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Nondestructive Evaluation for Remanent Life of 1Cr-0.5Mo Steel by Reversible Permeability

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Peak interval for reversible permeability is presented for nondestructively evaluating the remanent life of 1Cr-0.5Mo steel. The method to measure the peak interval of reversible permeability is based on the value of reversible permeability is the same as the differential value of the hysteresis loop. The measurement principle is based on the first harmonics voltage induced in a sensing coil using a lock-in amplifier tuned to a frequency of the exciting voltage. Results obtained for the peak interval of reversible permeability and Rockwell hardness on the aged samples decrease as aging time and the Larson-Miller parameter increase. We could estimate the remanent life of 1Cr-0.5Mo steel by using the relationship between the peak interval of reversible permeability and the Larson-Miller parameter, nondestructively.

Keywords : remanent life, 1Cr-0.5Mo steel, nondestructive evaluation (NDE), peak interval of reversible permeability (PIRP), Larson-Miller parameter (LMP)

1. Introduction

The microstructural change and solute segregation induced in a thermal environment frequently produce severe degradation with regards to the mechanical properties of steel. The matrix is softened by microstructural changes and solute depletion produces severe degradation of the mechanical properties of steel exposed to high temperatures for extended periods of time [1, 2]. The life of 1Cr-0.5Mo steel used for pressure vessels, such as the tubes for heat exchangers and the petroleum refinery, should be reduced by degradation. Therefore, for safety, it is necessary to effectively monitor the microstructural change and degradation of operating boilers. The value of reversible permeability could be used for estimating and monitoring not only the degradation but also the remanent life of 1Cr-0.5Mo steel.

Many researchers have been interested in destructive and nondestructive measurement methods to examine microstructural changes and mechanical damage in order to assure the safe operation of steel structures such as turbine and reactor pressure vessels [3-6]. Destructive methods are reliable and widely used for estimating the degradation and the remanent life of such material. However, the use of conventional destructive methods for material properties is of limited value since sampling material for specimens without damaging equipment is very difficult. Thus, a nondestructive evaluation technique to determine the remanent life of material is necessary. Although various nondestructive methods have been studied, the development of a nondestructive technique to quantitatively estimate material degradation has not yet been completed [4, 7].

In this work, we artificially prepared aged 1Cr-0.5Mo steel samples and measured Rockwell hardness (HRB) and reversible permeability (RP). The peak interval of reversible permeability (PIRP) could plausibly be used to evaluate remanent life during the nondestructive servicing of steel structures, such as tubes for heat exchangers and reactor pressure vessels.

2. Experiments

The test material was 1Cr-0.5Mo steel, which has been widely used as tubes for heat exchangers and as plates for pressure vessels [8]. The chemical properties of the sample are described in Table 1. The sample in the dimension of 50.0 mm × 26.6 mm × 5.0 mm were prepared and heat-treated at 700 ºC for 1 h, 30 h, 300 h, 1,070 h, and 3,000 h, respectively. This was to simulate the microstructures of long term served materials at an elevated temperature

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Table 1. Chemical composition of 1Cr-0.5Mo sample (mass%).

Composition	C	Si	Mn	P	S	Cr	Mo
ASME Spec.	0.15 Max	0.5 Max	0.30/0.61	0.25 Max	0.025 Max	0.81/1.25	0.44/0.65
Product analysis	0.143	0.239	0.627	0.005	0.005	1.01	0.49

Table 2. Decision of aging time at 700 °C for equivalent microstructure 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

because of 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 [8]

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

where T is aging temperature (K), C is material constant, and t is heat aging time (h). Since 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 time was summarized in Table 2.

The change in hardness properties were measured by a Rockwell hardness tester. In order to non-destructively measure the RP on specimens, we used a surface type probe with ferrite yoke. The yoke was used to measure RP in order to diminish the demagnetization effect for an open magnetic circuit. The yoke was surrounded by a pick-up coil, ac perturbing coil and dc magnetizing coil. The voltage induced in the pick-up coil with a reference as the perturbing field was measured by a lock-in amplifier (EG&G PAR 5210) [5]. The frequency of the perturbing field was 14 Hz. The RP was determined by selecting the reference mode at a single frequency. The slow varying magnetic field, which at maximum is 12.0 kA/m, was measured by a current using the voltage across a shunt resistor of 1 ohm. RP was measured during a slow varying cycle as a function of the current along the sample axis using an I/O acquisition board.

3. Results and Discussion

Incremental permeability (μ_Δ) refers to alternating field excitation for a specified static field value as follows;

$$\mu_\Delta = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H} \quad (2)$$

where μ_0 is magnetic constant, ΔB is incremental magnetic induction, and ΔH is incremental magnetic field. Reversible permeability (μ_{rev}) is the limiting value of the incremental permeability when the alternating field strength approaches zero as follows [8];

$$\mu_{rev} = \lim_{\Delta H \to 0} \mu_\Delta = \frac{1}{\mu_0} \lim_{\Delta H \to 0} \frac{\Delta B}{\Delta H} \quad (3)$$

The measurement method of the RP is based on the fact that the value of RP is the same as the differential value of the hysteresis loop. Fig. 1 shows that the changes in the RP profile depend on the aging time. As shown in Fig. 1, PIRP narrowed more and more as aging time increased. Fig. 2 shows the variation in the two properties of degradation for the 1Cr-0.5Mo steel. The HRB decreased monotonously for aging time, but the PIRP decreased abruptly with regards to short time (below 1,070 h) and the change became small after aging for an extended period of time. As shown in the Figs. 1 and 2, the PIRP and HRB decreased with the increase of aging time.

This phenomenon can be explained by the M_2C carbides precipitate and the M_7C carbides precipitate in pearlite formed at the grain boundary [9, 10]. The carbides, as a precipitate, are expected to hinder the domain wall motion, increasing the PIRP of 1Cr-0.5Mo steel after aging. However, the experimental results are contradictory by showing the decrease of PIRP. The result is probably due to the diffusion occurring out of C, Cr and Mo atoms to the grain boundary for the formation of carbides. The depletion of interstitial and substitutional solutes in the matrix is believed to reduce the residual stress, resulting in the magnetic softening of matrix. This magnetic softening effect overwhelms the magnetic hardening through precipitation, and the decrease of PIRP by high-temperature

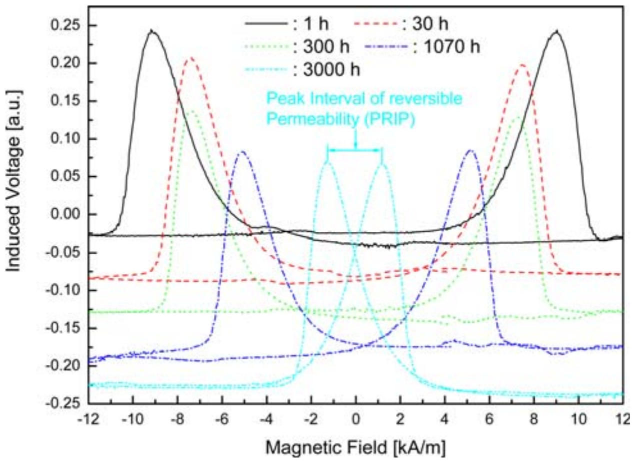

Fig. 1. (Color online) RP profiles for aging times (a) 1 h, (b) 30 h, (c) 300 h, (d) 1,070, and (e) 3,000 h. PIRP narrowed more and more as aging time increased.

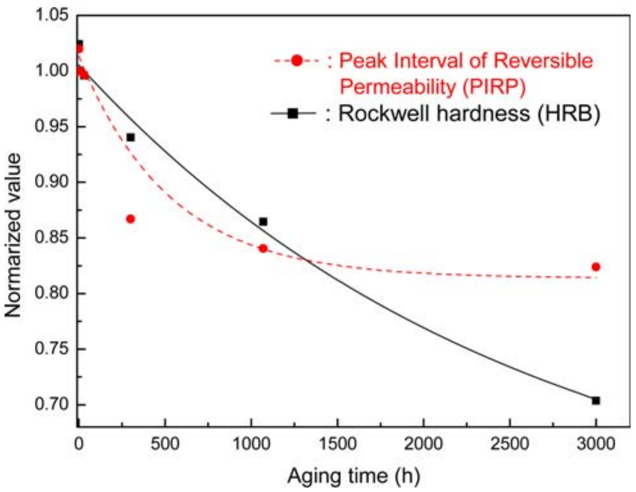

Fig. 2. (Color online) Normalized (a) PIRP and (b) HRB on aging time.

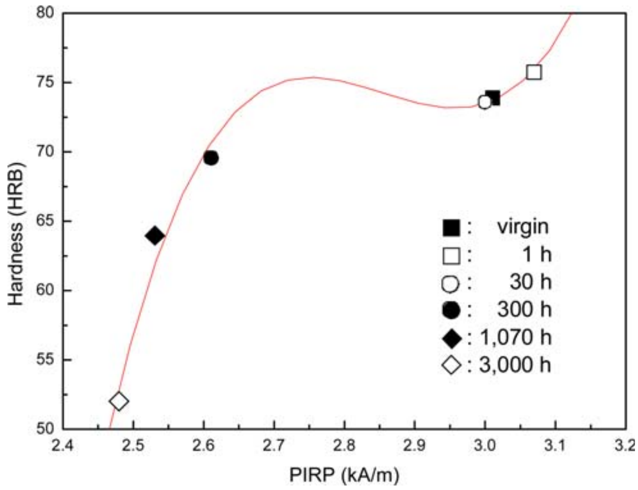

Fig. 3. (Color online) Relationship between HRB and PIRP. HRB is proportional to PIRP.

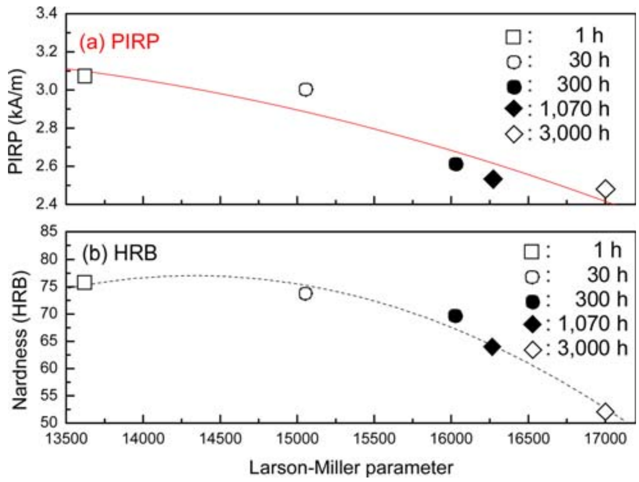

Fig. 4. (Color online) Relationship of (a) PIRP and (b) HRB on LMP. Two properties are inversely proportional to LMP.

aging is considered to be observed in 1Cr-0.5Mo steel [1].

The relationship between HRB and PIRP is shown in Fig. 3. The curve is fitted by the 3rd order polynomial. The relation is as follows;

$$HRB = A_1 + B_{11} \times PIRP + B_{12} \times PIRP^2 + B_{13} \times PIRP^3 \quad (3)$$

where A_1 B_{11}, B_{12} and B_{13} are -1.2×10^4, 1.27×10^4, -4.44×10^3, 5.19×10^2 and 30.19, respectively. In order to evaluate the integrity of the equipment during the service, the degradation of hardness is required. Thus, the PIRP could be used to nondestructively estimate the important hardness.

The variation of HRB and PIRP with a function of LMP is shown Fig. 4. The HRB and PIRP are fitted by the 2nd order polynomial. The relations are as follows;

$$PIRP = A_2 + B_{21} \times LMP + B_{22} \times LMP^2 \quad (4)$$

$$HRB = A_3 + B_{31} \times LMP + B_{32} \times LMP^2 \quad (5)$$

where A_2, A_3, B_{21}, B_{22}, B_{31} and B_{32} are -4.94×10^{-1}, -6.27×10^2, 6.37×10^{-4}, -2.74×10^{-8}, 9.83×10^{-2} and 3.43×10^{-6}, respectively. As shown in Fig. 4, LMP can be estimated by HRB and PIRP measured by the nondestructive method. If the PIRP is measured by the magnetic method using the surface type probe, the LMP is obtained at the line of Fig. 4(a). Thus, the remanent life (t) is calculated by equation (1), because a using time (T), and a material constant (C) are the known values. So, the nondestructive method such as HRB and PIRP can be used to estimate the remanent life of the serving equipment without causing damage.

4. Conclusions

A nondestructive method to evaluate the remanent life of 1Cr-0.5Mo steel by means of the PIRP was developed. The reversible permeability signal was measured using a surface type probe with ferrite yoke, and the PIRP decreased with the increase of aging time. The mechanical property such as HRB could be estimated by a magnetic property such as the PIRP because HRB was fitted by the 3^{rd} order polynomial to the PIRP. HRB and PIRP were decreased the 2^{nd} order polynomial to the Larson-Miller parameter. The magnetic property such as the PIRP measured by the nondestructive method could be used to nondestructively estimate the remanent life of 1Cr-0.5Mo steel.

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