Materials Science & Engineering A 626 (2015) 34–40

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

New insights to the effects of ausforming on the bainitic transformation

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ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form
11 December 2014
Accepted 13 December 2014
Available online 20 December 2014

Keywords:
Ausforming
Bainite transformation
Mechanical stabilization
Dilatometry

ABSTRACT

The effects of prior deformation conditions on the bainitic transformation are investigated using dilatometry and optical metallography. The influences of both deformation temperature and strain on bainite transformation kinetics and morphology are examined in superbainitic carbide-free steel. The transformation is retarded by deformation at high temperature due to the retardation of bainite growth by dislocation debris in deformed austenite. At low deformation temperatures, the initial transformation rate is accelerated due to the presence of prolific nucleation sites in deformed austenite. The growth rate is, again, retarded by deformation. The combined effect of accelerated nucleation and retarded growth results in a complex dependence of the phase transformation kinetics on applied strain. For small deformation strains at 300 °C, the overall transformation kinetics is faster than that in the non-deformed material. From a practical point of view, this provides an important opportunity to reduce the processing times for carbide-free bainitic steels. Interestingly, both the final transformed bainite and retained austenite fraction under these conditions are much higher than the non-deformed material. The retardation of growth dominates the overall transformation kinetics at large strains and low temperature leading to a high volume fraction of martensite in the final microstructure.

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1. Introduction

Plastic deformation can strongly influence phase transformations in steels. It is generally accepted that ferrite and pearlite transformations are promoted by prior deformation [1,2], while the formation of martensite is retarded [3–5] by prior deformation. For bainite precipitation, however, the effect of ausforming on the transformation kinetics is not very clear. Shipway et al. [6] summarized the effects of ausforming on bainitic transformation and claimed that the motion of the transformation interface is hindered by the accumulated debris of dislocations in the deformed austenite. Larn et al. [7] studied the effect of compressive deformation at 800 °C on subsequent bainite precipitation in Fe–Mn–Si–C steels and found that the overall transformation kinetics became slower and the final attained amount of bainite decreased in deformed austenite. Chiou et al. [8] investigated the effect of prior compressive deformation of austenite on the toughness in an ultra-low carbon bainitic steel. They argued that compressive deformation stifled the formation of sheaf-like parallel plates of bainitic ferrite. Yang et al. [9] and Davenport [10] reported that the bainitic transformation was retarded by ausforming to large strain. Lee et al. [11] gave similar results in their study on the effect of plastic deformation on the formation of acicular ferrite and found that the transformation to acicular ferrite was hindered and the final fraction of acicular ferrite was reduced in plastically deformed austenite. The above investigations seem to suggest that ausforming not only decreases the transformation rate, but also reduces the final amount of bainite formed.

Other researchers claimed that deformation accelerates the initial transformation rate (nucleation) but retards the later stages which are dominated by growth. Bhadeshia [12] and Singh [13] found that although the deformation of austenite did introduce more heterogeneous nucleation sites, the growth of the bainite plates was drastically reduced by deformation, resulting in slower overall transformation kinetics. The nucleation rate is larger in the heavily deformed regions but the overall rate of transformation is reduced because each nucleus then transforms to a smaller volume. Maki [14] claimed that although deformed austenite transformed faster initially, the net volume fraction of bainite that formed decreased when compared with undeformed austenite. Freiwillig et al. [15] also reported an initial acceleration of transformation to bainite from deformed austenite, but final transformed fraction decreased. Jin et al. [16] found that the

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http://dx.doi.org/10.1016/j.msea.2014.12.043
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isothermal decomposition of deformed austenite was significantly promoted as the incubation period was remarkably shortened for small strain (e.g. 5%) but the final amount of bainite formed was reduced. Edwards and Kennon [17] reported similar results.

In few cases, it was reported that the whole transformation process is promoted by ausforming. Gong et al. [18,19] studied the effect of ausforming on kinetics, morphology and crystallography of nano-scale bainite steel. It was found that the bainite transformation at 300 °C was promoted after the steel was compressed by small reduction at this temperature while ausforming at high temperature had little influence on bainitic transformation. These authors did not investigate the effect of large deformation strains.

In summary, three different results have been reported, indicating that the influence of deformation on the bainite transformation is still a controversial topic. It is noteworthy that most of earlier work has not systematically considered the effect of deformation temperature and strain on the bainitic transformation. Therefore, in order to further investigate the effects of ausforming on the bainitic transformation both deformation temperature and strain are varied in the present work. The steel of interest is a simple, Fe–C–Mn–Si, carbide-free bainitic steel. The transformation kinetics is examined using metallography and dilatometric analysis.

2. Experimental

A superbainite steel containing 0.4C, 2.8 Mn, 2.0 Si (wt%) was used in the present study. The steel was cast in the form of a 40 kg ingot using laboratory-scale vacuum furnace at ArcelorMittal Dofasco (Hamilton, Canada). The material was then hot-forged and air-cooled to room temperature. The steel was then tempered at 650 °C for 15 h in order to facilitate machining.

The specimens for the thermomechanical simulation tests were machined in the form of a cylinder of 8.0 mm diameter and 10 mm height. The thermomechanical treatments were performed using a Gleeble 1500 thermomechanical simulator. The processing schedules employed are illustrated in Fig. 1. In the first schedule, no deformation is applied to the material; the specimen is austenitized at 860 °C for 15 min before being cooled to 300 °C, at 10 °C s^{-1}, and isothermally transformed for 90 min. The isothermal holding temperature was controlled within the range of ±0.5 °C. After isothermal holding, the specimen was cooled to room temperature at a cooling rate of 30 °C s^{-1}. The effect of deformation was investigated at two different temperatures and strains. Schedule 1 in Fig. 1 was used to study the influence of high temperature deformation on bainitic transformation. The specimens were deformed, in compression, at 860 °C to strains of 0.25 and 0.50. The effect of low temperature deformation was studied using schedule 2 in which the specimens were deformed at 300 °C to strains of 0.25 and 0.50 before transformation. In all cases, the diameter change during the isothermal bainitic transformation was recorded using a laser extensometer. The specimens were also examined using standard optical metallography and Scanning Electron Microscopy (SEM).

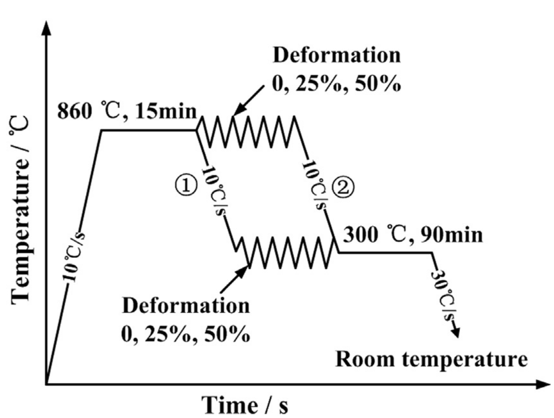

Fig. 1. Ausforming experiment procedures.

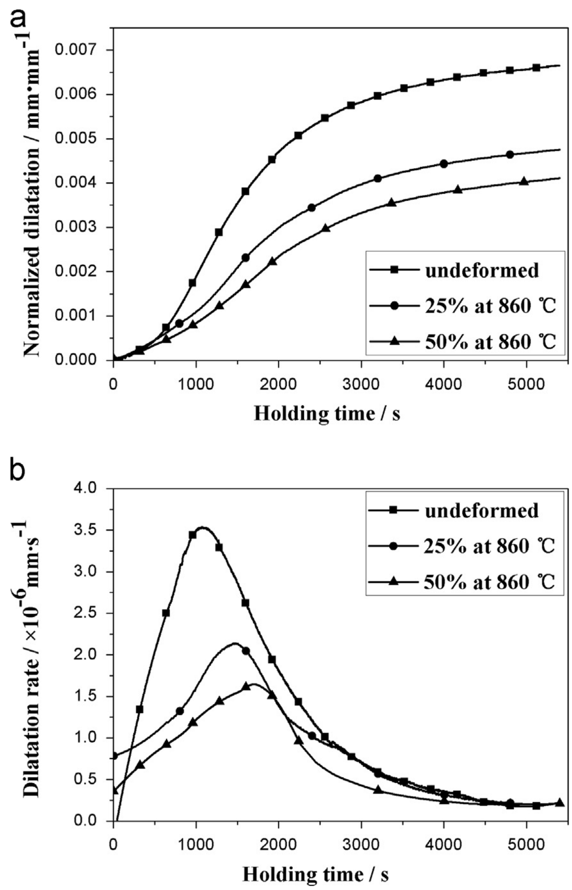

Fig. 2. (a) Dilation curves and (b) transformation rates showing the effect of ausforming at high temperature on bainitic transformation.

3. Results

3.1. Effect of ausforming at high temperature on bainitic transformation

Fig. 2 shows the recorded diameter changes during isothermal holding at 300 °C after ausforming at 860 °C. To a first order, the change in diameter is attributed to the volume change associated with the precipitation of bainite. Second order effects such as variant selection and transformation plasticity could occasionally complicate the interpretation of the recorded diameter changes. In the present case, however, the evolution of the diameter is largely due to the precipitation of bainite and, therefore, provides direct information on the kinetics of the reaction. In Fig. 2, the dilatation amount is normalized by dividing the instantaneous dilation by the sample diameter before transformation. It is clear from Fig. 2 that the largest volume change occurred for the non-deformed specimen. The application of a strain of 0.25 reduced the volume change obtained at the end of the transformation. Increasing the strain to 0.50 had the effect of further retarding the transformation

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