DOI 10.1007/s11595-017-1578-x

Effects of Mn on Microstructures and Properties of Hot Rolled Low Carbon Bainitic Steels

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Abstract: Two kinds of Mn-Si-Mo low carbon steels were designed to study the effects of Mn on the microstructures and properties of hot rolled low carbon bainitic steels. To reduce the production cost, a very low Mo content of 0.13% was added in both steels. After hot rolling, the mechanical properties of samples were tested. Microstructure was observed and analyzed by optical microscope and transmission electron microscope. The results show that the strength of tested steels increases with the increase in Mn content, while the elongation decreases. When Mn content increases, the bainite microstructure increases. The results can provide a theoretical basis for composition design and industrial production of low cost low carbon bainitic steels.

Key words: manganese; low carbon bainitic steel; hot rolling; strength

1 Introduction

As bainitic steels have both high strength and high toughness compared with austenite, pearlite and martensite steels, they have been widely applied in many industrial fields, such as car, bearing and railway systems *etc*. Bainitic steel has always been a hot topic for many years[1-9]. Ever since Irvine and Pickering (1957), it has been apparent that good mechanical properties can be achieved in bainitic steels by reducing their carbon concentrations. Irvine and Pickering compromised by choosing a low concentration of carbon at about 0.1 wt% but ensuring hardenability using boron and molybdenum. They were therefore able to produce fully bainitic steels by continuous cooling transformation[10]. Later, ultra low carbon bainitic steels usually adopt very low carbon contents. With the addition of Mn, Ni, Mo, Nb, B, Ti, *etc* alloy elements, bainite can be obtained within a wide range of cooling rates, but the production cost is relatively high[11-13]. In addition, Kang *et al*[14,15] reduced the content of Mo to about 0.25% and canceled the addition of B on the basis of Mo-B bainitic steel. Manganese was used to help reduce bainite start temperature and a certain amount of Si was added to suppress carbide precipitation. Thus Mn-Si-Mo bainitic steels composed of bainite ferrite and carbon-rich residual austenite were developed. Yang *et al*[16] studied the effect of tempering temperature on the microstructure and properties in a Mn-Si-Mo medium carbon steel with 0.2%-0.4% C, 2.0%-4.0% Si+Mn, 0.6%-0.9% Mo+Cr, and Nb+V+Ti<0.15%. Tensile strength and elongation of hot rolled steel were 700 MPa and 7%, respectively. After quenching and tempering, the strength and elongation increased to 1 400 MPa and 15%, but the production cost rose at the same time. Moreover, Li *et al*[17] designed a new bainitic steel with carbon content of 0.25%-0.35%. With the addition of Mn, Si, Cr and 0.02% Re, carbide-free austenite-bainite structure was obtained by casting and isothermal-quenching. Although the strength and toughness were both good, the production cost was relatively high owing to the addition of expensive element Re.

On the basis of the existing researches of bainitic steel, two kinds of Mn-Si-Mo low carbon steels were designed in the present study. Carbon contents were about 0.2%. To reduce the production cost, very low Mo content of 0.13% was added in both steels without other expensive alloy elements. Different Mn contents were designed to investigate the effects of Mn on the microstructure and properties of hot rolled low carbon

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(Received: Oct. 20, 2015; Accepted: Nov. 4, 2016)

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Funded by the National Natural Science Foundation of China (NSFC) (No. 51274154)

bainitic steels. The work provides theoretical basis for the composition design and industrial production of low cost low carbon bainitic steels.

2 Experimental

Steels used in this study were refined in a 50 kg vacuum induction furnace. To study the effects of Mn on the microstructure and properties of hot rolled low carbon steels, different Mn contents were added in two kinds of Mn-Si-Mo low carbon steels. The chemical compositions of tested steels are given in Table 1. With the same rolling technology, ingots were rolled to 12 mm plates by nine-pass rolling on 4-high reversal mill for two steels. The initial and final rolling temperatures were 1 100 ℃ and 870 ℃, respectively. After rolling, the steels were cooled to 500 ℃ at a cooling rate of 30 ℃/s, followed by air cooling to room temperature.

Table 1 Chemical compositions of steels/wt%

Steel	C	Si	Mn	Mo	P	S
1	0.22	1.48	0.97	0.13	≤0.02	≤0.01
2	0.23	1.47	1.94	0.13	≤0.02	≤0.01

Tensile tests were carried out on a UTM-5305 electronic universal tensile machine at room temperature. Tensile specimens were prepared according to ASTM standard and the strain rate was about 4×10^{-3} /s. Then the microstructures were observed by a Zeiss optical microscope (OM) and a JEM-2100F transmission electron microscope (TEM) operated at 120 kV using standard bright field imaging technique.

3 Results

3.1 Mechanical properties

Mechanical properties of the tested steels are given in Table 2. With Mn content changing from 0.97% to 1.94%, the tensile strength increases from 736 to 1 200 MPa, while the elongation decreases from 28% to 19%.

Table 2 Mechanical properties of steels

Steel	Yield stress /MPa	RM /MPa	A5 /%	RA /%
1	455	736	28	49
2	570	1 200	19	34

3.2 Microstructure

Metallographic samples were selected along the rolling direction. After grinding, polishing and etching, the microstructures were observed on a Zeiss OM, as shown in Fig.1. It is revealed that the microstructure of steel 1 is composed of ferrite, perlite and a small amount of bainite. Irregular polygonal ferrite accounts for the most of the structure with an average grain size of 7.55 μm. The microstructure of steel 2 consists of bainite and martensite. Martensite distributed unevenly, mainly concentrating on the segregation band.

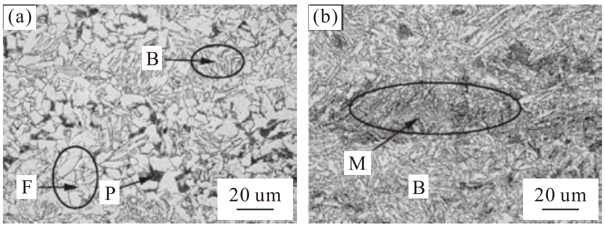

Fig.1 Optical images of steels: (a) Steel 1; (b) Steel 2

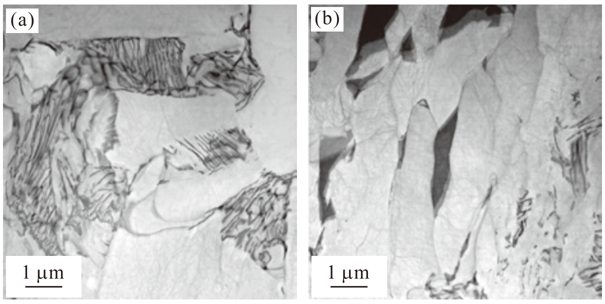

Fig.2 TEM images of steel 1

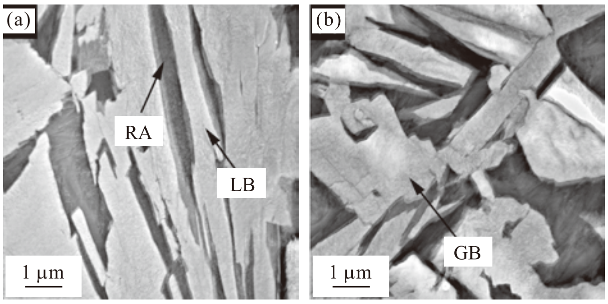

Fig.3 TEM images of steel 2

TEM was used to further study the microstructures of the two steels, as shown in Figs.2 and 3. The fine microstructure of lamellar pearlite can be clearly observed in Fig.2 and the average spacing of pearlite interlamination is 96.78 nm. Very small amount of martensite can also be observed in steel 1. Fig.3 indicates that bainite in steel 2 has two kinds of morphologies: lath-like bainite (LB) with residual austenite (RA) between laths (Fig.3(a)) and granular bainite (GB) (Fig.3(b)).

4 Discussion

According to the optical and TEM microstructures, it is clear that the microstructure of steel 1 is composed of ferrite, pearlite and a small amount of bainite, while the microstructure of steel 2 mainly consists of bainite with a small amount of martensite. The only difference between the two steels is the Mn content. Manganese is a strong austenite stabilizing element. Its diffusion velocity is far below that of C. Meanwhile, Mn can decrease the diffusion coefficients of C and Fe by increasing the self-diffusion activation energy of C and Fe[18]. Therefore, Mn can strongly impede the diffusion-controlled ferrite/pearlite transformation. In the present study, the microstructure of steel 1 contains ferrite and pearlite because of low Mn content. High temperature transformation was avoided for steel 2 due to high Mn content. Therefore, the microstructure of steel 2 consists of only bainite and martensite.

As for bainite transformation, Mn segregates at prior austenite grain boundaries[19]. On one hand, the segregation of Mn significantly suppresses the nucleation of bainite ferrite at grain boundaries[20]. On the other hand, the concentration spike of Mn is bound to cause pining-up effect on α/γ interphase movement, *i e,* solute drag effect, greatly delaying ferrite growth[21]. Moreover, Mn enrichment in the α/γ interphase decreases the activity of the carbon in austenite. Thus, the carbon concentration gradient in austenite will be reduced and so will the growth kinetics of ferrite. This is called the solute drag-like effect[22,23]. These two effects, *i e*, solute drag effect and solute drag-like effect, not only decrease the bainite start temperature, leading to fine microstructure, but also shift the whole bainite transformation region to the right-hand side of the CCT diagram. Wang *et al*[24] studied the effect of Mn on the CCT curve of Mn-Si steels and found that the transformation range of bainite can be separated from that of ferrite/pearlite when manganese content approaches a certain value. In the present study, when Mn content increases to 1.94%, the hardenability needed to avoid ferrite/pearlite transformation is obtained, resulting in the final bainite structure.

With the increase of Mn content from 0.97% to 1.94%, the strength of the tested steels changes from 736 to 1 200 MPa, which can be attributed to transformation strengthening and solid solution strengthening. The increase of the flow stress of a metal due to the presence of dispersed foreign atoms is referred to as solid solution hardening[25]. Mn dissolved in ferrite results in lattice distortion, leading to the improvement of strength. For the tested steels, the only difference is the Mn content. Yield stress difference between the two steels is 115 MPa. According to Eq.(1)[26], the influence of solid solution strengthening, *i e*, the increase of Mn content, on the yield stress is 30.56 MPa. In the present study, dislocations strengthening and precipitation strengthening can be considered the same for both steels because of the same processing route and no addition of microalloying elements. Thus the influence of transformation strengthening on the yield stress is 84.44 MPa.

$$\sigma_{\mathrm{ss}} = \sum K_i C_I \qquad (1)$$

where σ_{ss} is the increment of solid solution strengthening, K_{i} the strengthening coefficient for solid solution strengthening of solute *i*, and C_i the concentration of solute *i*. Table 3 shows the solid solution strengthening coefficients of each element in solution.

Table 3 Solid solution strengthening coefficients of each element in solution[26]

Solute *i*	C	N	Si	Mn	Cu	Mo	Ti	Nb
K_i	5 082	5 082	83	31.5	39	11	80	2 400

In summary, for low carbon steel with 0.2% C and 0.13% Mo, it is suggested that the Mn content should be about 2.0% to obtain bainite structure if no other expensive alloy elements are added.

5 Conclusions

Two kinds of Mn-Si-Mo low carbon steels were designed. After hot rolling, the microstructures were observed by OM and TEM. Mechanical properties were measured by tensile test. The results show that with the increase of Mn content, the strength of the tested steels increases due to transformation strengthening and solid solution strengthening, while the elongation decreases. When the Mn content increases the bainite microstructure increases. For low carbon steel with 0.2% C and 0.13% Mo, bainite can be obtained when the Mn content reaches about 2.0% if no other expensive alloy elements are added. The work provides a theoretical basis for the compositional design and industrial production of low cost low carbon bainitic steels.

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