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Effects of ausforming strain on bainite transformation in nanostructured bainite steel

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Abstract: The effects of ausforming strain on bainite transformation in high-carbon low-alloy nanobainite steel were investigated using a Gleeble 3500 thermomechanical simulator machine. The bainite transformation speed at 300°C was found to be accelerated by ausforming at 300, 600, and 700°C under applied strains ranging from 10% to 50% followed by isothermal transformation at 300°C. The ausformed bainite volume fraction varied with the ausforming strain because of the mechanical stabilization of the deformed austenite. Ausforming at low temperatures not only enhanced the bainite ferrite volume fraction but also refined the microstructure substantially. Although the amount of bainite ferrite might have been reduced with increasing strain, the microstructures were refined by ausforming.

Keywords: phase transformations; kinetics; bainite steels; nanostructured materials, ausforming

1. Introduction

Ausforming is the deformation of austenite at temperatures well below Ae_3 temperature followed by transformation to martensite or bainite [1]. Deformation can not only reduce the effective austenite grain size but also increase defects such as dislocations, stacking faults, low-angle grain boundaries, and twin boundaries. Ausforming offers numerous advantages, one of which is an increase in strength at the expense of a slight decrease in ductility. In addition, the refinement of austenite and the introduction of a high density of lattice defects strongly affect the martensite and bainite transformations [2–4].

Not all steels are suitable for ausforming—only those where austenite can remain stable during deformation at a relatively low temperature. From this viewpoint, a new type of nanostructured bainite (superbainitic) steel would be the best alloy for ausforming applications because of its deep bay in the region of the TTT diagram between the two C curves that represent the pearlite and bainite transformations [5–8]. With increasing interest in nanostructured bainite steel, studies of the effects of ausforming on nanobainite formation have been the subject of numerous investigations; extensive related research has been reported during the last five years [9–14]. Bainite transformation is now generally accepted as being promoted by ausforming at a relatively low temperature ($T < 600$°C). Although ausforming at 600°C does not affect variant selection [15], the nucleation of bainite can be promoted [16]. The effect of ausforming at higher temperatures such as 700°C has not been reported.

In addition to the ausforming temperature, another important parameter related to nanobainite steels is the deformation strain (ε). Although deformation accelerates the initial bainite transformation rate, the final volume fraction will be lower than that of undeformed nanobainite steels [17–19]. A recent study on superbainite steel containing 0.4C, 2.8Mn, 2.0Si (wt%) indicated that the bainite transformation is retarded by austenite deformation at high temperatures or by deformation with greater strain, whereas bainitic transformation can be promoted by a small strain at low temperatures [20]. Thus, a critical strain at low temperatures may exist.

The purpose of the work presented here is to investigate

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the influence of ausforming strain on the overall kinetics of bainite transformation in high-carbon nanobainite steel. Unlike the previous research, the ausforming temperature here was selected as high as 700°C and the strain covered 10%, 20%, 30%, and 50% during deformation at different temperatures.

2. Experimental

The chemical composition of the investigated steels was Fe–0.91C–1.65Si–2.07Mn–1.26Cr–0.25Mo–1.56Co–0.78Al (wt%). The studied alloy was prepared using a high-frequency induction furnace and was manually hot forged. After forging, the ingots were homogenized at 1250°C for 24 h. Cylindrical specimens with an effective diameter and length of 6 mm and 15 mm, respectively, were prepared for simulator experiments. The thermomechanical heat treatment was conducted using a Gleeble 3500 thermomechanical simulator described elsewhere [11]. Fig. 1 presents the experiment procedures of the ausforming process. The specimen was austenitized at 900°C for 15 min and then cooled to 700°C, 600°C, and 300°C and compressed plastically at a strain of 50%, 50% and 10%, 20%, 30%, and 50%, respectively, within 15 s, followed by isothermal transformation at 300°C until the transformation stopped. We also carried out a comparison experiment in which the specimens were austempered at 230°C and 300°C for 60 h and 6 h, respectively. The isothermal experiments were conducted using DIL 805 dilatometer described elsewhere [21]. Because the deformed samples resulted in a barreling effect and an inhomogeneous plastic strain distribution, we calculated the effective strain using the finite element method [15]. The indicative result (see Fig. 2) obtained by elastoplastic calculation was used to determine the region selection for microstructure examination. Microstructures of all specimens were examined by optical microscopy (OM) and scanning electron microscopy (SEM). The volume fraction of blocky austenite (V_γ) was determined by analysis of the microstructure graphs (including OM and SEM). The average value was then calculated to represent the V_γ.

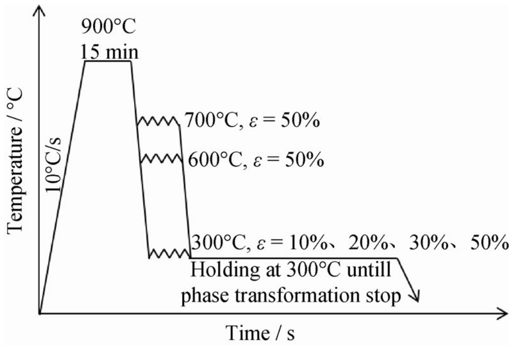

Fig. 1. Process regimes.

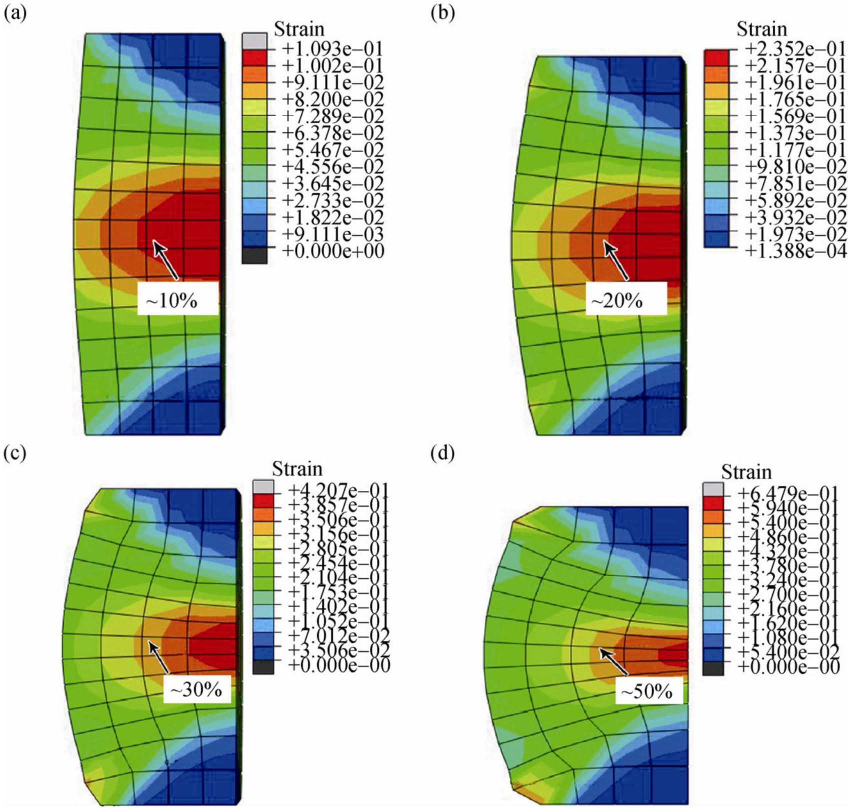

Fig. 2. Finite element analysis to estimate the effective strain distribution in the ausformed samples at different values of actual strain: (a) 10% compression; (b) 20% compression; (c) 30% compression; (d) 50% compression.

3. Results and discussion

3.1. Effect of ausforming strain on bainite transformation speed

In the present study, the bainitic transformation kinetics at different austempering temperatures was interpreted on the basis of the dilatometric amount (length change) of the samples caused by phase transformation from face-centered-cubic (fcc) austenite to body-centered-cubic (bcc) bainite ferrite [22]. The results of dilatometry experiments are illustrated in Fig. 3. The results in Fig. 3(a) and Fig. 3(b) were obtained using a DIL 805 dilatometer; those in Fig. 3(c) and Fig. 3(d) were obtained using a Gleeble 3500. To describe the growth behavior, we define the dilatation rate as the bainite transformation rate (BTR).

The completion times for bainite transformation at 230°C and 300°C are 50 h and 6 h, respectively. The maximum BTR, which occurred at 10 h 26 min, was approximately 1.24×10^{-3} μm·s^{-1} (Fig. 3(a)) for the samples transformed at 230°C; by contrast, the maximum BTR was 2.92×10^{-3} μm·s^{-1} at 2 h 48 min (Fig. 3(b)) in the case of the samples transformed at 300°C. Isothermal bainitic transformation of nanostructured bainite steel shows larger formation rate when transformed at higher temperatures.

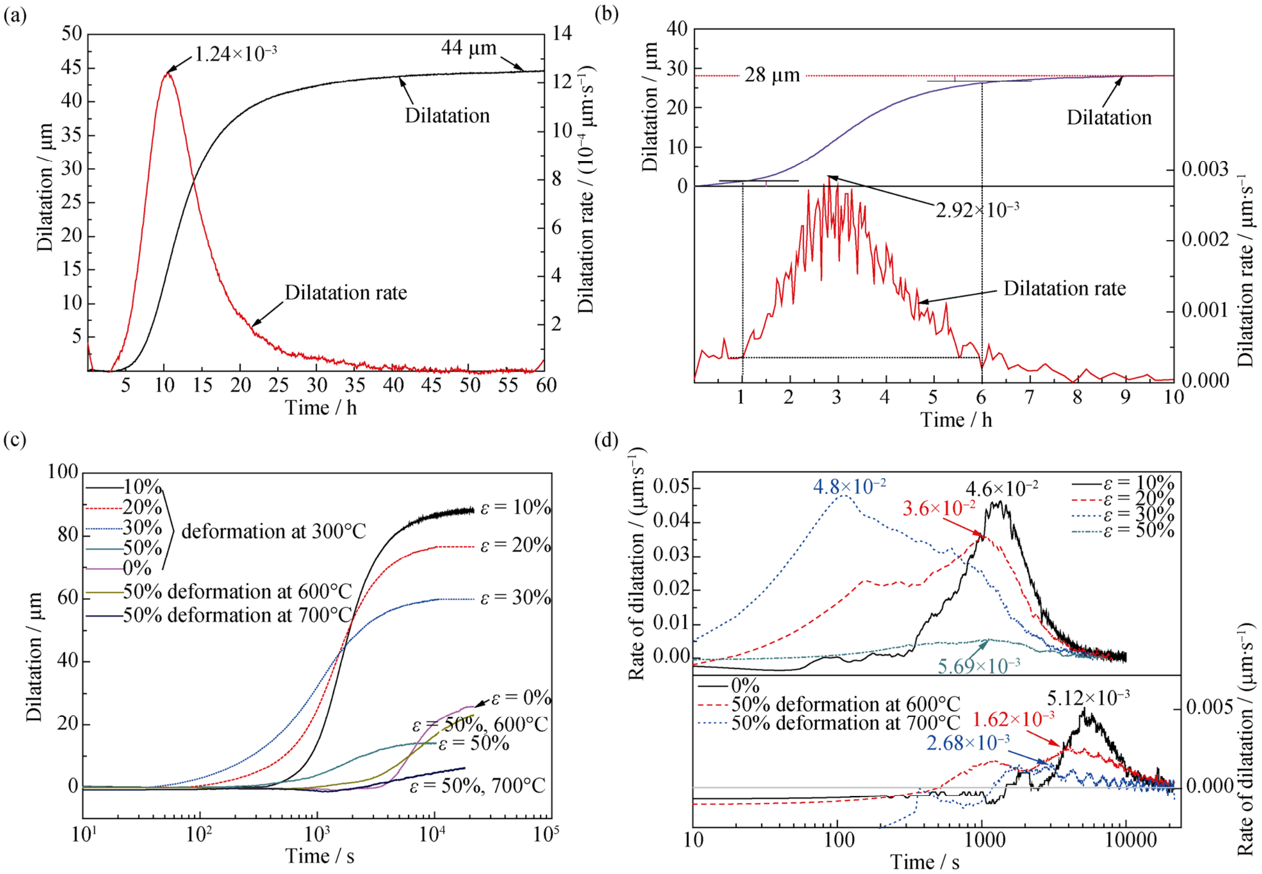

Fig. 3. Dilation curves recorded using a DIL 805 and a Gleeble 3500: (a) bainite transformation at 230°C; (b) transformation rate according to (a); (c) ausformed bainite transformation at 300°C influenced by different strains at 300, 600, and 700°C; (d) transformation rate according to (c).

The dilatometric curves show two different final dilatation values after the completion of bainite transformation when the samples were isothermed at 230°C and 300°C. Two different final values are observed because the bainite reaction in the absence of carbide precipitation is incomplete; the maximum amount of bainite ferrite is limited by the T_0' curve [1]. The reaction cannot proceed when the carbon content of retained austenite exceeds that given by the T_0' curve. That is, bainite ferrite can only form below the T_0' temperature. Consistent with the trend of increasing carbon content with decreasing temperature, the maximum amount of bainite ferrite formed at high temperatures was less than that formed at low temperatures.

Figs. 3(c) and 3(d) show the diameter changes caused by deformed austenite transforming into bainite ferrite. Notably, the dilatation can be affected by the shape change due to variant selection; thus, the dilatation cannot exactly correspond to the change of bainite fraction [18,20]. The bainite fraction can be quantitatively analyzed on the basis of the micrographs, as discussed in section 3.2. However, our objective here was to investigate the influence of austenite deformation on the BTR; we therefore did not modify the results by the real bainite amount. The results clearly indicate that deformation at either low temperature or high temperature shortens the incubation time. Furthermore, the incubation time decreases with increasing deformation strain when deformed at 300°C with a strain of 30% or less. The incubation time of the sample deformed with 50% strain at 300°C is shorter than that of the undeformed sample (ε = 0%). Deformation at high temperature (600°C or 700°C) can also shorten the incubation time. The maximum BTR in the ausformed sample was larger than that in the undeformed sample except in the case where deformation was applied at high temperature but all maximum BTRs appeared faster according to Fig. 3(d).

According to Fig. 3(d), during ausforming at 300°C with a strain of 10%, 20%, and 30%, the time required for the completion of the bainite transformation is less than 2.7 h. The finishing time for the sample deformed with 50% strain at 300°C is less than 1.7 h. Even though the starting transformation time can be shortened by deforming at high temperatures, the finishing time is approximately 6 h, which is the same as that of the undeformed sample (ε = 0%). The deformed austenite contains deformation faults and deformation stored energy. Compared with the high deformation temperatures (600°C/700°C), low deformation temperatures lead to greater deformation stored energy because of the high strength of austenite. At the same time, the compression of low-temperature austenite results in a greater defect density. Thus, ausforming at low temperatures provides more nucleation sites and extra transformation driving force (deformation stored energy). We concluded from the dilatometry experiments that ausforming at low temperatures accelerates the bainite transformation, whereas the finishing time decreases with the appearance deformation strain.

3.2. Effect of ausforming strain on microstructures

The micrographs of isothermally treated nanostructured bainite are shown in Fig. 4. A fully bainitic microstructure (Fig 4(a)) with a mixture (Fig. 4(c)) of thin bainite ferrite (black needles) separated by film austenite (light lamella) was obtained by isothermal treatment at 230°C for 60 h. Because of the incomplete reaction mechanism, the microstructure formed at higher temperatures (e.g., 300°C) consists of blocky retained austenite (white microstructure in Fig. 4(b)), lamellar bainite ferrite, and film retained austenite (Figs. 4(b) and 4(c)). The thicknesses of the bainite ferrite and the film austenite are (49.66 ± 14.45) nm and (57.25 ± 16.71) nm for samples austempered at 230°C and (110.43 ± 31.33) nm and (105.59 ± 28.69) nm for samples transformed at 300°C. Furthermore, a large amount of blocky retained austenite with an average size exceeding 2 μm is observed in Fig. 4(b). A small amount of martensite formed from untransformed blocky retained austenite is also observed in Fig. 4(d).

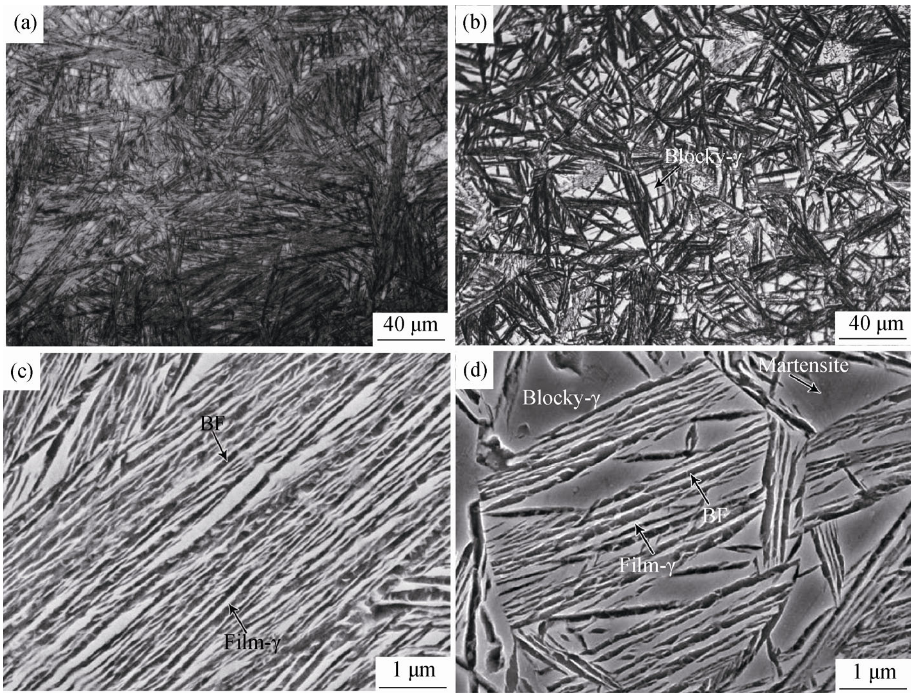

Fig. 4. Comparison of bainite transformed at different temperatures. OM images of samples transformed at (a) 230°C and (b) 300°C and SEM images of samples transformed at (c) 230°C and (d) 300°C.

The microstructures of ausformed nanobainite are shown in Fig. 5. Micrographs in Figs. 5(a) to 5(d) show the microstructures of samples isothermally transformed at 300°C after being ausformed at 300°C under different strains. All four of these samples gain fully bainitic structures without large blocky retained austenite compared with the non-ausformed sample (Fig. 4(b)). The microstructures obtained by ausforming at 600°C or 700°C with 50% strain are inhomogeneous. Blocky retained austenite and/or martensite appears in the microstructure (Fig. 5(e)), whereas pearlite gathers along the prior austenite grain boundaries (Fig. 5(f)). Higher-magnification images in Fig. 5 clearly illustrate the effect of ausforming on bainite ferrite and retained austenite. Large amounts of blocky retained austenite with an average size greater than 5 μm occupy 40% of the area of micrographs shown in Fig. 5(e). We concluded that ausforming at 600°C under 50% strain can retard bainite transformation by reducing the final bainite volume fraction. Despite the presence of pearlite in Fig. 5(f), the existence of large volume fraction of blocky austenite and martensite supports the same conclusion.

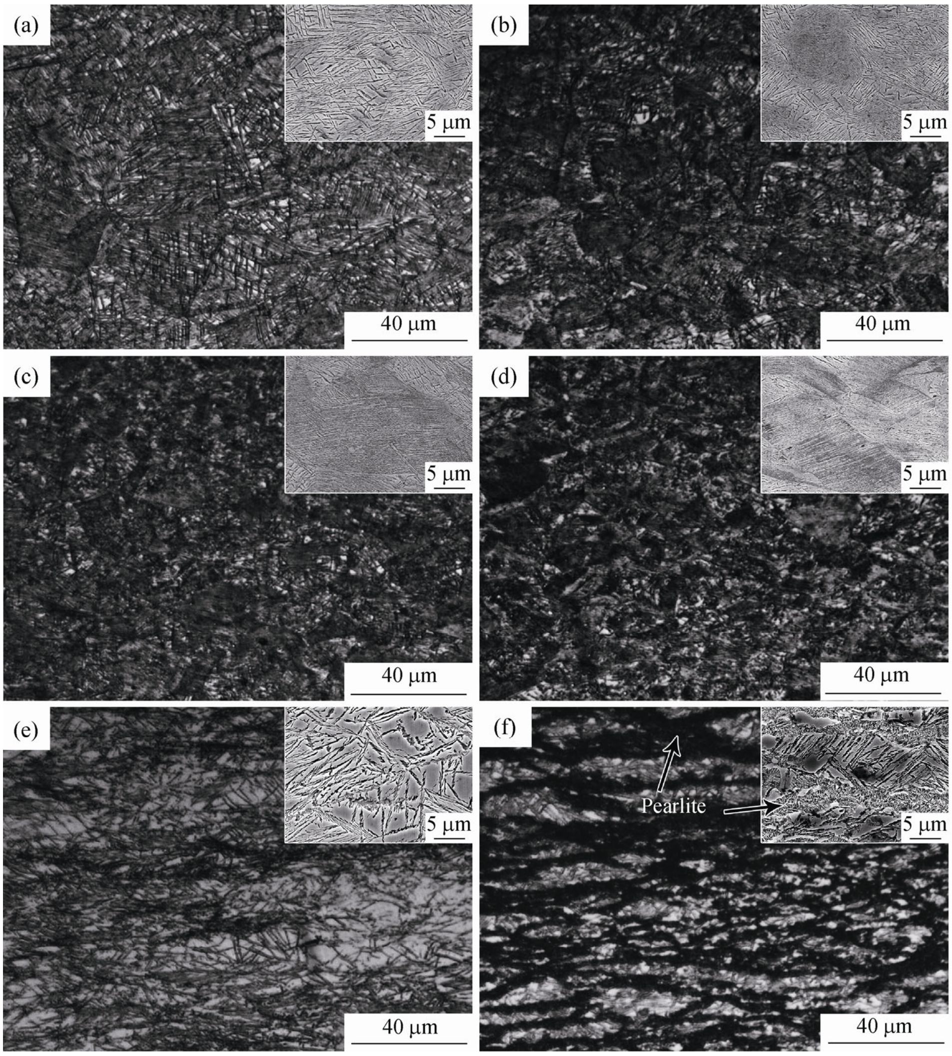

Fig. 5. Optical micrographs and inset high-magnification SEM images of samples ausformed at 300°C under (a) 10% compression, (b) 20% compression, (c) 30% compression, and (d) 50% compression and samples ausformed under 50% compression at (e) 600°C and (f) 700°C.

Distinguishing differences between microstructures obtained by ausforming at low temperatures is difficult. We therefore measured the volume fraction of visible retained austenite (blocky retained austenite) using optical micrographs (15 images were used) and the amount of retained austenite in all types containing blocky and film morphologies using high-magnification SEM micrographs (16 images were used). The phase compositions of low-temperature-ausformed samples are illustrated in Fig. 6. The results show that the final amount of bainite ferrite increases with increasing applied ausforming strain. The amount of bainite ferrite obtained from the austempering process (0%) is the smallest, but the amount of blocky retained austenite is the largest, reaching 42% (martensite in the austenite was not measured). Therefore, we concluded that ausforming at low temperatures accelerates bainite transformation by increasing the final amount of bainite ferrite. The blocky retained austenite can be eliminated via the ausforming process and isothermal transformation at 300°C. The ausforming process would be a good solution to eliminate large regions of blocky retained austenite that will transform under stress to hard and brittle martensite.

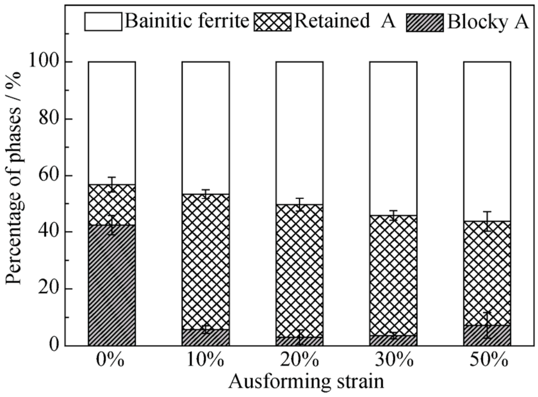

Fig. 6. Phase fractions of the microstructures obtained using different heat treatments.

The results of the thickness of lamellar structures displayed in Fig. 7 show that ausforming at low temperature led to a sufficient structure refinement. The bainite ferrite was refined with increasing ausforming strain. The average thicknesses of bainite ferrite and film retained austenite change from (110.43 ± 31.33) nm and (105.59 ± 28.69) nm to (49.66 ± 14.45) nm and (57.25 ± 16.71) nm, respectively, when the transformation temperature is lowered from 300°C to 230°C. These decreases in thickness are a consequence of the increased prior austenite strength and free-energy change caused by the lower temperature [23]. The prior austenite strength increased with increasing ausforming strain and increasing deformation energy, which accelerate the bainite formation, resulting in microstructure refinement. The reduced bainite ferrite thicknesses of the ausformed samples confirm this deduction. However, the thickness of film austenite increases with increasing strain when the ausforming strain does not exceed 30%. This phenomenon has also been observed in multi-step ausformed nanostructured bainite because of the mechanical stability of deformed austenite [12]. The thickness of retained austenite decreases to (98.65 ± 29.31) nm and is less than that of the non-ausformed sample when transformed at the same temperature (300°C).

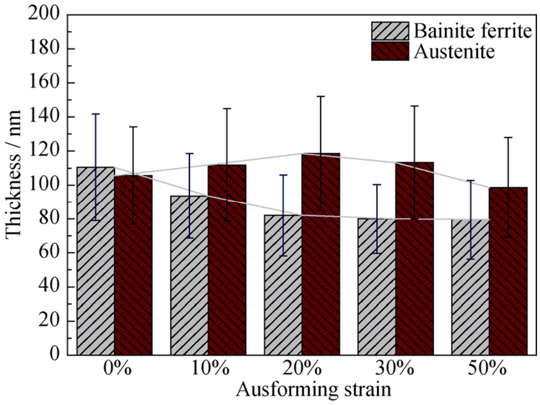

Fig. 7. Thickness comparison of bainite ferrite and film austenite in all obtained microstructures.

4. Conclusions

The effects of ausforming strain on isothermal bainite transformation behavior and microstructure were studied in high-carbon nanobainite. The results show that the effect of ausforming on bainite transformation varies with deformation temperature and strain. The results obtained are summarized as follows.

(1) Ausforming at 300°C was found to accelerate bainite transformation. Both the incubation period and the completion time decreased when the applied strain was 50% or less. The incubation time of isothermal transformation decreased with increasing ausforming strain when the total strain was less than 30%, but increased again when the strain reached 50%.

(2) In the case of ausforming at high temperatures (600–700°C) with a strain of 50%, the early stage of transformation could be accelerated but the completion time could not be shortened. Ausforming at 700°C led to the precipitation of pearlite and to the retardation of bainite formation by reducing the final amount of bainite.

(3) The amount of bainite ferrite increased with increasing strain (from 0% to 50%) after ausforming at a low temperature (300°C) followed by isothermal transformation. Deformation at high temperatures (600–700°C) with a total strain of 50% retarded bainite formation by decreasing its final volume fraction.

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