Effect of microalloying elements on microstructure and properties of quenched and tempered constructional steel

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Abstract: The effects of microalloying elements Nb, V and Ti on microstructure and properties of quenched and tempered steel were studied. Results showed that the addition of microalloying elements led to the formation of bainite and increased strength, while the austenization and ferrite transformation temperature was barely affected, i.e. 10°C. Microalloying elements shortened the incubation time for bainite transformation by refinement of austenite grain, and decreased the hardenability by forming carbides and therefore reducing the carbon content of super-cooled austenite. Either of them promoted the bainite transformation. The better tempering stability was ascribed to the as hot-rolled bainite microstructure and secondary carbide precipitation during tempering.

1. Introduction

For the high-strength low-alloy steels with quenched and tempered delivery conditions, it is necessary to add Cr, Ni and Mo elements to ensure the hardenability of the steel plate. The addition of these elements increases the carbon equivalent and welding crack sensitivity. Therefore, in order to ensure welding performance, the amount of these elements would be restrained. In this paper, a 450MPa grade quenched and tempered steel was selected as the research object. Two chemistry, i.e. with and without addition of Nb, V and Ti, were designed to investigate the effects of microalloying elements on the microstructure and mechanical properties.

2. Experimental

The experimental material is 450MPa grade quenched and tempered steel. The chemical composition of the experimental steels is listed in Table 1. Two chemical compositions are proposed, one of which is referred to as non-microalloyed, and the other is microalloyed.

| Elements                  | C    | Si   | Mn   | P    | S    | Ni+Cr+Mo | Nb + Ti+V |
|---------------------------|------|------|------|------|------|----------|-----------|
| Non-microalloyed          | 0.079| 0.24 | 1.02 | 0.006| 0.004| 1.9      | -         |
| Microalloyed              | 0.082| 0.29 | 0.97 | 0.006| 0.004| 1.9      | 0.087     |

The ingots were prepared by vacuum melting, and forged into 220mm×170mm×175mm in size. After homogenization at 1200°C for 150min, the ingots were rolled into 60 mm in recrystallization region. After holding, they were rolled into 20mm in non-recrystallization region and finishing rolling temperature of 840°C. Then, the hot-rolled plates were air cooled down to room temperature.
Subsequently, the hot-rolled samples were quenched and tempered. After holding at 900 °C for 50 min, they were immediately quenched into water, then reheated to 650 °C, 670 °C and 700 °C, respectively, with a holding time of 60 min.

Cylindrical specimens with 5 mm diameter and 25 mm length were cut from hot-rolled plates for the measurement of phase transformation temperature using dilatometer. According to GB/T 225-2006, bar samples with a dimension of $\varnothing 25 mm \times 100 mm$ were machined from forged ingots for JOMINY test. Specimens with the dimension of $\varnothing 10 mm \times 50 mm$ and $10 mm \times 10 mm \times 55 mm$ were prepared after heat treatment. Tensile tests and CVN tests were carried out at room temperature and -40 °C respectively. Microstructure characterizations were made by optical microscopy (OM) and scanning electron microscopy (SEM) with samples polished and etched for 13 s in the mixture of 4% nitric acid and alcohol.

3. Results

3.1 Effect of microalloying elements on microstructure and mechanical property of hot-rolled sample

The microstructures and mechanical properties of hot-rolled samples were shown in Fig. 1 and Table 2, respectively. As shown in Fig. 1, the microstructure of non-microalloyed sample is “P+F”. Because of the solute microalloying elements in austenite which delay the ferrite transformation, and promote bainite transformation [2], the microstructure of microalloyed sample is “B+F+P”. The differences in microstructures lead to better properties of microalloyed sample when compared with non-microalloyed one. The lower Impact energy was due to the process of air-cooling after rolling.

![Fig. 1 OM images of hot-rolled samples (a) non-microalloyed; (b) microalloyed](image)

| Elements          | Transverse | Longitudinal | -40°C AKv/J |
|-------------------|------------|--------------|-------------|
|                   | Rel/MPa    | Rm/MPa       | A/% Z/%     | Rel/MPa    | Rm./MPa | A/% Z/% | AKv/J |
| Non-microalloyed  | 350        | 530          | 23.0 80     | 335        | 570     | 20.0 79 | 41 62 50 |
| Microalloyed      | 501        | 738          | 18.0 54     | 507        | 790     | 21.5 66 | 24 31 48 34 |

3.2 Effect of microalloying elements on hardenability

The effect of microalloying elements on the transformation temperature was measured by dilatometer. Results were shown in Table 3. It is shown that the addition of microalloying elements, Nb, V, Ti, has little effect on the phase transformation temperature. The temperature of fully austenization for the microalloyed and non-microalloyed steels is 857.6 °C and 864.8 °C, respectively. Thus, the quenching temperature was chosen as 900 °C.
Table 3 Effect of microalloying elements on transformation temperature

| Elements       | Heating                      | Cooling                      |
|----------------|------------------------------|------------------------------|
|                | Start transformation temperature/°t | Finish transformation temperature/°t | Start transformation temperature/°t | Finish transformation temperature/°t |
| Non-microalloyed | 726.5                        | 857.6                        | 733.1                        | 671.9                        |
| Microalloyed   | 729.7                        | 864.8                        | 745.5                        | 678.5                        |

JOMINY tests were carried out with the specimen Ø25 mm×100 mm in size. The sample was heated to 900 °C, holding for 30 min, followed by water-quenching immediately. Variation in hardness as a function of the distance to the quenching surface is shown in Fig.2. It can be seen that, within 0 ~ 15mm, the hardness of non-microalloyed specimen is higher than that of microalloyed one, because the corresponding microstructure is martensite and bainite, respectively. However, for >15mm, the microstructures of both steels were bainite, while the hardness of microalloyed specimen was higher than that of microalloyed one, due to precipitation strengthening microalloying carbides. The JOMINY tests showed that microalloying elements contribute to the decreased hardenability.

![Fig.2](image1.png)

**Fig.2** Effect of microalloying elements on hardenability

The microstructures and mechanical properties of quenched specimens were shown in Fig.3 and Table 4, respectively. The microstructure of non-microalloyed steel is martensite (Fig.3(a)), and that of microalloyed steel is “bainite + small quantity of martensite”(Fig.3(b)). As shown in Table 4, the non-microalloyed steel achieved a higher yield strength but a lower plasticity.

![Fig.3](image2.png)

**Fig.3** Microstructure of two kinds of quenched and tempered steels (a) non-microalloyed; (b) microalloyed
Table 4 Effect of microalloying elements on properties of quenched specimens

| Elements         | Transverse |        |        |       | Longitudinal |        |        |
|------------------|------------|--------|--------|-------|--------------|--------|--------|
|                  | Rel/MPa    | Rm/MPa | A/%    | Z/%   | Rel/MPa      | Rm/MPa | A/%    | Z/%   | -40°C | AKv/J |
| Non-microalloying| 676        | 855    | 14.0   | 73    | 754          | 956    | 13.0   | 72    | 198   | 207  |
| Microalloying    | 596        | 857    | 17.0   | 71    | 610          | 846    | 17.0   | 71    | 133   | 152  |

3.3 Effect of microalloying elements on microstructure and properties of quenched and tempered steel

Effect of microalloying elements on microstructure and mechanical properties of quenched and tempered steel were studied. As shown in Fig.4, the microstructure of the non-microalloyed and microalloyed steels is tempered martensite and “bainite+massive ferrite+small amount of tempered martensite”, respectively. In Fig.5, it is suggested that the strength of the tempered specimen is lower than that of the quenched state. However, with the increasing of tempering temperature, the strength of non-microalloyed steel decreased and the plasticity increased. However, when tempered in the range of 650 °C -700 °C, the strength and plasticity of microalloyed steel had little change and showed good tempering stability.

Fig.4 Microstructure of quenched and tempered steel
Non-microalloyed: (a)650°C; (b)670°C; (c)700°C; Microalloyed: (e) 650°C; (f) 670°C; (g) 700°C
4. Discussion

The influence of microalloying elements, Nb, V and Ti, on the microstructures and properties of quenched and tempered steel mainly includes two aspects. One is the effect of microalloying elements on the transformation during quenching, the other is the effect of precipitation of microalloying elements on properties during tempering. The latter has been researched systematically\(^{[3-4]}\). Thus, the former would be discussed in detail.

It can be seen from Table 3 that the addition of Nb, V, Ti microalloying elements has little effect on the austenization temperature, with the same austenization temperature and cooling rate, the effect of microalloying elements on the microstructure transformation during quenching was explained by empirical formula designed for the heat treatment process. The critical cooling rate formula is shown in Formula 1. Formula 2 shows the critical cooling rate of martensite transformation when quenched in the oil. Formula 3 shows the expression for the calculation of the bainite transformation incubation period\(^{[5]}\). It can be seen from the formula that the effect of microalloying elements is not present. The microalloying elements precipitate in the form of carbides during the rolling and air-cooling, resulting in a decreased carbon content in austenite during quenching\(^{[6]}\). The additions of microalloying elements increase the transformation temperature of super-cooled austenite to martensite and critical cooling rate. On the other hand, it has already been confirmed that microalloying elements play a role on grain refinement during steel rolling. Due to the genetic function of the austenite grain size in the austenization process\(^{[7]}\), the addition of microalloying elements decreases the grain size of the supercooled austenite during quenching. According to the incubation period of bainite transformation, with the other chemical composition of the same, the addition of microalloying elements reduces the carbon content in the supercooled austenite and decreasing the grain size. The combination of these two factors shortens the incubation period of bainite transformation, promoting the transformation from supercooled austenite to bainite. Thus, the addition of microalloying elements promotes bainite transformation and inhibits martensite transformation.

\[
\text{Ms}=561-474C-33\text{Mn}-17\text{Cr}-17\text{Ni}-21\text{Mo} \quad (1)
\]

Where Ms represents martensite start temperature;

\[
\text{Log}v\text{M}=9.81-4.62C+1.10\text{Mn}+0.54\text{Ni}+0.50\text{Cr}+0.60\text{Mo}+0.00183\text{PA} \quad (2)
\]

Where \(v\text{M}\) presents critical cooling rate, \(\text{PA}\) represents austenization condition.

**Fig.5** Effect of microalloying elements on property of quenched and tempered steel.
\[
\tau_B = \frac{(2.34 + 10.1C + 3.8Cr + 19Mo) \times 10^{-4}}{\beta \times \exp \left(\frac{-27500}{RT} \right) \times (\Delta T)^2 \times 2^{(6-1)/2} J_0 \int_0^X \exp[X^2(1.9C + 2.5Mn + 0.9Ni + 1.7Cr + 4Mo - 2.6)] \times \frac{2(1-X)}{3} \times \frac{2X}{3} (1 - X)^{\frac{2X}{3}}}
\]

Where \(\tau\) represents incubation period, \(T\) represents transformation temperature, \(\beta\) represents correction factor, \(X\) represents transformation, \(\Delta T\) represents degree of supercooling, \(G\) represents grain size.

5. Conclusions

1. Microalloying elements have little effect on the thermodynamics of phase transformation in the quenched and tempered steel.

2. Microalloying elements can increase critical cooling rate and shorten the incubation period of bainite transformation, therefore promote bainite transformation during quenching process.

3. The better tempering stability was ascribed to the hot-rolled bainite microstructure and secondary carbide precipitation during tempering in microalloyed steel.

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