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Nondestructive Evaluation of Residual Life of 1Cr-1Mo-0.25V Steel by Reversible Magnetic Permeability

K. S. Ryu, S. H. Nahm*, Y. I. Kim**, K. M. Yu, Y. B. Kim, Y, Cho***, D.Son***

Div. of Electromagnetic Metrology, Korea Research Institute of Standards and Science
P.O.Box 102, Yusong, Taejon 305-600, Korea
* Div. of Industrial Metrology, Korea Research Institute of Standards and Science,
P.O.Box 102, Yusong, Taejon 305-600, Korea
** Div. of Chemical Metrology and Materials Evaluation, Korea Research Institute of
Standards and Science, P.O.Box 102, Yusong, Taejon 305-600, Korea
*** Department of Physics, Hannam University, Taejon 300-791, Korea

Abstract

We present a new procedure to evaluate the residual life of 1Cr-1Mo-0.25V steel by reversible magnetic permeability. The method is based on the existence of the first harmonics in the differential magnetization around the coercive force. The apparatus is based on the detection of the voltage induced in a coil using a lock-in amplifier tuned to a frequency of the exciting one. Results obtained for the first harmonics and Vickers hardness on the aged samples show that the peak interval of reversible permeability and Vickers hardness decrease as ageing time increases. The correlation between Vickers hardness and the peak interval of the reversible permeability could well be used to evaluate the residual life of 1Cr-1Mo-0.25V steel, nondestructively.

1. Introduction

The microstructural change and solute segregation induced at an elevated temperature or radiational environment frequently produce severe degradation of the mechanical properties of steel. Many researchers [1-3] have interest in the nondestructive measurement methods for examining the microstructural changes and mechanical damage in order to assure the safe operation of steel structure such as turbine rotors and reactor pressure vessels. Although various nondestructive methods have been studied, the development of nondestructive technique to estimate material degradation quantitatively has not been completed yet [1-3].

When the voltage induced in pick-up coil is symmetric without the bias field, the only odd harmonics of the fundamental frequency of the driving field are present even though the magnetization of core material is nonlinear. The external field causes the shift in a *B-H* loop and the induced voltage becomes asymmetrical, giving rise to the even harmonics. However, the analysis of harmonics profiles for small perturbing field along the magnetization curve is not available, relating the profiles with the microscopic magnetization processes.

In this work, we prepared isothermally aged 1Cr-1Mo-0.25V steel samples, and measured the peak interval of reversible permeability and Vickers hardness. The peak interval of reversible permeability is the twice of coercive field strength. Using the linear relation between coercive field strength and Vickers hardness, we are trying to suggest a method for estimating residual life of steel structure such as turbine rotors and reactor pressure vessels, nondestructively .

2. Experimental procedure

The sample in this study was 1Cr-1Mo-0.25V steel, which has been widely used for turbine rotor material. The samples in dimension of 55 mm × 5 mm × 1 mm were aged at 630 ℃ for 453 h, 933 h, 1,322 h, 1,820 h, 3,640 h and 5,460 h, respectively.

They were prepared to simulate the microstructures of long term served materials at elevated temperature because of difficulty to obtain aged materials on site. Finally seven kinds of specimens with different microstructures were prepared. The required aging time was determined on condition that the amount of Fe diffusion was the same at each temperature by the theory of self-diffusion of Fe [4]. Table 1 shows the ageing time at 630 °C for equivalent microstructure serviced at 538 °C.

The changes of coercive field strength were investigated by lock-in amplifier (EG&G PAR 5210), and the changes of hardness were measured by a micro-Vickers hardness tester (Future-tech corp. FN-7). To measure the reversible permeability, the specimens were magnetized by sinusoidal wave current of 0.05 Hz with maximum applied magnetic field of 8.0 kA/m.

Table 1 Determination of ageing time at 630 °C for equivalent microstructure serviced at 538 °C.

Ageing time at 630 °C (h)	453	933	1,322	1,820	3,640	5,460
Time served at 538 °C (h)	25,000	50,000	75,000	100,000	200,000	300,000

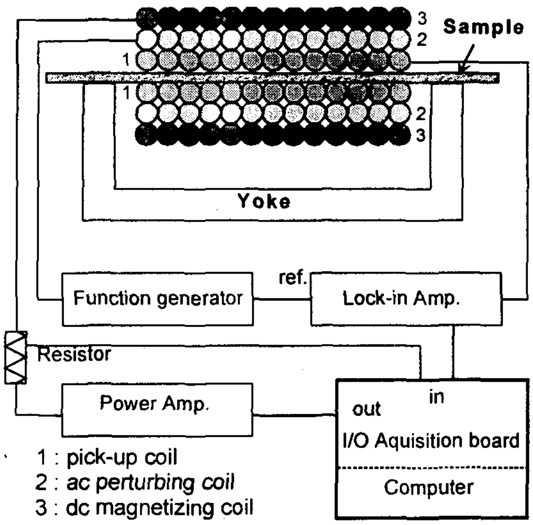

Fig.1. Block diagram for the measurement of first harmonics profiles.

A block diagram for reversible permeability measurement is shown in Fig.1. The sample is surrounded by pick-up coil, ac perturbing coil and dc magnetizing coil. The induced voltage in pick-up coil was measured by the lock-in amplifier with a reference as the perturbing field. A reversible permeability was chosen by selecting the reference mode at single frequency.

The slow varying magnetic field was measured by the current using the voltage across a shunt resistor of 1 Ω. A reversible permeability was measured during a cycle of slow varying field as a function of the current along the sample axis using an I/O acquisition board.

3. Results and Discussion

In general, when a small perturbing field $h(t)$ with slow varying field H_0 is applied to a magnetic material, the perturbing field induces minor loops along a major loop. It is hard to prove that the magnetization processes on a minor loop are the same as those on the major loop, but induced magnetization m is phenomenologically expressed in power series of h [5].

$$H = H_o + h = H_o + h_o \sin(\omega t) \tag{1}$$

$$m = \chi_1 h + \chi_2 h^2 + \chi_3 h^3 + \cdots \tag{2}$$

where χ_1 is linear magnetic component, and $\chi_2, \chi_3, \cdots$ are nonlinear higher order components.

The induced magnetization causes the voltage $E(H_o, h_o)$ in a sample pick-up coil. $E(H_o, h_o)$ is given by the time derivative of magnetic flux, which is proportional to the magnetization. After a little algebra, $E(H_o, h_o)$ is written as follows [6]

$$E(H_o, h_o) \propto \frac{dm}{dt} = E_1 \cos \omega t + E_2 \sin 2\omega t - \cdots \tag{3}$$

with $$E_1 = A\omega(\chi_1 h_o + (3/4)\chi_3 h_o^3 + \cdots)$$

$$E_2 = A\omega(\chi_2 h_o^2 + \chi_4 h_o^4 + \cdots) \tag{4}$$

where A is constant representing the geometry of pick-up coil. It is noted that the coefficient of odd harmonics, E_1, E_3, $\cdots$, are derived from the odd power and reflect nonlinear magnetization. Whereas even harmonics coefficients are derived from the even power and represent the asymmetry of minor magnetization loops, related to the transition of magnetization slope due to the nucleation, transformation, annihilation of domains [7].

Fig.2 shows the profiles of reversible permeability for ageing time. The field interval

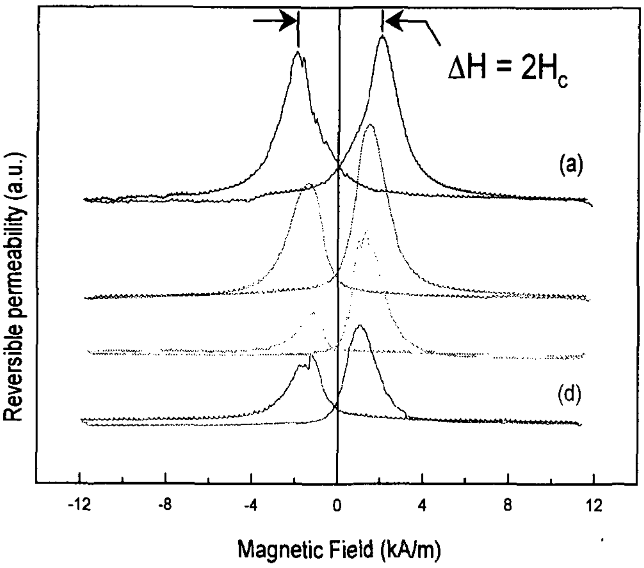

Fig.2. Reversible permeability profiles for ageing times (a) as-received, (b) 933 h, (c) 1,820 h, and (d) 5,460 h.

ΔH becomes narrow with the increase of ageing time. Fig.3 shows the change of coercive field strength on ageing time. As shown in the figure, as the ageing time increases, the coercive field strength decreases according to the increase of ageing time. It is due to the magnetic softening by diffusion of carbon atoms from matrix to grain boundary to form carbides [3].

Fig.4 shows the change of Vickers hardness depending on ageing time. As the ageing time increases, the hardness decreases sharply in the early stage of ageing time.

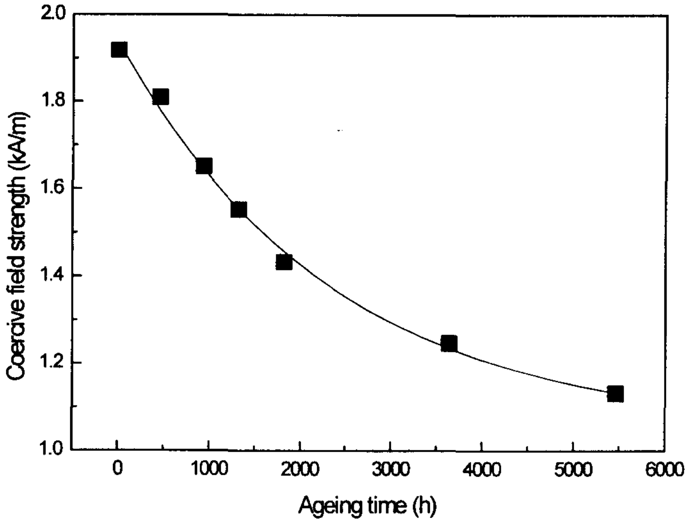

Fig.3. Dependency of coercive field strength on ageing time.

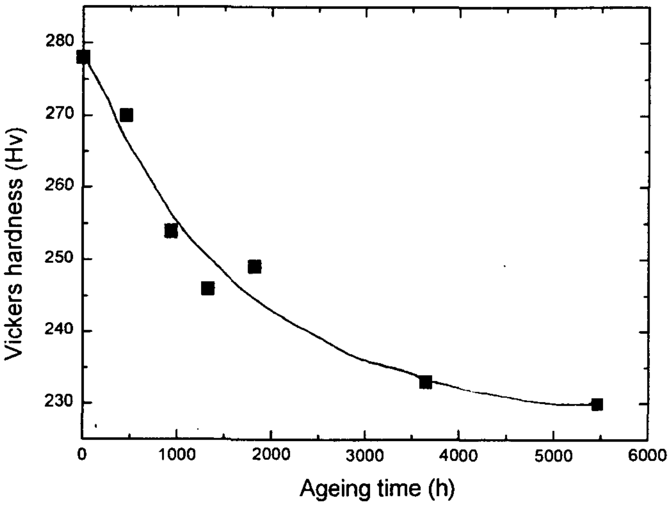

Fig.4. Dependency of Vickers hardness on ageing time.

The coercive force decreases linearly with the decrease of Vickers hardness as shown in Fig.5. The low coercive force is caused by the decrease of pinning of the domain walls, the easy wall motion due to decreased amounts of point defects, and internal residual stresses which influence mechanical hardness. Therefore, even if only the magnetic properties are available, the remaining life can be estimated from the existing relation of hardness and life estimation parameter such as G parameter [8,9].

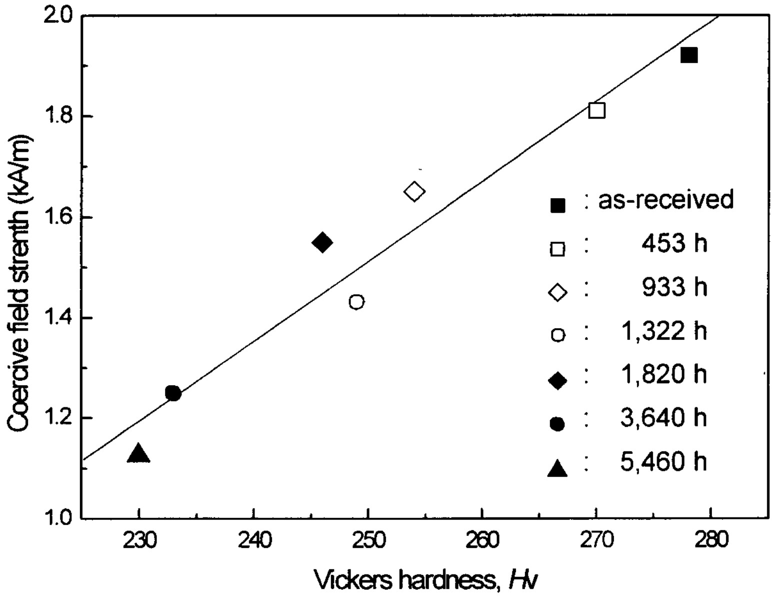

Fig.5. Relationship between the coercive field strength and Vickers hardness for ageing time.

The coercive field strength is given as a function of Vickers hardness by the slope of Fig.5:

$$H_c = \left(1.57 \times 10^{-2}\right) \times H_v - 2.42 \qquad (5)$$

The Vickers hardness can be calculated by coercive field strengths, the results are given in Table 2.

Fig.6 shows the dependence on hardness ratio with G′ parameter. We can obtain softening curve using the calculated Vickers hardness by measuring coercive field strength. We can estimate the residual life of turbine rotor steel by softening curve in this figure.

Table 2 Vickers hardness calculated by coercive field strength.

Ageing time (h)	as-received	453	933	1,322	1,820	3,640	5,460
H_c (kA/m)	1.92	1.81	1.65	1.55	1.43	1.25	1.13
Hv Calculated by H_c	276	269	259	253	245	234	226

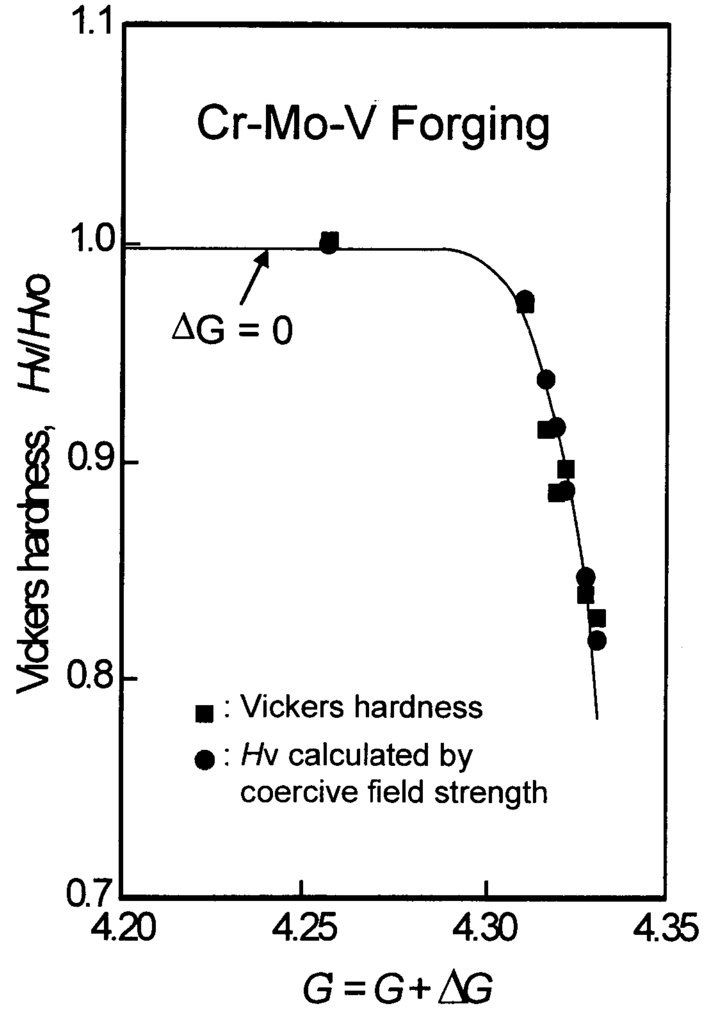

Fig.6. Comparison of G′ parameter calculated by Vickers hardness and coercive field strength.

Conclusions

The coercive field strength calculated by interval of reversible permeability decreases as the ageing time increases, and it is proportional to mechanical hardness of 1Cr-1Mo-0.25V steel. The Vickers hardness is calculated by coercive field strength by linearity, and the ratio of calculated hardness with G′ parameter is plotted. Using the plotted softening curve, we can estimate residual life of turbine rotors, nondestructively .

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