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Nano-twin in surface modified bainite induced by laser surface modification

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ABSTRACT

The medium-carbon bainite was surface modified by laser remelting and following isothermal transformation (LRFIT). The austenite nano-twin has been detected in the surface modified bainite by transmission electron microscopy (TEM). The austenite nano-twin films and blocks are embedded in bainitic ferrite with a thickness less than 10 nm, and the twinning occurred on the $(\bar{1}11)$ plane in the $[\bar{1}11]$ direction. The nano-hardness and the creep ratio of the nano-twin has been measured by nano-mechanical tester. The result suggests that, the surface modified bainite with nano-twin shows a satisfied mechanical properties. The nano-hardness and creep ratio of the nano-twin in surface modified bainite is 9.5 ± 0.5 GPa and $7.5 \pm 0.3\%$, respectively.

1. Introduction

NANOBAIN, consisting of nano-scale crystals of bainitic ferrite (α) and retained austenite (γ), has attracted much attention as a promising candidate for high tensile strength steel [1]. In bainite steels, the residual austenite can exist as: (1) the nano-scale films, which is located between neighboring subunits of bainitic ferrite; and (2) the submicron block structure, which is located between the sheaves of bainite.

The mechanical properties of the bainite steel can be improved at a relatively low preparation temperature. Moreover, an effective method of preparing nano-materials is deformation twins with care, which can reduce the scale of the crystal size [2].

The presence of nano-twins introduces extra hardening, which is probably due to the Hall–Petch effect at nano-scale. The twinning tendency of face-centered-cubic (fcc) metal is largely determined by its relatively low stacking fault energy. The deformation twinning usually occurs with the slip of partial dislocations, and the interaction activated between twin boundaries and dislocations is of particular interest for improving strength and ductility [3,4].

It has been reported that plastic relaxation of the bainite transformation occurring in the neighboring austenite can generate accommodation twinning [5–7].

As one of the advanced surface treatment techniques, laser remelting (LR) has the advantage of high energy density, fast cooling rate, and good flexibility of control [8]. During the LR surface modified, thermal stress can be remained and then influence the bainite accommodation transformation.

In this work, a medium carbon high silicon bainite steel was surface modified by laser remelting and following isothermal transformation (LRFIT) method, and the microstructure and mechanical properties of nano-twin in the surface modified bainite was investigated.

2. Experimental materials and methods

The compositions of the bainite steel investigated in this work was Fe–0.54C–2.6Si–1.82Mn–1.0Cr–0.45Ni–0.3Mo (wt%). The Ms temperature of the steel was measured to be 230 °C by Gleeble-3800 thermomechanical simulator equipment. The LRFIT specimens with a dimension of $40 \times 20 \times 10$ mm^3 were machined. The specimens were laser remelted by CO_2 laser device in an Argon protection box at constant temperature of 250 °C. The laser power (P) of 1.8 kW, and the laser spot diameter (D) of Φ3 mm were settled during the LRFIT surface modification.

Field emmision scanning electron microscopy (FESEM, Hitachi S4800) and transmission electron microscopy (TEM, JEM-2010) were used to observe the microstructure of the surface modified bainite. X-ray diffractometer (XRD, D/max-2500/PC) was used to determine the fraction of retained austenite (Vc) and other structural parameters, such as the lattice parameters and

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crystallite size. During the test, $40° < 2\theta < 120°$ with a step size of 0.02° was set and the dwell time was 10 s. The data was analyzed using the Materials Analysis Using Diffraction (MAUD) program. Micro-hardness tester (FM-ARS 9000) with a load of 200 gf, and the Nano-mechanical tester (TriboIndent) with load of 5 mN and dwell time of 5 s were conducted for hardness determination. Moreover, the hardness mapping has been performed by a regular array of 10×10 indentations covering a $45 \times 45\ \mu m^2$ area.

3. Results and discussion

The XRD patterns of the specimens after the Rietveld refinement are shown in Fig. 1. The polynomial background function, total incident X-ray intensity, austenite phase fraction, crystallite size and applicable lattice parameters were determined.

As can be seen in Fig. 1, the medium carbon high silicon bainite is primarily consisted of bainitic ferrite (bcc) and retained austenite (fcc) in both the original and surface modified specimens. Further observation shows that the peaks of the XRD patterns are broadened after LRFIT surface modification. The peak broadening can be associated to the crystallite size, and the two structures with different lattice parameters due to the different carbon contents in the bainitic ferrite.

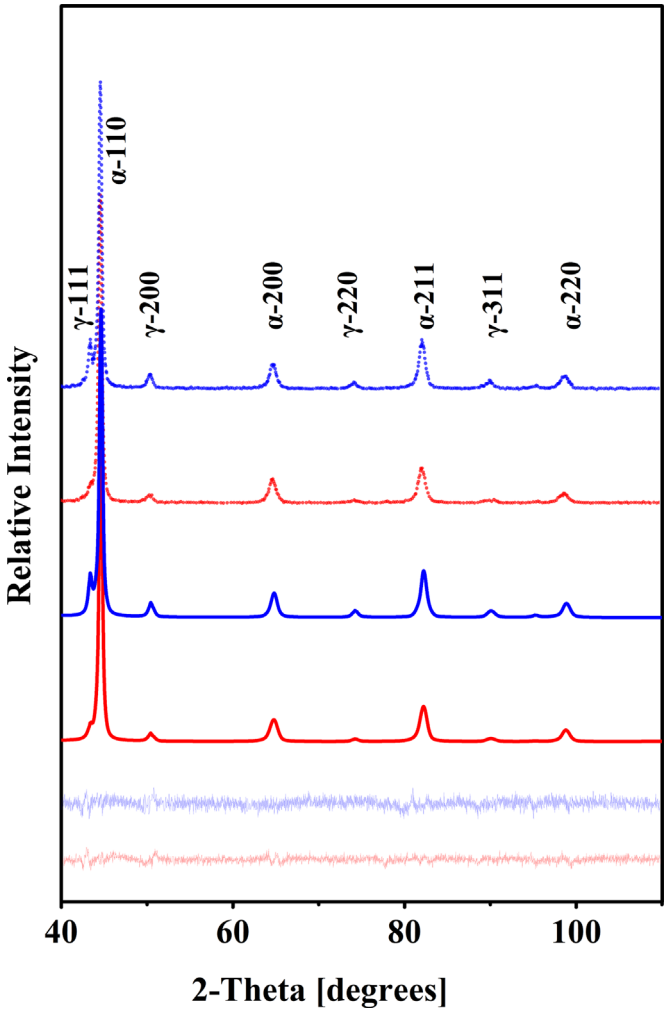

Fig. 1. XRD patterns for original bainite (blue short dot) and LRFIT surface modified bainite (red short dot), Rietveld refinement patterns for original bainite (blue solid) and LRFIT surface modified bainite (red solid). (For interpretation of the reference to color in this figure legend, the reader is reffered to the web version of this article.)

As reported in the Ref. [9], the bainitic ferrite, which can be formed by isothermal holding between 200 °C and 350 °C, did not present as a cubic structure. Therefore, a tetragonal structure with an I4/mmm space group, which is similar to the crystal structure of ferrous martensite, was used in the Rietveld refinement in this work.

The crystal structure of bainitic ferrite is $a = 2.864 \pm 0.001$ Å, and $c = 2.874 \pm 0.001$ Å in the original specimen. After the LRFIT surface modification, the crystal parameters of bainitic ferrite change to $a = 2.861 \pm 0.001$ Å, and $c = 2.878 \pm 0.001$ Å. Besides, the crystal parameter of retained austenite ($a = b = c$) changes from 3.6120 ± 0.001 Å to 3.6141 ± 0.001 Å, and the crystal dimension of retained austenite greatly decreases from 77.5 ± 2.5 nm to 37.5 ± 2.5 nm after the LRFIT surface modification. Moreover, the volume fraction of retained austenite also reduces from $18 \pm 1.04\%$ to $12 \pm 0.88\%$, which in turn increases the carbon-solubility in bainitic ferrite.

Fig. 2 illustrates the microstructures of the bainite in original state and as-LRFIT state. The original bainite microstructure which was produced during the isothermal holding at temperature 250 °C for 24 h is shown in Fig. 2a. As can be seen in Fig. 2a, the original microstructure of the bainite consists of bainitic ferrite of darker long and slender morphology and retained austenite of film and blocky morphology. While, the LRFIT specimen shows a clear ultra-fine-grain structure in the studied surface modified bainite during LRFIT process, as shown in Fig. 2b. Meanwhile, it is possible to distinguish the submicron blocks of residual austenite come to be difficultly identified inside the bainitic ferrite plates, which effectively prevents the large regions of untransformed austenite decomposing into hard, brittle martensite under stress. It is confirmed that the ultra-fine-grain of bainitic ferrite could leads to a dramatic improvement in toughness [10,11]. As shown in the enlarged SEM morphology (Fig. 2c) of the surface modified bainite, large amount of nano-scale parallel-texture with a width less than 50 nm was found to be embedded in the block residual austenite regions.

Transmission electron microscopy (TEM) was used to further investigate the nano-scale parallel-texture structure. Fig. 3a–b shows the bright-field TEM image and its selected area electron diffraction (SAED) pattern of film austenite and block austenite, respectively.

As can be seen in Fig. 3(a-1)–(b-1), austenite nano-twin films and blocks are embedded in bainitic ferrite with a thickness less than 10 nm. The existence of austenite nano-twin films leads to significant decrease in the crystal size of residual austenite evident from XRD result (Fig. 1).

The SAED patterns illustrated in Fig. 3(a-2)–(b-2) show that the twinning occurred on the $(\bar{1}11)$ plane in the $[\bar{1}11]$ direction. As shown in the patterns, the dislocation debris are evident in both the bainitic ferrite and the surrounding austenite. Under an applied shear stress with an appropriate orientation, the partial dislocation glides on the (111) slip plane across the grain to form a stacking fault. On this basis, it can be formed on adjacent slip planes by the dynamic overlapping of two extended partial dislocations with stacking faults. The overlapped stacking fault forms a two-layer twin nucleus. The twin can grow thicker by adding more stacking faults on either side of the twin [2].

Concerning the SAED pattern result as shown in Fig. 3(a-2), the secondary mechanical twinning occurs on the $(\bar{1}\,\bar{1}\,1)$ plane in the $[\bar{1}\,\bar{1}\,1]$ direction. The interior angle between the primary and secondary mechanical twin directions was measured on Bright-field TEM images to be 70°, which is in good agreement with the calculated angle of 70° between the $[\bar{1}\,\bar{1}\,1]$ and $[\bar{1}11]$ directions. It is inferred that the formation of secondary twin is a possible mechanism for accommodating shear strains induced by twin-band intersections in the intersecting area [12].