Met. Mater. Int., Vol. 21, No. 5 (2015), pp. 929~935
doi: 10.1007/s12540-015-5156-5

Effect of Ausforming on the Stability of Retained Austenite in a C-Mn-Si Bainitic Steel

Hai-jiang Hu[1,2], Guang Xu[1,*], Li Wang[2], Ming-xing Zhou[1], and Zheng-liang Xue[1]

[1]The State Key Laboratory of Refractories and Metallurgy, Hubei Collaborative Innovation
Center for Advanced Steels, Wuhan University of Science and Technology, Wuhan, 430081, China
[2]State Key Laboratory of Development and Application Technology of Automotive Steels (Baosteel Group),
Shanghai, China

(received date: 25 March 2015 / accepted date: 30 April 2015)

The effect of ausforming on the stability of retained austenite in a C-Mn-Si bainitic steel was investigated through metallography, X-ray diffraction and dilatometry. The geometrical relationships of the amount of bainite transformation and the volume fractions of retained austenite with deformation strains were studied. The results show that the degree of promotion of small strains on bainite transformation is nonlinear because of the dual effects of accelerated nucleation and retarded growth caused by ausforming. The transformed bainite fraction first increased and then decreased with increased small strains. It indicates that there is a maximum degree of the promotional function corresponding to a certain small strain at low temperature. Although small strains promote bainite transformation, a larger quantity of retained austenite exists at room temperature due to the suppressed martensite transformation during the cooling process after bainite transformation. The carbon content in retained austenite increases with the amount of baintie transformation, which contributes to the stability of austenite. Compared with the stabilizing effect due to carbon enrichment, mechanical stabilization caused by ausforming has a decisive effect on determining the volume fraction of retained austenite after isothermal bainite transformation.

Keywords: metals, deformation, microstructure, phase transformation, X-ray diffraction

1. INTRODUCTION

Ultra-fine bainitic steels have prompted significant and continued interests in the area of advanced high strength steels (AHSS) development. An excellent combination of strength and ductility can be obtained through the contribution of ultra-fine and carbide-free bainite microstructure and a certain amount of retained austenite (RA) [1,2]. The blocky or film-like retained austenite surrounded by lath bainite can enhance elongation by providing the transformation-induced plasticity (TRIP) effect [3,4]. The mechanical properties of carbide-free bainitic steel are closely related to the quantity and stability of RA which are affected by several factors. Many previous researches have been conducted to investigate the stability of RA. It is commonly recognized that the stability of austenite is affected by chemical composition and morphology [5-11].

The addition of C and Mn, which are strong austenite stabilizers, can result in a high austenite stability at room temperature [5,6]. Feng *et al.* [7] studied the effect of Nb on the stability of RA and found that austenite in Nb steel exhibits high stability due to the high stacking fault energy of RA caused by the dissolved Nb in the final multi-phase microstructure. Xiong *et al.* [11] reported that martensite transformation takes place in high carbon blocky RA at the onset of deformation, while low carbon film-like RA, despite having much lower carbon content, is stable at strains up to 12%. In addition, Kammouni *et al.* [12] investigated the effect of bainite transformation temperature on RA fraction and stability in microalloyed TRIP steels. It was found that this temperature affects the size and morphology of the RA which play important roles on its stability.

Although many works on RA have been presented, only few studies that expound on the effect of ausforming on RA have been reported. Prior-austenite deformation affects bainite transformation during the isothermal heat treatment of bainitic steels [13,14]. The rejection of excess carbon to surrounding austenite from newly formed bainite can result in the change of carbon concentration in untransformed austenite [15], which influences the final fraction and stability of RA at room temperature.

In the present study, isothermal heat treatment after prior-austenite deformation has been applied to a C-Mn-Si super

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*Corresponding author: xuguang@wust.edu.cn bainitic steel. The purpose of this work is to investigate the effect of ausforming on the fraction and morphology of RA after isothermal bainitic transformation. Also, the qualitative and quantitative relationships of the amount of bainite with RA fraction have been analyzed.

2. EXPERIMENTAL PROCEDURE

The chemical composition of the tested steel was Fe-0.4C-2.0Si-2.8Mn-0.04Al (wt%). The material was refined in a vacuum induction furnace and casted into a small ingot followed by hot rolling to the flat of 10 mm thickness. Samples for dilatation test were machined to a cylinder of 10 mm diameter and 15 mm height. The top and bottom surfaces of the samples were polished conventionally to keep the measurement face level and minimize the effect of surface roughness. The bainite and martensite starting temperatures are 434 °C and 248 °C, respectively, calculated by MUCG83 software developed by Bhadeshia at Cambridge University. The ausforming treatments were performed using a Gleeble-3800 thermomechanical simulator according to the processing schedules illustrated in Fig. 1. The specimens were heated to 900 °C at 10 °C s^{-1} for austenitization. After holding for 15min, the austenized specimens were cooled to 300 °C at 10 °C s^{-1} followed by compression deformation at 1 s^{-1} to strains of 0.1, 0.2, and 0.3, respectively, and then isothermally transformed for 90 min. Also, an undeformed sample was tested using the same route to make a comparison. The isothermal holding temperature was controlled within the range of ±0.5 °C. After isothermal holding, the specimens were cooled to room temperature at a cooling rate of 10 °C s^{-1}. In all cases, the diameter change during the isothermal bainitic transformation was recorded using a laser extensometer.

After thermomechanical and isothermal holding treatments, a microstructure examination of each specimen was conducted using a Nova400Nano field emission scanning electron microscope (SEM) at an acceleration voltage of 20 kV after etching with 4% nital. The volume fraction of RA in different samples was determined using an X'Pert diffractometer with Co Kα radiation under the following conditions: acceleration voltage, 40 kV; current, 150 mA; and step, 0.06°.

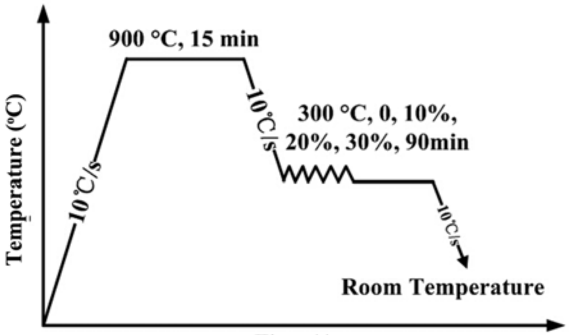

Fig. 1. Ausforming experiment procedures.

3. RESULTS

3.1. Microstructures

Microstructures of the steels with different ausforming strains were observed by SEM, as shown in Fig. 2. The lath-like bainite sheaves were obtained in the non-deformed sample after isothermal holding for 90 min at 300 °C. Fig. 2 (where the arrows point) also shows the film-like or blocky unformed austenite. During the final cooling to room temperature, a section of the blocky austenite was transformed into martensite. Compared with the non-deformed sample, the bainite sheaves of the deformed samples are obviously finer and the bainite fractions also increase. According to previous work [16], deformed austenite contains more deformation faults which provide more nucleation sites for bainitic transformation, resulting in finer bainite morphology. Bainite sheaves are normally restricted by grain boundaries and smaller austenite grains result in shorter bainite sheaves. In addition, a large blocky RA existing in the non-deformed sample was broken into pieces in deformed specimens after bainite transformation, as shown by arrows in Figs. 2c~d. In-situ observation results indicate that bainite sheaves nucleate on grain boundaries, in grains, at twin lines and pre-formed bainite plates [17,18]. Various selected bainite laths partitioned the untransformed austenite, resulting in the broken morphology. Therefore, ausforming affects bainite

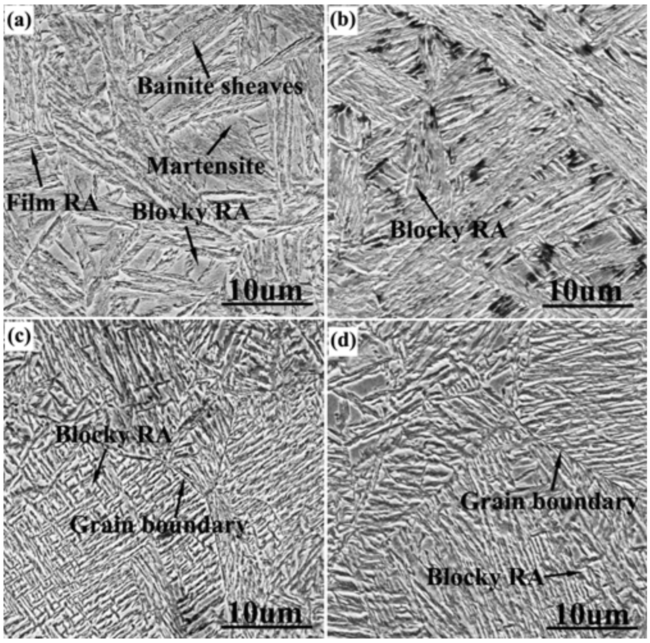

Fig. 2. SEM microstructures of different deformed samples after bainitic transformation for 90 min at 300 °C: (a) no deformation, (b) 10%, (c) 20%, and (d) 30%.

transformation, determining the final austenite morphology and amount.

3.2. Thermal dilatometry

During the isothermal holding process, the amount of bainite transformation directly affects the proportion of untransformed parent phase, which influences the volume fraction of RA at room temperature. Quantitative analysis on the effect of ausforming on bainite transformation was conducted by thermal dilatometry. Figure 3 shows the recorded diameter changes during bainite precipitation in specimens deformed and isothermally transformed at 300 °C. Since transformation temperature is constant, the diameter increment can represent the volume fraction of bainite transformed from the parent austenite. In Figure 3, the dilatation amount is normalized by dividing the instantaneous dilatation by the sample diameter before transformation. It is obvious that the smallest volume change occurs for the non-deformed specimen. The application of strains promotes the volume change at the end of the transformation. It indicates that the deformation at 300 °C causes an increment of the final amount of bainite transformation. The largest normalized dilatation is achieved at a strain of 0.1. Interestingly, the volume change decreases with an increase in strain. It means that the increased bainite amount is nonlinear with strains. However, the transformation rate curves in Fig. 3b manifest that the initial precipitation rate of bainite increases with the strain increasing from 0.1 up to 0.3. A certain quantity of deformation faults and debris were produced by ausforming, facilitating the nucleation for bainite transformation at the initial stage of isothermal holding. Simultaneously, deformed austenite contains more stacking faults that promote bainite transformation. These two factors contribute to the larger volume change in the deformed samples. It should be noted that the high dislocation density regions due to large strain can lead to the mechanical stabilization of austenite. Consequently, the growth of bainite sheaves in the 0.3 strain sample is quickly hindered at the subsequent holding process. In previous work [16], when the deformation strain was increased up to 0.5 at 300 °C, the final bainite volume fraction of the deformed sample was even less than the non-deformed one. This demonstrates that the mechanical stabilization caused by deformation becomes more serious with the increasing strain.

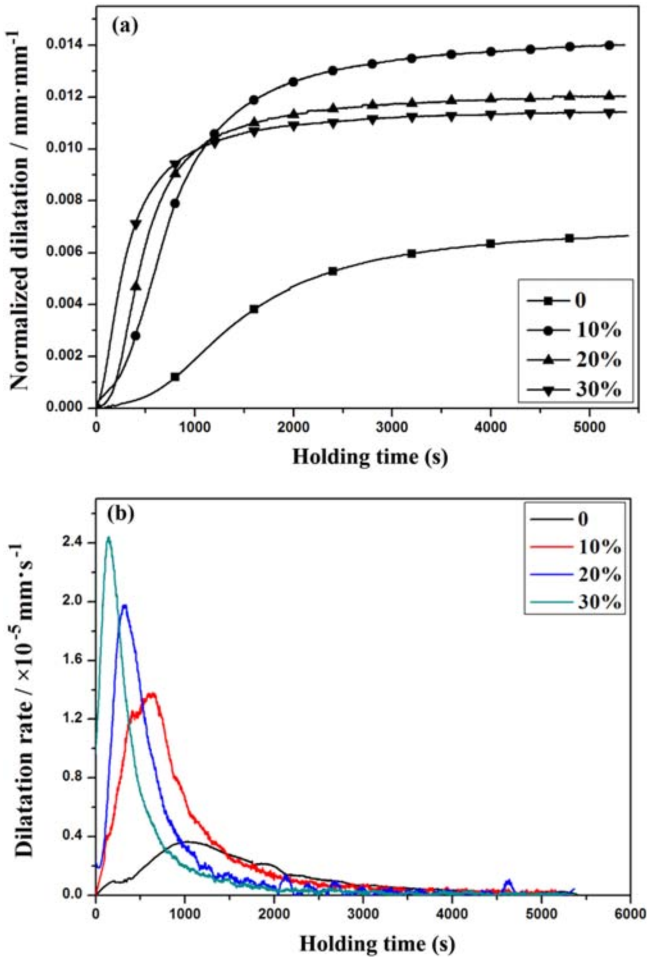

Fig. 3. (a) Dilatation curves and (b) transformation rates showing the effect of ausforming on bainitic transformation.

3.3. X-ray diffraction

To clarify the quantitative relation between deformation strain and retained austenite, X-ray diffraction analysis was conducted. The volume fraction of RA was calculated based on integrated intensities of (200)α, (211)α, (200)γ, (220)γ, and (311)γ diffraction peaks. XRD diffractograms for the non-deformed material as well as the materials deformed at 10%, 20% and 30% are given in Fig. 4. The volume fractions of RA were calculated using the method described in Ref. [19] and the results are presented in Fig. 5a. The RA fraction (~6.8%) in the non-deformed material is much less than that of the deformed materials. As the strain increases, more untransformed austenite remains in the deformed samples at room temperature. It suggests that more prior austenite tends to be stable after deformation in spite of the accelerated bainite transformation. For ausformed specimens, the acceleration of bainite precipitation along with the increase in the amount of RA implies that less austenite will transform into martensite once specimens are quenched to room temperature. This is consistent with the point that prior deformation can strongly retard the formation of martensite [20-22]. Furthermore, it is interesting to find that a saturated volume fraction of RA seemingly exists because of its little change with the strain varying from 0.2 to 0.3. This could be attributed to the combination effect of bainite transformation and mechanical stabilization of austenite.

The carbon content in RA was estimated using the Eq. [23]: $C_\gamma = (\alpha_\gamma - 0.3578)/0.0033$, where C_γ is the carbon content in RA and α_γ is the lattice parameter of RA, which is

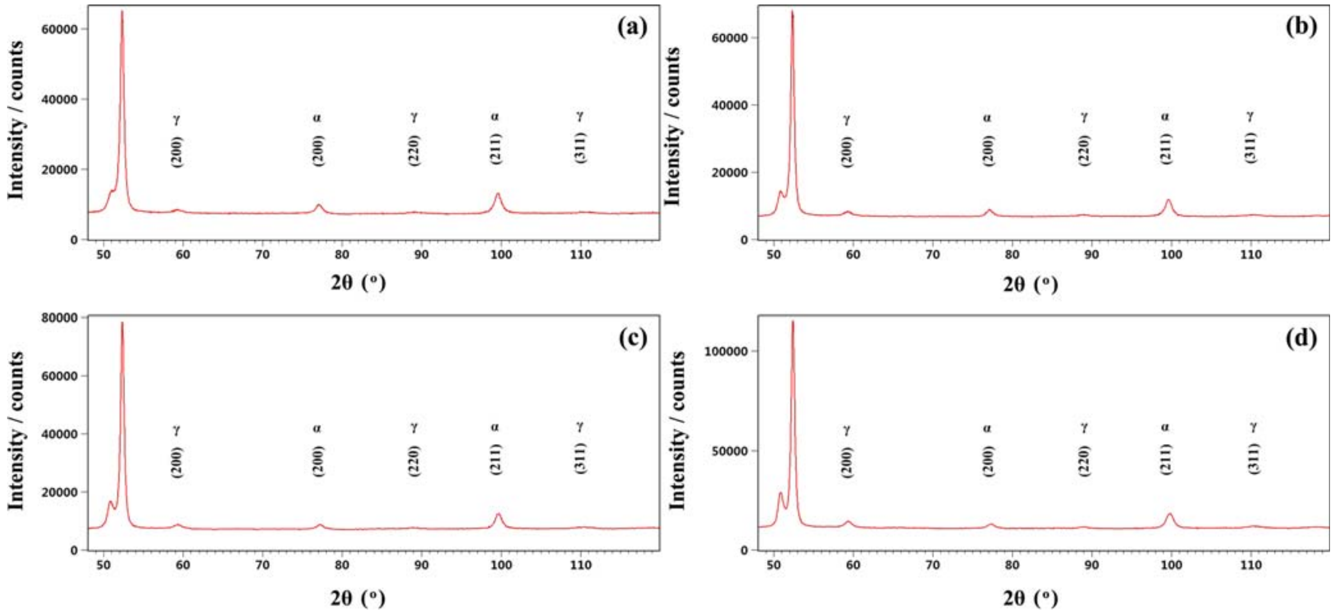

Fig. 4. X-ray diffraction experiments: (a) no deformation, (b) 10% deformation at 300 °C, (c) 20% deformation at 300 °C, and (d) 30% deformation at 300 °C.

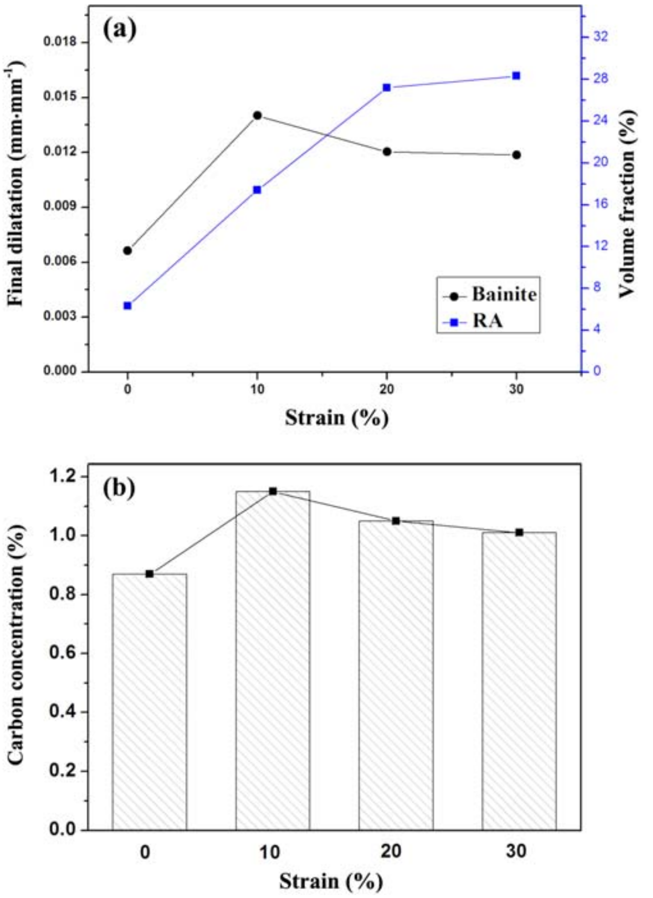

Fig. 5. (a) Final dilatation for complete bainite transformation and volume fraction of RA at room temperature and (b) carbon content in RA with different deformation strains.

determined by the position of three austenite peaks using Cohen's method, considering that Si and Mn have little effects on the lattice parameter of retained austenite [24]. The calculated data are given in Fig. 5b. The deformed sample with a strain of 0.1 has higher carbon concentration in RA (~1.15 wt%) than the non-deformed sample (~0.87 wt%). Subsequently, the carbon content reduces with the increase in strain (~1.05 wt% for 0.2 and ~1.01 wt% for 0.3). The change of carbon concentration in RA with the change in strain is in accordance with the bainite volume fraction. Previous discoveries found that the rejection of carbon to the surrounding austenite from the newly formed bainite occurred during subsequent transformation process [15,25]. Thus, an excessive carbon concentration was obtained in the deformed samples due to the precipitation of more bainite.

4. DISCUSSIONS

4.1. Accelerated bainite transformation

Isothermal bainite transformation can be promoted during the whole holding process by ausforming at low temperature, which has been proven by many researches [13,14,16]. In the present work, a further study on the geometrical relationship between bainite transformation and ausforming strains was carried out by thermodilatometry. With the increasing strain, the initial bainite transformation rate becomes faster, but the final bainite fraction tends to be reduced. Shipway [26] and Bhadeshia [27] claimed that bainite transformation was accelerated during the early stage due to the high density of lattice defects introduced by austenite deformation but was retarded during the final stage due to work hardening of austenite resulting in a smaller bainite amount than the non-deformed materials. However, although ausforming can cause mechanical stabilization, the final bainite amount in the deformed samples is obviously larger than that of the non-deformed material, which is different from the works mentioned above. The final bainite volume fraction in the deformed austenite seems to depend on applied strain. Ausforming has dual effects on bainite transformation, that is, the combined effect of accelerated nucleation and retarded growth. Compared with the non-deformed sample, the application of a 0.1strain provides more nucleation sites for bainite precipitation but only causes little mechanical stabilization, resulting in faster transformation kinetics and larger bainite amount. Bainite transformation is further initially accelerated with the increase in strain because of more nucleation sites. However, the hindrance effect increases more rapidly than the positive factor with the strain varying from 0.1 to 0.2 and 0.3, leading to the reduced quantity of bainite. The growth of bainite nuclei is retarded with increased strain because of smaller austenite grain size and more defects after applying a larger strain. This is in accordance with the assumption that the volume transformed per nucleus in deformed austenite is smaller [27].

A previous work [16] pointed out that bainitic transformation can be promoted by a small strain at 300 °C. The prime difference in this work is that the varying tendency of the promotional effect with the increase of small strain was investigated. The result manifests that the degree of promotion of small strain on bainite transformation is non-linear because of the dual effects of accelerated nucleation and retarded growth caused by ausforming. This is a new result different from Ref. [16]. The maximum amount of bainite transformation occurs at the strain of 0.1. It indicates that there is a peak value of the degree of promotion corresponding to a certain small strain at low temperature.

4.2. Stability of retained austenite

As mentioned previously, austenite stability depends on grain size, morphology and carbon enrichment. Retained austenite in the present work exists in two forms, i.e. blocky and film types. After deformation, large blocky austenite is almost completely partitioned into small pieces. During isothermal holding, a part of parent austenite transforms to bainite while the remaining austenite will partially transforms to martensite in the subsequent cooling to room temperature. Thus, the volume fraction of RA at room temperature is also correlated with martensite transformation besides the amount of bainite transformation. From the SEM micrographs, martensite in the deformed materials is in smaller quantity compared with the non-deformed sample, resulting in a larger quantity of RA at room temperature. Austenite grain size is reduced by deformation. A reduction in the austenite grain size is well known to increase austenite stability by suppressing martensite transformation [28-30]. Lee *et al.* [31] also reported that the small grain size of austenite was the primary cause for the presence of RA at room temperature compared with the two other austenite stabilization factors (i.e. chemical composition and dislocation density). Note that the mechanical stabilization of deformed austenite during bainite transformation is different from that of martensite transformation. During isothermal holding, the growth of bainite sheaves is retarded by large amounts of matrix dislocations and debris caused by heavy deformation. As for martensite transformation, austenite can be stabilized due to the depressed shear which is concerned with the increased density of dislocation [32].

Additionally, carbon-content plays an important role in determining the volume fraction of austenite remained after bainite transformation. The T_0 and para-equilibrium A_{e3} phase boundaries, shown in Fig. 6, are plotted according to the values calculated by MUCG 83.Mod software [33]. It is suggested that bainite reaction occurs only when the carbon concentration of the existing austenite is lower than that determined by the T_0 curve [34]. It can be seen that the measured carbon concentrations in the RA of both deformed and undeformed materials lie between the T_0 and A_{e3} lines. Therefore, bainite transformation ceases and the residual austenite is stabilized due to the excess carbon. Interestingly, the volume fractions of RA for samples with different strains did not decrease with decreased carbon concentration. It indicates that mechanical stabilization caused by ausforming plays a more important role than the stabilizing effect due to carbon enrichment.

In summary, the effect of ausforming on the stability of retained austenite depends on the strains applied to the materials. The amount of untransformed austenite (normally termed as residual austenite [35]) after bainite transformation for 90 min at 300 °C is determined by the transformed bainite

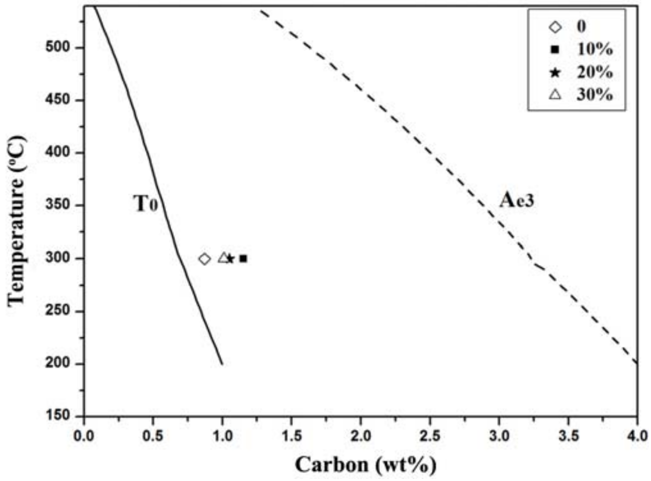

Fig. 6. Calculated phase boundaries with XRD data representing the carbon concentration of retained austenite.

fraction, while the amount of retained austenite at room temperature results from the synthetic effects of bainite amount during isothermal holding at 300 °C and martensite transformation in the subsequent cooling process after bainite transformation. The amount of bainite transformation is at maximum in the sample with strain of 0.1 (Fig. 5a). The residual austenite at the end of isothermal holding is the smallest and the carbon content is the highest in residual austenite. Martensite transformation during cooling from thermal holding temperature of 300 °C to room temperature is hindered because of chemical and mechanical stabilization, resulting in more RA in the sample with a 0.1 strain than the undeformed sample. This is another new result different from Ref. [16]. In addition, the lower carbon concentration of residual austenite in the sample with a 0.3 strain (Fig. 5b) results in weaker chemical stabilization. However, the volume fraction of RA increases due to more serious mechanical stabilization during subsequent cooling process, manifesting that mechanical stabilization caused by ausforming has a decisive effect on determining the volume fraction of RA. This is also a new finding not reported in Ref. [16].

5. CONCLUSION

In this work, the effect of ausforming on the stability of retained austenite in a C-Mn-Si bainitic steel was investigated through metallography, X-ray diffraction and dilatometry. The geometrical relationship of the amount of bainite transformation and the deformation strain was studied. Primary discussions about volume fractions of RA varied with ausforming conditions were given according to qualitative and quantitative diagrams. The results are as follows:

(1) The carbon content in residual austenite increases with the amount of baintie transformation, which contributes to the stability of austenite. Compared with the stabilizing effect due to carbon enrichment, the mechanical stabilization caused by ausforming has a decisive effect on determining the volume fraction of RA.

(2) The degree of promotion of small strain on bainite transformation is nonlinear because of the combined effect of accelerated nucleation and retarded growth. There is a peak value of the promotional degree corresponding to a certain small strain at low temperature.

(3) The amount of RA at room temperature depends on the synthetic effects of bainite amount during isothermal holding and martensite transformation in the subsequent cooling process after bainite transformation. Although a small strain promotes bainite transformation, more RA exists at room temperature due to the suppressed martensite transformation.

ACKNOWLEDGEMENTS

The authors are grateful to the financial supports from the National Natural Science Foundation of China (NSFC) (No. 51274154), the National High Technology Research and Development Program of China (No. 2012AA03A504), the State Key Laboratory of Development and Application Technology of Automotive Steels (Baosteel Group), and the key project of Hubei Education Committee (No.D20121101).

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