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Bainitic Transformation and Properties of Low Carbon Carbide-Free Bainitic Steels with Cr Addition

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Abstract: Two low carbon carbide-free bainitic steels (with and without Cr addition) were designed, and each steel was treated by two kinds of heat treatment procedure (austempering and continuous cooling). The effects of Cr addition on bainitic transformation, microstructure, and properties of low carbon bainitic steels were investigated by dilatometry, metallography, X-ray diffraction, and a tensile test. The results show that Cr addition hinders the isothermal bainitic transformation, and this effect is more significant at higher transformation temperatures. In addition, Cr addition increases the tensile strength and elongation simultaneously for austempering treatment at a lower temperature. However, when the austempering temperature is higher, the strength increases and the elongation obviously decreases by Cr addition, resulting in the decrease in the product of tensile strength and elongation. Meanwhile, the austempering temperature should be lower in Cr-added steel than that in Cr-free steel in order to obtain better comprehensive properties. Moreover, for the continuous cooling treatment in the present study, the product of tensile strength and elongation significantly decreases with Cr addition due to more amounts of martensite.

Keywords: chromium; bainitic transformation; microstructure; mechanical properties; retained austenite

1. Introduction

Silicon (Si), manganese (Mn), molybdenum (Mo), and chromium (Cr) are important alloying elements in advanced high strength steels (AHSS), such as dual phases (DP) steel, quenching and partitioning (Q&P) steel, quenching-partitioning-tempering (QPT) steel, and carbide-free bainitic steel [1–5]. The amount of these elements in AHSS influences not only the transformation behavior, but also the microstructure and properties of the steel. Therefore, the optimization of the chemical composition in AHSS is always an interesting subject [6–8].

There is a continuous interest in the effects of Cr in AHSS. Han et al. [9] reported that DP steel with more Cr presents better elongation and a lower yield ratio. Li et al. [10] investigated a Cr-bearing low carbon steel treated by a Q&P process. A lath martensite, retained austenite, and lower bainite triplex microstructure was obtained, in which the tensile strength ranges from 1200 MPa to 1300 MPa and the total elongation ranges from 10% to 15%. Jirková et al. [11] found that the yield strength and elongation increase with Cr content in a Q&P steel. Ou et al. [6] investigated the microstructure and properties of QPT steels with Cr addition from a 1.35 wt. % to a 1.65 wt. %. They found that with increasing Cr content, the yield strength decreases, and the elongation first increases and subsequently decreases. Optimal microstructures and properties of steels were obtained at 1.45 wt. % and 1.55 wt. % Cr, respectively, in their study. In addition, Cr is often added in bainitic steel to increase its hardenability, so that a relatively smaller cooling rate can be used to avoid high temperature ferritic transformation and bainite can be obtained more easily [12–16]. However, this does not mean that Cr promotes bainitic transformation itself, because the increase in hardenability is mainly caused by the inhabitation of Cr on ferritic transformation. So far, only a few studies have discussed the effect of Cr on bainitic transformation. Bracke and Xu [17] stated that Cr reduces the kinetics of lower bainitic transformation in a continuous cooling process. But the effect of Cr on isothermal bainitic transformation, which is an important process to produce advanced high strength bainitic steel, is rarely reported. Therefore, it is necessary to further investigate the effects of Cr on bainitic transformation, microstructure, and the properties of bainitic steels.

In the authors' previous study, the effect of Cr on isothermal bainitic transformation was investigated [18]. However, high temperature ferritic transformation occured before isothermal bainitic transformation due to a lower cooling rate and only one heat treatment procedure was used. In the present study, two kinds of heat treatment procedure are designed, i.e., isothermal bainitic transformation (including three transformation temperatures) and continuous transformation. The effects of Cr on bainitic transformation, microstructure, and the mechanical properties of low carbon bainitic steels were investigated. The present study is more comprehensive, and some new findings different from the authors' previous study are obtained. The results are useful to the optimization of the chemical composition of low carbon bainitic steels.

2. Materials and Methods

2.1. Materials

Two low carbon bainitic steels with different Cr contents were designed and their compositions are given in Table 1. The steels were refined and cast in the form of 50 kg ingots using a laboratory-scale vacuum furnace followed by hot-rolling and then air-cooling to room temperature.

Table 1. Chemical compositions of two steels.

Steels	C	Si	Mn	Cr	Mo	N	P	S
Cr-free	0.218	1.831	2.021	/	0.227	<0.003	<0.006	<0.003
Cr-added	0.221	1.792	1.983	1.002	0.229	<0.003	<0.006	<0.003

2.2. Thermal Simulation Experiments

Thermal simulation experiments were conducted on a Gleeble 3500 simulator (DSI, New York, NY, USA). Cylindrical specimens with a diameter of 6 mm and a length of 70 mm were used. As shown in Figure 1, two kinds of heat treatment were designed for the two steels, i.e., austempering and continuous cooling. During austempering treatment, the specimens were heated to 1000 °C to obtain full austenite structure, followed by fast cooling to the isothermal bainitic transformation temperatures (400 °C, 430 °C, and 450 °C) at 30 °C/s. The bainite start temperature (B_S) and martensite start temperature (M_S) for Cr-free steel are calculated to be 524 °C and 376 °C, respectively, using the MUCG 83 program developed by Bhadeshia at Cambridge University, and they are 501 °C and 353 °C, respectively, for Cr-added steel, so that the austempering temperatures are set as 400, 430, and 450 °C. Meanwhile, 1000 °C is higher than the Ac_3 point, and the cooling rate of 30 °C/s is fast enough to avoid ferritic and pearlitic transformations (Section 3.1.1). In addition, during continuous cooling treatment, the specimens were first heated to 1000 °C and then held for 900 s, followed by cooling to room temperature at a rate of 0.5 °C/s. The dilatations along the radial direction were measured for all of the specimens during the entire experimental process.

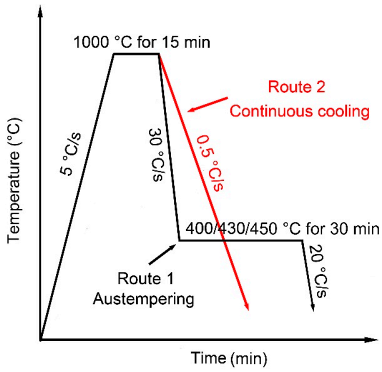

Figure 1. Experimental procedures.

2.3. Microstructure Examinations and Tensile Tests

After the thermal simulation experiments, the microstructures of the simulated specimens were examined by a Nova 400 Nano scanning electron microscope (SEM) (FEI, Hillsboro, OR, USA). In order to determine the volume fraction of retained austenite (RA), X-ray diffraction (XRD) experiments were carried out on a BRUKER D8 ADVANCE diffractometer (Bruker, Karlsruhe, Germany), using unfiltered Cu Ka radiation and operating at 40 kV and 40 mA. In addition, tensile tests were carried out on a UTM-4503 electronic universal tensile tester (SUNS, Shenzhen, China) with a cross-head speed of 1 mm/min at room temperature. Four tensile tests were repeated for each heat treatment procedure, and the corresponding average values were calculated. Then, the tensile fractures of the specimens were observed by SEM.

3. Results and Discussion

3.1. Isothermal Transformation

3.1.1. Dilatation

Figure 2 shows the dilatation versus temperature during the entire austempering treatments (400 °C) for the Cr-free and Cr-added steels. The measured Ac_1 and Ac_3 temperatures for the Cr-free steel are about 777 °C and 906 °C, respectively, and those for Cr-added steel are about 775 °C and 905 °C, respectively. Full austenite microstructures can be obtained at 1000 °C in the two steels, because the austenization temperature (1000 °C) is higher than Ac_3. Chromium addition has little effect on the Ac_1 and Ac_3 temperatures. In addition, the dilatation versus temperature curves are straight lines during the cooling process from 1000 °C to 400 °C at 30 °C/s, indicating that austenite does not decompose before the isothermal holding at 400 °C. Moreover, the apparent increase in the dilatation at 400 °C is caused by the bainitic transformation during isothermal holding.

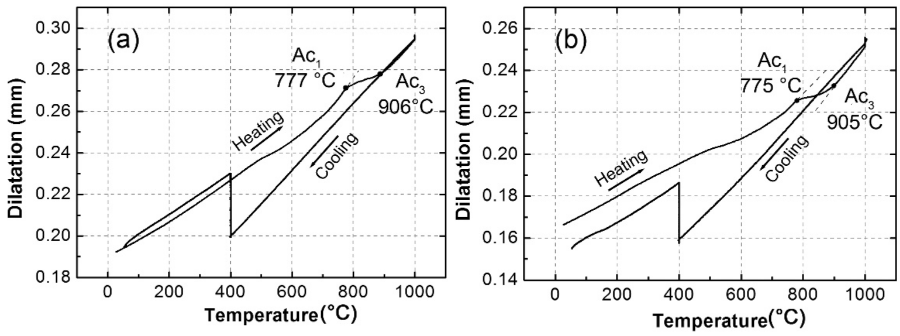

Figure 2. The dilatation versus temperature during the entire austempering treatment (400 °C) for the Cr-free and Cr-added steels: (**a**) Cr-free steel and (**b**) Cr-added steel.

The dilatation (representing the transformation amount) versus time during the isothermal holding at 400 °C, 430 °C, and 450 °C for the two steels is presented in Figure 3a. Chromium hinders the bainitic transformation kinetics, and decreases the final amount of bainitic transformation at all three temperatures. It is interesting to find that the hindrance of Cr on bainitic transformation is more obvious at higher temperatures (430 °C and 450 °C) compared with that at a lower temperature (400 °C). The time-temperature-transformation (TTT) curves of the two steels in Figure 3b, which are calculated by software JMatPro, also demonstrate that the kinetics of bainitic transformation are hindered by Cr addition. The time required to initiate bainitic transformation (2% relative transformation fraction) is listed in Table 2. The experimentally measured values are compared with the calculated values (JMatPro). The comparison shows that the calculated values are larger than the measured values, so that the kinetics of bainitic transformation calculated by JMatPro are slower compared to the experimentally measured one.

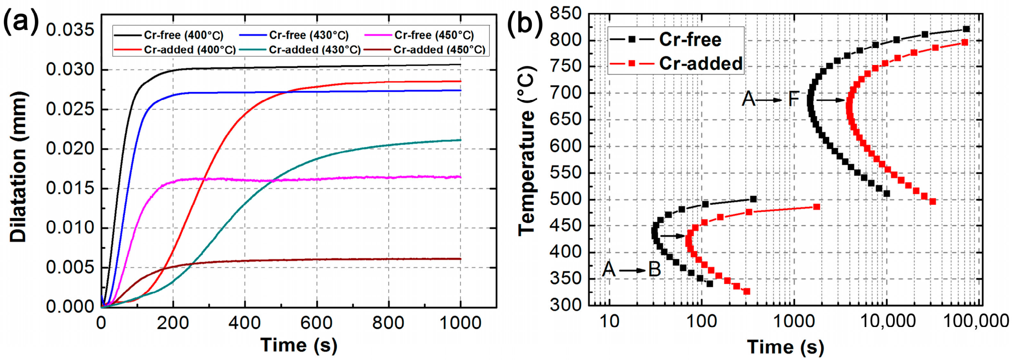

Figure 3. (**a**) The dilatation versus time during the isothermal holding at 400 °C, 430 °C, and 450 °C for the two steels; (**b**) Calculated time-temperature-transformation (TTT) curves of the Cr-free and Cr-added steels showing the start of transformations from austenite A to ferrite F and from austenite to bainite B. It shows that the kinetics of bainitic transformation are hindered by Cr addition.

Table 2. The time needed to initiate bainitic transformation (2% relative transformation fraction).

Steels	Transformation Temperature (°C)	Experimentally Measured Data (s)	Calculated Data (s)
Cr-free	400	6.0	39.4
Cr-added	400	19.4	79.8
Cr-free	430	17.9	31.0
Cr-added	430	45.0	74.3
Cr-free	450	15.3	35.8
Cr-added	450	30.1	129.8

According to the displacive approach of the bainitic transformation proposed by Bhadeshia [19,20], bainitic transformation is expected to occur when:

$$\Delta G_{\mathrm{m}} < G_{\mathrm{N}} \tag{1}$$

$$\Delta G^{\gamma\to\alpha} < -G_{\mathrm{SB}} \tag{2}$$

where $\Delta G^{\gamma\to\alpha}$ is the driving force from γ to α, G_{SB} is the stored energy of bainite (about 400 J/mol), ΔG_{m} is the maximum driving force for the nucleation of bainitic ferrite with paraequilibrium carbon partitioning, and G_{N} is the universal nucleation function. Equation (1) ensures that there is a detectable nucleation rate, and Equation (2) ensures that a diffusionless growth of bainite can occur [19,20]. The values of ΔG_{m} and $\Delta G^{\gamma\to\alpha}$ versus temperature in Cr-free and Cr-added steels are calculated using the MUCG 83 program, and the results are shown in Figure 4. ΔG_{m} and $\Delta G^{\gamma\to\alpha}$ decrease with Cr addition, so that it is more difficult to meet the requirements of bainitic transformation (Equations (1) and (2)) in Cr-added steel. As a result, bainitic transformation is hindered by Cr addition. In addition, it is shown in Figure 4 that the $\Delta G^{\gamma\rightarrow\alpha}$ decreases from −1012 J/mol to −900 J/mol by Cr addition at 400 °C, and it decreases from −864 J/mol to −753 J/mol at 430 °C. The decreased driving forces account for 11% and 13% at 400 °C and 430 °C, respectively, indicating that the decreased driving force accounts for a larger proportion at a higher transformation temperature. A similar result can be obtained for ΔG_m. Therefore, the hindrance of Cr on bainitic transformation is more obvious at higher transformation temperatures.

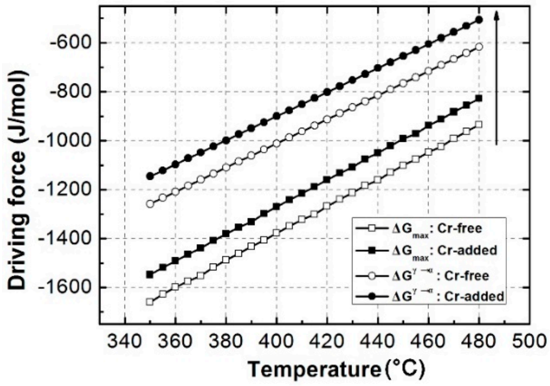

Figure 4. The values of ΔG_m and $\Delta G^{\gamma\rightarrow\alpha}$ versus temperature in Cr-free and Cr-added steels.

3.1.2. Microstructures

The typical microstructures of the Cr-free and Cr-added steels treated by austempering are shown in Figures 5 and 6. The microstructures contain lath-like bainite ferrite (BF), RA, and martensite (M). A selected region is magnified and presented in Figure 5c,d. It shows that ultra-fine BF is separated by film RA. No carbides are observed due to high silicon content [20–22]. When the transformation temperature is 400 °C (Figure 5), the amount and morphology of bainite in the two steels show no significant difference. However, the amount of bainite obviously decreases and the amount of martensite obviously increases with Cr content at 430 °C and 450 °C (Figure 6). This is consistent with the dilatation results (Figure 3).

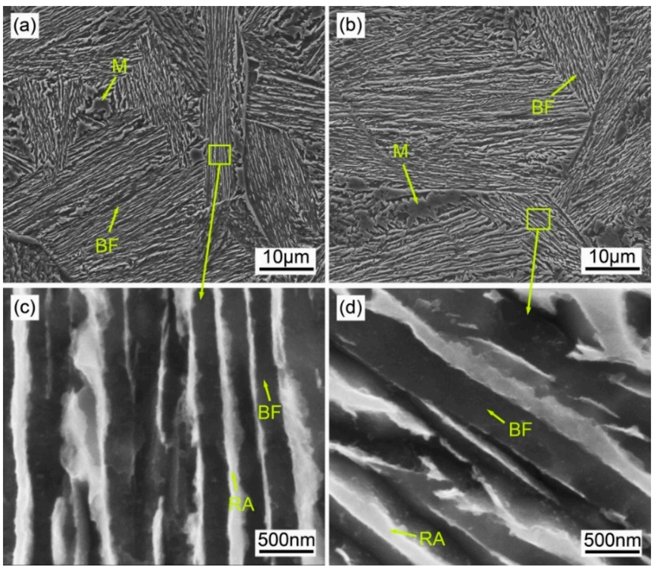

Figure 5. The typical microstructures of the Cr-free and Cr-added steels treated by austempering at 400 °C: (**a**,**c**) Cr-free steel; (**b**,**d**) Cr-added steel. M, martensite; BF, bainite ferrite; RA, retained austenite.

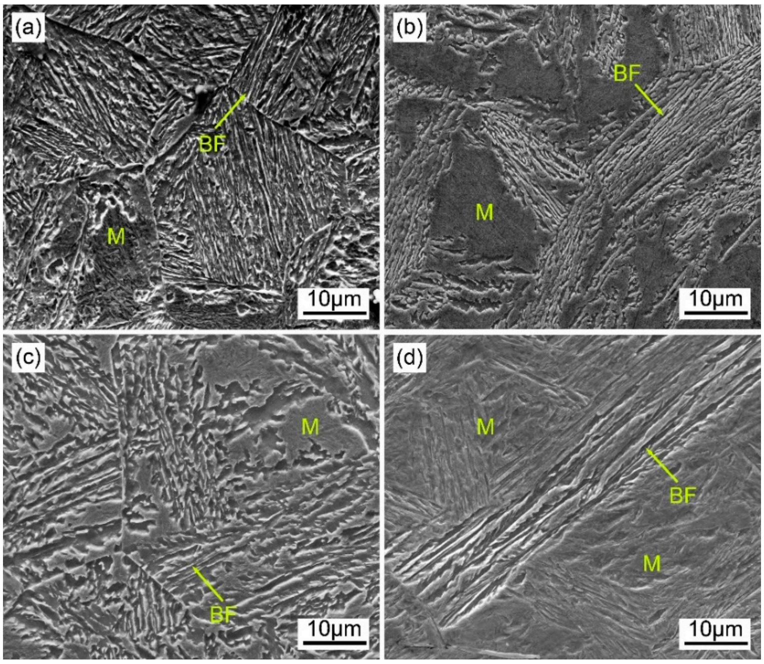

Figure 6. The typical microstructures of the Cr-free and Cr-added steels treated by austempering at 430 °C and 450 °C: (**a**) Cr-free steel, 430 °C; (**b**) Cr-added steel, 430 °C; (**c**) Cr-free steel, 450 °C; (**d**) Cr-added steel, 450 °C.

In addition, the volume fractions of RA (V_γ) in two the steels are calculated according to the integrated intensities of (200)α, (211)α, (200)γ, and (220)γ diffraction peaks based on the following equation [23,24].

$$V_i = \frac{1}{1 + G(I_\alpha / I_\gamma)} \tag{3}$$

where V_i is the volume fraction of austenite for each peak, I_α and I_γ are the corresponding integrated intensities of ferrite and austenite, and the G value is chosen as follows, 2.5 for $I_\alpha(200)/I_\gamma(200)$, 1.38 for $I_\alpha(200)/I_\gamma(220)$, 1.19 for $I_\alpha(211)/I_\gamma(200)$, and 0.06 for $I_\alpha(211)/I_\gamma(220)$ [23,24]. The results show that the volume fraction of RA increases from 6.3 vol. % to 10.1 vol. % with the addition of Cr for austempering at 400 °C, and it slightly increases from 4.0 vol. % to 4.8 vol. % for 430 °C austempering. This is because the stability of austenite is enhanced by Cr addition. In addition, the carbon content in RA (C_γ) is calculated according to the (200)γ and (220)γ diffraction peaks using the method in reference [24] and the results are given in Table 3. The carbon content in RA decreases with Cr addition, because the amount of bainitic transformation, which is accompanied by the partitioning of carbon from bainite ferrite to RA, is smaller in Cr-added steel.

Table 3. The tensile results and RA characteristics of two tested steels treated by austempering. YS, yield strength; TS, tensile strength; TE, total elongation; PSE, product of strength and elongation.

Steel	YS (MPa)	TS (MPa)	TE (%)	PSE (GPa%)	V_γ (vol. %)	C_γ (wt. %)
Cr-free (400 °C)	772 ± 16	977 ± 36	15.8 ± 0.3	15.4 ± 0.79	6.3 ± 1.1	1.18 ± 0.11
Cr-added(400 °C)	649 ± 16	1083 ± 16	18.3 ± 0.4	19.8 ± 0.52	10.1 ± 0.7	1.14 ± 0.08
Cr-free (430 °C)	620 ± 15	986 ± 13	18.5 ± 0.3	18.2 ± 0.55	4.0 ± 0.2	1.13 ± 0.06
Cr-added (430 °C)	786 ± 20	1185 ± 26	11.7 ± 0.9	13.9 ± 0.98	4.8 ± 0.3	0.99 ± 0.03
Cr-free (450 °C)	795 ± 17	1051 ± 19	13.6 ± 0.6	14.3 ± 0.42	3.6 ± 0.4	0.96 ± 0.05
Cr-added (450 °C)	1050 ± 21	1263 ± 23	5.7 ± 0.3	7.2 ± 0.58	2.8 ± 0.2	0.71 ± 0.03

3.1.3. Mechanical Properties

The tensile results of Cr-free and Cr-added steels treated by austempering are given in Table 3. The typical comparison of the engineering strain-stress curves between Cr-free and Cr-added steels treated by austempering is shown in Figure 7. It shows that when the transformation temperature is lower (400 °C), Cr-added steel shows lower yield strength (YS) compared with Cr-free steel due to more amounts of softer phase (austenite) in Cr-added steel. However, the tensile strength (TS) and the total elongation (TE) increase with Cr addition, resulting in the increase in the product of strength and elongation (PSE, TS × TE). One reason for the increase in tensile strength is that Cr acts as the role of solution strengthening. In addition, it is known that RA transforms to martensite during a tensile test, and thus improves the strength and plasticity simultaneously, which is generally termed as the transformation induced plasticity (TRIP) effect [25,26]. There is more RA in Cr-added steel treated by austempering at 400 °C, so that the strength and plasticity of the steel are higher. Moreover, when the transformation temperatures are higher (430 °C and 450 °C), the yield strength and the tensile strength increase, whereas the total elongation significantly decreases with Cr addition. The increase in strength is mainly caused by the obvious increase in martensite amount (Figure 6) and the solution strengthening of Cr. However, more amounts of martensite decreases the plasticity obviously. As a result, the PSE decreases. Therefore, at a lower transformation temperature, Cr addition increases the comprehensive property of the steel, whereas it decreases the comprehensive property of the steel at higher transformation temperatures. Moreover, in the present study, Cr-free steel shows a better comprehensive property at 430 °C, whereas Cr-added steel shows a better comprehensive property at 400 °C. Therefore, the austempering temperature should be lower for Cr-added steel than for Cr-free steel in order to obtain a better comprehensive property.

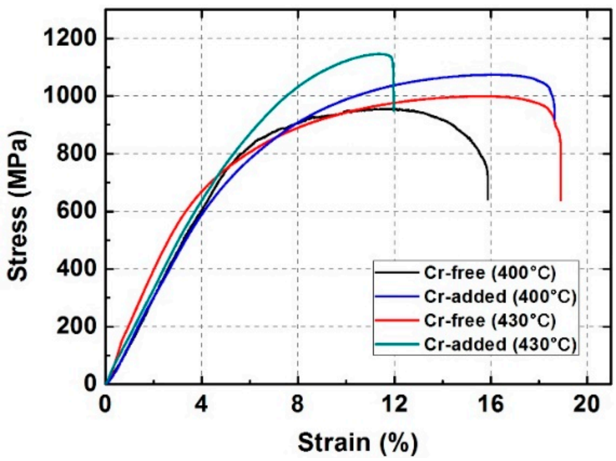

Figure 7. Typical comparison of the engineering strain-stress curves between the Cr-free and Cr-added steels treated by austempering.

Figure 8 shows the typical morphologies of tensile fractures in the two steels treated by austempering at 400 °C. Many dimples are observed in the two steels, indicating that the fracture is ductile. The fracture morphologies in the two steels show no significant difference.

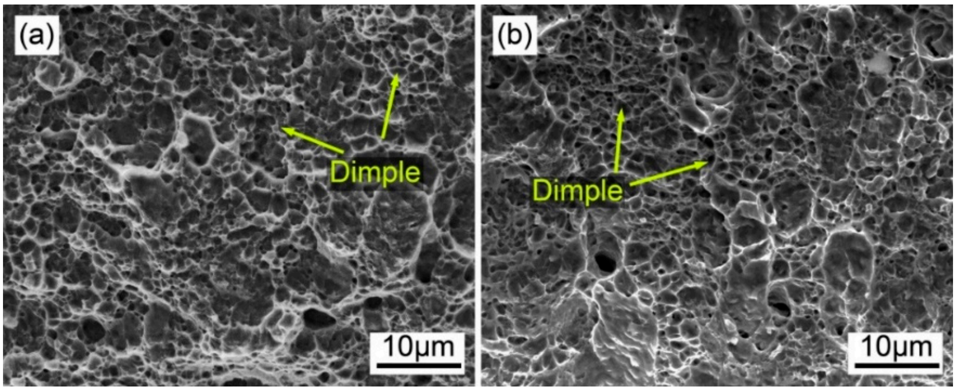

Figure 8. Morphologies of tensile fractures in two steels treated by austempering at 400 °C: (**a**) Cr-free steel; (**b**) Cr-added steel.

Carbide-free bainitic steel with ultra-fine bainitic ferrite and film-like RA is developed by Caballero et al. [12–15]. Cr is added in this advanced bainitic steel. They found that when Mn is replaced by Cr, the strength of the steel with 0.2 wt. % C decreases significantly during a continuous cooling process [15]. However, isothermal treatment is not studied in their studies. Sugimoto and his co-workers [27,28] investigated the effects of alloying elements (Cr, Mo, Ni, etc.) on the microstructure, the retained austenite, and the mechanical properties of bainitic steels treated by austempering. Their results showed that compared to the Cr-free steel, Cr addition increases the comprehensive property (PSE) of the steels at all studied austempering temperatures. The authors' previous study [18] also reported that Cr addition improves the comprehensive property of the steel austempered at 350 °C. However, the present study finds that at a lower transformation temperature (400 °C), Cr addition increases the comprehensive property of the steel, whereas Cr addition decreases the comprehensive property of the steel at higher transformation temperatures (430 °C and 450 °C). The difference between the previous result [18,27,28] and the present result may be because the austempering temperatures used in previous studies are relatively lower. In addition, the effect of Cr on bainitic transformation was not studied in references [27,28]. The authors' previous study [18] reported that Cr addition increases the amount of isothermal bainitic transformation at 350 °C, because high temperature ferritic transformation occurs in Cr-free steel and consumes some untransformed austenite before austempering, whereas no ferritic transformation occurs in Cr-added steel. In the present study, there is no ferritic transformation before isothermal bainitic transformation, and it is found that Cr addition decreases the bainite amount due to a decreased chemical driving force for bainitic transformation, and this effect is more significant at higher transformation temperatures.

3.2. Continuous Transformation

3.2.1. Dilatation

The dilatation versus temperature during cooling process for the two steels treated by continuous cooling is presented in Figure 9a. Ferrite transformation occurs at a relatively high temperature due to a slow cooling rate (0.5 °C/s). The calculated M_S temperatures for Cr-free and Cr-added steels are 376 and 353 °C, respectively, so that the region between a and b in the Cr-free steel and the region between c and d in the Cr-added steel contain not only bainitic transformation, but also martensitic transformation. The transformation start temperature decreases from 537 °C (point a) to 450 °C (point c) with Cr addition. In addition, D_1 and D_2 (Figure 9a) are dilatations caused by bainitic and martensitic transformations. D_2 is larger than D_1, indicating that the volume fractions of bainitic and martensitic transformations increase with Cr addition. This may be because the bainitic and martensitic transformations in Cr-added steel occur in lower temperature regions, so that the undercooling of the transformation is larger. In addition, the continuous cooling transformation (CCT) curves for the two steels are calculated using the software JMatPro (Figure 9b). It is obvious that the temperatures of ferritic, pearlitic, and bainitic transformations all decrease with Cr addition, which is consistent with the experimental results. As shown in Figure 9b, the calculated bainite transformation start temperatures for Cr-free and Cr-added steels are 482 °C and 451 °C, respectively, for a cooling rate of 0.5 °C/s. The calculated value (451 °C) is almost the same as the measured value (450 °C, Figure 9a) for Cr-added steel, whereas the calculated value (482 °C) is obviously lower than the measured value (537 °C, Figure 9a) for Cr-free steel.

In addition, the relative change of transformation fraction versus temperature during the cooling process from point a to b in Cr-free steel, and from point c to d in Cr-added steel, are calculated using the lever rule and the results are shown in Figure 10b. An example is given in Figure 9a. At a certain temperature, the relative volume fraction of transformation is determined as ON/MN [29,30]. In general, the transformation kinetics are hindered by Cr addition (Figure 9b). This is because the lower transformation temperature region makes the diffusion of carbon slow down during the nucleation process of bainitic transformation [20]. In addition, the slope of the transformed fraction curves (df/dT) is shown in Figure 10c. The slope represents the transformation rate. There is a peak value in each slope curve, which corresponds to the maximum transformation rate. First, the maximum transformation rate appears later in Cr-added steel, indicating that the transformation is delayed by Cr addition. Second, the maximum transformation rate in Cr-added steel is larger than that in Cr-free steel. The faster transformation rate may be caused by martensite transformation.

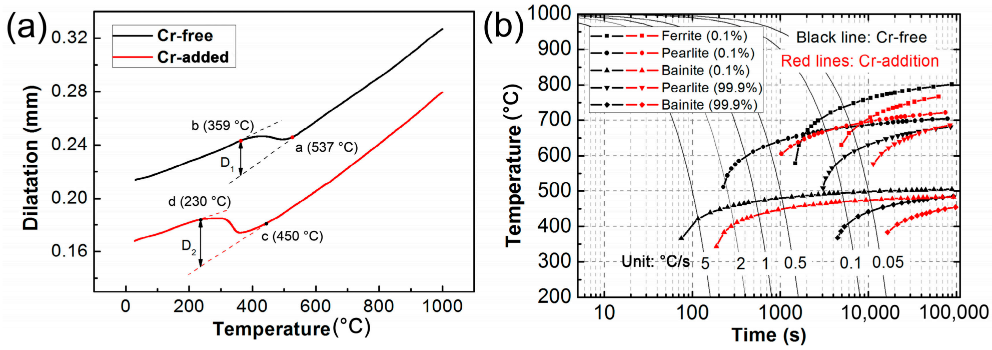

Figure 9. (**a**) The dilatation versus temperature during cooling process for the two steels treated by continuous cooling; (**b**) Calculated continuous cooling transformation (CCT) curves for the two steels.

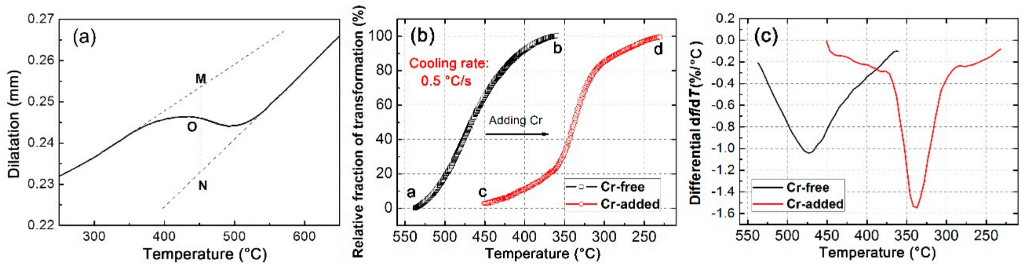

Figure 10. (**a**) The example of lever rule; (**b**) The relative change of transformation fraction versus temperature during the cooling process (cooling rate: 0.5 °C/s) from point a to b (Figure 9a) in Cr-free steel, and from point c to d (Figure 9a) in Cr-added steel; (**c**) The slope of the transformed fraction curves (df/dT).

3.2.2. Microstructure

The typical microstructures of the Cr-free and Cr-added steels treated by continuous cooling are shown in Figure 11. The microstructure is significantly different between the two steels. The microstructure in Cr-free steel contains lath-like bainite (LB), granular bainite (GB), polygon ferrite (PF), and martensite/austenite (M/A) constitution, whereas the microstructure in Cr-added steel contains LB, a large amount of M, and a small amount of PF and RA. No carbides are observed. The volume fractions of different phases are determined using the software Image-Pro Plus 6.0 (Media Cybernetics, Rockville, MD, USA) according to the grayscale and morphology of different phases. There is about 48 vol. % bainite (GB + LB) in Cr-free steel, whereas the volume fraction of bainite (mainly LB) in Cr-added steel is about 24 vol. %. This is consistent with the result obtained by the lever rule (Figure 10b), in which the volume fraction bainite is about 22 vol. % in Cr-added steel. The amount of PF decreases with Cr addition due to the solute-drag effect of Cr [31]. The amount of M significantly increases because the transformation temperature region decreases by Cr addition and large amount of transformation occurs below M_S temperature (Figure 9a). PF presents more irregular morphology. The regions showing bainite morphologies in the two steels are magnified and presented in Figure 11c,d. It is obvious that bainite is coarse in Cr-free steel, whereas it is significantly refined in Cr-added steel due to the lower transformation temperature. In addition, XRD results show that the volume fraction of RA decreases from 8.7 vol. % to 2.3 vol. % with the addition of Cr. This is because there is more ferrite and bainite in Cr-free steel. It is known that carbon diffuses into the surrounding untransformed austenite during ferritic and bainitic transformation, which stabilizes the untransformed austenite [20].

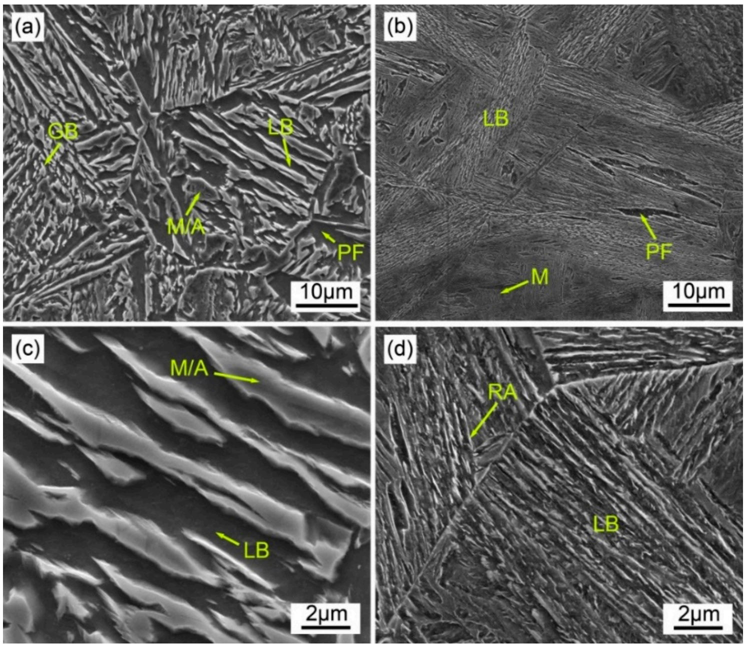

Figure 11. The typical microstructures of the Cr-free and Cr-added steels treated by continuous cooling: (**a**,**c**) Cr-free steel; (**b**,**d**) Cr-added steel. LB, lath-like bainite; GB, granular bainite; PF, polygon ferrite; M/A, martensite/austenite.

3.2.3. Mechanical Properties

The tensile results of Cr-free and Cr-added steels treated by continuous cooling are given in Table 4. The engineering strain-stress curves of the two steels are shown in Figure 12. Compared with Cr-free steel, the yield strength and tensile strength in Cr-added steel is increased because there is more hard martensite in Cr-added steel. However, more amounts of martensite in Cr-added steel significantly decreases the elongation of the steel. As a result, the PSE in Cr-added steel obviously decreases. Moreover, the tensile fractures of the two steels are shown in Figure 13. The fracture in the Cr-free steel mainly consists of dimples, whereas a large amount of quasicleavage morphologies are observed in the Cr-added steel, indicating that the plasticity is better in Cr-free steel. Therefore, Cr addition is harmful for the properties, especially ductility, of low carbon bainitic steel under a continuous cooling treatment.

Table 4. The tensile results and RA characteristics of two tested steels treated by continuous cooling.

Steel	YS (MPa)	TS (MPa)	TE (%)	PSE (GPa%)	V_γ (vol. %)	C_γ (wt. %)
Cr-free	662 ± 13	1054 ± 15	13.2 ± 0.8	13.9 ± 0.56	8.7 ± 0.7	1.05 ± 0.05
Cr-added	812 ± 15	1145 ± 21	6.9 ± 0.2	7.9 ± 0.15	2.3 ± 0.2	0.82 ± 0.04

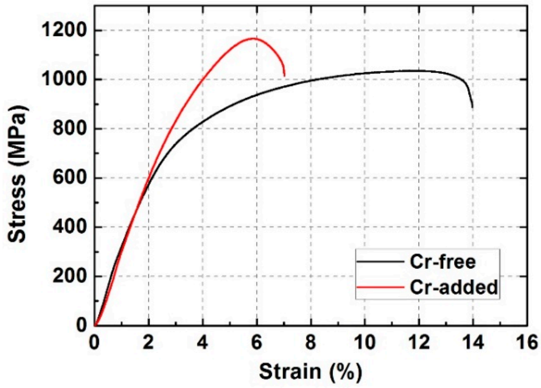

Figure 12. The engineering strain-stress curves of Cr-free and Cr-added steels treated by continuous cooling.

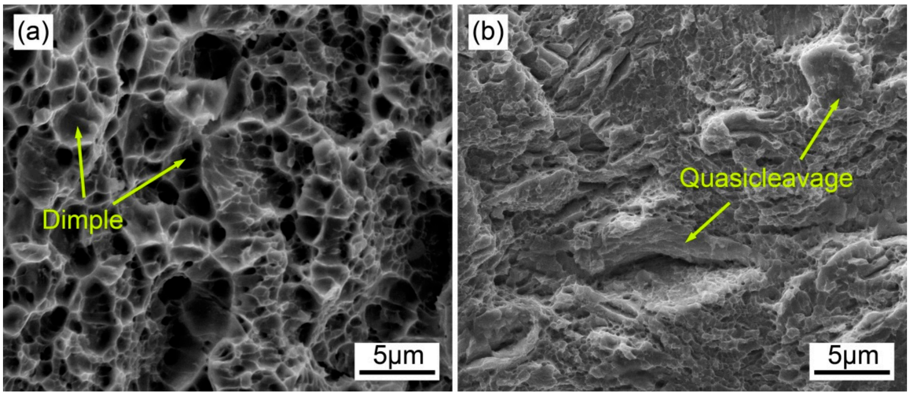

Figure 13. The tensile fractures of two steels treated by continuous cooling: (**a**) Cr-free steel; (**b**) Cr-added steel.

4. Conclusions

Two kinds of heat treatment procedure (austempering and continuous cooling) are designed. The effects of Cr addition on the bainitic transformation, the microstructure, and the properties of low carbon carbide-free bainitic steels are investigated. The following conclusions can be drawn:

(1) Chromium addition hinders the isothermal bainitic transformation kinetics and decreases the amount of isothermal transformation due to the decrease in chemical driving force for nucleation and growth of bainite. The hindrance of Cr on bainitic transformation is more significant at higher transformation temperatures because the decreased chemical driving force accounts for a larger proportion.

(2) Chromium addition increases the strength and elongation simultaneously for austempering treatment at a lower temperature. However, when the austempering temperature is higher, the strength increases and the elongation obviously decreases by Cr addition, resulting in the decrease in the product of tensile strength and elongation. In addition, the austempering temperature should be lower in Cr-added steel than that in Cr-free steel in order to obtain better comprehensive properties.

(3) For continuous cooling treatment in the present study, the amount of RA decreases, and the yield strength and tensile strength increases, but the total elongation obviously decreases in Cr added steel due to more amounts of martensite. The product of tensile strength and elongation significantly decreases.

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Abbreviations

The following abbreviations are used in this manuscript:

SEM	scanning electron microscope
XRD	X-ray diffraction
BF	bainite ferrite
RA	retained austenite
M	martensite
LB	lath-like bainite
GB	granular bainite
PF	polygon ferrite
YS	yield strength
TS	tensile strength
TE	total elongation
PSE	product of strength and elongation
TRIP	transformation induced plasticity

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