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Effect of austenite grain size on transformation of nanobainite and its mechanical properties

Tao Jiang [a], Hongji Liu [b], Junjie Sun [a], Shengwu Guo [a], Yongning Liu [a,*]

[a] State Key Laboratory of Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi' an Jiaotong University, Xi'an 710049, People's Republic of China

[b] Equipment Manufacturing College, Hebei University of Engineering, Handan 056038, People's Republic of China

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ABSTRACT

Nanobainite steels display an excellent combination of outstanding strength and ductility. However, the transformation rate and impact toughness of nanobainite still need to be improved. In this work, the effect of refining austenite grain size to an ultrafine one on bainite transformation and its mechanical properties were investigated using a steel with composition of 0.8C-1.5Si-2.0Mn-1.0Cr-0.24Mo-1.0Al-1.6Co. The results show that refining austenite grain from 53 μm to 3 μm can accelerate the bainite transformation significantly, but almost half amount of the bainite is no longer typical nanostructured bainite, and plenty of undesirable blocky austenite which is harmful to the toughness of the steel remains at the same time. When grain is in medium dimension (18 μm), the best impact toughness of 51 J/cm^2 occurs with corresponding strength of 2034 MPa and ductility of 14%.

1. Introduction

Nanostructured bainite was first discovered in high carbon high silicon steels by Bhadeshia et al. [1–8], and it displays a combination of high strength and good ductility. The nanobainite is usually obtained through an isothermal transformation at low temperature above martensite-start temperature (*Ms*), leading to alternative distribution of nanoscale plate of bainitic ferrite and film-like retained austenite [7,9,10]. Since the discovery of nanostructured bainitic steels [6–8,11,12], many researchers have been striving to explore both transformation mechanism and improvement on mechanical properties. Up to now, nanobainite steels appear to show prominent strength (above 2 GPa), outstanding ductility and a certain degree of toughness [10,11,13,14].

Unsatisfactorily, it usually takes days or even weeks to complete the nanobainite transformation, which decreases its production efficiency [6,9,15–17]. Garcia-Mateo and Caballero [16] reported that refining the austenite grain size and adding Co and Al to a high carbon steel could accelerate the bainite transformation, and it showed that the time to complete the bainite reaction was reduced from 24 h to 10 h when austenite grain size was reduced from 44 μm to 28 μm. But Wu et al. [18] argued that the transformation of super bainite was accelerated by a coarse austenite grain size (about 66 μm) rather than a fine one (about 33 μm). And Bhadeshia [3] declared that the effect of austenite grain size on the overall kinetics of isothermal bainite transformation in steels was determined by the growth rate of bainite ferrite. Specifically speaking, when the overall reaction was limited by a slow growth rate, a refinement of the austenite grain structure leaded to an acceleration of the transformation rate. Conversely, for rapid growth, a fine austenite grain would retard the overall reaction rate.

As is known, both tensile strength and toughness are of great importance to the application of engineering materials. Although nanobainite steels have excellent tensile performances, outstanding wear resistance, and as well as remarkable rolling contact fatigue (RCF) performance [19,20], it seems that the impact toughness still remains poor [20–24]. Bhadeshia [9] suggested that the impact toughness of nanobainite steels was poor, and it might be impossible to improve this particular parameter.

Up to now, little research has been reported about the bainite transformation characteristic with an ultrafine prior austenite grain size. In this work, refining austenite grain size from a coarse one (53 μm) to an ultrafine one was (3 μm) was designed, and the effect of austenite grain size on microstructure, transformation rate and the mechanical properties of a nanobainite steel were studied.

2. Material and experimental procedure

The chemical composition (wt%) of the steel in this study is Fe-0.8C-1.5Si-2.0Mn-1.0Cr-0.24Mo-1.0Al-1.6Co. The steel was melt in

* Corresponding author.
E-mail address: ynliu@mail.xjtu.edu.cn (Y. Liu).

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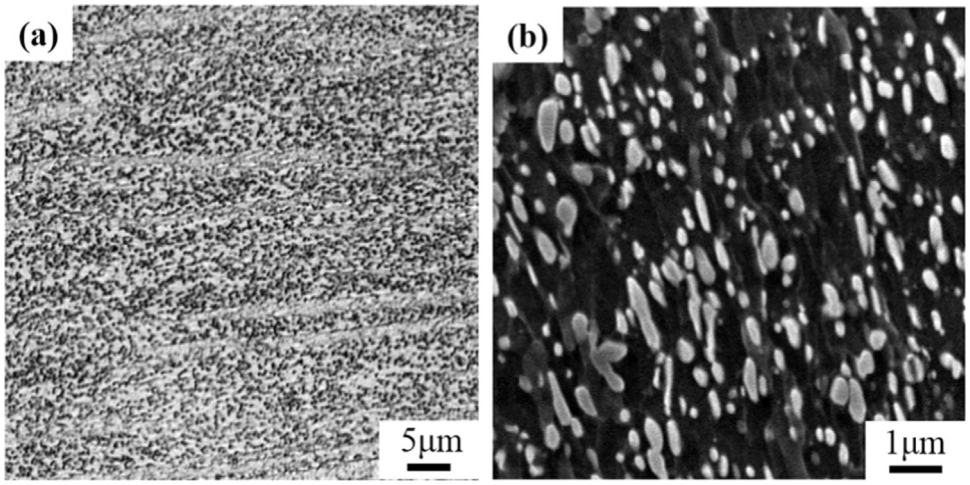

Fig. 1. Optical micrograph (a) and SEM micrograph (b) of the sample after warm rolling.

a vacuum induction furnace, and then the 10 kg ingot was homogenized at 1200 °C for 2 h. The ingot were hot rolled in several passes at a finishing temperature about 900 °C, and then cooled in air to room temperature. Warm rolling process was taken subsequently to further refine the microstructure at 600 °C with a total reduction of 75%. The optical micrograph and SEM micrograph of the samples after warm rolling are shown in Fig. 1. It can be seen that the microstructure of granular cementite dispersed on ferrite matrix appears, and the grain size of cementite is about 0.3 μm. The specimens were austenitized at 820 °C for 10 min, 900 °C for 10 min and 980 °C for 1 h respectively to obtain different austenite grain sizes, then transferred to a salt bath for austempering at 250 °C for 1 h/3 h/6 h/12 h/36 h respectively to achieve various amounts of nanostructured bainite.

To reveal the microstructure, metallographic samples were cut, ground and polished following standard procedures. A 4% Nital etching solution was used to reveal bainitic microstructure, and the microstructure was observed with optical microscope MA200 and scanning electron microscope JEOL JSM-6390. Since the prior austenite grain boundaries have not been revealed directly, the prior austenite grain sizes were estimated by an indirect method which was based on the length of the first-formed sheaf of bainite in prior austenite grain according to OM micrographs and SEM micrographs. The volume fraction of bainite was obtained through an image analysis software (image-pro plus 6.0). The TEM samples were sliced into 0.5 mm thick disks by electrode discharging, and mechanically ground down to 30 μm in thickness on waterproof abrasive paper, and then thinned to perforation by ion milling at ambient temperature. The TEM samples were observed on a JEOL JEM-2100 (Tokyo, Japan). Quantitative X-ray diffraction analysis was conducted to determine the volume fraction of retained austenite (V_γ%) and its mass fraction of carbon content (W_C %). The polished samples were then step-scanned in a Shimadzu xrd-7000 using Cu Kα radiation. The volume fraction of retained austenite was calculated from the integrated intensities of (111), (200) and (220) in austenite peaks, and those of (110), (002) and (112) planes of ferrite. The austenite carbon content (W_C %) was estimated using the following equation [25]:

$$W_C = \frac{a_\gamma - 3.5780 - 0.00095W_{Mn} + 0.0002W_{Ni} - 0.0006W_{Cr} - 0.0056W_{Al} - 0.0031W_{Mo} - 0.0018W_V}{0.33} \times 100\% \quad (1)$$

where a_γ is the parameter of austenite, measured by using X-ray diffraction; W is the mass fraction of the elements in austenite. Because only carbon is interstitial atom among these elements which can diffuse during austempering, the mass fractions of the elements except carbon in austenite are almost the same as the mass fractions of elements in the alloy.

Tensile tests were performed on Instron 1195 testing machine at room temperature at a strain rate of 0.1 $mm \cdot s^{-1}$. And the specimen's dimension is 2.5 mm in thickness, 10 mm in width and 30 mm in gauge length. The Charpy impact of U-notched ($5 \times 10 \times 55$ mm) samples was measured by a 150 J Charpy testing machine at room temperature and all reported values are the averages of three measurements.

3. Results and discussion

3.1. Microstructure characterization

Prior austenite grain sizes of samples austenitized at 820 °C for 10 min, 900 °C for 10 min and 980 °C for 1 h were determined to be about 3 ± 1.5, 18 ± 5 and 53 ± 13 μm respectively. Fig. 2(a), (b) and (c) show the optical micrographs (OM) of the samples with three different prior austenite grain sizes subjected to austempering at 250 °C for 12 h, and these samples are hereafter designated as AGSI, AGSII and AGSIII respectively. The bright area of the OM is blocky retained austenite (BRA) and the dark needle-like structure is nanostructured bainite (NB). It can be seen that the bainite transformation of AGSI and AGSII almost finished, and there is still lots of untransformed blocky austenite in AGSIII. In addition, as the average size of prior austenite grain increases, the average size of bainitic ferrite increases.

Fig. 2(d), (e) and (f) show the corresponding SEM micrographs. It is noted that when prior austenite grain size is about 3 μm, almost half amount of the bainite is no longer nanostructured bainite. The bainitic ferrite (BF) has larger size and irregular morphology compared with nanostructured bainite. Another extremely important feature in Fig. 2(d) is that lots of small-sized blocky austenite exists in the structure. Fig. 2(e) and (f) show the typical structure of nanostructured bainite which consists of bainitic ferrite plates and film-like retained austenite. Because of the low bainite transformation rate in AGSIII, the bainitic transformation is uncompleted, leading to plentiful untransformed blocky austenite.

To further reveal the fine details of the microstructure, TEM micrographs of AGSI, AGSII and AGSIII are demonstrated in Fig. 3. As is shown in Fig. 3(a) and (c), besides a mixture of slender platelets of bainitic ferrite (BF) and thin film-like retained austenite (FRA), blocky retained austenite (BRA) can be easily found in the samples. And the structure of AGSII is almost entirely a mixture of