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Effects of ausforming temperature on bainite transformation, microstructure and variant selection in nanobainite steel

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Abstract

The bainite transformation behavior after plastic deformation of austenite, i.e., ausforming was studied by in situ neutron diffraction and ex situ experiments, and the effects of ausforming temperature was made clear. Ausforming, at a low temperature (573 K) was found to accelerate bainite transformation and produce a characteristic microstructure, whereas at a high temperature (873 K), ausforming had little influence. The reason for the different results stems from the dislocation structure introduced in austenite; planar dislocations remaining on the active slip planes are believed to assist bainite transformation, accompanied by strong variant selection. The variant selection rule that focuses on Shockley partial dislocation was verified from electron backscatter diffraction results.

Keywords: Bainite; Ausforming; Phase transformation; Crystallography; Neutron diffraction

1. Introduction

Nanobainite steel, proposed by Bhadeshia and co-workers [1–3], has awakened great interest, because this new generation of ultrahigh-strength steel exhibits a tensile strength >2 GPa and an excellent toughness of 30 MPa m$^{1/2}$. Steels designed to contain ~1.0C and 1.5Si (in mass%) show very slow bainite transformation at 473–673 K, leading to a remarkable nanoscaled structure composed of bainitic ferrite lath and film austenite with no cementite precipitation [2–4]. Slow transformation, requiring several days to finish, is necessary for the fabrication of large-scale machine components that require homogeneous microstructure with low residual stresses in the products. However, there is a need for more rapid heat treatment, and therefore Al and/or Co have been added to increase the chemical driving force for bainite transformation. As an alternative accelerating method, it was found that a small amount of ausforming accelerated nanobainite transformation [5]. However, Shirzadi et al. [6] reported a contradicting result that ausforming followed by isothermal holding at 573 K neither accelerated bainite transformation nor assisted variant selection. Note that their ausforming temperature was 873 K, whereas the temperature in the present study was 573 K. Hence, the objective of this study is to confirm the influence of ausforming temperature on bainite transformation. To obtain more insight into the bainite transformation mechanism after ausforming, in situ neutron diffraction and transmission electron microscopy (TEM) observations were performed.

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The transformation process is typically investigated by interrupting the quenching at an elevated temperature as a means to freeze the microstructure, although austenite transforms to martensite. However, in situ neutron diffraction can track the transformation at high temperatures, even if a thermomechanically controlled process (TMCP) such as ausforming is employed, and can give global information complementary to the microstructure observations.

As previously reported [1,2], the microstructure of nanobainite obtained without ausforming consists of very thin bainitic ferrite lath and carbon-enriched retained austenite film. The crystal orientation between austenite γ and bainitic ferrite α was reported to be near the Nishiyama–Wassermann (N–W) relationship [7], ($\{111\}\gamma//\{011\}\alpha$, $\langle 112\rangle\gamma//\langle 110\rangle\alpha$), rather than the Kurdjumov–Sachs (K–S) relationship [8], ($\{111\}\gamma//\{011\}\alpha$, $\langle 011\rangle\gamma//\langle 111\rangle\alpha$) [5,9]. In most austenite grains, all 12 variants (equivalent N–W relationships) are observed in non-ausformed nanobainite. In contrast, in ausformed nanobainite, the length of the ferrite lath shortens, and the number of variants in individual austenite grains decreases, showing a characteristic ultrafine microstructure [5]. According to a recent report by Takayama et al. [9], variant selection becomes weaker as the formation temperature decreases, and therefore the cause of strong variant selection accompanying ausformed nanobainite formed at extremely low temperature must be clarified.

Variant selection in martensite, bainite or ferrite transformations from plastically deformed austenite has already been thoroughly investigated. In particular, variant selection in martensitic transformation has been studied extensively [10–15], with emphasis on the roles of dislocations and residual stress. Moreover, variant selection has been reported in ferrite transformation, but its occurrence is not as strong as in martensitic transformation [10,16,17]. The role of the austenite deformation structure on variant selection during phase transformation still needs to be investigated, mainly because crystallographic information on the parent austenite is lacking as the transformation is complete upon cooling, i.e., little or no austenite remains at room temperature in low-alloyed steels. Recently, Miyamoto et al. [18] have developed a method for predicting the austenite orientation from the product phase. Using this technique, they studied variant selection in ausformed lath martensite with a 0.15 mass% carbon steel. They proposed a simple variant selection rule that the habit plane of the selected variant is parallel to the active slip plane of the austenite, although direct observation of the dislocation structure in the austenite is absent. As mentioned in their report [18], their proposal is quite similar to previous observations for ausformed nanobainite [5]. If Si is added to a carbon-bearing steel to suppress carbide precipitation, carbon-enriched austenite could easily be retained even at room temperature. Therefore, in a bainite steel containing Si and C, it is possible to investigate the variant selection mechanism directly on the basis of dislocation observations at room temperature, because the parent austenite phase is retained [5,19]. The dislocations remaining on the operating slip plane are considered to accelerate nucleation and the growth of a new grain of body-centered cubic (bcc) or body-centered tetragonal (bct) lattice phase. Butrón-Guillén et al. [20] and Wittridge and Jonas [11] reported that glide perfect dislocation facilitated phase transformation with the corresponding K–S variant, whereas Jonas et al. [21] pointed out that partial dislocations are responsible for the appearance of selected N–W variants. However, such variant selection models have not been sufficiently verified experimentally. Therefore, the details of the variant selection mechanism in ausformed bainite as well as ausformed martensite in a high-C steel are studied, and the differences between the two products are elucidated.

2. Experimental

The chemical composition of the steel used in this study was Fe–0.79C–1.98Mn–1.51Si–0.98Cr–0.24Mo–1.06Al–1.58Co (wt.%); it was prepared by vacuum induction melting in consultation with the published literature [1,22]. The ingot was homogenized at 1473 K for 14.4 ks, followed by hot rolling in the temperature range 1473–1273 K to reduce the thickness of the ingot from 40 mm to 10 mm through ten successive passes. Cylindrical specimens 6 mm in length and 4 mm in diameter were prepared by spark wire cutting for compression tests. Ausforming, a TMCP, was conducted with a hot compression machine, whose details are reported in Ref. [23]. The specimens were austenitized at 1173 K for 600 s, rapidly cooled down to 873–523 K, compressed plastically to a 15% reduction within 10 s, and held isothermally for different times. Similar experiments were performed with in situ neutron diffraction using ENGIN-X at ISIS, where some specimens were either further cooled or heated to 573 K after ausforming to examine the influence of the ausforming temperature. During the experiment, the temperature was measured using a thermocouple. The specimens were cooled down to the deformation temperature at a rate of 10 K s^{-1} and compressed to a 15% reduction in 10 s or 25% reduction in 16 s. After unloading to 0.4 MPa, the specimens were cooled or heated to the isothermal phase transformation temperature, followed by air cooling.

The specimens were sectioned longitudinally and polished following a conventional metallographic technique, where 2% nital etchant was used to reveal the microstructure. The central area of each specimen was observed by optical microscopy (OM) and scanning electron microscopy (SEM) using a Hitachi 4300 microscope. The specimens for electron backscatter diffraction (EBSD) examination were prepared by mechanical grinding and then polished with a colloidal silica slurry. The EBSD measurement was performed with an accelerating voltage of 20 kV, a tilt angle of 70° and a step size of 0.1 μm. The crystallographic information obtained for the γ and α phases was compared simultaneously. A specimen was sec-