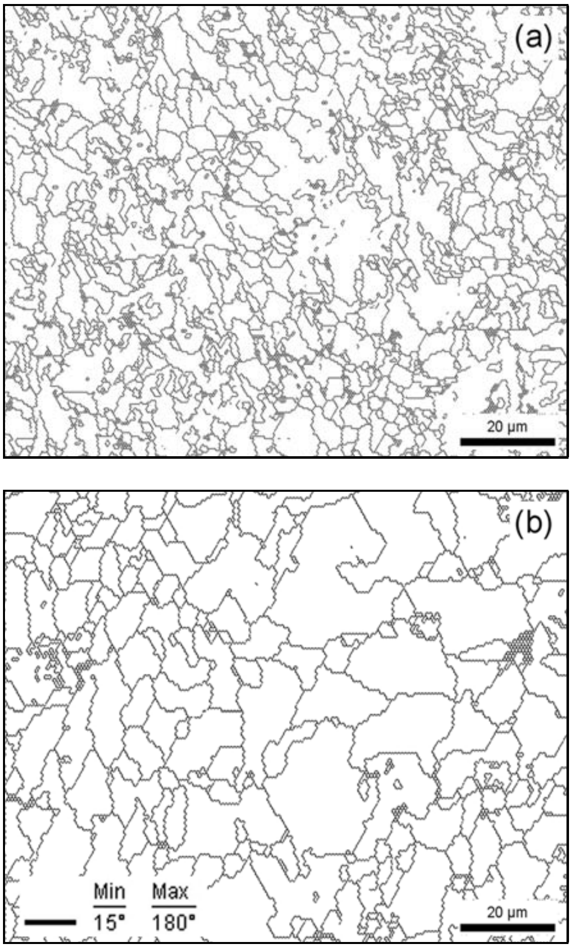

Fig. 6. Misorientation maps at tolerance angle of 15° of A steel (a) and B steel (b).

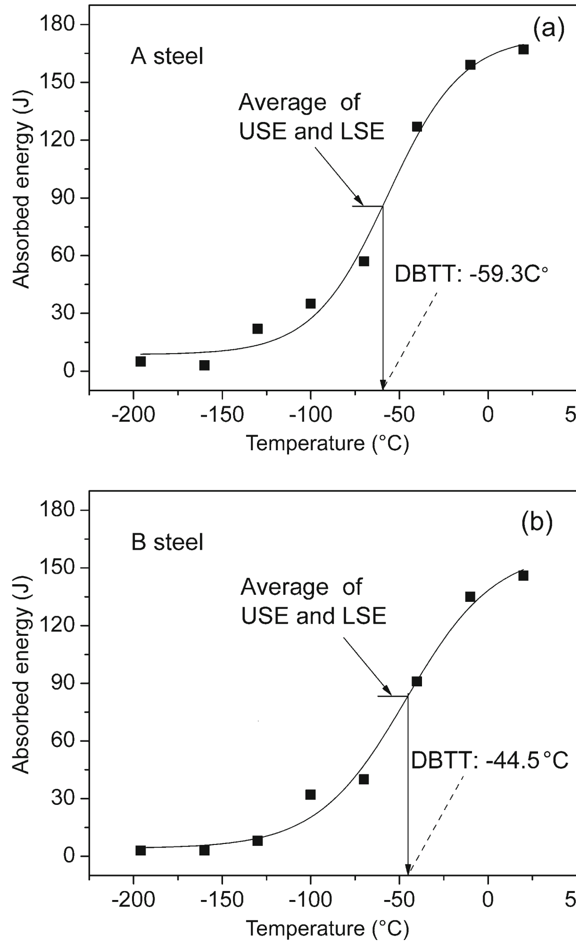

Fig. 8. Ductile-brittle transition curves of A and B steels.

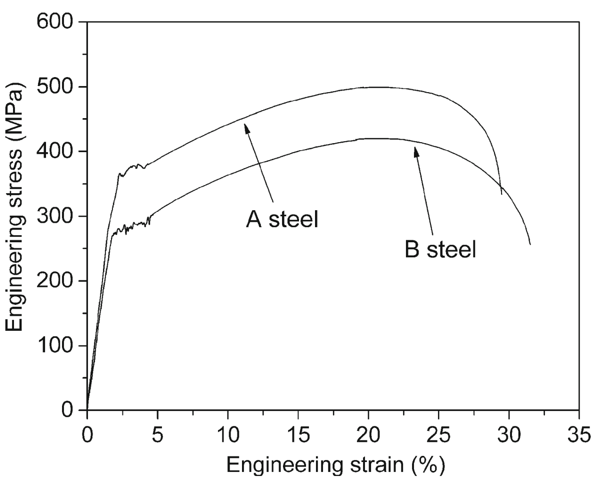

Fig. 7. Stress-strain curves of A and B steels.

Moreover, UFC can also control transformation behaviour of supercooled austenite. After hot rolling, under UFC + LC model, plain low carbon steel can be quickly cooled to a given lower temperature of 650 ℃. So carbon and other elements (i.e., Mn and Si) have no enough time to diffuse, which can inhibit diffusion transformation of austenite against PF and P. During LC after 650 ℃, austenite partially decomposes into PF and P, and remaining austenite transforms into BF and AF at much lower temperature. Accordingly, a certain amount of BF and AF appear in the microstructure besides PF by precisely controlling cooling path under UFC + LC model.

Plain low carbon steel treated by UFC + LC model displays higher mechanical strength as a consequence of above microstructural characteristics. Compared with LC model, UFC results in finer metallographical microstructure. More importantly, there are a great amount of grain boundaries with misorientations of 2–7° (i.e., dislocation substructures) within BF and AF in the microstructure obtained by UFC + LC model. Zhu et al. [16] reported that grain boundaries with tolerance angle of 2–7° in BF define the microstructural unit that governs the yield stress of bainitic steel by an empirical relationship between dislocation cell size and flow stress proposed by Kuhlmann-

-Wilsdorf [17]. Therefore, overall grain size with regard to the yield stress under UFC + LC model is further lowered for this reason (Fig. 4), which results in significant grain refinement strengthening effect. Moreover, a large amount of tangled dislocations distributed within BF and AF (Figs. 3a,b) can also raise strength of plain low carbon steel by dislocation strengthening mechanism.

Plain low carbon steel cooled by UFC + LC model also exhibits excellent low-temperature toughness as a consequence of fine EGS determined by grain boundaries with misorientation of 15° or more. Ductile-brittle transition phenomenon in body-centered cubic metal materials is associated with competition between the cleavage fracture stress and the yield stress, and DBTT is defined as the temperature at which cleavage fracture stress is equal to yield stress [18]. Grain refinement can heighten both cleavage fracture stress and yield stress, however, strengthening effect for cleavage fracture stress is more remarkable than that for yield stress [19, 20]. Therefore, grain refinement can contribute to a more significant increase in the cleavage fracture stress, which eventually leads to the decrease in the DBTT.

5. Conclusions

1. UFC can efficiently control transformation products in a plain low carbon steel. By precisely controlling cooling path under UFC, a certain amount of BF and AF appear in the microstructure besides plenty of fine PF and scarce degenerate P.

2. BF and AF contain plenty of grain boundaries with misorientations of 2–7°, which further refines the microstructure associated with strength under UFC + LC model.

3. In comparison with LC model, plain low carbon steel under UFC + LC model shows higher strength because of grain refinement and dislocation strengthening effects, and lower DBTT as a consequence of microstructural refinement.

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