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The effect of carbon contents on intragranular ferrite formed in the V-Ti-N microalloyed steel with a carbon content gradient prepared by controlling the surface decarburization

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ABSTRACT

The V-Ti-N microalloyed steel with a carbon content gradient was innovatively obtained through surface decarburization. Then, the effect of carbon contents on intragranular ferrite (IGF) formation was studied. With the carbon contents increasing from 0.39% to 0.47% (mass percent), the volume fraction of IGF decreases from 8.2% to 4.6%, but the number of IGF has no significant change. The critical size of IGF nuclei was calculated on the basis of classic heterogeneous nucleation theory. According to the results of calculation and statistics, with the carbon content increasing from 0.39% to 0.47%, the number of IGF nuclei does not decrease significantly. When the carbon content is relatively low, some (Ti, V)(C, N) particles precipitating in austenite matrix may also act as the nuclei of IGF to refine the pearlite-ferrite microstructure.

1. Introduction

The IGF nucleation on particles in austenite has been used to refine the microstructure of ferrite-pearlite steels when sufficient deformation of austenite is hardly applicable such as the hot die forging [1,2] and the heat affected zone formed during welding [3–5]. Ishikawa et al. [6] revealed that the V(C, N) particles on MnS inclusions were the main nucleation sites of IGF in V-N steels for hot forging because of the Baker-Nutting orientation relationship ($(001)_\alpha//(001)_{V(C, N)}$, $[110]_\alpha//[100]_{V(C, N)}$) between V(C, N) particles and ferrite. Furuhara et al. [7] found out that the V(C, N) particles precipitating on MnS inclusions could hold incoherent orientation relationships with austenite and MnS inclusions simultaneously, which is beneficial to IGF nucleation. In recent years, titanium was also added to V-N steels because its nitride could strongly inhibit austenite grain growth. Zhao et al. [8] found that the (Ti, V)(C, N) particles on MnS inclusions were the main IGF nuclei in V-Ti-N steels for hot forging. Moreover, related studies also indicated that the Mn-depleted zone formed around Ti_2O_3 particles could drive the IGF nucleation [9–11], which provided a new prospect for IGF formation in Ti bearing steels.

Carbon is the basic alloying element in steels, and its content has significant influence on the microstructure and properties of steels, as well as the formation of IGF [12]. Generally, in order to investigate the effect of carbon contents on steels, several steels with different carbon contents need to be smelted and characterized respectively. As a result, the research cycle is extended. Furthermore, the carbon contents obtained in this way are not continuous but discrete. Therefore, the effect of carbon contents on IGF formation was mainly studied by calculation, and the experimental study was not sufficient. With the proposition of Materials Genome Initiative [13], the high throughput preparation and characterization of materials have become the focus of studies. The study cycle can be reduced significantly by quick preparation and characterization of a series of materials with different chemical compositions. When the steel is heated at high temperature, the carbon atoms diffuse to the surface of steels and react with oxygen, which reduces the carbon content and properties, such as strength, hardness and fatigue resistance [14–17]. This phenomenon is called surface decarburization and should be reduced in the industry production. On the other hand, it was reported that the surface decarburization could also be used to make compositionally graded materials [18]. This indicated that the surface decarburization may be used to study the effect of carbon contents on the steels.

The paper expounded the decarburization mechanism on the surface of hypoeutectoid steels. The V-Ti-N microalloyed steel containing carbon in gradient was innovatively obtained through surface decarburization. Then, the effect of carbon contents on IGF formation was studied. In the meanwhile, the study provided a new idea for quick preparation and characterization of steels with different carbon

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2. Experimental

The steel selected for this investigation was obtained from a commercial hot-rolled bar of 110 mm in diameter and has the chemical composition (wt%) of 0.47 C, 0.92 Mn, 0.35 Si, 0.046 S, 0.09 V, 0.022 Ti and 0.015 N. The specimens with the size of 20 × 20 × 25 mm were cut at 1/2 radius position of the hot-rolled bar.

In order to study the surface decarburization behavior of the steel, the specimens were heated at 750, 800, 850, 900, 950, 1000, 1050, 1100, 1150, 1200, 1250 °C for 0.5 h, then furnace cooled to ambient temperature. According to the experimental results, the heat treatment process for preparing the steel with a carbon content gradient was developed. After the heat treatment, the specimens were cooled by two methods. One specimen was furnace cooled to ambient temperature, and the other one was furnace cooled to 800 °C then water quenched.

The specimen furnace-cooled was etched by 4% nital to observe the microstructure. The microhardness of the specimen furnace-cooled was tested to measure the decarburized depth. Furthermore, TEM specimens for observation of V-Ti particles were prepared by a carbon extraction replica technique with the specimens water-quenched. The composition and elemental distribution of V-Ti particles were determined via energy dispersive spectroscopy analysis. The observation and test were performed by the ZEISS Axio Scope A1 optical microscope (OM), the FEI Quanta FEG 450 field emission scanning electron microscope (FESEM), the JEM 2100HR transmission electron microscope (TEM) and the LEICA VMHT30M microhardness tester.

3. Results

3.1. The Mechanism of Surface Decarburization in Different Temperature Ranges and Preparation of the Steel With a Carbon Content Gradient

After heating at different temperature for 0.5 h then cooling in furnace, the surface decarburization is shown in Fig. 1. According to the JmatPro software calculation, the A_1, A_3 and G temperatures of the experimental steel are confirmed to be 717, 769 and 899 °C, respectively. The surface decarburization shows different morphologies in different temperature ranges. At 750 °C, only ferrite decarburization was formed. At 800 °C, both ferrite and partial decarburization were formed. At 1000 and 1200 °C, only partial decarburization was formed.

As is shown in Fig. 2, the surface decarburization mechanism of hypoeutectoid steels is closely related to the heating temperature ranges [19–21].

In the temperature range of A_1–A_3, decarburization proceeded in the $\alpha + \gamma$ phase field all the time. According to the Gibbs phase rule, the number of freedom degrees is zero in the two-phase field at temperature and pressure constant, which suggests that the carbon content can't change freely. As a result, only the ferrite decarburized layer consisting of pure ferrite is produced through $\gamma \rightarrow \alpha$ phase transformation, and the carbon content suddenly decreases from C_B to $C_{\alpha 1}$. In the temperature range of A_3–G, the carbon content is C_B in the γ single-phase field at the beginning. According to the Gibbs phase rule, the number of freedom degrees is one in the single-phase field at temperature and pressure constant, which suggests that the carbon content can change freely, so a partial decarburized layer forms with the carbon content continuously changing in C_B–$C_{\gamma 2}$. The ferrite decarburization forms when the carbon content decreases into the $\alpha + \gamma$ phase field with the decarburization proceeding, and the carbon content suddenly decreases from $C_{\gamma 2}$ to $C_{\alpha 2}$. Above G temperature, the decarburization proceeded in the γ single-phase field all the time, so a partial decarburized layer forms with the carbon content continuously changing in C_B–$C_{\gamma 3}$, and the $C_{\gamma 3}$ may decreases to zero with the decarburization proceeding. Above all, when the steel is heated above G temperature for a long time, the steel with a carbon content gradient from 0 to C_B may be obtained.

The decarburized depth after heating at different temperature for 0.5 h is shown in Fig. 3. With heating temperature increasing from 800 °C to 1200 °C, the partial decarburized depth increases simultaneously. In order to get a wide carbon content gradient, the specimens were heated at 1200 °C for 4 h. Then, the specimens were cooled to ambient temperature by the two methods mentioned above.

3.2. The Carbon Content Gradient and Microstructure

After heating at 1200 °C for 4 h, the microstructure of the specimen furnace-cooled is shown in Fig. 4. Only partial decarburization consisting of ferrite and pearlite was formed. From the surface to the inner, the volume fraction of ferrite decreases gradually, and the surface microstructure is almost pure ferrite. It indicates that the carbon content gradient from 0 to 0.47% has formed.

The microhardness of the specimen furnace-cooled is shown in Fig. 5. The hardness increasing gradually reflects the carbon content gradient. The partial decarburized depth was confirmed to be 3365 μm.

According to Fick's second law, the relationship between depth from the surface x (m) and carbon contents C_x (mass·%) is shown in Eq. (1):

$$\frac{C_B - C_x}{C_B - C_S} = 1 - \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right) \quad (1)$$

where C_B (mass·%) and C_S (mass·%) are the carbon content of bulk and surface respectively, D ($m^2 \cdot s^{-1}$) is the diffusion coefficient of carbon in

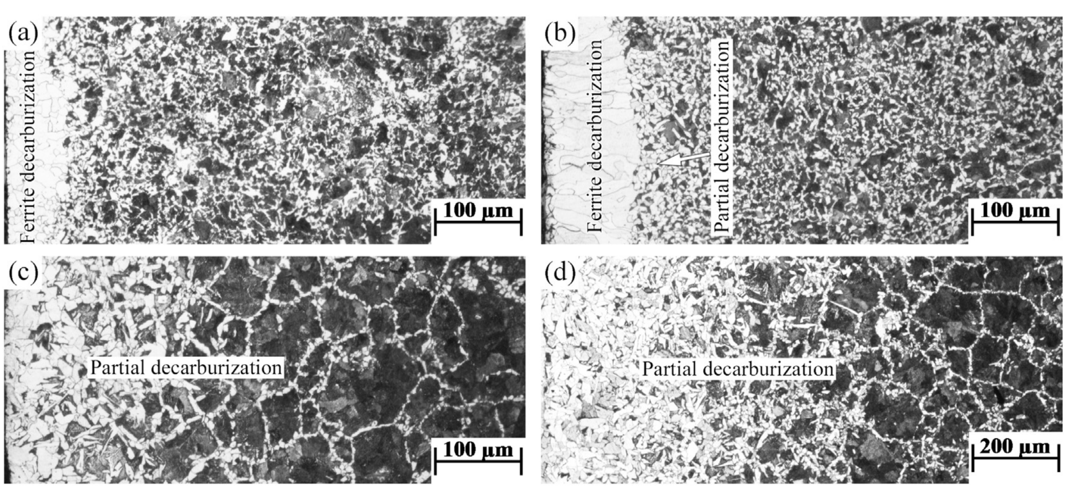

Fig. 1. The decarburization after heating at different temperature for 0.5 h: (a) 750 °C; (b) 800 °C; (c) 1000 °C; (d) 1200 °C.