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Study on the performance and strain aging behavior of solid-solution state low-carbon steel

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ABSTRACT

Herein, the strain aging behavior of low-carbon steel subjected to heating at 850 °C followed by a 5-min holding time and water cooling cycle was studied. Various aging periods were tested using a 2% pre-deformation and baking step at 170 °C. The aging performance was characterized by tensile testing. Furthermore, the organizational structure variation was analyzed with transmission electron microscopy (TEM) and by measuring the internal friction of the low-carbon steel. Finally, age hardening mechanisms were discussed. The test results indicated that when the aging period ranged between 5 and 100 min, both the yield strength and tensile strength declined rapidly and the bake-hardening (BH) value decreased from 104.6 MPa to −13.2 MPa. In addition, morphological differences were observed: fine carbides gradually formed in the microstructure and continued to coarsen over time. Furthermore, the height of the Snoek peak decreased rapidly and was accompanied by the appearance of 3 internal friction peaks, denoted P_1, P_2 and P_3. When the aging period exceeded 100 min, the yield strength, tensile strength and BH value varied only slightly. Moreover, the number of carbides in the microstructure decreased, and their morphology coarsened. Furthermore, the height of the Snoek peak decreased slowly and was accompanied by the gradual disappearance of 2 of the internal friction peaks, P_1 and P_2.

1. Introduction

As the requirements for energy saving measures and emission reduction in the automotive industry have become more stringent, bake-hardened (BH) steel has been applied more extensively in automobile manufacturing [1]. The use of BH steel has attracted significant attention because it ensures passenger safety and decreases car weight [2–6]. The essence of BH processing is strain aging strengthening. Notably, 3 different steel microstructures can form during the strain aging process [7–9]. One type of microstructure is formed by the segregation of interstitial carbon atoms and nitrogen atoms on dislocations or crystal boundaries under stress induction. The second type, Cottrell atmospheres, is formed by the pin dislocations of carbon atoms and nitrogen atoms. The third type is formed by the precipitation of carbides or nitrides at dislocations. The extent of these 3 variations result in differing age hardening effects. The age hardening effect affects by the chemical composition, annealing process, pre-deformation and aging process of the steel [3,4,7,8,10–12]. The cooling rate of the annealing process affects the grain size and segregation of the carbon atoms onto crystal boundaries while the aging period influences the progression of the aging process [13,14]; thus, both of these factors affect the age hardening effect [9,15]. The internal friction of a material is highly sensitive to the behavior of carbon atoms [16]. In the literature [17–20], an internal friction method has been adopted to analyze the diffusion of interstitial carbon atoms into dislocations during the aging process. This paper focuses on the study of supersaturated low-carbon steel. In particular, it examines the micro-phenomena that occur during the aging process, including the diffusion of interstitial carbon atoms onto dislocations. For analysis, the nucleation and growth of carbides must firstly be integrated; then, the BH mechanism can be investigated.

2. Materials and methods

The experimental material used in this study comprised cold-rolled low-carbon steel with the following chemical composition (mass fraction, %): C, 0.21; Si, 0.01; Mn, 0.21; P, 0.011; S, 0.0075; Al, 0.019 and N, 0.002, with the remaining mass fraction composed of Fe. The tested steel was heated at 850 °C in a box-type resistance furnace. The temperature was held for 5 min and then cooled with water. Subsequently, the steel was subjected to a 2% pre-deformation and aging process conducted at 170 °C for 5 min, 33 min, 100 min, 200 min or 750 min. The BH value after simulated baking was measured according to GB/T24174-2009, which defines the BH value as the difference between the flow stress after the 2% pre-strain and the lower yield strength after

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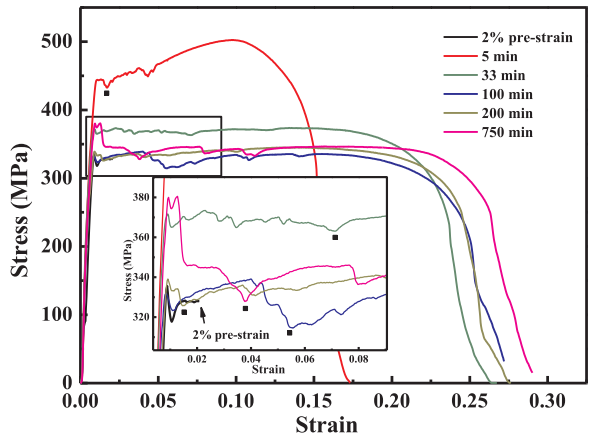

Fig. 1. Stress-strain curves under different aging periods.

baking. A UTM-5305 electronic universal testing machine was used to test these properties with a tension rate of 5 mm/min. The microstructures of the strain-aged specimens were observed with transmission electron microscopy (TEM). Internal friction measurements were conducted using 2 methods of natural oscillation and forced vibration with an MFP-1000 multi-functional internal friction instrument. The forced vibration frequencies tested were 0.5, 1, 2 and 4 Hz, and the dimensions of the specimens were 1 mm × 2 mm × 50 mm.

3. Results

3.1. Effect of the aging period on the stress-strain curve and BH value

The stress-strain curves of solid-solution state specimens, shown in Fig. 1, were obtained after samples were subjected to 2% pre-deformation and different aging periods at 170 °C. With aging periods of 5–10 min, the yield and tensile strengths decreased gradually compared with those with an aging period of less than 5 min. Furthermore, the yield point elongation and ultimate elongation both increased continuously. With aging periods of 100–750 min, the yield strength, tensile strength and elongation varied only slightly.

The variations in the BH values for different aging periods, shown in Fig. 2, were obtained from the curves presented in Fig. 1. When the aging period was less than 100 min, the BH value decreased continuously as the aging period increased, resulting in an age softening phenomenon. When the aging period exceeded 100 min, the BH increased slightly but was maintained at approximately 0 MPa as the aging period increased. The lower yield of the specimen obtained after

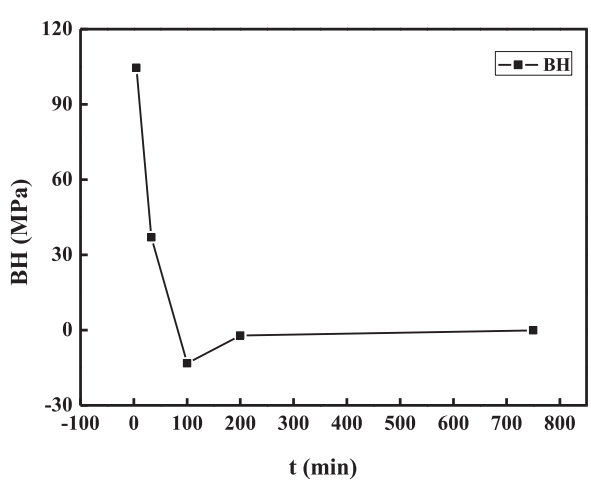

Fig. 2. Bake hardening (BH) value under different aging periods.

the aging process was proportional to the BH value because the BH value was calculated according to GB/T 24174-2009. Together, Fig. 1 and Fig. 2 show that the lower yield stress obtained was different when the aging period increased and the lower yield stress decreased continuously before the aging period reached 100 min. The gradual decrease in the lower yield stress resulted in a gradual decrease in the BH value.

3.2. Effect of the aging period on microstructure

Fig. 3 shows TEM images of the microstructure of a solid-solution state specimen exposed to a 2% pre-deformation and different aging periods. A certain number of dislocations were observed in the solid-solution state specimen that had not undergone aging treatment (Fig. 3a). After an aging period of 5 min, fine carbides precipitated inside the crystal grains (Fig. 3b). After an aging period of 33 min, the precipitated fine carbides coarsened (Fig. 3c). The number of carbides decreased significantly as the aging period increased to 100 min (Fig. 3d) as well as to 200 min (Fig. 3e). The variations in microstructure indicate that, during the strain aging process of the solid-solution state specimen, the carbides first precipitated and then gradually coarsened. Finally, the carbides dissolved as the aging period increased.

3.3. Effect of the aging period on the internal friction spectra

Fig. 4 shows the internal friction temperature spectra of the original specimen and the solid-solution state specimen of the steel tested. In Fig. 4, the measured internal friction values are depicted as solid points, and the real internal friction peak after subtracting the background internal friction is depicted as a solid line. The solid-solution state specimen exhibited 4 internal friction peaks within the range of 200–700 K. In accordance with the specified peak temperatures and activation energies, the peak found within the range of 310–340 K was determined to be the Snoek peak and the peak found within the 470–530 K range was determined to be the Snoek-Kê-Köster (SKK) peak [21–24]. A comparison between the internal friction spectra before and after the solid-solution treatment shows that the Snoek peak of the solid-solution state specimen was much higher than that before treatment. According to the literature [25,26], the Snoek peak height is proportional to the concentration of solid-dissolved carbon atoms. Therefore, the results indicate the solid-solution treatment significantly increased the concentration of interstitial carbon atoms in the ferrite. Fig. 5 shows the internal friction-temperature spectra of solid-solution state specimens for different strain aging periods. The Snoek peak was present in the internal friction spectra for all different aging periods, and its peak height decreased as the aging period increased. Among the decreases in peak height observed, the peak height was significantly lower and decreased slowly when the aging period was shorter than 33 min compared with aging periods 33 min and greater. The difference in the reduction rate indicates that, with shorter aging times, a large number of carbon atoms solid-dissolved in the ferrite lattices leave their interstitial positions, causing a rapid decline in their concentration. During longer aging times, the quantity of solid-dissolved carbon atoms leaving interstitial positions is less.

Fig. 5 shows that the internal friction temperature curves for different aging periods exhibited other internal friction peaks in addition to the Snoek peak, which are denoted P_1, P_2 and P_3 and correspond to the following approximate temperature ranges: 470–530 K, 520–570 K and 560–630 K, respectively. When the aging period was 100 min (Fig. 5d), only 1 internal friction peak was present in the temperature range of 520–600 K, which can be attributed to the superposition of the P_2 and P_3 peaks. When the aging period was 200 min (Fig. 5e), only the P_3 internal friction peak was observed. With the exception of these 2 aging periods, the P_1, P_2 and P_3 peaks were all observed on the curves for all other aging periods. The temperature range of the P_1 peak was near that of the SKK peak; thus, according to the activation energy of

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