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Study on the key role of hierarchical microstructure for strength and plasticity in a lath martensitic steel

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Abstract. In this paper, the effect of substructure of lath martensite on the mechanical properties was discussed in detail. Results indicated that prior austenite grain, packet and block increase with the increasing of quenching temperature. A good linear relationship exists between the packet, block and prior austenite, which reveal that the size of packet, block depends on prior austenite grain. However, lath is increased with not determined by prior austenite grain. Based on the EBSD analysis, the large ratio of the low angle orientation boundaries determines the better plasticity is obtained in coarse grain. Therefore, the refining of martensite lath or the increase of the low angle orientation plays an important role on improving the plasticity in lath martensite steel.

1. Introduction

Low-carbon martensite steel belongs to an important family of advanced high strength or ultra-high strength steels due to an excellent combination of strength, plasticity and toughness. Recently, extensive researches have attempted to build the relationship between the multi-level microstructures and the mechanical property. These results indicated that microstructure is the effective control unit for strength and toughness of martensite, such as prior austenite size (dr) [1-3], packet size (dp) [4-7] and block size (db) [8-10]. However, with the plasticity many investigations attended to plastic deformation processing and mechanisms, few reports concerned with the effective control unit of macroscopic plasticity in low-carbon martensite steels. The work aims at revealing the relationship between macroscopic plasticity and micro-structure and providing a new way in the design of new material with the high strength and high plasticity based on 20CrNi2Mo steel.

2. Experimental procedure

2.1. Experimental material

The low-carbon 20CrNi2Mo steel was utilized in the present study. The chemical composition of the tested steel in weight percent is: C 0.20, Si 0.25, Mn 0.66, P 0.01, Cr 0.64, Cu 0.02, Ni 1.69, and rest Fe. The tested steel was rolled into Φ 80mm round bars, and forged into Φ17mm round bars. Finally, three set of samples were heated up 1000 ℃, 1100 ℃ and 1200 ℃ for full austenitization and quenched into 5wt% iced brine, then tempering at 250 ℃ for 2 h, respectively. Therefore, the martensite multi-level microstructures are determined via the different quenching temperature.

2.2. Microstructure and mechanical property

The martensite multi-level microstructures, consisting of prior austenite grain, packet, block and lath, were observed by means of OM, FESEM, EBSD and TEM.The specimens were polished and etched in a super-saturation picric acid for optical microscopy (Leica, DMI5000M), to observe the prior austenite grain. And the martensite packets of tested steel were measured by scanning electron microscopy (ZEISS, SUPRA40) after etched from 4% Nital solution. In order to analysis martensite blocks, EBSD images with an orientation imaging microscopy system were used to present it. The samples for EBSD were made in the way of mechanical and vibrating polishing for 10 h, from the VibroMetTM2 vibratory polisher. The lath width was statistically measured by a high-resolution transmission electron microscopy (Tecnai G2 F20 S-TWIN, HR-TEM).The uniaxial tension test of the tested steel was executed on a MTS system.The dimension of tensile samples was prepared from the round bars with the size of Φ7×115.

3. Results and discussions

3.1. Quantitative microstructure analysis

A quantitative microstructure analysis of the various quenching temperature is listed in Table 1 from about averaging 400 grains, 300 packets, 300 blocks and 150 laths. Result shows that the different size of prior austenite grain is obtained based on the different quenching temperature from 15.3μm to 90.3μm. Meanwhile, according to the result from Table 1 and Fig.1, the martensite packets and blocks are increased from 9.8μm to 31.6μm and from1.4μm to 2.78μm, respectively, with the increase of quenching temperature in consistent with prior austenite grain. But the lath width is decreased from 0.342μm to 0.201μm.

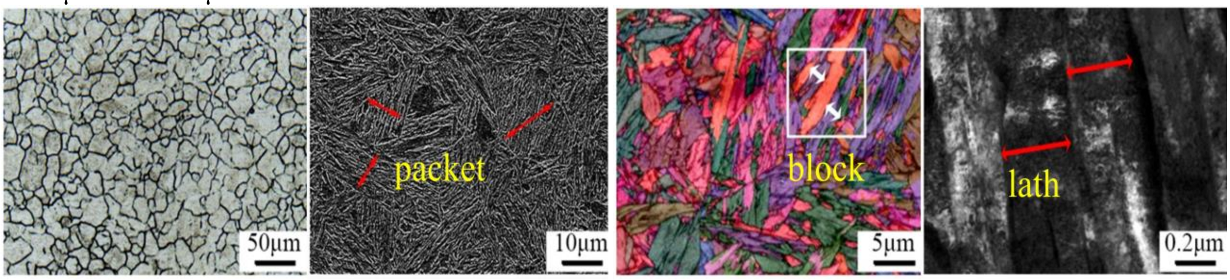


Figure 1. The observation of the martensite microstructure for B1 sample

Table 1. The result of the martensite microstructure for tested steel

No.	Grain dr/μm	Packet dp/μm	Block db/μm	Lath dl/μm
B1(1000℃)	15.3	9.8	1.4	0.342
B2(1100℃)	19.9	11.7	1.64	0.275
B3(1200℃)	90.3	31.6	2.78	0.21

3.2. Effect of martensite microstructures on the yield strength

The martensite packet is a lath groups with the same habit plain in a prior austenite grain, while the block represents a lath groups with the same orientation in a packet. It suggests that the martensite packet and block may depend on the prior austenite grain. The result in Table 1 reveals that the packet and block are increased by 3.22 times and 1.99 times with the coarsening of grains. Furthermore, the following linear relationships in Fig.2 (a) between microstructural parameters can be obtained for the steel, which demonstrate that the packet and block depend on the prior austenite grain, the equation (1) and (2) can describe well the relationship.

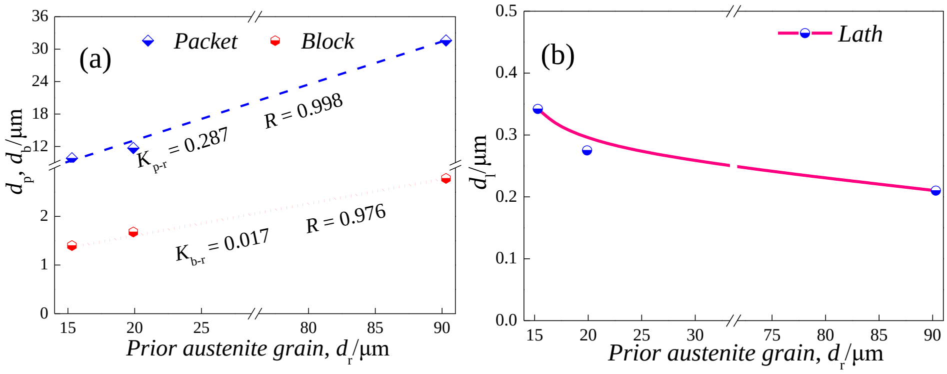


Figure 2. Relationship between (a) martensite packet, block, (b) lath and prior austenite grain

$$d_p = 0.287 d_r \quad (1)$$

$$d_b = 0.017\, d_r \quad (2)$$

However, Fig.2 (b) shows that lath is not determined by the prior austenite grain. The previous works had demonstrated that dl depends on the nucleation rate and martensite start temperature (Ms) [8], with independence on the prior austenite grain. As well, the higher nucleation rate is determined.

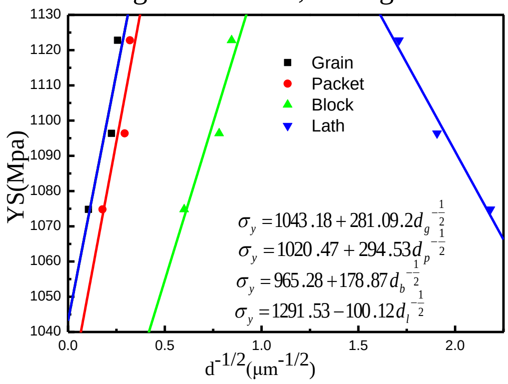
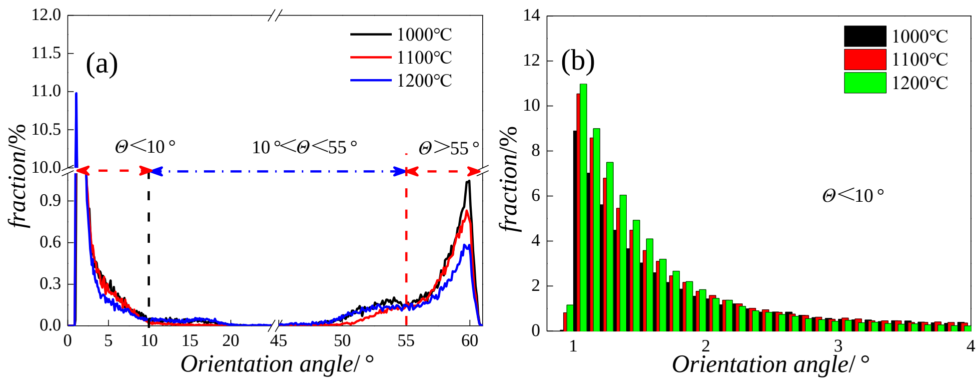


Figure 3. Plots of the yield strength vs. reciprocal square root of substructure

In addition, as shown in Fig.3, Hall–Petch relations are presented for the various substructures. Consequently, the block should be the effective grain size due to the far lower size than the packet size and the prior austenite grain size

3.3. Effect of prior austenite grain on the crystal orientation



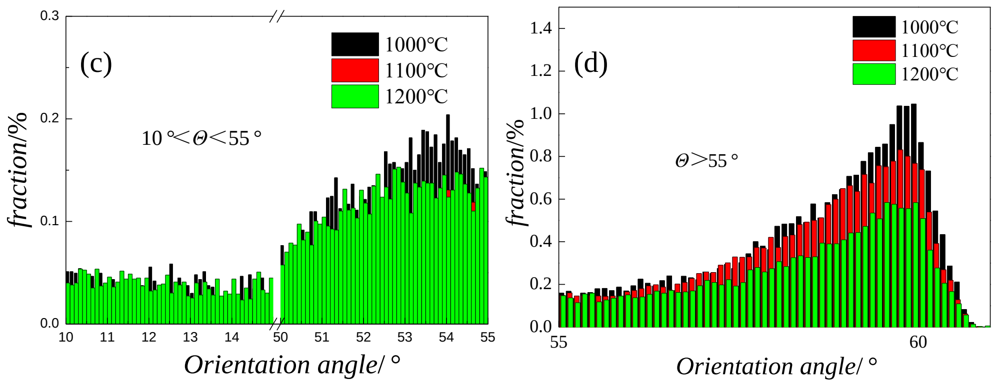


Figure 4. The distribution of orientation from different processes for tested steel, (a) The whole, (b) Θ<10°, (c) 10°<Θ<55° and (c) Θ>55°

In this paper, the martensite orientation is proposed by Tango software, as shown in Fig.4. It is found that the orientation distributions for tested steel are same with the range of 0.8°-62.5°. And the orientation distributions are divided into 3 sections, such as Θ<10°, 10°<Θ<55° and Θ>55°, which are used to represent the boundaries of lath, grain, packet and block [8]. Further observation, the orientations of Θ<10° and Θ>55° in fine grain are different from coarse grain: the number of Θ<10° in coarse grain is higher than fine grain, and the number of Θ>55° is lower than fine grain. It is because the size and number of the multi-level microstructure for different heats are different.

3.4. Effect of martensite microstructures on the plasticity

The mechanical properties for tested steel was obtained by the uniaxial tension test and showed in Fig. 5. And the higher strength is obtained in fine grain because of the more high-angle orientation. In addition, in low-carbon lath martensite steel, the packet and block play more important role in strength.

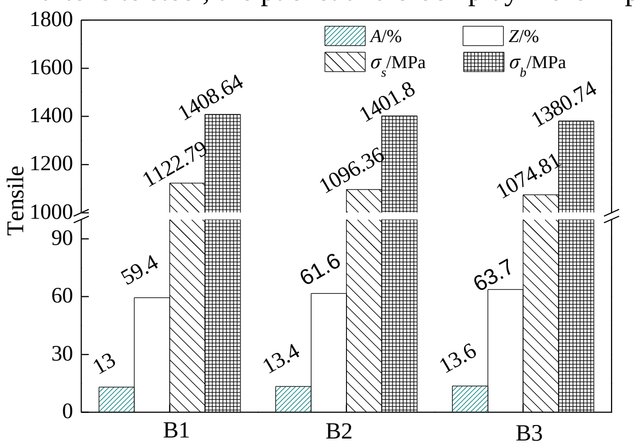


Figure 5. The mean value of the mechanical properties for tested steel

However, the plastic parameters of A% and Z% increase with the coarsening of prior austenite grain from Fig.5, this is contrary to the conventional understanding The increase amplitude of A% and Z% is obtained with 4.6%, and 7.2%. It can be illustrated from two points [12]: (1) In finer grain, the micro-crack is easy to form and propagate along the grain boundaries for the more high-angle boundaries. On the contrary, the more low-angle boundaries decrease the crack initiation, and it is difficult for the crack propagation along the grain boundaries. Therefore, the crack will encounter more laths to improve the plasticity; (2) In lath martensite steel, the fracture is controlled by the strain or the crack propagation. Thus, the prior austenite grain is not effective grain of plasticity.

4. Conclusions

In the present work, the effect of substructure of lath martensite on the mechanical properties was discussed in detail. The main conclusions can be summarized in the following:
(1) Prior austenite grain size, packet and block width increased as the quenching temperature increased, a pretty linear relationship meet between packet width, block width and prior austenite grain size, respectively. The results indicated that the width of block and packet in lath martensite are dependence on the prior austenite grain size.
(2)Yield strength with prior austenite grain size, packet size and block width obeyed Hall-Petch relationship regardless of the variation of quenching temperature. The block should be the effective grain size due to the far lower size than the packet size and the prior austenite grain size
(3) Based on the EBSD analysis, the orientation distribution of tested steels corresponding to different microstructures showed that more high angle boundaries exists in fine microstructure, while more low angle boundaries exists in coarsen microstructure.
(4)The low angle boundary can increase the compatible deformation capability of multi level microstructures, improving the plasticity of lath martensite.

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Acknowledgments

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