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Surface modification of low-carbon nano-crystallite bainite via laser remelting and following isothermal transformation

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ABSTRACT

The low-carbon carbide-free bainite was surface modified by laser remelting and following isothermal transformation (LRFIT). The microstructure and nanomechanical properties of the bainite were investigated by scanning electron microscopy (SEM), X-ray diffractometer (XRD), transmission electron microscopy (TEM) and nanomechanical tester. The microstructure of the surface modified bainite can be refined and the hardness distribution interval of the surface of bainite can be obviously improved. Meanwhile, the nanohardness of the modified bainite is evidently increased from 5.605 GPa to 5.868 GPa. The martensite start temperature of the steel can be declined by LRFIT at a relative lower temperature due to the decrease of the retained austenite (RA) fraction and the bainite can be obtained at the temperature which is lower than the martensite start temperature of the original specimen.

1. Introduction

Carbide-free bainite has attracted attention for its excellent mechanical properties. The high strength and toughness of bainite are ascribed to its microstructure consisting of bainite-ferrite (BF) and carbon-enriched retained austenite (RA) [1]. Generally, the precipitation of cementite in the bainite can be effectively suppressed by adding silicon, which in turn maintains its dual-phase microstructure [2].

F. G. Caballero et al. [3–5] developed a high-carbon high-silicon bainite steel through isothermal transformation at low temperatures, and a nanobainite steel (high toughness of 30 MPa $m^{1/2}$ and high strength of 2500 MPa) with microstructure of the nanoscale bainite plate (50 nm) and RA films can be prepared. M. Zhang et al. [6] found that high hardness (592-628 HV) bainite can be obtained in supercooled austenite with medium carbon high-silicon composition during the deformation and following austempering at 250 °C.

The mechanical properties of bainite steel is closely associated with its strength of the parent-austenite [2]. The stability and strength of the parent-austenite can be enhanced by adding carbon, manganese or chromium, which in turn reduces the bainite start transformation temperature (Bs). These previous positive achievements have made it possible for bainite transformation at low temperature [6,7].

Recent literatures show that, the strength of parent-austenite can be improved by refining its grain size, and the martensitic transformation was postpone. The low Ms temperature makes it possible to obtain the bainite steel at a low temperature by refining the parent-austenite grain size [8,9].

As one of advanced surface treatment techniques, laser remelting (LR) has the advantage of high energy density, fast cooling speed, and flexibly and quickly controlling it has been widely applied to refine the austenite grain size of alloys [10,11]. However, martensite transformation usually occurs during the LR process at a room-temperature. In this work, the carbide-free bainite was surface modified by LR at an expected temperature. The microstructure and mechanical properties of the surface modified bainite were investigated, and the effect of carbon redistribution in nano-crystallite bainite was analyzed.

2. Materials and methods

The chemical composition of the steel is given in Table 1. The Ms temperature of the steel was calculated to be 362 °C by MUCG83 thermodynamic model [12]. The size of the specimens for laser remelting and following isothermal transformation (LRFIT)

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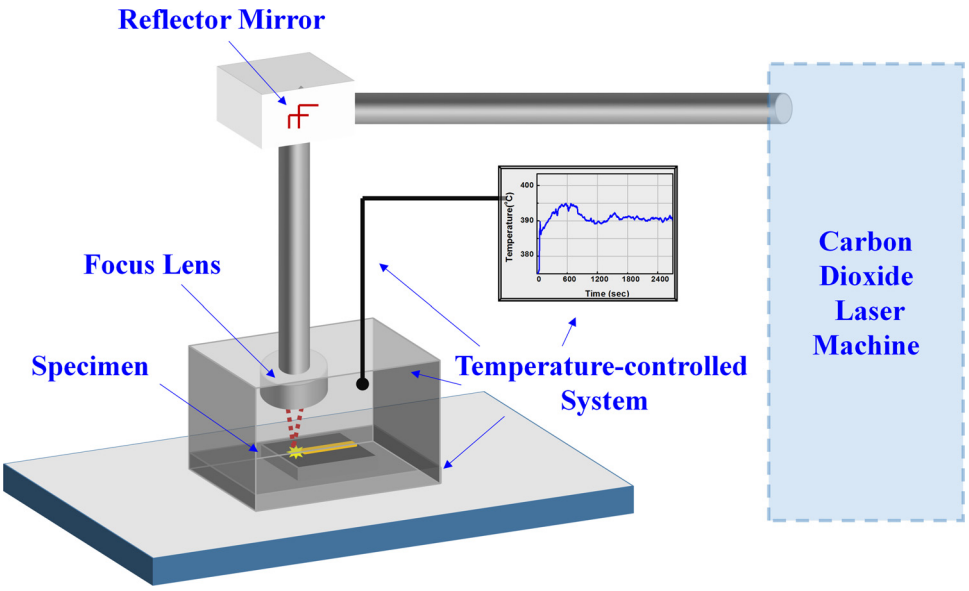

Fig. 1. Equipment schematic of the LRFIT.

experiment was machined as $40 \times 20 \times 10\,mm^3$ and sand-blasted was conducted to enhance laser absorptivity.

Fig. 1 shows the equipment schematic of the LRFIT. The LRFIT process can be regarded as three steps. Firstly, the specimens were placed into an argon protection box at $350 \pm 3\,^{\circ}C$. Moreover, the surface of the specimens was laser remelted by high power transverse-flow CO_2 laser device. The laser power (P) used was 1.8 ± 0.2 kW, the defocusing amount (δ) was 5.0 mm, the laser spot diameter (D) was $\Phi 3.0 \pm 0.1$ mm, and the overlap rate (ε) was 8%~12%. The laser scanning speed (v) was 450, 900 and 2250 mm min^{-1}, respectively for each specimen. The energy density of each specimen can be calculated by $E = P/(D \cdot v)$ and E were approximately equal to 1.33 (E_1), 0.67 (E_2) and 0.27 (E_3) kW mm^2 min^{-1}. Finally, the specimens at the box which held the temperature with $350 \pm 3\,^{\circ}C$ for 1.0 h after LR.

The detailed surface microstructure of the specimens was observed by scanning electron microscopy (SEM, Hitachi S4800). The specimens were treated as unstressed state and then quantitative X-ray diffraction (XRD) analysis was used to determine phase structure and volume fraction of each phase in the modified bainite. A scan was performed by using a D/max-2500/PC X-ray diffractometer. During the experiment, $40^{\circ} < 2\theta < 120^{\circ}$ with a step size of 0.02° was set and the dwell time was 10 s. The data was analyzed by the Materials Analysis Using Diffraction (MAUD) program [13,14]. Transmission electron microscopy (TEM, JEM-2010) was used to analyze the microstructure of the specimens. Nanomechanical tester (TriboIndent) with load of 5 mN was conducted for hardness determination.

3. Results and discussion

As shown in Fig. 2(a), the typical microstructure of untreated carbide-free bainite specimen is consisted of BF and RA. The microstructure of the modified bainite is still a mixture of BF and RA. Moreover, the microstructure is refined and uniformly distributed, which can be seen in Fig. 2(b–d). The bainitic microstructure can be obtained at the temperature lower than its original Ms temperature (362 °C) due to the refined parent-austenite formation in the LRFIT processes [6–8]. Furthermore, the blocky RA has been disappeared by the decreasing of laser energy density.

Table 1
Chemical composition of the steel.

Element	C	Si	Mn	Cr	Ni	Mo	Fe
wt.%	0.24	2.0	1.4	1.0	0.4	0.3	Bal.

The XRD pattern and the Rietveld refinement data of the specimens presented in Fig. 3 demonstrate that only BF and RA are presented, and cementite is failed to precipitate. The insert graphs in Fig. 3(a) are the amplification of BF (2 1 1) and austenite (3 1 1) diffraction peaks. According to the Bragg diffraction, BF (2 1 1) peak is deviated to low angle in LRFIT specimens, which indicates that the lattice constant of BF is increased. The BF lattice has been inflated in a certain degree, equally important, the FWHM of RA (3 1 1) peak is increased, which means that austenite crystallite size is reduced distinctly.

In order to quantitatively analyze the crystal structure of each phase in the bainite prepared by LRFIT, the XRD data is analyzed using Rietveld refinement method, and the fitting graph of LRFIT specimen at E_2 is shown in Fig. 3(b). The error curves of fitting result and XRD data curves are smooth at the bottom of Fig. 3(b), which demonstrates that the fitting results are verified by the experimental results. The phase fraction, crystallite size and BF lattice constant of each specimen are simultaneously calculated by Rietveld refinement, which are shown in Fig. 3(c). With the reduced laser energy density, the lattice constant of BF was increased from 2.8692 Å to 2.8704 Å. F.G. Caballero et al. [15] identified that the substitution elements do no segregation at the temperature of bainite transformation. Therefore, the variation of lattice constants could be caused by the interstitial carbon element solution. In addition, the RA fraction of the specimen is decreased from 17.2% (untreated) to 10.6% (LRFIT with E_3). The carbon content in the austenite and ferrite occupies octahedral interstices, however, the solid solubility amount of the carbon is different in each phase [16]. Therefore, it is confirmed that more carbon is dissolved in BF as the volume fraction of RA decreasing in the modified bainite.

As shown in Fig. 3(c), the crystallite size of the bainite is greatly decreased by LRFIT process. From the data analysis, we can find that the crystallite size of BF is decreased from 86.3 nm to 67.0 nm, and the crystallite size of RA is decreased from 58.1 nm to 32.3 nm. Nevertheless, the crystallite sizes of BF and RA are changed non-significantly with the reduced laser energy density. Compared with the isothermal temperature of original specimen, that of the