

# New Insights to the Promoted Bainitic Transformation in Prior Deformed Austenite in a Fe-C-Mn-Si Alloy

Hai-jiang Hu, Guang Xu\*, Ming-xing Zhou, and Qing Yuan

The State Key Laboratory of Refractories and Metallurgy, Key Laboratory for Ferrous Metallurgy and Resources Utilization of Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China

(received date: 15 June 2016 / accepted date: 5 September 2016)

The varying trends of the amount and rate of bainitic transformation with strains at low temperature were investigated through metallography, X-ray diffraction and dilatometry. The results show that deformation at 573 K promotes bainitic transformation, whereas the promotion degree on bainite transformation by ausforming is nonlinear with strains. The amount of bainite in deformed austenite first increases and then decreases with the increase of strains. There exists a maximum value of the promotion effect corresponding to a critical small strain at a low temperature. Bainitic transformation rate can be increased by ausforming at low temperature, whereas a large strain weakens the acceleration effect. The amount of bainite in deformed materials is synthetically depended on the effect of enhanced nucleation and repressed growth. In addition, the volume fraction of retained austenite is not completely consistent with carbon content, indicating that ausforming plays a important role in determining the amount of austenite.

**Keywords:** metals, phase transformation, microstructure, deformation, dilatometry

## 1. INTRODUCTION

In recent years, an increased attention was paid to the exploration on new advanced high strength steel (AHSS) [1-2]. Since low-temperature carbide-free bainitic steel was discovered by Bhadeshia and coworkers [3-10], it has been termed as a member of third-generation AHSSs and gradually become a hot topic of steel research field. A low-temperature carbide-free bainitic microstructure which consists of a bainite matrix, retained austenite and some martensite is optimal to achieve a good combination of strength, ductility and toughness. However, in carbide-free bainite steels, bainitic transformation can take several days to complete transformation in low temperatures [3-4,9]. In order to accelerate low-temperature bainitic transformation, Co- and Al-containing alloys were designed [11]. In doing so, the time to finish bainitic transformation is drastically decreased, but still unpractical for commercial scenario because several days are still needed to complete bainitic transformation and also Co is very expensive for production.

Many researches also reported the effect of ausforming on bainitic transformation. The results are controversial and can be totally divided into three categories. One viewpoint is that the overall bainitic transformation might be slowed and even

ceased by mechanical stabilization caused by deformation [12-14]. Another category of the influence of ausforming on bainitic transformation is that heterogeneous nucleation becomes frequent in deformed austenite which can accelerate the initial bainite precipitation, but the growth of bainite sheaves by a indiffusion mechanism is hindered by forests of dislocations, resulting in a small amount of bainite than unformed austenite [15-17]. Different from above two viewpoints, Gong *et al.* [18-19] found that bainite transformation was accelerated by ausforming at 573 K with a strain of 15%, not only at the beginning but also throughout the transformation, while deformation at high temperatures nearly had no effect on bainitic transformation. It seems that a concordant result concerning the influence of ausforming on bainite transformation has not been obtained. Thus further investigation was conducted in the previous work [20]. The overall bainitic transformation was retarded by ausforming at high temperatures, while the situation at low deformation temperatures is different. For a small applied strain at 573 K, the whole transformation kinetics was accelerated. However, when the strain became larger, only the initial transformation rate was accelerated, the final amount of bainite became smaller.

According to previous studies, it might be determined that bainitic transformation is promoted by small deformation at low temperature. The problem is that the relationship between the amounts of bainite with various small strains is not fully clear. Although Gong *et al.* [18,19] pointed out that the applied

\*Corresponding author: xuguang@wust.edu.cn  
©KIM and Springer

strains (0.15 and 0.25) at 573 K promoted bainitic transformation, they did not definitely clarify the how the amount of bainite change with strains at low deformation temperature, which has been investigated in the present work. Shipway and Bhadeshia [12] investigated the mechanical stabilization of bainite, and found the maximum available volume fraction of bainite decreases in deformed austenite. They also claimed that when the strain was increased beyond a critical value, the volume fraction of bainitic transformation can achieve the same level to that of undeformed austenite. They explained it by that the accelerated nucleation could compensate for the hindered growth when the applied strain was large enough. It can be concluded that the composite effect of enhanced nucleation and hindered growth results in a complicated dependence of the bainitic transformation kinetics on ausforming. Therefore, it is necessary to clarify the links between volume fractions of bainite and small strains at a low temperature. In this work, the amounts of bainite under different strains at low temperature were investigated and the microstructural characteristics varying with deformation were examined. The quantitative relation between bainitic transformation and deformation was studied using dilatometric analysis.

## 2. EXPERIMENTAL PROCEDURE

The material with the chemical composition of 0.41 C, 2.80 Mn, 2.01 Si, 0.04Al and balance Fe (wt%) was used in this study. The microstructure consists of nano-scale bainite, austenite plates and martensite. In order to obtain these microstructures, it is necessary to carry out the bainitic transformation at low temperatures. A key requirement is therefore a chemistry which suppresses the martensite starting temperature ( $M_s$ ). In addition, a high Si content is needed to suppress cementite precipitation. The steel was hot rolled to the flat with thickness of 12 mm. Specimens for thermal simulation experiments were cylinders of 8 mm diameter and 12 mm height. The specimens were polished to minimize the effect of surface roughness on measurement value. The tests were performed on a Gleeble-3800 thermal simulator according to the experiment procedures shown in Fig. 1. All samples were austenized at 1173 K for 15min followed by cooling to 573 K and then deformed with different amounts of 5%, 10%, 20%, 30% and 40%, respectively. After deformation, all samples were isothermally kept at 573 K for 90 min. In addition, an undeformed specimen was tested with the same technology to make comparison. The  $M_s$  of the tested steel is 521 K which can ensure the occurrence of bainite transformation and avoid martensite transformation during isothermal holding. After isothermal treatment, the samples were cooled down to the ambient temperature. In each test, the change of dilatation which can represent bainitic transformation during the isothermal holding at 573 K was collected by a laser extensometer.

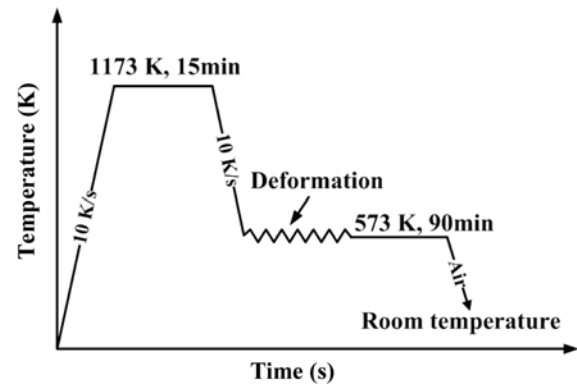


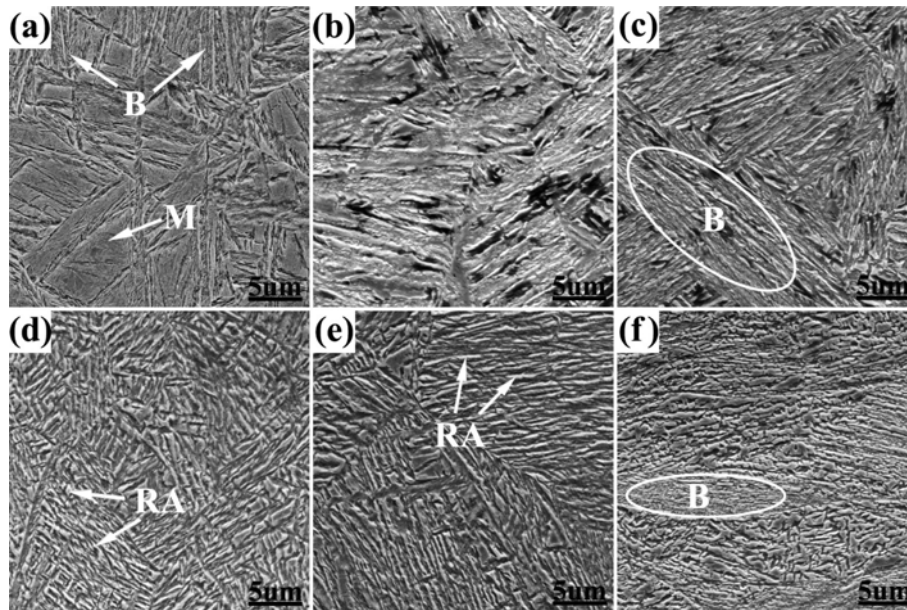
Fig. 1. Ausforming experiment procedures.

After ausforming tests, microstructures of specimens were examined by Nova400Nano scanning electron microscope (SEM). The metallographic specimen for SEM is etched by 4% nital. Retained austenite (RA) in each specimen was detected by X'Pert diffractometer equipped with  $CoK\alpha$  radiation. The parameters for X-ray tests are as follow: acceleration voltage, 42 kV; current, 150 mA; step,  $0.05^\circ$ . The calculation of RA is based on integrated intensities of (200)<sub>a</sub>, (211)<sub>a</sub>, (200)<sub>g</sub>, (220)<sub>g</sub>, and (311)<sub>g</sub> diffraction peaks obtained by X-ray diffractogram (XRD).

## 3. RESULTS AND DISCUSSIONS

### 3.1. Characterization of microstructure

Microstructures of the all samples after dilatometric tests were shown in Fig. 2. The microstructures in both deformed and undeformed samples consist of plates of bainite (B), RA and martensite (M). Bainite sheaves are clearly distinguishable from blocky martensite, shown by arrows in Fig. 2a. Also film-like and blocky RAs can be observed, as shown by arrows in Figs. 2d and 2e. Bainite in non-deformed specimen seems to grow in various orientations with random selection, while selected bainitic variants (ellipse in Figs. 2c and 2f) occur in deformed samples. This may be explained by that ausforming at a low temperature brings a characteristic dislocation microstructure, resulting in strong variant selection of bainite transformation [19]. After ausforming, especially with large strains, the bainite sheaves tend to be finer and shorter. Deformed austenite brings large amounts of dislocations and subgrains which can offer nucleation spots for bainitic transformation, leading to the finer bainite morphology. Meanwhile, bainite sheaves are limited by dislocations and grain boundaries, so shorter bainite sheaves are obtained. Additionally, the formation of the long bainite sheaves in the specimen with a strain of 0.1 (Fig. 2c) is due to the combination effect of orientation selection and individual free space for the growth of bainite. It is well known that bainitic transformation has the characteristic of incomplete reaction [21], thus blocky martensite



**Fig. 2.** SEM microstructures for samples under different deformation strains followed by isothermal holding for 90 min at 573 K: (a) no deformation, (b) 5%, (c) 10%, (d) 20%, (e) 30% and (f) 40%.

transformed from residual austenite exists in the final microstructure, marked by arrow in Fig. 2a. When the samples are subjected to deformation, large blocky martensite disappears basically, which may be caused by two reasons. One is that parent austenite grains are divided into small ones by ausforming, the other is that the residual austenite is segmented into pieces by bainite sheaves, finally resulting in the disappearance of large blocky martensite. The above explanations also accounts for the occurrence of small blocky RA in some deformed specimens at ambient temperature.

### 3.2. Stabilization of austenite

XRD analysis was conducted to measure the volume fraction of RA. The results are shown in Table 1 and Fig. 3. Table 1 gives the volume fractions of the various phases for different ausforming samples. The volume fraction of bainite was calculated by Image Pro-Plus software using the method in Ref. [22]. It can be seen that the amount bainite increases in all deformed samples compared with the undeformed one. The X-ray results show that the amount of RA first increases with the increased strains, and the maximum value reaches to ~28.2% corresponding to the strain of 0.3, but then decreases to ~15.5% when the strain increases to 0.4. Anyhow, the deformed samples contain more RA than the undeformed sample, confirming that ausforming intensifies the stabilization of prior austenite.

Generally, the stabilization of austenite depends on grain size, morphology and carbon content. A reduction of original austenite grain size contributes to the stabilization of austenite by inhibiting martensite transformation [23]. After deformation, large amounts of defects and subgrains are introduced into

**Table 1.** Quantitative data on microstructures for different deformed specimens

Deformation strain	B (%)	M (%)	RA (%)
Non-deformed	49.8±2.1	42.3±1.9	7.9±0.9
0.05	58.6±2.5	24.6±1.5	14.0±1.3
0.1	71.9±3.0	10.7±1.2	17.4±1.3
0.2	64.3±2.9	8.6±1.0	27.1±1.8
0.3	60.5±2.5	11.3±1.1	28.2±1.9
0.4	54.7±2.1	29.8±1.5	15.5±1.2

parent austenite, which can provide more nucleation sites. Thus, large quantity of bainite sheaves in small size form. These small sized bainite sheaves partition the residual austenite into small pieces. As mentioned above, a reduction of residual austenite size contributes to decrease martensite transformation, resulting in more RA. In Table 1, compared with the undeformed specimen, the amount of martensite in the deformed specimen is small, leading to more RA at room temperature. However, the volume fraction of RA in the deformed specimen with a strain of 0.4 decreases relatively compared with that in samples with 0.2 and 0.3 strains. Excess carbon can partition into surrounding austenite from newly formed bainite during bainitic transformation, which can result in the stabilization of untransformed austenite [21]. Compared to the samples deformed with strain of 0.2 and 0.3 at 300 °C, smaller amount of bainite is obtained in the sample of a 0.4 strain, resulting in a relative low carbon concentration in residual austenite. Thus, more martensite could be transformed from residual austenite during the subsequent cooling to room temperature, leading to smaller amount of RA. Figure 3 shows the change tendency of RA and

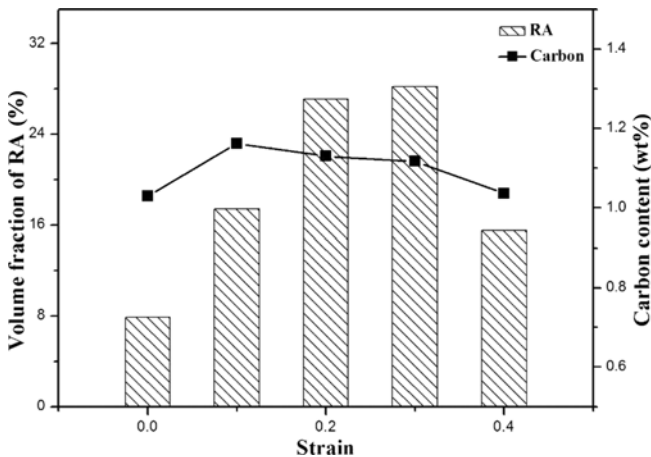


Fig. 3. Volume fractions of RA and corresponding carbon content in samples with different strain.

its corresponding carbon concentration with deformation strain. Both the amount of RA and corresponding carbon concentration first increases and then decreases with strain. However, the variation trend of carbon concentration is not completely consistent with the quantity of RA despite higher carbon content can enhance the stability of austenite. It indicates that the stabilization of RA is determined by the combined influence of carbon content and ausforming strain. When the ausforming strain becomes large, mechanical stabilization caused by deformation plays a more important role than chemical stabilization due to carbon enrichment. Therefore, although carbon content decreases when the strain increases from 0.1 to 0.3, the amount of RA increases.

### 3.3. Promoted bainitic transformation by ausforming

Figure 4 shows the dilatation changing with time during bainitic transformation in specimens ausformed and transformed at 573 K, as well as the transformation rates. Because of the constant transformation temperature and the negli-

ble effect of small stress on phase transition, the dilatation can reflect the change of bainite amount. The dilatation data in Fig. 4a was normalized by dividing the accumulated dilatation by the equal diameter of the sample before bainite precipitation. Apparently, the smallest volume change caused by bainite precipitation occurs in the non-deformed specimen. The volume change is increased by the application of strains, indicating that the deformation at 573 K causes an increment to the final amount of bainite.

Furthermore, the initial transformation rates are also accelerated by ausforming compared with the sample without deformation, as shown in Fig. 4b. It can be seen that the acceleration degree on bainitic transformation by ausforming is gradually enhanced with the strain increased from 0.05 to 0.3. The maximum transformation rates  $\sim 2.4 \times 10^{-5} \text{ mm s}^{-1}$  is achieved at the strain of 0.3. Also the maximum transformation rate occurs earlier when the sample is applied to a larger strain. This might be explained by following suggestion. For bainite transformation at low temperature propagating according to a subunit mechanism that the rate is mainly determined by nucleation instead of growth, accelerating the nucleation rate will affect the overall transformation rate significantly [24,25]. The deformed austenite at 573 K provides large amounts of defects as nucleation sites, and more favorable nuclei could be produced by larger strains. Thus it is reasonable to obtain a faster initial transformation rate at a higher strain. However, the bainitic transformation kinetics is receded to  $\sim 1.2 \times 10^{-5} \text{ mm s}^{-1}$  when the strain is increased to 0.4 again. It indicates that the transformation rate is not only controlled by nucleation rate, but also related to the growth of bainite. When the deformation degree is high enough to cause serious mechanical stabilization, the growth of bainite nucleus is hindered once it is formed. Then the volume fraction of bainite transformed per nucleus in deformed austenite is reduced [16], resulting in a relative low transformation rate. In the work by Gong *et al.* [19], bainitic transformation was further accelerated with the

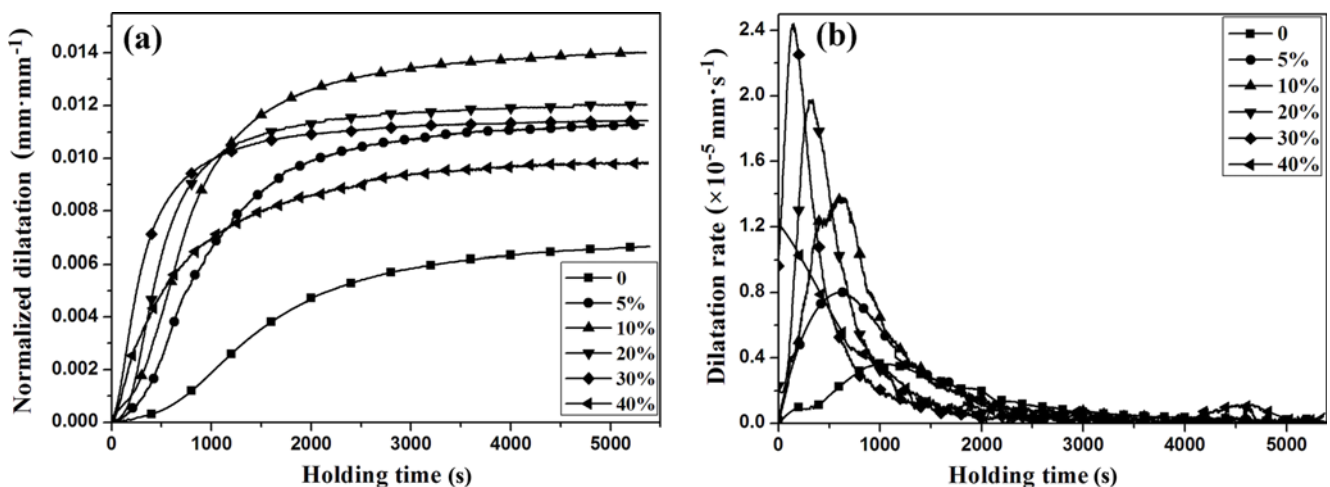


Fig. 4. (a) Dilatation curves and (b) transformation rates showing the effect of ausforming on bainitic transformation.

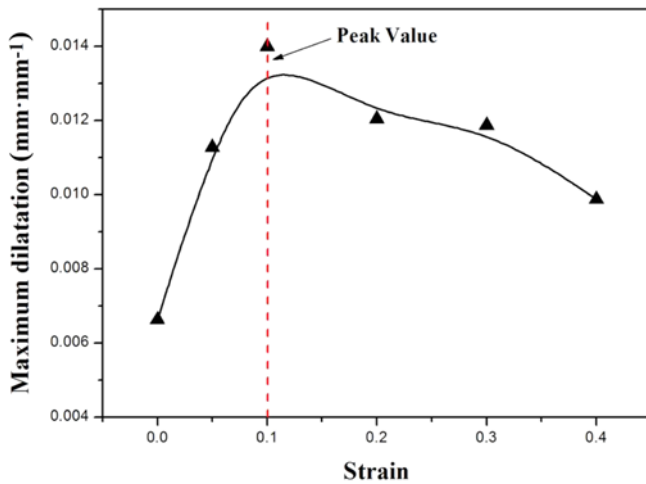


Fig. 5. The tendency of the maximum amount of bainite changing with different deformation strains.

strain increasing from 0.15 to 0.25 at 573 K, which is consistent with the results of the present work. However, they did not clarify the change trend of the amount of bainite with strains at low deformation temperature. In the present work, it is clearly clarified that a maximum fraction of bainite is obtained in deformed austenite with strain of 0.1 at 573 K.

### 3.4. Peak value strain

In order to clearly show the changing tendency of promotion effects on bainitic transformation by small strains, the maximum amount of bainite varying with deformation strains is given in Fig. 5. It is obvious that the largest final dilatation  $\sim 0.014$  corresponding to the maximum amount of bainite (71.9%) is achieved at a strain of 0.1 noted by peak value. After that, the maximum dilatation decreases with strain. The amount of bainite changes nonlinearly with the increase of strain, meaning that the promotion effect on bainitic transformation by ausforming at low temperature is not continuously enhanced with the increased strains. Ausforming has contradictory effects on bainitic transformation, i.e. the enhanced nucleation and hindered growth of bainite sheaves. At the same time bainitic transformation is related to parent austenite grain size and small austenite grains lead to less bainite amount [26]. Compared to the undeformed austenite, the deformed austenite with a strain of 0.1 provides larger amounts of nucleation spots for bainite transformation but only brings slight hindrance to the growth of bainite, resulting in a faster transformation rate and larger volume fraction of bainite. Bainite precipitation is further initially accelerated by a larger strain because of more facilitated nucleation sites. Nevertheless, the retardation effect of mechanical stabilization and smaller austenite grains rises more rapidly than the facilitated nucleation when the strain increases to 0.3 and 0.4, resulting in the decreased amount of

bainitic transformation.

Most studies just focus on whether the plastic deformation promotes bainite transformation at low temperature [11-19,25], while few researches have been reported concerning the varying rule of promotion effect with deformation strains at low temperature. It is the first time to observe that there is a maximum value of promotion degree on bainitic transformation by deformation at a low temperature. The strain, corresponding to the largest amount of bainite transformation, can be defined as peak value strain (PVS). When the deformation strain is smaller than the PVS, the final volume fraction of bainite increase with an increased strain, and it decreases once the strain beyond the PVS. It may be presumed that the amount of bainite transformed from deformed austenite would decrease to the same degree as that of the undeformed austenite when the ausforming strain increases to a certain value. In fact, it has been demonstrated in the previous work [20] that when the deformation strain was 0.5 at 573 K, the volume fraction of bainite was smaller than that of the undeformed austenite.

## 4. CONCLUSION

In the present work, a further study about promotion effects on bainitic transformation by ausforming was conducted by metallography, X-ray diffraction and dilatometry. The results show that the promotion degree on bainite transformation by small strains is nonlinear, and there exists a maximum value of the promotion effect corresponding to a small strain at 573 K. The strain corresponding to the largest amount of bainite transformation is defined as peak value strain (PVS). Bainitic transformation rate can be increased by ausforming at low temperature, while a large strain weakens the acceleration effect. The maximum amount of bainite in deformed materials is synthetically depended on the effect of accelerated nucleation and retarded growth.

## ACKNOWLEDGEMENT

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

## REFERENCES

1. W. Bleck and F. Gerdemann, *Mater. Manuf. Process.* **26**, 43 (2011).
2. F. G. Caballero, C. García-mateo, C. Capdevila, and C. G. Andrés, *Mater. Manuf. Process.* **22**, 502 (2007).
3. F. G. Caballero, H. K. D. H. Bhadeshia, K. J. A. Mawella, D. G. Jones, and P. Brown, *Mater. Sci. Tech. Ser.* **18**, 279 (2002).

4. C. Garcia-Mateo, F. G. Caballero, and H. K. D. H. Bhadeshia, *ISIJ Int.* **43**, 1238 (2003).
5. F. G. Caballero and H. K. D. H. Bhadeshia, *Curr. Opin. Solid St. M.* **8**, 251 (2004).
6. H. K. D. H. Bhadeshia, *Mater. Sci. Forum* **500-501**, 63 (2005).
7. C. Garcia-Mateo and F. G. Caballero, *ISIJ Int.* **45**, 1736 (2005).
8. C. Garcia-Mateo, F. G. Caballero, and H. K. D. H. Bhadeshia, *Mater. Sci. Forum* **500-501**, 495 (2005).
9. C. Garcia-Mateo and F. G. Caballero, *Int. J. Mater. Res.* **98**, 137 (2007).
10. F. G. Caballero, M. K. Miller, S. S. Babu, and C. Garcia-Mateo, *Acta Mater.* **55**, 381 (2007).
11. C. Garcia-Mateo, F. G. Caballero, and H. K. D. H. Bhadeshia, *ISIJ Int.* **43**, 1821 (2003).
12. P. H. Shipway and H. K. D. H. Bhadeshia, *Mat. Sci. Technol.* **11**, 1116 (1995).
13. R. H. Lam and J. R. Yang, *Mat. Sci. Eng. A* **278**, 278 (2000).
14. C. S. Chiou, J. R. Yang, and C. Y. Huang, *Mater. Chem. Phys.* **69**, 113 (2001).
15. S. B. Singh and H. K. D. H. Bhadeshia, *Mater. Sci. Technol.* **12**, 610 (1996).
16. H. K. D. H. Bhadeshia, *Mat. Sci. Eng. A* **273-275**, 58 (1999).
17. X. J. Jin, N. Min, K. Y. Zheng, T. Y. Hsu, and Z. Y. Xu, *Mat. Sci. Eng. A* **438-440**, 170 (2006).
18. W. Gong, Y. Tomota, M. S. Koo, and Y. Adachi, *Scripta Mater.* **63**, 819 (2010).
19. W. Gong, Y. Tomota, M. S. Koo, Y. Adachi, A. M. Paradowska, J. F. Kelleher, et al. *Acta Mater.* **61**, 4142 (2013).
20. H. J. Hu, H. S. Zurob, G. Xu, D. Embury, and G. R. Purdy, *Mat. Sci. Eng. A* **626**, 34 (2015).
21. H. K. D. H. Bhadeshia and A. R. Waugh, *Acta Metall.* **30**, 775 (1982).
22. H. J. Hu, G. Xu, L. Wang, Z. L. Xue, Y. L. Zhang, and G. H. Liu, *Mater. Design* **84**, 95 (2015).
23. S. Lee, S. J. Lee, and B. C. De Cooman, *Scripta Mater.* **65**, 225 (2011).
24. H. K. D. H. Bhadeshia, *Mater. Sci. Technol.* **21**, 1293 (2005).
25. J. G. He, A. M. Zhao, C. Zhi, and H. L. Fan, *Scripta Mater.* **107**, 71 (2015).
26. G. Xu, F. Liu, L. Wang, and H. J. Hu, *Scripta Mater.* **68**, 833 (2013).