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Research of microstructure of spherical graphite iron by electropulsing annealing

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ABSTRACT

This paper investigated the solid-state graphitization of spherical graphite iron by electropulsing annealing. The results indicated that the electropulsing annealing can accelerate the decomposition of cementite, improve the diffusion ability of carbon in the matrix and make more neonatal graphites in small size be formed. With the increase of electropulsing annealing temperature, the graphitization rate is accelerated. At the high temperature and the quick heating rate, the solid-state graphitization can be finished in a short time. Analysis shows that electropulsing annealing promotes the nucleation of graphite and the decomposition of cementite, consequently, the solid-state graphitization of spherical graphite iron is accelerated.

1. Introduction

Higher tensile strength and elongation are necessary for the application of spherical graphite iron pipe. There are plenty of cementites in the as-cast spherical graphite iron pipe due to the intensive quench effect of the mould. The existence of brittle cementite makes the mechanical properties of spherical graphite iron dropped. The high temperature graphitization annealing is usually employed to remove the cementites of the as-cast spherical graphite iron pipe, which requires long time and leads to energy waste. The traditional technologies are usually applied to accelerate the solid-state graphitization by reducing the content of carbide formation elements, increasing the content of the element accelerating the solid-state graphitization, and adjusting the annealing temperature and holding time, etc. However, these routine techniques are not the promising way to make a further progress.

The application of electropulsing are booming in the fields of materials and engineering. The microstructure improvement of solid-state metals has been achieved by the high density pulse electric current with apparent electromigration (Hummel, 1994) and electroplastic effects (Molotskii, 2000) mainly in the field of recrystallization (Zhou et al., 2004), superplastic deformation (Liu et al., 2003) and metal-working (Tang et al., 1998, 2003). Now there is not report about applications of the electropulsing annealing to the solid-state graphitization of the spherical graphite iron. Therefore, this paper studied the solid-state graphitization of the spherical graphite iron under the high voltage pulse current. In addition, the nucleation of graphite and the decomposition of cementite by electropulsing annealing were analyzed.

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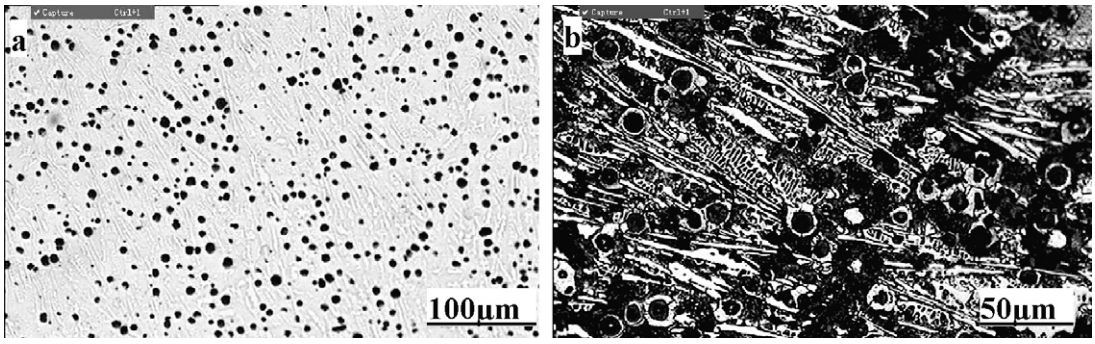

Fig. 1 – The as-cast structure of spheroidal graphite iron. (a) Without etch. (b) Etch.

2. Experimental

The studied material was an as-cast spherical graphite iron with the composition (in wt.%) of 93.501Fe, 3.449C, 2.79Si, 0.02S, 0.05P, 0.14Mn, 0.028Mg, 0.03Ti. The specimens were cut from the centrifugal spherical graphite iron pipe, and their dimensions were 80 mm in length, 8 mm in width and 2 mm in thickness. When the specimens were treated by the pulse current, they were connected with a high voltage pulse power source by using copper clamping fixture. The pulse duration of an electropulsing was about 90 μs and the maximum current density $j_m \approx 1.9\,kA/mm^2$. The peak temperature and heating rate of specimens were controlled by adjusting pulse current voltage. The sample temperature was measured by an IRTec Plus2000 infrared thermometer. The specimens were heated to 880 °C within 2 min and held for 3 min at 880 °C by the electric resistance furnace and pulse current, respectively. The specimens were heated to 750 °C, 850 °C within 2 min and 1100 °C within 30 s to study the effect of the temperature and time on the solid-state graphitization by electropulsing.

The microstructure of the sample was observed by the metallographic microscope (AXiovher200MAT). The specimens were polished and etched for several times in order to observe the nucleation position of graphite. The subsequence is heavy etch, polish, light etch and polish. The size and fraction of graphite and cementite were quantitatively analyzed by employing micrograph analytic technique. The average circle degree of graphite is calculated by the equation: $P = 4\pi S/L^2$, where, S is the area of graphite, L is the circumference of graphite. The electron probe analytic apparatus (EPMA-1600) was employed to observe the concentration distribution of carbon around the cementite. The sample was etched lightly in order to obtain the accurate concentration of carbon. The accelerating voltage was 15 kV, the electron beam was 69.98 nA, the diameter of the electron beam spot was 1 μm, and the step length was 0.2 μm. For mechanical measurements, the samples after high temperature annealing with and without pulse current were both cooled in furnace from 880 to 700 °C and held for 20 min to obtain the ferrite matrix.

3. Results

The microstructure of as-cast spherical graphite iron is shown in Fig. 1. It can be clearly seen that there are a large number of flake or strip cementites, small quantity pearlite and ferrite in the as-cast spherical graphite iron pipe due to intensive quench effect of the mould. Fig. 2(a) and (b) are the microstructures of the specimens with traditional high temperature graphitization annealing. Compared with the as-cast microstructure, the amount of cementite decreases, and the graphite size becomes somewhat larger, indicating that the carbon atom from the cementite chiefly adheres on the original graphite during the traditional high temperature graphitization annealing. The microstructures of the specimens with the electropulsing annealing are shown in Fig. 2(c)–(e). It indicates that a large number of small neonatal graphites appear besides the larger original graphite. As the arrow shown in Fig. 2(e), the neonatal graphite appears in the austenite near the cementite/austenite interface. In addition, some neonatal graphites appear at other position, which indicates that the cementite are decomposed completely and some small neonatal graphites stay in the position of the disappeared cementites.

The quantitative analysis results of the graphite and cementite are listed in Table 1. It can be seen from the table that the specimens by electropulsing annealing have less volume fraction of cementite and more volume fraction of graphite compared with the specimens by conventional isothermal annealing. For those original graphites, the average diameter is increased and the graphite sphere becomes circler in the specimens by electropulsing annealing. In the specimens by electropulsing annealing, the number of small neonatal graphite is about 27 cm^{-2} and their average diameter is about 6.02 μm. Obviously, the electropulsing annealing accelerates the nucleation of graphite and decomposition of

Table 1 – The quantitative analysis results about the graphite and cementite

Condition	A	B	C	D
Volume fraction of graphite (%)	8.37	9.78	12.47	30.73
Volume fraction of cementite (%)	37.29	30.28	2.99	0.56
Average diameter of graphite (μm)	14.57	19.19	24.14	27.03
Average circle degree of graphite (P)	0.59	0.58	0.65	0.71

Note: A is the as-cast spherical graphite iron. B is the sample annealed at 880 °C for 3 min. C is the sample annealed at 880 °C for 3 min by electropulsing annealing. D is the sample which is heated to 1100 °C within 30 s.