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Effect of Isothermal Aging on the Magnetic Properties of 1Cr-0.5Mo Steel

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Magnetic properties and Rockwell hardness of 1Cr-0.5Mo steel have been investigated as a function of isothermal aging time. Our results showed that coercivity, hysteresis loss and Rockwell hardness in the aged samples decreased as aging time increased. This phenomenon was analyzed using optical microscopy and scanning electron microscopy. A significant diffusion of Cr and Mo atoms formed M_2C and M_7C carbides, lowering the matrix strength. M_2C and M_7C carbides partially segregated inside grains, diffused into grain boundaries, and finally resulted in a soft ferrite matrix and a hard grain boundary. The magnetic and mechanical softening of the matrix is likely to govern the properties of the sample more than the hardening of the grain boundary by carbide precipitations.

Keywords : 1Cr-0.5Mo steel, coercivity, hysteresis loss, Rockwell hardness, carbide, isothermal aging

1. Introduction

The mechanisms of material degradation are classified as softening and embrittlement. Softening occurs as a result of the coarsening of carbides and the recovery of dislocations caused by a long service time at elevated temperature. Embrittlement occurs in Cr-Mo steel and Cr-Mo-V steel, which are used in heat resistant equipments in a plant over a long period of time. Embrittlement is the typical degradation phenomenon and is caused by the segregation of impurity elements to the grain boundary and by the coarsening of carbides [1, 2].

The microstructural changes and solute segregation induced in steel by a thermal or radiational environment frequently produce severe degradation of the mechanical properties. The structure-sensitive magnetic properties are coercivity, permeability, hysteresis loss and remanence, and the structure-insensitive properties are saturation magnetization, saturation magnetostriction, magnetic moment per atom, Curie point, and to a certain extent, anisotropy [3]. It has been recognized that techniques based on magnetic measurement offer great potential because they are highly sensitive to changes in several metallurgical factors [4-6].

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In this work, we prepared isothermally aged 1Cr-0.5Mo steel samples and obtained the coercivity and hysteresis loss, which are structure-sensitive magnetic properties, by measuring the hysteresis loop. We measured the hardness by using a Rockwell hardness (HRB) tester. The changes in the magnetic properties and HRB were analyzed by using optical and scanning electron microscopy (SEM) to examine the microstructures.

2. Experimental

The test material was 1Cr-0.5Mo steel for hot finished seamless steel tubes, which have been widely used as tubes for heat exchangers and as plates for pressure vessels [7]. Its chemical properties are shown in Table 1. The samples, which had dimensions of 50.0 mm (l) × 26.6 mm (w) × 5.0 mm (t), were prepared and aged at an elevated temperature of 700 °C for periods of 1 h, 30 h, 300 h, 1,070 h, and 3,000 h.

The aim was to simulate the microstructures of materials that have served a long term at an elevated temperature, due to the difficulty in obtaining aged materials on site. Thus six kinds of specimens with different microstructures were prepared. The periods of heat treatment for the simulation were selected based on the Larson-Miller parameter (LMP) as follows;

Table 1. Chemical composition of test material (mass %).

C	Si	Mn	P	S	Cr	Mo
0.143	0.239	0.627	0.005	0.005	1.01	0.49

$$LMP = T(C + \log t) \quad (1)$$

where T is aging temperature (K), C is the material constant, and t is heat aging time (h). Because the change in this parameter is a function of time and temperature, its current value may be used to estimate an equivalent thermal history for a given operating time. The estimated temperature can then be used in conjunction with standard stress-rupture data to estimate the remanent life. The aging times at elevated temperature are shown in Table 2.

Changes in magnetic properties were investigated by a ballistic method [8] and the change in hardness was measured by using a Rockwell hardness tester. To measure the hysteresis loop, the specimen was magnetized by a triangular wave current of 0.05 Hz with a maximum applied magnetic field of 4.5 kA/m. Microstructures were examined using optical microscopy and SEM.

3. Results and Discussion

The principal processes for controlling magnetization response are the pinning of magnetic domain walls and the retardation of wall motion due to increased amounts of point defects, precipitated carbides and internal residual stress, which also influence the mechanical hardness [9].

The microstructural features capable of pinning these walls are the same as those which influence the dislocation curves of the movement. The hysteresis loops of the as-received specimen and the specimens aged at 700 °C for 1 h, 30 h, 300 h, 1,070 h, and 3,000 h are shown in Fig. 1. The coercivity calculated from Fig. 1 is shown in Fig. 2. In these figures, the coercivity is decreased by aging for 1 h, but then it increases as the isothermal aging time is increased from 1 h up to 30 h. For aging times longer than 30 h, coercivity decreases with increasing aging time.

A hysteresis loss is the area of a hysteresis loop. The change in the hysteresis loss, as calculated from the hysteresis loops in Fig. 1, is shown in Fig. 3. In this figure, the hysteresis loss drastically decreases as aging time increases up to 300 h, and then decreases steadily as aging time is further increased.

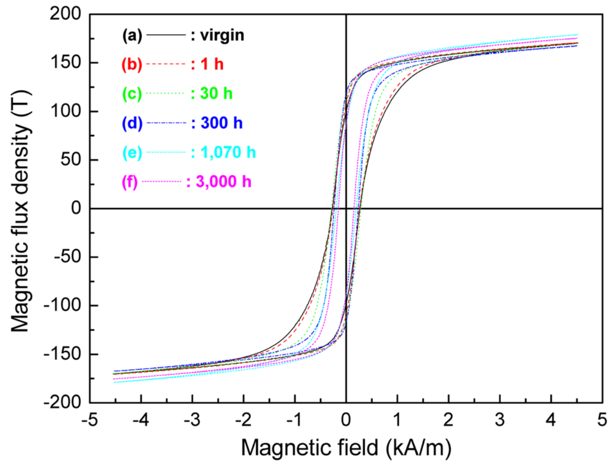

Fig. 1. (Color online) Hysteresis loops for aging times of (a) 0 h, (b) 1 h, (c) 30 h, (d) 300 h, (e) 1,070 h, and (f) 3,000 h.

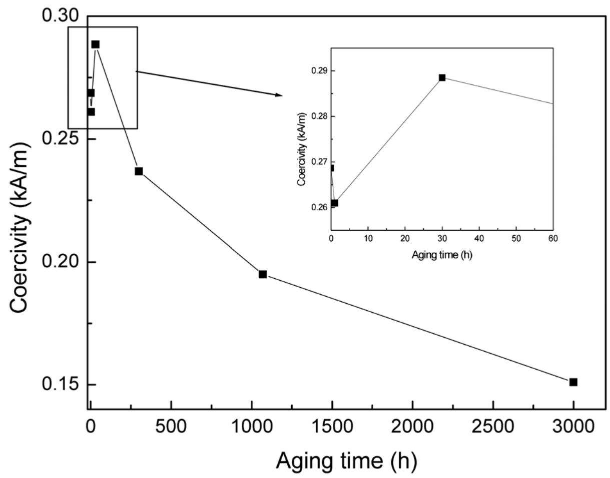

Fig. 2. Coercivity calculated at measured hysteresis loops. Coercivity increases as aging time is increased up to 30 h (after decreasing for an aging time of 1 h, as shown in insert), but it decreases gradually as aging time increases beyond 30 h.

Fig. 4 shows the dependence of normalized mechanical hardness and coercivity on aging time. As shown in the figures, both the hardness and the coercive force decrease as the aging time increases, with coercive force decreasing more than hardness.

According to Biss and Wada's previous research [7], both the as-received specimen and the 1 h heat-treated

Table 2. Determination of the aging time at 700 °C that will give an equivalent microstructure to a material that served at 593 °C.

Aging time at 700 °C	1	30	300	1,070	3,000
Service time at 593 °C	50	2,450	32,580	135,980	433,000
Larson-Miller parameter	13,622	15,059	16,032	16,569	17,005

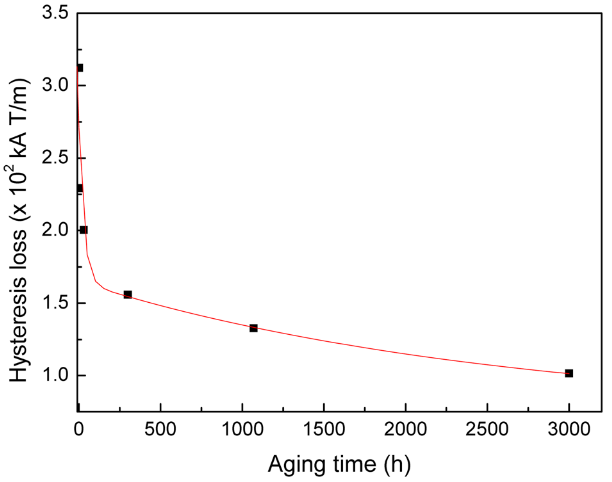

Fig. 3. (Color online) Hysteresis loss caculated at measured hysteresis loops. Hysteresis loss decreases drastically with increasing aging time for aging times below 300 h, but smoothly decreases as aging time increases further.

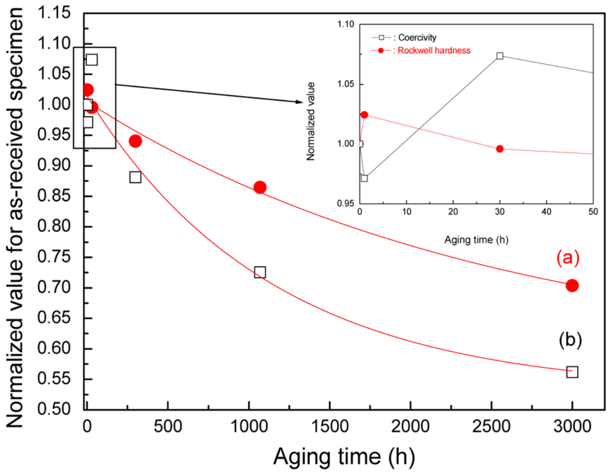

Fig. 4. (Color online) Dependence of normalized coercive force and Rockwell hardness on aging time. As shown in insert, HRB decreases as aging time increases to 30 h (after increasing for an aging time of 1 h); this is the opposite to coercivity.

specimen can be related to the reheat-treated specimen.

In a short-term heat treatment, large amounts of carbide precipitates, which have chemical compositions similar to cementite, form without lowering Cr and Mo content in the ferrite matrix and result in the hardness, coercivity and hysteresis loss increases in the 1 h heat-treated specimen. Thus, no significant change in microstructure is observed in Figs. 5(b) and 6(b) in comparison with their own virgin microstructures in Figs. 5(a) and 6(a). Meanwhile, decreases in hardness, coercivity and hysteresis loss with increasing heat treatment time are explained by

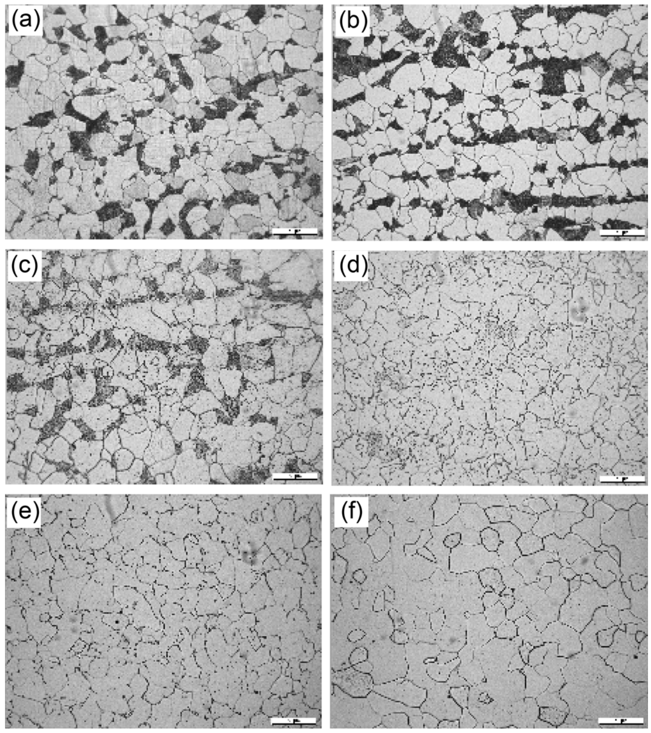

Fig. 5. Optical micrography of the thermal aged 1Cr-0.5Mo steel with different aging times of (a) 0 h, (b) 1 h, (c) 30 h, (d) 300 h, (e) 1,070 h, and (f) 3,000 h.

bainite decomposition and diffusion of Cr and Mo atoms [7]. In a long-term heat treatment, significant diffusion of Cr and Mo atoms forms M_2C and M_7C carbides, lowering the matrix strength. Moreover, decomposition of the metastable bainite phase means that the specimen hardness and magnetic properties decrease with increasing heat treatment time. A significant dissolution of the bainite and pearlite microstructures is observed from Figs. 5(c) and (d). Then M_2C and M_7C carbides partially segregated inside grains, diffused into grain boundaries, and finally resulted in a soft ferrite matrix and hard grain boundary.

4. Conclusion

The effect of isothermal heat treatment on structure-sensitive magnetic properties and hardness has been investigated for 1Cr-0.5Mo steel. Coercivity and Rockwell hardness gradually decreased as aging time increased. The changes in the coercivity and Rockwell hardness originated in the microstructure. In a short-term heat treatment, no significant change in the microstructure was observed. The decrease in the hardness with increasing heat treatment time is explained by bainite decomposition and diffusion of Cr and Mo atoms. In a long-term heat treatment, significant diffusion of Cr and Mo atoms led to the

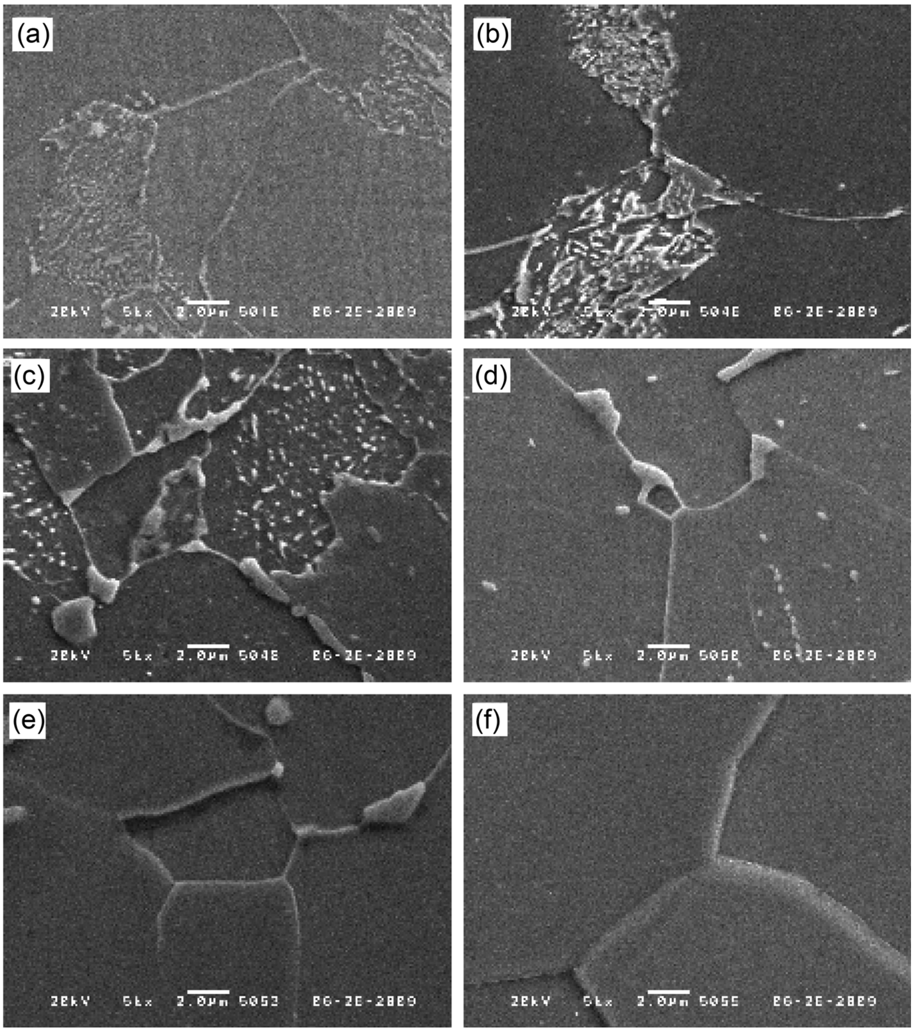

Fig. 6. SEM micrography of the thermal aged 1Cr-0.5Mo steel with different aging times of (a) 0 h, (b) 1 h, (c) 30 h, (d) 300 h, (e) 1,070 h, and (f) 3,000 h.

formation of M_2C and M_7C carbides, lowering the matrix strength. The magnetic and mechanical softening of the matrix is likely to govern the properties of the sample more than the hardening of the grain boundary by carbide precipitations.

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