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Effect of Cyclic Annealing on Microstructure and Mechanical Properties of Medium Carbon Steel

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Abstract: The microstructure and mechanical properties of medium carbon steel after cyclic heat treatment were investigated. The effects of cyclic numbers and long time annealing on the microstructure and mechanical properties of the experimental steel were compared. A short-duration (5 min) holding at 1023 K (above A_1 temperature) and a short-duration (3 min) holding at 893 K are adopted in each cyclic heat treatment. The spheroidization is accelerated during cyclic heat treatment, and the spheroidizing ratio grows with cyclic numbers. After 12-cycle heat treatments, there are few incompletely spheroidized regions in the specimens, and cementite lamellae mostly change into cementite particles. The morphological character of cementite for 12 cycles is similar to that undergoing annealing for 10 h at 973 K. The strength of the experimental steel after 5-cycle heat treatment is the lowest in the following cyclic heat treatment, but it is still higher than that of specimens with subcritical annealing over a long period (10 h). After 12-cycle heat treatment, the strength of the experimental steel is close to that of the normalized steel, and the plasticity is the best in all heat-treated specimens.

Key words: rapid spheroidizing; mechanical property; cyclic annealing; cementite; medium carbon steel

The spheroidizing of cementite, in high carbon and medium carbon steels, is one of the most important processes to enhance steel properties. Fine carbide particles are used to refine the ferrite grains and form ($\alpha+\theta$) microduplex structures in high carbon steels, which can improve the properties of carbon steels[1-4]. In medium carbon steels, the spheroidization of cementite can provide high ductility and deformability for posterior cold heading application[5,6]. Although various reports have addressed the physical metallurgical principles of spheroidizing[3-8], much remains unknown in detail regarding the mechanisms involved and their adequate control. Conventional subcritical annealing often takes a long time to complete cementite spheroidizing[5-8]. In recent years, some investigations[9-14] have shown the potential of cyclic heat treatment techniques to accelerate several solid state metallurgical processes. Sahay et al.[9] found that cyclic annealing accelerated grain growth in aluminum-killed grade steels and also accelerated bainite transformation during cyclic austempering in 1080 steel[10]. Saha et al.[11-13] studied the structural characteristic and mechanical properties of low, medium, and high carbon steels after cyclic heat treatments. Each cycle in their work takes a short-duration (several minutes) at above A_{c3} (A_{cm}) temperature followed by forced air-cooling to room temperature. The authors previously investigated the rapid spheroidizing behavior of cementite in high carbon steel (1080 steel) during cyclic heat treatment above and below A_1 temperature[14].

However, the effects of cyclic annealing (above and below A_1 temperature) on the mechanical properties and microstructural evolution of medium carbon steel require further research. The present study aims to examine the effect of cyclic annealing on microstructure and mechanical properties of medium carbon steel and compare with the spheroidizing behaviors during subcritical annealing for a long time. The rapid spheroidizing process in medium carbon

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steels are discussed and compared with that in high carbon steels.

1 Experimental Procedure

In the experiment, medium carbon steel rods were used. Their chemical composition (in mass%) was C 0.42, Mn 0.60, Si 0.26, S 0.015, P 0.02, and Fe balance. The rods with ϕ15 mm×120 mm were austenitized at 1133 K for 30 min and then air-cooled to room temperature, resulting in a normalizing microstructure (ferrite+pearlite). The as-transformed rods were subjected to cyclic heat treatment for different cycles from 1 cycle to 12 cycles. Each cycle consisted of a short-duration (5 min) holding at 1023 K (above A_1 temperature), followed by forced air-cooling (cooling rate of 2—3 K/s) to 893 K and holding for 3 min. The treated specimens were then air-cooled to room temperature. Fig. 1 shows the cyclic heat treatment curves. The as-transformed rods were also subjected to annealing at 973 K for 10 h.

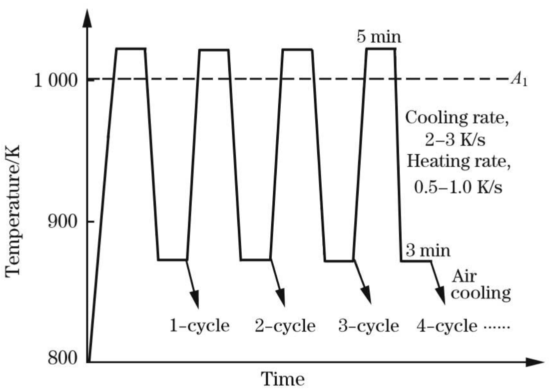

Fig. 1 Cyclic heat treatment curves

The microstructure of treated rods was observed with optical microscopy (OM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The specimens for SEM and OM observation were etched with 4% nital, after mechanical polishing. The SEM and TEM observations were performed with a KYKY-2800 scanning electron microscope and a JEM-2010 transmission electron microscope with an acceleration voltage of 200 kV, respectively. Standard tensile test was carried out for all specimens with 40 mm gauge length in an electronic universal material testing machine (Inspekt-table 100) with a moving chuck velocity of 3 mm/min under ambient conditions. The fracture surfaces were also observed by SEM (KYKY-2800).

The shape and sizes of cementite in the treated specimens were determined from SEM images. Image analysis software digitized an image from a photograph, and the stained carbides were identified and separated for analysis. The cementite particles were considered as elliptical spheroids with an aspect ratio, which was the minor axis to the major axis. A cementite particle with an aspect ratio, in the range of 0.7—1.0, in agreement with that in the literatures[13,14], was determined as a cementite spheroid. The particles with aspect ratios of less than 0.7 and the cementite particles with non-round geometry were not considered as spheroids. At least several micrographs were taken with magnifications from 1000 to 20000 for each specimen. The total number of measured particles ranged from approximately 600 to 1000, depending on the material and cyclic periods.

2 Results and Discussion

2.1 Microstructural evolution

Fig. 2 shows the as-transformed microstructure of the experimental steel. Fig. 2(a) is the optical microstructure, which shows a normalized microstructure of hypoeutectoid steels with proeutectoid ferrite and pearlite. Some cementite particles and a small amount of net carbides in grain boundary are also found in the treated specimens, and the transformed pearlite has typical lamellar morphology (Fig. 2(b)).

The TEM and SEM images (Figs. 3—5) of the specimens indicate the spheroidization mechanism of cementite. It can be seen that the spheroidizing ratio of cementite grows with the increase of cyclic numbers from Figs. 3—5.

The microstructure of the specimen subjected to heat treatment for 1 cycle is shown in Fig. 3. Broken cementite lamellae and some cementite spheroids are found in the pearlite region of the specimens after 1 cycle, as shown in Fig. 3(b). Partially dissolved, fragmented cementite lamellae indicate that the dissolution of cementite in the pearlitic region remains incomplete during the short time holding at 1023 K (5 min) and 893 K (3 min) for 1 cycle. During the short time holding above A_1 temperature (1023 K), the cementite lamellae are broken into fragmented lamellae (Fig. 3). When the specimen is cooled to 893 K (below A_1 temperature), the dissolution of cementite is terminated, and the broken lamellae partially change into cementite particles when holding at this temperature (Fig. 3(b)). This process in middle carbon steels is similar to that in high carbon steels[13,14]. Fig. 4 shows the microstructure of the specimen subjected to heat treatment for 7 cycles. It is clearly seen that some spheroidizing regions exist in