Effective rare earth on isothermal transformation kinetics in high strength-toughness tool steel

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Abstract. The effect of rare earth on phase transformation kinetics in new high strength-toughness drilling tool steel during isothermal transformation has been investigated systematically, and the TTT diagrams were obtained. The results show that rare earth improves the value of phase transformation activation energy; The TTT diagrams have been shifted to right and down with the increment of rare earth, and nose temperature decreased from 385℃ to 350℃ in drilling tool steel.

1. Introduction
Under the severe wear of rocks and corrosion conditions of high-pressure water (or gas), the rock and oil drilling tools bear composite force of bending force, pulling force, stress and twisting force. Its fatigue life is only from tens of minutes to tens of hours. The market of drilling tools sales nearly $10,000,000,000 every year. And the annual consumption of drilling tools is nearly 100 times of China. How to further improve it’s fatigue life is great significance to win the international market on China’s mining industry. In this paper, the effect of rare earth on isothermal transformation kinetics in new high strength-toughness drilling tool steel was systematic researched. Which was on the basis of study on the effects of rare earth elements in this kind of drilling tool steel sub-structure [1-6].

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Foundation item: Research project of Tianjin Municipal Education Commission (20130319); Research project of Tianjin Metallurgical vocation-technology Institute (201115)

2. The experimental method
The experimental steel was smelted in LF furnace. After the deoxidation and desulfurization, adding different amount of the mixed rare earth of cerium and lanthanum. The composition of experimental steel was in Table 1:

| Sample No | C       | Mn    | Si    | Rare earth | S     | P     |
|-----------|---------|-------|-------|------------|-------|-------|
| 1         | 0.18~0.22 | 1.85~2.2 | 0.95~1.2 | 0.008      | ≦0.015 | ≦0.01 |
| 2         | 0.18~0.22 | 1.85~2.2 | 0.95~1.2 | 0.022      | ≦0.015 | ≦0.01 |

The experimental steel was processed into thin slices of 12mm×12mm×5mm after hot-rolling. It was heated to 900℃ with 30℃/min heating rates by the chamber type electric furnace. After 20
minites, then quickly put it into 300°C, 350°C, 400°C, 450°C, 500°C of salt bath respectively. The experimental steel in salt bath isothermal at different time was quenched by ice brine. The martensite point was measured by DIL-402C static and dynamic thermal expansion instrument. NO 1 steel’s Ms and Mf points were 386°C and 225°C; NO 2 steel’s Ms and Mf points were 370°C and 200°C. Combining with microscopic test and hardness measurement, determination of bainite volume fraction of different heat treatment conditions was tested by quantitative metallography.

Fig. 1 Microstructure of experimental steel in isothermal 1000s at 400°C
(a) No. 1 steel(RE=0.008%); (b) No. 2 steel(RE=0.022%)

3. Experimental results and analysis

3.1 Effect of rare earth on isothermal transformation kinetics in new high strength-toughness drilling tool steel

Rare earth added to the steel can have a great effect on the bainite transformation. Figure 2 showed the macro kinetics of experimental steel during isothermal phase transformation of bainite. The effect of rare earth had varied greatly on isothermal kinetics between in Mf ~ Ms points and above Ms points in experimental steels.
Figure 2(a) showed the isothermal transformation kinetics curves of 300℃, which can be divided into two stages. In the first zone, the transformation rate of two kinds of contents of rare earth in experimental steel is fast. In contrast, the transformation rate of NO 1 steel was faster than NO 2 steel, which incubation period was more lag. This is because that rare earth can reduce the activity coefficient of carbon in austenite and lead to the chemical driving force of bainite transformation increased. In the preliminary stage of bainite transformation, rare earth improved the hardenability and slowed the rate of bainite transformation. So in the same isothermal time, the volume fraction of bainite was less in NO.2 steel. In the second zone, the phase transformation speed of NO.2 steel was faster than NO.1. But the curve (Figure 2(b)) of isothermal transformation kinetics in 350℃ was the opposite. In the first zone, the incubation period of NO.2 steel has significantly shorter. In the second zone, however, rare earth mainly through segregation on ferrite / island phase interface pinning movement phase interface to reduce the phase change rate. In this stage, rare earth can delay the phase change process and prolong the completion time of phase transition [7-8].

Figure 2 (c), (d), (e) were described the characteristics of isothermal transformation kinetics above Ms points. Statistics indicate that the time of phase transition of NO.2 steel was more than NO.1 steel. In this isothermal temperature range from 400℃ ~ 500℃The dominant factor of bainite transformation hysteresis was that rare earth improve experimental steel hardenability.

3.2 The effect of rare earth on the phase transformation activation energy of experimental steel
At different isothermal temperatures, in order to study the effect of rare earth on bainite transformation kinetics, we made the data graph 2 and graph 3 that reflected the relationship between the volume fraction of bainite and the phase transformation activation energy of experimental steel.
In Fig.3 and Fig.4, $t_{15}\%$, $t_{50}\%$, $t_{90}\%$ referred to the time of the volume fraction of bainite reached to 15%, 50%, 90%; $Q_{15}\%$, $Q_{50}\%$, $Q_{90}\%$ referred to the phase transformation activation energy of the volume fraction of bainite reached to 15%, 50%, 90%. $\lg t$ and 1/T is basically linear relation, the line took turn at 400℃, whose slope of the line was $-\frac{Q}{R}$. It’s the minimum value of the phase transformation activation energy when reached 50% transformation of bainite. With the increasing of the volume fraction of bainite, the value of Q was increased rapidly above 400℃. Under the same conditions, the value of Q of NO.2 steel was always higher than that of NO.1 steel.

3.3 Effect of rare earth on the TTT diagram of experimental steel

Figure 5 was the TTT diagrams of the experimental steel, which showed the relationship between the volume fraction of bainite and logarithmic transformation time at different temperatures.

The results showed that rare earth makes the TTT diagrams to the right and down. Nose temperature was 385℃ in NO.1 steel but 350℃ in NO.2 steel. The incubation period of NO.2 steel was longer than NO.1 steel at 300℃ ~ 400℃. However, the opposite situation appears at 400℃ ~ 500℃.
Fig. 6 TEM fine microstructure of bainite of experiment steel by air cooling
(a) No.1 steel (RE=0.008%); (b) No.2 steel (RE=0.022%)

Rare earth atom been located defect and sub grain boundary had an important impact[9] on the growth of bainite. Figure 6 shows that when the fraction of rare earth of solid solution was increased, rare earth can lead to refine subplates and subunits through stepped grow growth of bainite. Which had been segmented by the retained austenite film. The bainite subplates width and sub-unit size of NO.2 steel were 200nm ~ 900nm and 30nm ~ 150nm respectively. The value of rockwell hardness and impact toughness were HRC44 and 200J/cm2, which was better than NO.1 steel. The microstructure consisted of refined lath bainite and retained austenite films can significantly improve the strength and toughness of experimental steel.

4. Conclusion
(1) Rare earth can shorten the bainite transition time at 300℃ ~ 400℃ isothermal; But it has lengthened the bainite transformation time at 400℃ ~ 500℃ isothermal in new high strength-toughness drilling tool steel.
(2) Rare earth made the TTT diagrams to the right and down and increased the activation energy of phase transition.
(3) The new high strength-toughness drilling tool steel can obtain lath bainite in air cooling condition. With the increase of rare earth, the sub-structure of bainite was more refined.

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