Effect of isothermal time and alloy elements on bainitic transformation below Ms in medium Mn Steels

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Abstract. For Fe-C-Mn-Si system, the effect of cobalt, aluminium, manganese and isothermal time on the bainitic transformation, especially the kinetics of isothermal bainitic transformation below Ms temperature, was studied by dilatometry and scanning electron microscope (SEM). The microstructure of the steels at room temperature was observed and the results showed that cobalt could increase the transformation rate of isothermal bainitic transformation below Ms temperature and aluminium had the opposite effect. And higher content of manganese could also lead to slower bainitic transformation. The incubation time of isothermal bainitic transformation almost disappeared below Ms temperature. The bainitic transformation plays an important role on the redistribution of carbon, so it could be used to improve the austenite stability and increase the plasticity of the steel.

1. Introduction
Under the trend of energy saving and emission reduction, automobile lightweight is an inevitable trend of automobile industry development. Nowadays, advanced high strength steels (AHSS) plays an important role in automobile lightweight and safety. So, it has been widely used in automobile industry. A great many researchers begin to pay attention to the 3rd generation AHSS, because they have the advantages of both low cost and high strength-plasticity product after developing from the 1st and 2nd generation AHSS. At present, the researches of the 3rd generation AHSS mainly focus on obtaining multi-phase structures including residual austenite by different technical routes. The 3rd generation AHSS maintain high plasticity mainly by transformation induced plasticity (TRIP) effect and use multiple strengthening mechanism to obtain high strength[1].

In the field of 3rd generation AHSS, medium Mn steels attracted much attention because of their low cost and good mechanical properties. For medium Mn steels, bainitic transformation was also an important topic. In most studies, the heat treatment process was subcritical annealing in two-phase region, which could obtain annealed martensite (lath-structure ferrite) and residual austenite[2]. Because the formation of ferrite in medium Mn steels decreased the strength significantly, bainite, which had better strength than ferrite, could be used to increase the strength of medium Mn steels and maintain the strength-plasticity product at the same time. However, because of the high hardenability, martensite formed in medium Mn steels even by air cooling. So, few studies reported the formation of bainite in medium Mn steels.

Bainitic transformation could be affected by composition and process parameters including temperature and time. Previous works[3] showed that bainitic ferrite plates could form in the low temperatures treatment and the low-temperature reaction could take 2–60 days over the range of 125–325°C. Co and Al could decrease the bainitic transformation time significantly. Except for
composition, prior martensite and isothermal time could also affect bainitic transformation. Girault et al. [4] reported that in Fe-0.1C-1.5Mn-1.5Si systems with the increase of the isothermal time bainite volume fraction increase and the retained austenite was gradually stabilized. Bainitic transformation below the martensite start temperature (Ms) were reported in Fe-0.2C-3.51Mn-1.52Si alloys by microstructural analysis and the effect of prior martensite was discussed[5], but the relationship between microstructure and isothermal time was not further discussed.

In summary, the bainitic transformation could be used to design and improve the mechanical properties of AHSS, but it could be affected by different factors as composition, process parameters including isothermal time. Before bainitic transformation was used to improve the mechanical properties of medium Mn steels, the bainitic transformation kinetics should be analyzed in detail, especially the effect of composition and process parameters. In this work, the effect of Mn, Co, Al, and isothermal time on bainitic transformation were studied by dilatometry. Isothermal heat treatment below Ms was discussed in CMnSi steels, in order to reveal the correlation between microstructure and isothermal time. In 0.2C-2.82Mn-1.6Si alloy below Ms with the increase of the isothermal time bainite volume fraction increase and the retained austenite was gradually stabilized. And it could provide theoretical basis for the design retained austenite.

2. Material and Methods

2.1. Chemical compositions of t experimental steels
For the improvement of composition, several element were mainly studied as C, Si, Mn, Al, Co, Cr, etc. The C element was not only an indispensable element for solid solution strengthening, but also a strong austenite stabilizer. C and Mn were normally used to control the austenite stability by partition, because austenite stability was one of the most important factor for the mechanical properties of the steels based on TRIP effect. Si was mainly used to inhibit the formation of carbides. Generally, Al and Co could be used to increase the Gibbs free energy difference of Gγ→Gα[6] and accelerate austenite decomposition. Five experimental steels(A, B, C, D and E) were fabricated by vacuum furnace and casted to ingots. Then, the ingots were forged to slabs. The tested composition was shown in Table 1, in which Fe-0.21C-3.92Mn-1.60Si for A steel was reference composition. B and C steels were used to analyze the effect of Al and Co, respectively. D and E steels were used to analyze the effect of Mn content. The slabs were homogenized at 1200°C for 2h before hot rolling. 6mm slabs were manufactured by seven pass rolling with the finish rolling temperature at 870°C and finally quenching to room temperature by water.

| No. | Steels    | C   | Mn   | Si   | Al   | Co   |
|-----|-----------|-----|------|------|------|------|
| A   | Ref       | 0.21| 3.92 | 1.60 | 0.01 | -    |
| B   | Ref+Al    | 0.21| 4.05 | 1.65 | 1.40 | -    |
| C   | Ref+Co    | 0.20| 3.95 | 1.61 | 0.03 | 1.97 |
| D   | Ref-Mn    | 0.20| 2.82 | 1.58 | 0.02 | -    |
| E   | Ref+Mn    | 0.21| 5.14 | 1.58 | 0.02 | -    |

2.2. Experimental methods
As Fig.1, the samples were cooled down to the quenching temperature (QT) below Ms after full austenitization, in order to compare the bainitic transformation kinetics below Ms in different alloys. The heat treated steels were electropolished after cutting and hand polishing. Smart Lab 9kW X-ray diffractometer(XRD) were used to test the phase volume fraction and average carbon content of retained austenite at room temperature. The morphology was observed by JSM-7001F field emission scanning electron microscope.
Samples were selected from the hot rolling slabs and the critical phase transformation point was tested by DIL805 phase transformation tester (TA Instruments Corporation USA). Main heat treatment parameters and the transformation points tested results were shown in Table 2. In Ref-Mn alloy the isothermal time included 60 s, 300 s, 500 s, and 1800s to analyze the effect of isothermal time on bainitic transformation and final microstructure. In Ref+Mn alloy the bainitic transformation was very slow so that the isothermal time was up to 28800 s.

Table 2. Experimental steels and corresponding key transformation temperature

| Steels   | Heating rate (°C/s) | Austenitization temperature (°C) | Austenitization time (s) | Ac1 (°C) | Ac3 (°C) | Ms (°C) | Cooling rate (°C/s) | QT (°C) | Isothermal time (s) |
|----------|---------------------|----------------------------------|--------------------------|----------|----------|---------|---------------------|---------|--------------------|
| Ref      | 1000                | 1000                             | 180                      | 733      | 830      | 315     | 1                   | 290     | 1800               |
| Ref+Al   | 1050                | 1050                             | 300                      | 747      | 1020     | 331     | 1                   | 290     | 1800               |
| Ref+Co   | 1000                | 1000                             | 500                      | 747      | 830      | 324     | 1                   | 290     | 1800               |
| Ref+Mn   | 1000                | 1000                             | 180                      | 743      | 840      | 350     | 5                   | 330     | 300, 500, 1800     |
| Ref+Mn   | 1000                | 1000                             | 180                      | 719      | 788      | 283     | 1                   | 240     | 28800              |

3. Results and discussion

3.1. Effect of isothermal time on bainitic transformation below Ms temperature

The changes in length as a function of temperature with different time were shown in Figure 2a. Figure 2a indicated the effect of the isothermal time on the secondary Ms. When the isothermal time was 1800s, the retained austenite was stable in final quench. And the secondary Ms temperatures in final cool stage were 295°C, 120°C, 95°C, respectively, when isothermal time was 60s, 300s, 500s. It showed that the retained austenite increased with the increase of bainite because the bainitic transformation could make carbon enrich into untransformed austenite. Figure 2b showed the effect of the isothermal time on the bainitic transformation kinetics during the isothermal section. The incubation time of isothermal bainitic transformation almost disappeared below Ms temperature. It was mainly because that prior martensite increased the dislocation density. As shown in Figure 2b, with the increase of isothermal time the bainite volume fraction increased within 1800s and the bainite volume fraction remained stable after around 600s isothermally. Therefore in 0.21C-2.82Mn-1.58Si alloy the bainitic transformation reached transformation stasis around 600 s at 330°C.
3.2. Effect of isothermal time on microstructure

Figure 3a showed phases volume fractions of the microstructure including prior martensite (PM), bainite (B), secondary martensite (SM) and retained austenite (RA). As shown in Figure 3a with the increase of isothermal time the bainite volume fraction gradually increase corresponding to Figure 2. And the volume fraction of retained austenite was from 5.5% to 11.7% with the increase of isothermal time. As shown in Figure 3b volume fraction and carbon content of retained austenite firstly increased significantly and then gradually stabilized. Figure 3a and Figure 3b showed that volume fraction of bainite and retained austenite increased with increase of isothermal time. Carbon contents of retained austenite are presented in Figure 3b. It indicated that bainite enrich the carbon of untransformed austenite.

After full austenitization the samples were quenched to below Ms temperature and the athermal martensite formed, namely, the prior martensite. Then the samples were treated isothermally at 330 °C. During the isothermal stage the prior martensite was tempered and it was called tempered martensite (TM) in final microstructure. As shown in Fig.4 the final microstructure consisted of tempered martensite, bainite, secondary martensite and retained austenite. Generally lower bainite consisted of bainitic ferrite and cementite. However below Ms temperature the bainite ferrite could be thin plate and the retained austenite was between the bainite ferrite plates. Due to the presence of silicon the cementite was retarded. Therefore carbides may not occur inside the ferrite plates for example the bainite (B) as shown in Fig.4. However silicon only retarded cementite and could not suppressed the carbides. Therefore with the increase of isothermal time the particles of carbide occurred platelets whereas the tempering of martensite led to the precipitation of carbides inside martensite. Therefore the lower bainite and tempered martensite were difficult to distinguish from topography and it was
marked as TM/B (tempered martensite/bainite) as shown in Fig. 4. Also the bainite volume fraction was greater as the isothermal treatment prolong time from 60 s to 500s, neither was secondary martensite. The results corresponded to Fig. 3a.

![SEM micrographs of 0.2C-2.82Mn-1.6Si at 330 °C isothermally for (a) 60 s, (b) 300 s, and (c) 500s.](image)

Figure 4. SEM micrographs of 0.2C-2.82Mn-1.6Si at 330 °C isothermally for (a) 60 s, (b) 300 s, and (c) 500s.

3.3. Effect of composition on bainitic transformation below Ms temperature

Figure 5 showed the dilatometry results of isothermal holding below Ms temperature. The heat treatment was essentially a one-step Q&P process and very evident bainitic transformation can be observed in all cases, even in the most stable Ref+Mn system. It should be noticed that Figure 5b showed the transformation kinetics in a normalize manner, i.e. the fraction of bainite with respect to the amount of austenite at the beginning of the isothermal holding. In the reference system, during the course of isothermal holding, approximately the same amount of isothermal bainite formed as the amount of the prior martensite, which certainly would affect the carbon distribution and hence the austenite condition upon final quenching. As expected, a lower Mn level lead to a faster transformation kinetics and it nearly finished within around 600s at 330°C in the Ref-Mn system.

![Dilatometry results of isothermal transformation below Ms temperature.](image)

Figure 5. Dilatometry results of isothermal transformation below Ms temperature. (a) dilatation curves; (b) volume fraction of bainite during the isothermal stage normalized to the amount of austenite at the beginning of isothermal holding.

However, in the Ref+Mn system, the isothermal holding at 240°C resulted in very slow bainitic transformation, which be attributed to the more Mn content. It should be emphasized that apparently the presence of the prior martensite is a very effective way to introduce bainite in the 5 wt% medium Mn system, in which otherwise bainite is very difficult to form. Compared Ref steel with Ref+Co steel, Co could promote the bainite transformation, and the bainite transformation would increase the stability of retained austenite becase the secondary Ms temperature almost disappeared. In summary, Co and Al had opposite effect on bainite transformation, but similar effect on stability of retained austenite. So, Co and Al could be used to design bainite transformation in AHSSs. Moreover, the results of beginning of the isothermal holding also revealed that the incubation time of bainitic
transformation reduced to nearly 1s in all cases, which could be attributed to a high potential nucleation site provided by the presence of prior martensite[7].

4. Conclusion
In this study, effects of isothermal time and composition on bainitic transformation kinetics were discussed and correlations between bainitic transformation below Ms temperature and austenite stability were analyzed.

Significant bainitic transformation took place below Ms temperature namely during one-step Q&P process in 0.2C-(2.82-5.14)Mn-1.6Si steels. Co addition significantly accelerated the bainitic transformation while Al and Mn retarded the isothermal bainitic transformation below Ms temperature.

The isothermal bainitic transformation below Ms temperature enriched carbon in the retained austenite and hence controlled the stability of retained austenite in final quench. The design of retained austenite could provide a theoretical basis for design of Q&P steels and medium Mn steels.

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