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Comprehensive Analysis of the Effect of Ausforming on the Martensite Start Temperature in a Fe-C-Mn-Si Medium-Carbon High-Strength Bainite Steel

Abstract

The comprehensive effect of strain and ausforming temperature on the martensite start temperature (M_S) of a medium-carbon bainite steel was investigated by thermal simulation, optical microscope, scanning electron microscope, etc. It is already known that small strain increases the M_S, while larger strain decreases the M_S. However, the effect of ausforming temperature on the MS has not been reported and clarified. In this study, the concepts of critical strain (ε_c) and saturated strain (ε_s) are proposed. The M_S at the critical strain is equal to the M_S of the nondeformed specimen. The saturation strain, which is first observed, is the strain value, and the M_S does not further decrease with the increasing strain. The results show that the M_S depends on the strain amount of ausforming but is not affected by the ausforming temperature. Moreover, with the increase of strain amount and ausforming temperature, the length of the martensite laths decreases. In addition, the hardness of the specimen increases with the increase of the ausforming strain amount, whereas the ausforming temperature has little effect on the hardness.

Disciplines

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Comprehensive analysis of the effect of ausforming on martensite start temperature in a Fe-C-Mn-Si medium-carbon high-strength bainite steel

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Abstract: The comprehensive effect of strain and ausforming temperature on the martensite start temperature (M_S) of a medium-carbon bainite steel was investigated by thermal simulation, optical microscope (OM), scanning electron microscope (SEM) etc. It is already known that small strain increases the M_S, while larger strain decreases M_S. But, the effect of ausforming temperature on M_S has not been reported and clarified. In this study, the concepts of critical strain (ε_c) and saturated strain (ε_s) are proposed. The M_S at the critical strain is equal to the M_S of the non-deformed specimen. The saturation strain, which is first observed, is the strain value, and the M_S at which does not further decrease with the increasing strain. The results show that the temperature of M_S depends on the strain amount of ausforming, but is not affected by the ausforming temperature. Moreover, with the increase of strain amount and ausforming temperature, the length of the martensite laths decreases. In addition, the hardness of specimen increases with the increase of ausforming strain amount, whereas the ausforming temperature has little effect on the hardness.

Keywords：ausforming; martensite start temperature; critical strain; saturation strain; microstructure; hardness

1 Introduction

The strength of steels is one of the main indexes in developing the new generation steels. Bainite steel with better mechanical properties is one of the advanced high strength steels [1-4]. Bhadeshia and Caballero proposed a novel nano-structured superbainite steel with an ultimate tensile strength of 2.5 GPa [5-7]. A very low transformation temperature near the martensite start temperature (M_S) is necessary to obtain the nano-structured bainite plates. In addition, ausforming is an indispensable step in the production of metals. It has been proved that ausforming affects the M_S. Therefore, the investigation on the effect of ausforming on the M_S is significant for the control of the transformation and microstructure of the superbainite steel.

It is generally acknowledged that the deformation causes the mechanical stabilization of austenite, i.e. M_S decreases after deformation [8-14]. For example, the effect of ausforming on martensite transformation and microstructure in a medium-carbon Si-Al-rich alloy was investigated by Zhang et al. [8,9]. They found that ausforming decreased the M_S due to resisting of γ-α interface motion by dislocation debris. The similar results were reported in Refs. [10-14]. However, a different result was proposed by He et al. [15]. They studied the effect of ausforming amount on the M_S in a 0.22 C (wt.%) low-carbon steel and claimed that a small deformation increases the M_S, while a large deformation decreases the M_S temperature. Summarizing the results of existing references, it is known that ausforming strain amount has various effects on the M_S, so it is significant to further study the effects of ausforming strain amount on M_S.

More important, so far, the effects of the ausforming temperature and carbon content on the M_S have not been reported and clarified. Therefore, the studies on the effect of ausforming temperature and carbon content on the M_S are necessary. In the present study, three different ausforming temperatures with different strain amounts were designed to investigate the effects of the ausforming temperature, strain amount and carbon content on the temperature of M_S. The work is meaningful for the control of the transformation, microstructure and mechanical properties in nano-structured bainite steels.

2 Materials and methods

The experimental steel is a Fe-0.40C-2.21Mn-1.54Si-0.22Mo (wt.%) high-strength bainite steel. The steel was refined and cast in the form of 50 kg ingot using a laboratory-scale vacuum furnace, followed by hot-rolling and air-cooling to room temperature. And then the experimental steel was tempered at 700 °C for 24 h to minimize interior stress and facilitate machining. The specimens for the thermal simulation experiments were machined to cylinders of 6 mm diameter and 15 mm height. The thermal simulation experiments were conducted on a Gleeble-3500 simulator. The specimens were heated to 900 °C at 10 °C s^{-1} and isothermally held for 5 min for austenitization. And then, the austenization specimens were respectively quenched to 860, 600 and 300 °C at a high cooling rate. The cooling rate was fast enough to avoid the high temperature transformation. Subsequently, the specimens were compressed to strains of 5 %, 8 %, 15 %, 30 % and 50 % at a strain rate of 10 s^{-1}, respectively. Finally, all deformed specimens were quenched to ambient temperature.

The specific experimental procedures were shown in Fig. 1. Besides, a specimen without deformation was directly quenched to ambient temperature after austenization at 900 °C to measure the M_S of non-deformed specimen. After thermal simulation experiments, all specimens were mechanically polished and etched with 4% nital. The microstructure was observed using a Zeiss optical microscope (OM) and a Nova 400 Nano scanning electron microscope (SEM). The hardness was measured using a Vickers hardness tester.

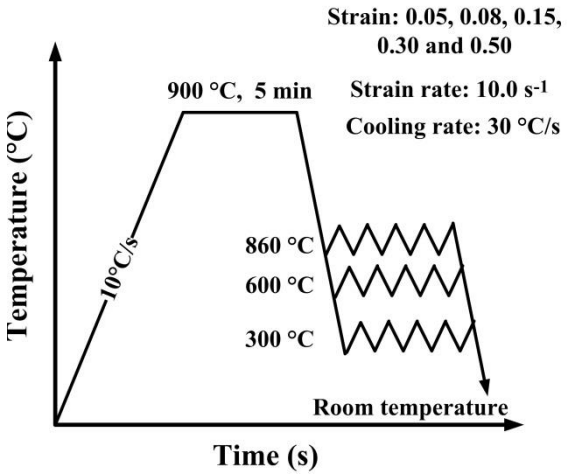

Fig. 1 Experimental procedure

3 Results and discussion

3.1 Analysis on the dilation

Figure 2a presents an example (5 % strain deformation at 600 °C) to illustrate the diameter change of specimen with temperature during the whole thermal simulation process. The specimen was heated from ambient temperature to 900 °C for austenization, resulting in the dilatation increasing (from point A to B). Then, the specimen was cooled to 600 °C, resulting in the decrease in dilatation continuously (from point B to C). After that, the specimen was compressed to 5% strain at 600 °C,

causing the vertical increase in dilatation (from point C to D). At last, the deformed specimen was cooled to ambient temperature and the dilatation decreased first and then increased. The inflection point represented the beginning of martensite transformation and corresponding temperature (M_S) was measured according to the tangent method [16].

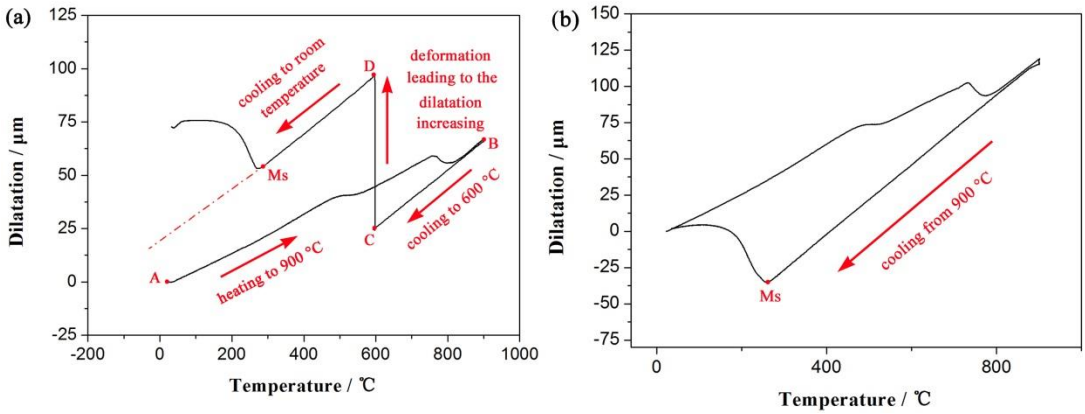

Fig. 2 Example of dilatation change with temperature during the whole process: (a) 600 °C+0.05 strain specimen; and (b) non-deformation specimen

As is widely known, high temperature diffusive transformation such as ferrite and bainite transformation is companied with the rejection of carbon atoms into surrounding untransformed austenite, resulting in the increase of the chemical stability of untransformed austenite [17-19], and thereby decreases the M_S. In addition, ausforming also affects ferrite and bainite transformation by providing heterogeneous nucleation [20-22], which may shorten the incubation time of transformation. Moreover, transformation may happen during deformation as well. To eliminate the influence caused by ferrite and bainite transformation on M_S, the cooling rate should be high enough to avoid ferrite and bainite transformation. Figure 2b shows the temperature-dilatation curves of specimen without deformation. The dilatation went

down straightly, indicating that no transformation happened before M_S. The dilatation for deformed specimen (Fig. 2a) also went down straightly after deformation. Therefore, the cooling rate in the present study was high enough to avoid high temperature transformation.

For the deformation process, the deformation time can be calculated using following Equation (1):

$$-\ln(L/L_0) = \dot{\varepsilon} \cdot t \quad (1)$$

where L and L_0 is the height of specimen after and before deformation, respectively. The $\dot{\varepsilon}$ is the strain rate ($\dot{\varepsilon}$=10 s^{-1}), and t is the consuming time for deformation. The calculated time is 0.068 s for 0.05 strain. According to author's previous study [23], there was no transformation during deformation.

In addition, it has been proved that stress influences the M_S as well [24, 25]. The applied stress on the specimen for deformation was immediately unloaded after deformation. Figure 3 shows the stress during the whole simulation experiment for specimen with 15 % strain at 300 °C, illustrating that there was little stress during the cooling process after deformation. This means that the M_S was not affected by stress. Hence, it can be concluded that the changes of M_S in the present study were only affected by ausforming, rather than other factors such as transformation and stress before or during martensite transformation.

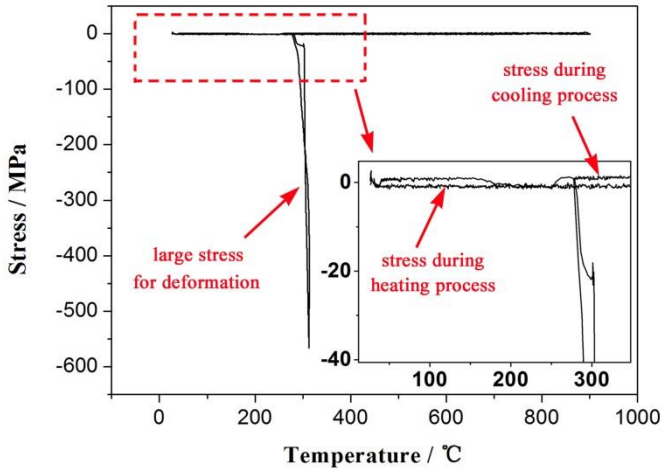

Fig. 3 The change of stress during the whole simulation test for specimen with 0.15 strain at 300 °C, illustrating the little influence of stress on M_S during cooling process

3.2 Critical strain and saturation strain

The M_S were determined based on the temperature-dilatation curves. Figure 4 presents the curve of temperature and dilatation during cooling process of specimens without deformation and deformed to 0.05 strain at 300, 600 and 860 °C, respectively. During the cooling process, the undercooled austenite started to transform into martensite when the temperature reached M_S, resulting in obviously increase in dilatation. The M_S for specimen without deformation was 269 °C and M_S for specimens with 0.05 strain at different ausforming temperatures were 284, 282 and 284 °C, respectively. Thus, compared with non-deformation, the ausforming with 0.05 strain at different temperatures caused the increase of M_S.

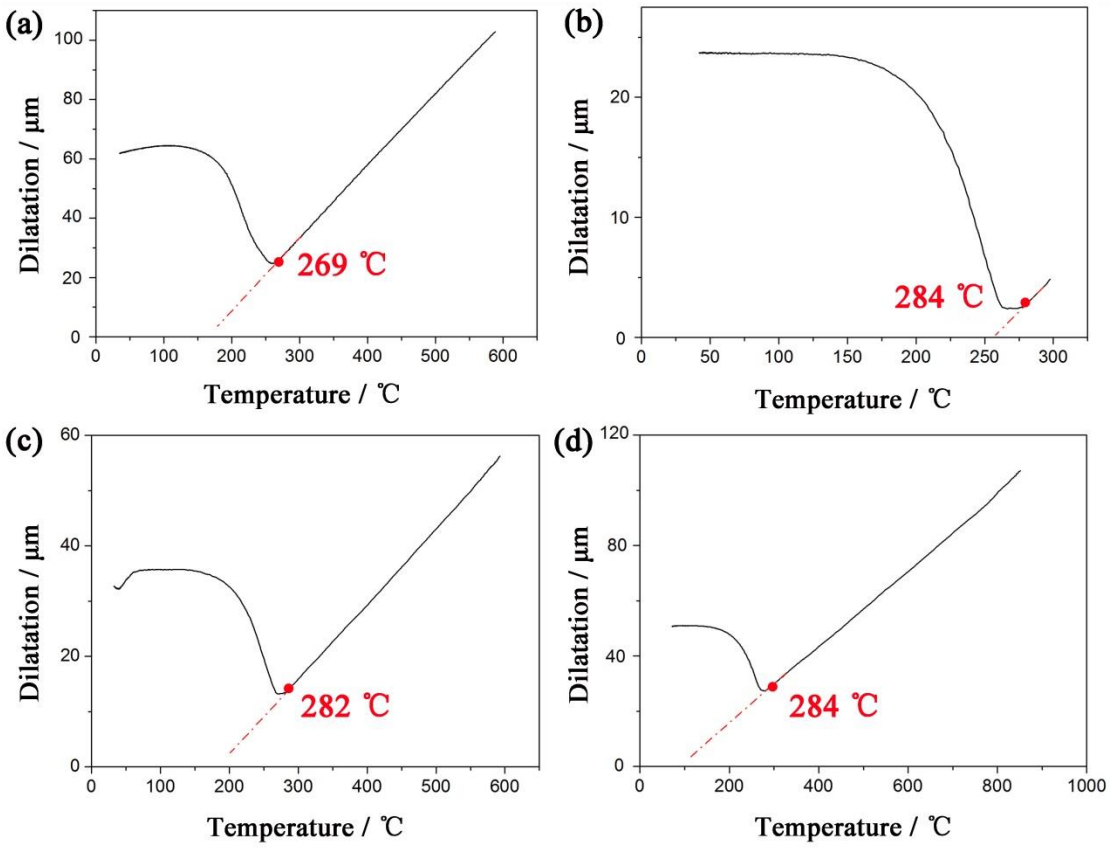

Fig. 4 Temperature-dilatation curves illustrating the M_S of different specimens: (a) without deformation; (b) 300 °C+0.05 strain; (c) 600 °C+0.05 strain; and (d) 860 °C+0.05 strain

The M_S for other deformed specimens were obtained using the same method and given in Fig. 5. It is clear that compared with the specimen without deformation, the M_S of deformed specimens first increased with strain, and then reached the peak value at the strain of 0.05. As the strain further increased, the M_S decreased. There was a critical strain (ε_c) between 0.05 and 0.15 strain, which was the inflection point of the effect of ausforming on the M_S. Compared with the M_S of non-deformed specimen, the ausforming increases the M_S temperature before reaching to ε_c, while it decreases the M_S after ε_c. In addition, the M_S reached a stable value at strain of 0.15, indicating that the increase of strain amount after 0.15 strain had no significant influence on the

M_S. The strain amount corresponding to the stable M_S is termed as saturation strain (ε_s).

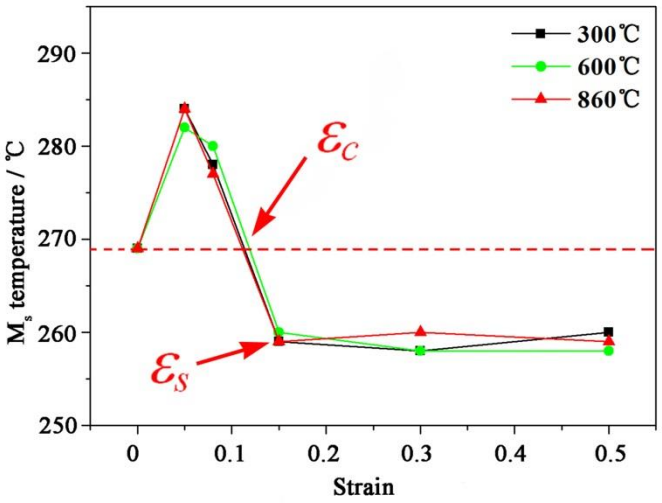

Fig. 5 The change of M_S with strain amount and ausforming temperature

Figure 5 illustrates the effects of strain amount and ausforming temperature on the M_S, indicating that the M_S did not change with ausforming temperature but was distinctly affected by the deformation amount. The M_S firstly increased with the increasing strain, and then reached the peak value when the strain amount was 0.05. As the strain amount increased sequentially to 0.15, the M_S decreased sharply and was apparently smaller than the M_S of specimen without deformation. The further increase in deformation amount after 0.15 strain had no significant effect on the M_S, i.e. the M_S tended to be constant. No matter at which temperature the specimen was deformed, the M_S of specimen deformed for 0.05 strain was higher than that of non-deformed specimen. The M_S of specimen with 0.15 strain was lower than that of non-deformed specimen. This manifests that there must be a critical deformation amount ε_c (shown in Fig. 5). The M_S increased by a small strain less than ε_c and decreased at a strain larger than ε_c.

The M_S is affected by the size of austenite grains according to the Hall-Petch formula (2) [26]:

$$Ms = Ms^s - kd^{-1/2} \quad (2)$$

where the Ms is the martensite start temperature of polycrystalline material, and the Ms^s is the martensite start temperature of single crystal material, of which the diameter is regarded as infinity. The k is constant and the d is diameter of parent phase grain (undercooled austenite). Therefore, the function of M_S and $d^{-1/2}$ is linear as shown in Fig. 6, indicating that the M_S should increase with the diameter of the parent phase grain. Figures 7a–c displays the micrographs of prior austenite grains (PAG) and prior austenite grain boundaries (PAGB) of samples with different strains at 860 °C. The values of PAG were calculated by Image-Pro Plus software based on the diagonal method. Two diagonals are drawn randomly in each grain. The average value of the two diagonals is calculated as the size of this grain. Finally, the average value of the sizes of all grains is selected as the grain size of the whole micrograph. In order to achieve the higher accuracy, at least the results of three micrographs are reported for each sample. The average sizes of PAG for samples deformed at 860 °C with 0.05, 0.15 and 0.50 strain were measured as 13.4 ±2.3, 10.3 ±1.7, and 6.2 ±1.5 μm, respectively. Similarly, the PAG size of other samples deformed at 360 °C and 600 °C with different strain amounts was also measured. The results are shown in Table 1. It is obvious that the size of deformed austenite grains decreases with increasing strain. In this study, however, the M_S increased with the strain when the deformation amount was small. Then, the M_S decreased and tended to be constant as the strain increased

further. Hence, the M_S not only depended on the size of austensite grains, but also was affected by ausforming. In addition, the length of martensite laths is related to prior austenite grain size. The smaller austensite grain size results in shorter length of martensite laths. Hence, when the strain is large, the length of martensite laths is shorter (Fig. 11) due to smaller austenite grains. Although the length of martensite laths decreases with the increase of strain, the M_S temperature is not changed with the same trend, indicating that the length of martensite laths depends on not only the M_S temperature, but also, more importantly, strain amount.

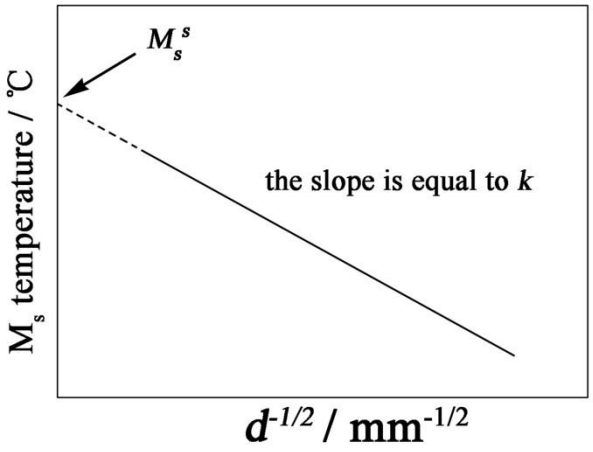

Fig. 6 The relationship between M_S and $d^{-1/2}$ according to Hall-Petch formula

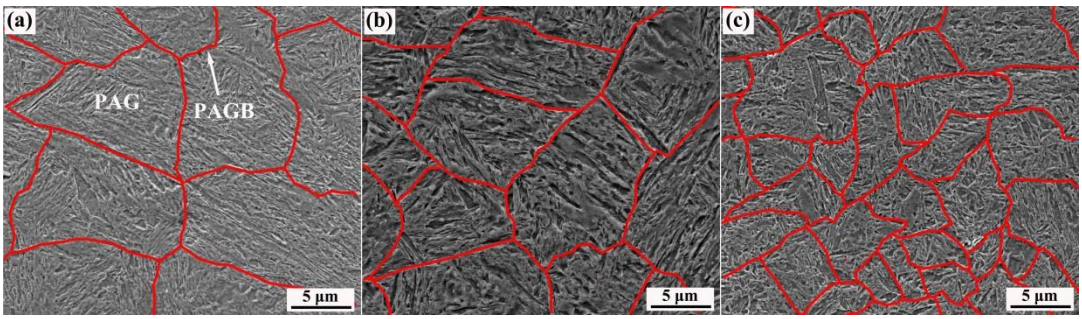

Fig. 7 Examples of PAG for samples deformed at 860 °C with different strains: (a) 0.05; (b) 0.15; and (c) 0.50

Table 1 The measured PAG of different deformed samples

Deformation temperature	Strain amount		
	0.05	**0.15**	**0.50**
300 °C	24.2±3.1	17.6±2.5	11.6±1.4
600 °C	18.4±1.8	13.1±1.4	9.5±1.7
860 °C	13.4±2.3	10.3±1.7	6.2±1.5

The displacive mechanism of martensitic transformation is generally accepted [27-29]. The formation of martensite consists of nucleation and growth. In a deformed austenite grain, the deformation leads to the formation of geometrically necessary dislocations (GNDs) at the austensite grain boundaries and randomly distributed dislocations within the austensite grains [30,31]. As the strain increases, the average of the density of GNDs increases linearly and the GNDs accumulate near the austenite grain boundaries. For the specimens with small strain, martensite transformation preferentially nucleates at the dislocations accumulated at the austenite grain boundaries before the formation of martensite. Once the primary martensite nucleates at the dislocations, the defect generated in the α-γ interfaces may immediately trigger further martensitic transformation in an autocatalytic chain-like manner. The small strain offers the preferential nucleation sites for martensitic transformation compared with the specimen without deformation. As a result, the M_S increases with strain smaller than the critical strain. The similar results were reported in Refs. [32-34].

With the further increasing strain (Fig. 5), however, the M_S decreased and then tended to be constant. When the strain was 0.08, the M_S was lower than that at 0.05 strain but still higher than that of non-deformed specimen. Besides, as the strain increased to the critical deformation amount ε_c, the M_S further decreased to be equal the M_S of non-deformed specimen. When the strain was larger than ε_c, the M_S of

deformed specimen was lower than that of non-deformed specimen and decreased with the increasing strain until saturation strain (ε_s). Regarding to the deformed specimens, the competitive relationship between nucleation and growth affects the martensitic transformation and M_S. As the strain increases, the increasing amount of dislocations remains inside the deformed austenite grains and leads to a high density of dislocations, both which restricts the growth of martensite laths. Furthermore, the appearance of subgrains induced by large strain also retards the growth of martensite laths. Therefore, the martensite transformation was delayed and the M_S decreased.

When the strain increased from 0.15 to 0.50, the M_S tended to be constant. The restricting effect of deformation on the M_S was saturated when the strain was 0.15. In Kundu's research [31], the dislocations introduced by large strain also accumulate at the boundaries of subgrains, thus providing nucleation sites for martensitic transformation at a later stage. The martensite laths forming at the boundaries of subgrains rapidly grow and stop at the other side of the subgrain boundaries. The dislocations accumulated at the subgrain boundaries are saturated when the strain is large enough [15]. Hence, the extent to which the saturated dislocations promote nucleation does not change with increasing strain, resulting in basically stable M_S.

In previous study, the effect of ausforming strain amount on the M_S in a low-carbon bainite steel was studied by He et al. [15]. They claimed that the small strain increases the M_S while large strain decreases the M_S. The similar result was obtained in a medium-carbon bainite steel in the present research. However, in their study, the critical strain amount ε_c was about 0.23 for a low-carbon steel, while it was

about 0.10 for a medium-carbon steel in this study. This means that the critical strain depends on the chemical composition of steel, especially carbon content. Moreover, the saturated strain ε_s was not observed and defined in previous study, whereas it was firstly observed and defined in the present study. Compared with low-carbon steels, medium-carbon steels contain more carbon and other alloying element such as manganese (Mn) and silicon (Si), resulting in more elastic distortion. On the other hand, the solute atoms segregated on the dislocations have the pinning effect on the dislocations. Thus, more serious work hardening happens in medium-carbon steels, causing the decrease of ε_c. In addition, summarizing the experimental results of the two kinds of steels, it can be inferred that although the appeared in medium-carbon steel but not in low-carbon steels, the ε_s may still appear in low-carbon steel when a certain very large strain was loaded.

The regression equation reflecting the influence of strain amount on M_S is given as following Equation (3) using the software of Origin 8.0:

$$M_s = 269.4511 + 361.3568\varepsilon - 2929.44\varepsilon^2 \quad (3)$$

where the ε is the strain amount, indicating that the M_S follows the parabola law before the ε_s. Figure 8 presents the measured value and the corresponding simulated curve (ε<0.15). The correlation coefficient is 0.94609, meaning that the Equation (3) is of good precision.

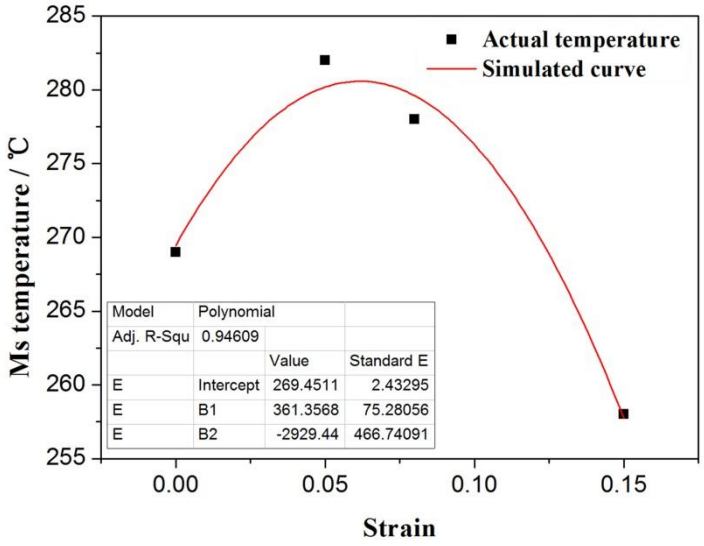

Fig. 8 M_S change following the parabola law at the strain before reaching the ε_s

3.3 Effect of ausforming temperature on M_S

It is observed in Fig. 5 that different ausforming temperatures (300, 600 and 860 °C) had no significant effect on M_S, critical strain ε_c and saturated strain ε_s. The stress-strain curves during the compression deformation process at different ausforming temperatures are presented in Fig. 9. It indicates that no dynamic recrystallization occurred for all deformation conditions. Obvious dynamic recovery happened at 600 and 860 °C, while little dynamic recovery occurred at 300 °C. Theoretically, the density of the dislocations near austenite grain boundaries in the specimens deformed at 300 °C should be higher than that in other two specimens with deformation at 600 and 860 °C. It should have led to the different M_S in different specimens at different ausforming temperatures. However, according to the results in Fig. 5 the ausforming temperature has little effect on M_S. It implied that the influence of austenite grain size cannot be ignored.

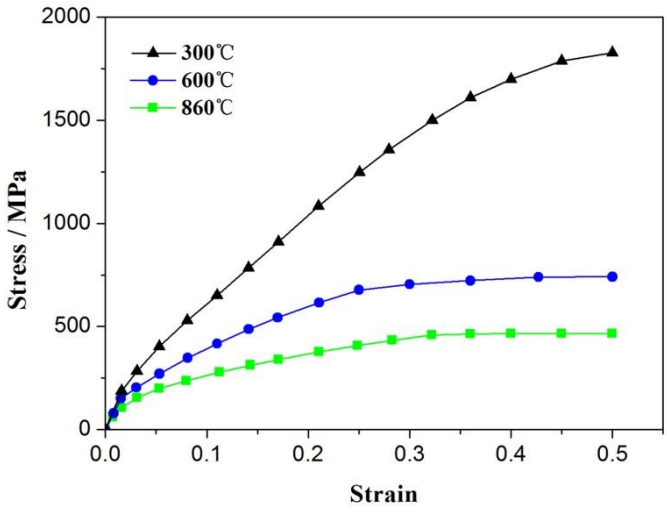

Fig. 9 Stress-strain curves of the specimens deformed at 300, 600 and 860 °C, indicating no dynamic recrystallization happened

The OM microstructures at different deformation conditions are shown in Fig. 10. It illustrates that the size of austenite grains at 860 °C (Figs. 10e and 10f) was apparently smaller than that at 300 °C (Figs. 10a and 10b). For the specimens deformed at different temperatures, the higher ausforming temperature caused the smaller density of dislocations, leading to the decrease of M_S. But smaller grain size at high ausforming temperature provided more nucleation sites for martensite transformation. It is the combination of the dislocation density and austenite grain size that affects the M_S, contributing to the little influence of ausforming temperature on M_S. It is a main novelty in this study.

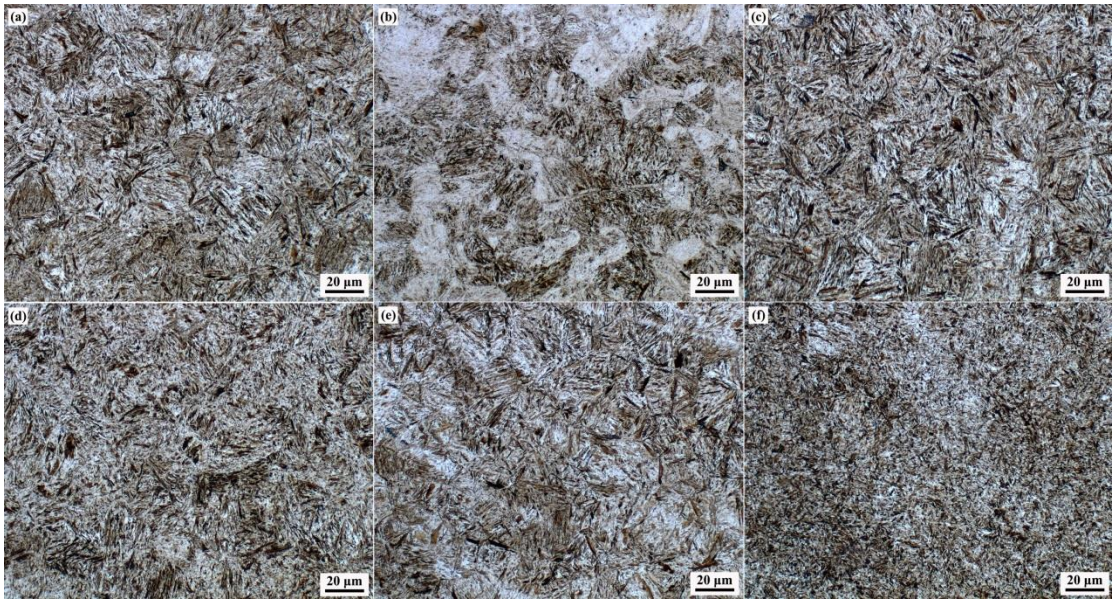

Fig. 10 The OM microstructure of different specimens: (a) 300 °C+0.05 strain; (b) 300 °C+0.50 strain; (c) 600 °C+0.05 strain; (d) 600 °C+0.50 strain; (e) 860 °C+0.05 strain; and (f) 860 °C+0.50 strain

3.4 Microstructure

The microstructure illustrates that the size of the austenite grains decreased with the increasing ausforming temperature (Fig. 10). The austenite grains tended to be broken by the deformation at a high temperature. For the specimens deformed at 860 °C, the austenite grains were the finest at the same strain amount, leading to the shortest martensite laths. The micrographs with a higher magnification of 10000x of the specimens treated by different ausforming conditions are presented in Fig. 11, indicating that the growth of martensite laths in original austenite is hindered by subgrain boundary (Fig. 11c). And the similar phenomenon was also observed in Ref. [15]. In addition, martensite laths grow from the prior austenite grain boundary (PAGB), as marked with arrow in Figs. 11a-e. It is difficult to observe the martensite laths on PAGB in Fig. 11f due to the finest microstructure. In addition, it also can be

observed that the martensite laths of non-deformed specimen (Fig. 11a) were longer than those of deformed specimens. It can be observed that the length of martensite laths decreased with the increasing strain (Figs. 11b-d and Figs. 11e-g). The growth of martensite laths was limited in austenite grains. When the strain amount was small (ε=0.05), the prior austenite grains were larger, resulting in the longer martensite laths. The prior austenite grains became smaller with the increase of strain, leading to the shorter martensite laths (Figs. 11d and 11g). This is attributed to the growth retardation of martensite by subgrain boundaries. For specimens with the largest strain of 0.50, the parent austensite grains were obviously broken, resulting in the shortest martensite laths. Moreover, compared with the specimens deformed at 300 °C, the size of martensite laths at 860 °C was shorter. This is because austenite grains are easily broken at high ausforming temperature.

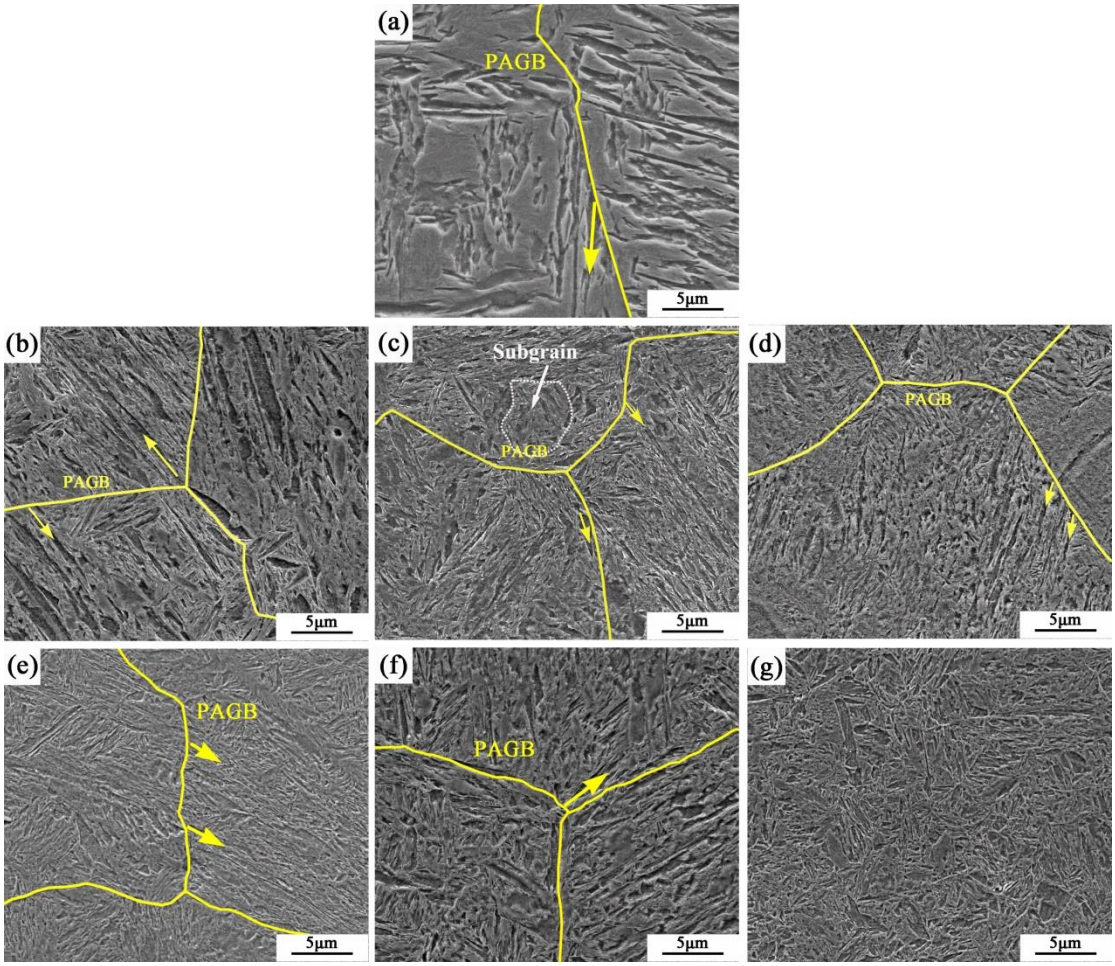

Fig. 11 The SEM microstructure of specimens treated by different processes: (a) without deformation; (b) 300 °C+0.05 strain; (c) 300 °C+0.15 strain; (d) 300 °C+0.50 strain; (e) 860 °C+0.05 strain; (f) 860 °C+0.15 strain; and (g) 860 °C+0.50 strain

3.5 Effect of ausforming on the hardness

The hardnesses of different specimens were given in Fig. 12. It indicates that the work hardening caused the increase of hardness with strain amount, while the ausforming temperature had little effect on the hardness. When the ausforming temperature was same, the increasing strain led to the decrease in the austensite grain size and the increase in the dislocation density, contributing to the increase of harness with strain. The change in hardness is related to the morphology of martensite laths. Smaller austenite grain hinders the growth of martensite laths. Hence, when the strain

amount is large, the martensite laths are refined (Fig. 11), resulting in a larger hardness of the microstructure. Therefore, the hardness increased with strain. It is noted that the ausforming temperature had no significant effect on the hardness, which was consistent with the effect of ausforming temperature on the M_S. Therefore, the hardness was mainly affected by the austensite grain size and the dislocation density in this study, while the M_S had no obvious influence on it.

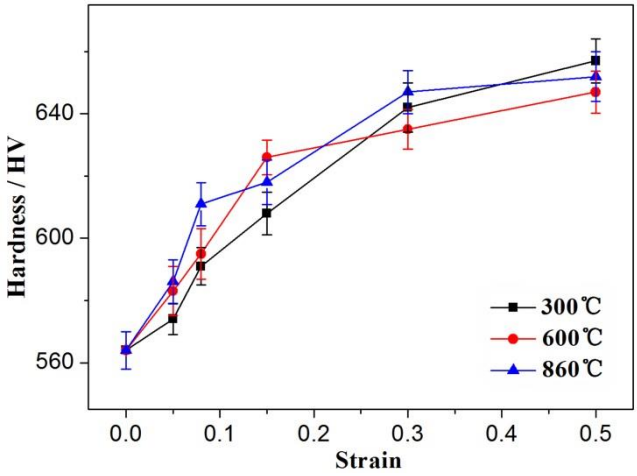

Fig. 12 The Vicker's hardness of specimens

In the present study, the effect of ausforming deformation on M_S mainly focuses on the compressive strain. The purpose of the present research is to provide theoretical reference for industrial production. The deformation on austenite in industrial production is normally compressive deformation. Therefore, tensile deformation and hydrostatic stress was not studied here. The effect of tensile deformation and hydrostatic stress on M_S should be conducted in the future study.

4 Conclusions

The effects of ausforming on the M_S in a Fe-C-Mn-Si medium-carbon bainite steel were investigated. The following conclusions can be drawn:

(1) The saturation strain ε_s is firstly observed and defined. The M_S tends to be constant when the strain is larger than ε_s. Moreover, the critical strain ε_c is proposed. The strain smaller than ε_c increases the M_S, whereas the M_S decreases at the strain larger than ε_c.

(2) The ausforming temperature does not affect the M_S. The critical strain ε_c and saturation strain ε_s are not affected by the ausforming temperature.

(3) The length of martensite laths decreases with the increase of ausforming temperature and strain amount.

(4) The hardness of specimens increases with strain amount, while it is not affected by the ausforming temperature.

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Table captions

Table 1 The measured PAG of different deformed samples

Deformation temperature	Strain amount		
	0.05	**0.15**	**0.50**
300 **°C**	24.2±3.1	17.6±2.5	11.6±1.4
600 **°C**	18.4±1.8	13.1±1.4	9.5±1.7
860 **°C**	13.4±2.3	10.3±1.7	6.2±1.5

Figures captions

Fig. 1 Experimental procedure

Fig. 2 Example of dilatation change with temperature during the whole process: (a) 600 °C+0.05 strain specimen; and (b) non-deformation specimen

Fig. 3 The change of stress during the whole simulation test for specimen with 0.15 strain at 300 °C, illustrating the little influence of stress on M_S during cooling process

Fig. 4 Temperature-dilatation curves illustrating the M_S of different specimens: (a) without deformation; (b) 300 °C+0.05 strain; (c) 600 °C+0.05 strain; and (d) 860 °C+0.05 strain

Fig. 5 The change of M_S with strain amount and ausforming temperature

Fig. 6 The relationship between M_S and $d^{-1/2}$ according to Hall-Petch formula

Fig. 7 Examples of PAG for samples deformed at 860 °C with different strain amount: (a) 0.05; (b) 0.15; and (c) 0.50

Fig. 8 M_S change following the parabola law at the strain before reaching the ε_s

Fig. 9 Stress-strain curves of the specimens deformed at 300, 600 and 860 °C, indicating no dynamic recrystallization happened

Fig. 10 The OM microstructure of different specimens: (a) 300 °C+0.05 strain; (b) 300 °C+0.50 strain; (c) 600 °C+0.05 strain; (d) 600 °C+0.50 strain; (e) 860 °C+0.05 strain; and (f) 860 °C+0.50 strain

Fig. 11 The SEM microstructure of specimens treated by different processes: (a) without deformation; (b) 300 °C+0.05 strain; (c) 300 °C+0.15 strain; (d) 300 °C+0.50 strain; (e) 860 °C+0.05 strain; (f) 860 °C+0.15 strain; and (g) 860 °C+0.50 strain

Fig. 12 The Vicker's hardness of specimens