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Nucleation and growth characteristics of graphite spheroids in bainite during graphitization annealing of a medium carbon steel

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ABSTRACT

The evolution of microstructure in bainite during graphitization annealing at 680 °C of Jominy-quenched bars of an Al-Si bearing medium carbon (0.4C wt%) steel has been studied and compared with that in martensite by using light, scanning and transmission electron microscopy. The results show that the graphitization process in bainite is different from that in martensite in many aspects such as the initial carbon state, the behavior of cementite, the nucleation-growth feature and kinetics of formation of graphite spheroids during graphitization annealing, and the shape, size and distribution of these graphite spheroids. The fact that the graphitization in bainite can produce more homogeneous graphite spheroids with more spherical shape and finer size in a shorter annealing time without the help of preexisting coring particles implies that bainite should be a better starting structure than martensite for making graphitic steel.

1. Introduction

The formation of graphite spheroids (GSs) in cast iron has promoted its development by leaps and bounds. It took a long time to find the way to produce the graphite phase in a nodular form to replace a flake one, ameliorating the properties of cast iron, especially the extensibility and toughness, and this application is still significant to the auto industry even today [1–14]. The graphitization in carbon steel with graphite nodularization is also an important phase transformation process as graphite phase can act as a lubricant and a spheroid shape would present more uniform mechanical properties [15–24]. Recently, with the gradually increasing awareness of environment protection, there is an urgent need to find pollution-free lead-free cutting steel, for which the graphitic steels with GSs could be an ideal candidate having the advantages of good cuttability and machinability to ditch the elements such as S and Pb that are harmful to the environment. However, the graphitization treatments normally require a dozens of or even more than 100 h in the early days [15–17]. Such a long reheating time means uneconomical for commercial production. For the graphitization process in carbon steels, the spheroidization and decomposition of cementite are important steps at the early stages because the rate of these two steps can directly influence the efficiency of the transformation [25–27]. To solve the issue of a long annealing time, adding the elements to decrease the stability of cementite or increase the nucleation of graphite were considered as effective measures [17–20]. The presence of silicon in steel can destabilize cementite and promote the precipitation of graphite [18–19], but the addition of aluminum and boron can result in the precipitation of nitride which promotes the nucleation of graphite phase may lead to the formation of irregularly shaped graphite particles with preferred nucleation sites [22,26,28–29]. So far, previous researches are mainly using starting structure of either pearlite or martensite, and the latter is considered a better starting structure as quenching treatment can greatly accelerate graphitization process [16–17,19,23], while much less effort has been made on studying the formation of graphite nodules with a bainite as starting structure, except for the formation of irregularly-shaped graphite phases in B-treated carbon steel under different heat treatments [30]. In particular, no much effort has been done on the microstructural evolution in bainite during graphitization process, although there are some evidences showing a different graphitization behavior [22,31]. In this paper, we focus on studying the microstructural evolution during graphitization annealing of Jominy quenched medium carbon steel samples bearing high Si and Al contents, including the initial carbon state in starting structures, the spheroidization and decomposition of cementite, and the nucleation and growth characteristics of GSs in bainite, and compare them with those in martensite using light microscopy, scanning electron microscopy and transmission electron microscopy.

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2. Materials and experimental

The material investigated is a 50 kg vacuum melt provided by Swinden Technology Centre, Tata steel, Rotherham, UK with a chemical composition of Fe-0.38C-1.82Si-1.44Al-0.07Mn wt%. It was homogenized and forged to 25 mm diameter bar, from which Jominy end-quench specimens were machined. In the Jominy end-quench process, a 100 mm long and 25 mm diameter bar was heated to 1150 °C for half an hour in an argon atmosphere. Using this method, an advantage is that a range of microstructures including martensite and bainite with the same treatment can be observed from the edge to the centre along the length of the bars [31]. Graphitization annealing of the samples was made at 680 °C for 15 min to 64 h.

Characterization of microstructural evolution during graphitization process was performed by light microscopy (LM, Lecai DMILM Microsystem), scanning electron microscopy (SEM, FEI Helios Nanolab 600i) and transmission electron microscopy (TEM, FEI Tecnai TF20). The samples for light microscopy were polished using standard procedure and etched using a 5% Nital solution. The samples prepared for light microscopy were also used for secondary electron (SE) imaging and energy dispersive X-ray spectroscopy (EDS). The working voltage of SE imaging and EDS were 10 kV. The 3-mm TEM thin foil samples were first mechanically ground to a thickness of around 80 μm using established method from the slices cut from the Jominy bars using a Buehler diamond saw, and then electropolished by a Struers Tenpol-5 twin-jet unit using an electrolyte of 10% perchloric acid, 30% 2-butoxyethanol and 60% ethyl alcohol at 20 mA, 15 V and around −10 °C. A Gatan 691 dual-mill precision ion polishing system (PIPS) was also used for preparing or further thinning of some samples. Some interface samples were prepared by FEI Helios Nanolab 600i, a dual-beam focused ion beam (FIB)/SEM system.

3. Results

3.1. Light microscopy

Light micrographs showing the microstructural evolution of bainite and martensite as starting microstructures during graphitization annealing process are presented in Fig. 1. The micrographs in Fig. 1a and b show the typical structures in bainite and martensite, respectively. The distributions of carbon in the two regions start to change during the annealing for the period of first 0.15 h, as shown in Fig. 1c and d. After 0.75 h annealing, it can be seen that some small spheroids start to form in the bainite region (Fig. 1e), whereas no apparent spheroids can be found in the martensite region (Fig. 1f). After 1.5 h annealing, some spheroids can be observed in martensite region (Fig. 1g) which is similar to that in bainite region after 0.75 h annealing, implying that the graphitization process in martensite region is lagged behind around half an hour. With further dissolution of carbides, the spheroids in bainite grow up. After 3 h graphitizing annealing, the spheroids formed in these two different structures have different sizes and distributions, as shown in Fig. 1i and j. In martensite, there are still some carbides remaining, whereas in bainite, fewer carbides can be observed, implying that the graphitization process in bainite is basically completed. After 64 h graphitizing annealing, the size and distribution of GSs in these two regions have not changed too much. For both bainite and martensite regions, the spheroids are formed on the prior austenite boundaries as well as inside the grains. By counting the number of GSs on light micrographs, it is found that in bainite, there is an average spheroid distribution of about 1900 mm^{-2}, with an average size around 5 μm, whereas in martensite, there is an average spheroid distribution of about 750 mm^{-2}, but with a size distribution from 3–12 μm, indicating the GSs in bainite region have a smaller size and a more uniform distribution.

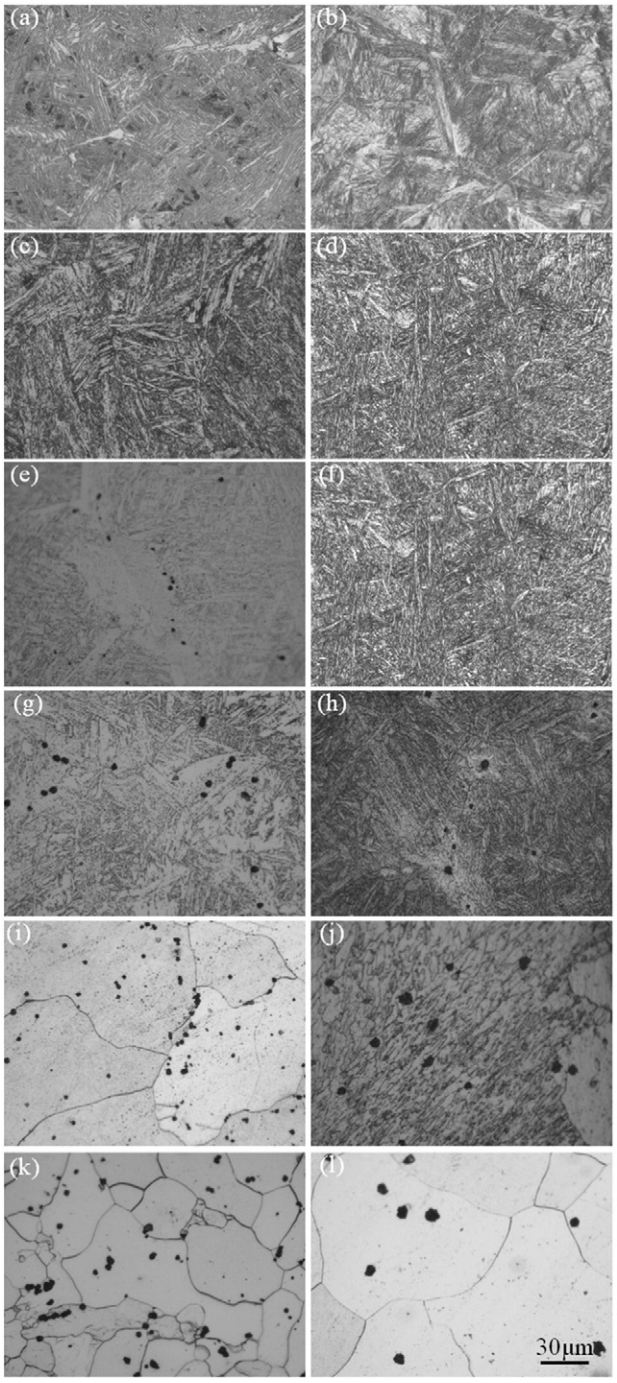

Fig. 1. Light micrographs of a bainite region after graphitizing annealing (a) as-quenched; (c) 0.15 h; (e) 0.75 h; (g) 1.5 h; (i) 3 h; (k) 64 h; light micrographs of a martensite region after graphitizing annealing (b) as-quenched; (d) 0.15 h; (f) 0.75 h; (h) 1.5 h; (j) 3 h; (l) 64 h.

3.2. Scanning electron microscopy

SEM and EDS elemental mapping can provide more detailed information on the behavior of cementite and the nucleation and growth of GSs in both bainite and martensite. Fig. 2 shows the initial microstructures of bainite (Fig. 2a) and martensite (Fig. 2b). EDS elemental mapping results show that there are a high-carbon area and a low-carbon area in bainite (Fig. 3a), whereas in martensite region, carbon appears more uniformly distributed (Fig. 3b).