Journal of Magnetics 6(1), 27-30 (2001)

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

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

(Received 8 September 2000)

We present a new procedure to evaluate the residual life of 1Cr-1Mo-0.25V steel from reversible magnetic permeability. The method is based on the existence of 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 the frequency of the exciting coil. Results obtained for the first harmonics and Vickers hardness on aged samples show that the peak interval of reversible permeability and Vickers hardness decrease as aging time increases. The correlation between Vickers hardness and the peak interval of the reversible permeability may be used to evaluate the residual life of 1Cr-1Mo-0.25V steel, nondestructively.

1. Introduction

The microstructural change and solute segregation induced by elevated temperature or a radiation environment frequently produce severe degradation of the mechanical properties of steel. Many researchers [1-3] have investigated 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 a pick-up coil is symmetric, without a bias field, only odd harmonics of the fundamental frequency of the driving field are present even though the magnetization of the core material is nonlinear. An external field causes the shift in a *B-H* loop and the induced voltage becomes asymmetrical, giving rise to even harmonics. Analysis of harmonic profiles for small perturbing fields along the magnetization curve might permit us to relate the profiles to 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 the Vickers hardness. The peak interval of reversible permeability is twice the 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. Samples 55 mm × 5 mm × 1 mm were aged at 630 °C for 453 h, 933 h, 1,322 h, 1,820 h, 3,640 h, and 5,460 h.

These samples were prepared to simulate the microstructures of materials after long serve at elevated temperature, because of the difficulty in obtaining samples actually aged in serve. Finally seven specimens with different microstructures were prepared. The required aging time was determined by the condition that the amount of Fe diffusion should be 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 after service at 538 °C, for the indicated times. The equivalent times at 538 °C are 55 times longer than the ageing times at 630 °C.

The changes of coercive field strength were measured as described below, and the changes of hardness were measured by a Vickers micro hardness tester (Future-tech corp. FN-7). To measure the reversible permeability, the specimens were magnetized by a sinusoidal current at 0.05 Hz with maximum applied magnetic field of 12.0 kA/m.

A block diagram for the reversible permeability measurement is shown in Fig. 1. The sample is surrounded by a

Table 1. Determination of aging time at 630 °C for equivalent microstructure after service at 538 °C

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

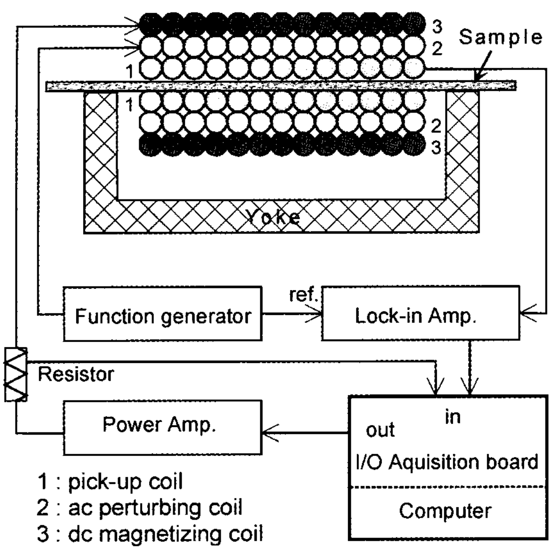

Fig. 1. Block diagram for the measurement of first harmonics profiles.

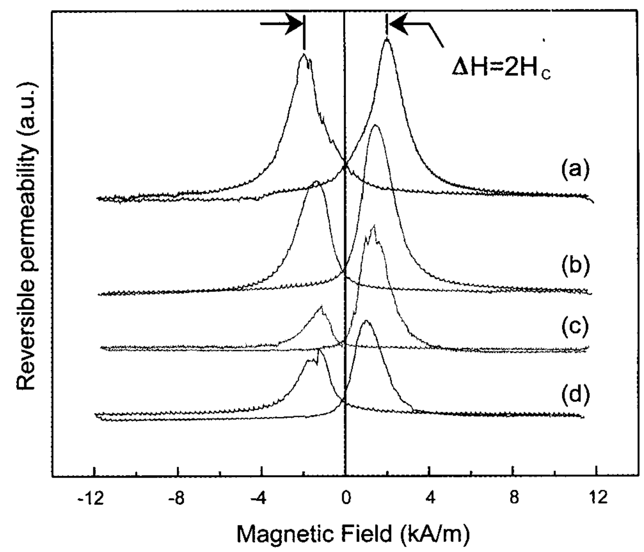

Fig. 2. Reversible permeability profiles for aging times at 630 °C (a) as-received, (b) 933 h, (c) 1,820 h, and (d) 5,460 h.

pick-up coil, an ac perturbing coil, and a dc magnetizing coil. The induced voltage in the pick-up coil was measured by a lock-in amplifier (EG&G PAR 5210) with a reference frequency of 20 Hz, the frequency of the perturbing field.

A reversible permeability was chosen by selecting the reference mode at single frequency. The slowly varying d.c. magnetic field was measured from the voltage across a shunt resistor of 1 Ω in series with the d.c. magnetizing coil. The reversible permeability was measured during a cycle of slowly 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 $h(t)$ plus a slowly 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 the induced magnetization m can be phenomenologically expressed as a 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 the linear magnetic susceptibility component, and χ_2, χ_3, ··· are nonlinear higher order components.

The induced magnetization induces a voltage $E(H_0, h_0)$ in the pick-up coil. $E(H_0, h_0)$ is given by the time derivative of magnetic flux, which is proportional to the magnetization. After a little algebra, $E(H_0, h_0)$ 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 coefficients of the odd harmonics, E_1, E_3, ···, are derived from the odd powers of h_o and reflect nonlinear magnetization, whereas the even harmonics coefficients are derived from the even powers and represent the asymmetry of minor magnetization loops, related to the transition of magnetization slope due to the nucleation, translation, and annihilation of domains [7].

Fig. 2 shows the profiles of reversible permeability for different aging times. The field interval ΔH, which is taken as twice the coercive field H_k, becomes narrower with the increase of aging time. Fig. 3 shows the change of coercive field strength with aging time. As shown in the figure, as the aging time increases, the coercive field strength decreases. This is due to magnetic softening by diffusion of carbon atoms from matrix to grain boundaries to form carbides [3].

Fig. 4 shows the change of Vickers hardness with aging time. As the aging time increases, the hardness decreases sharply and then tends toward a constant value.

The coercive field decreases linearly with the decrease of Vickers hardness as shown in Fig. 5. The low coercive field

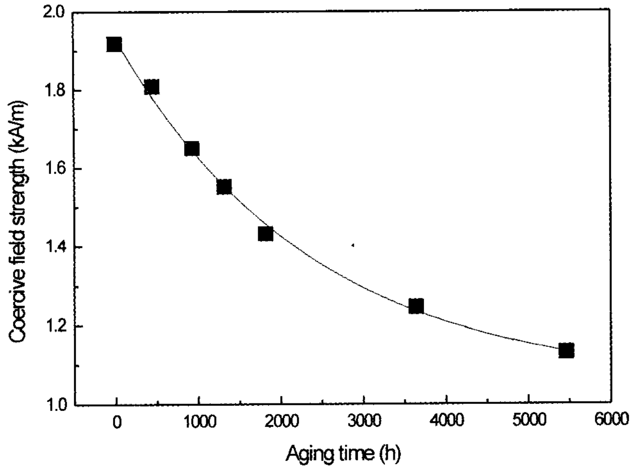

Fig. 3. Dependency of coercive field strength on aging time at 630 °C.

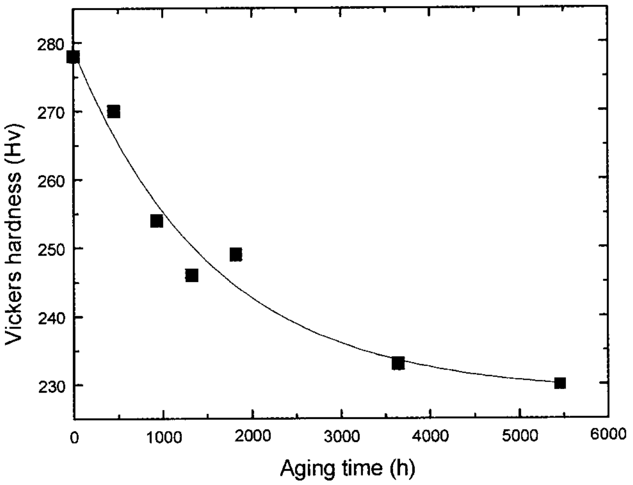

Fig. 4. Dependency of Vickers hardness on aging time at 630 °C.

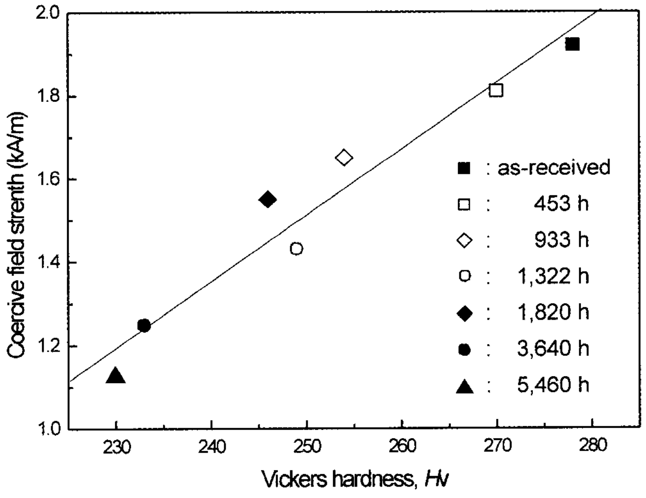

Fig. 5. Relationship between the coercive field strength and Vickers hardness for aging time at 630 °C.

Table 2. Vickers hardness calculated from 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
H_v calculated from H_c	276	269	259	253	245	234	226
H_v measured	278	270	254	246	249	233	230

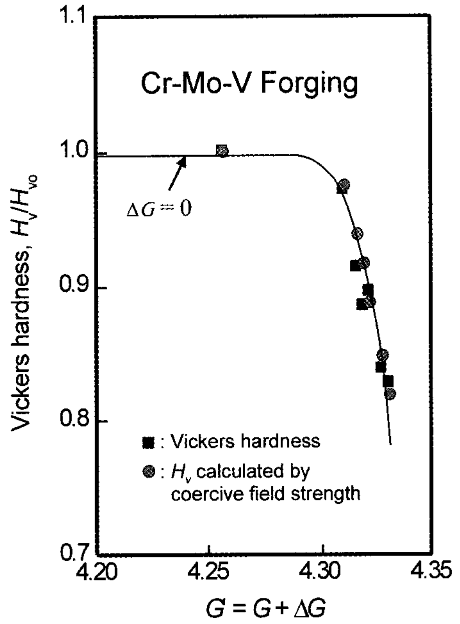

Fig. 6. Comparison of G' parameter calculated by Vickers hardness and coercive field strength. H_{vo} is the Vickers hardness of the as-received sample.

is caused by decreased of pinning of the domain walls, easier wall motion due to decreased density of point defects, and lower 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 parameters such as the G parameter which is the logarithm of the Larson-Miller parameter [8, 9].

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

$$H_c=(1.57\times10^{-2})\times H_v-2.42 \tag{5}$$

The Vickers hardness can then be calculated from the measured coercive field strength. The results are given in Table 2.

Fig. 6 shows the dependence of the relative hardness on the G' parameter, which is a time, temperature, and stress variable. The G' parameter is defined by

$$G'=G+\Delta G \quad \text{kA/m} \tag{6}$$

The value of ΔG is $0.000194(\sigma-103)$ when σ is 103 MPa or more, and 0 when σ is below 103 Mpa. We can obtain the softening curve using the Vickers hardness calculated from the measured coercive field strength. We can estimate the residual life of turbine rotor steel from this softening curve.

Conclusions

The coercive field strength measured by the interval between reversible permeability peaks decreases as the aging time increases, and it is proportional to mechanical hardness of 1Cr-1Mo-0.25V steel. The Vickers hardness is calculated from the coercive field strength using a linear experimental relation, and the ratio of calculated hardness vs. the G' parameter is plotted. Using the plotted softening curve, we can estimate residual life of turbine rotors, nondestructively.

References

[1] Y. Watanabe and T. Shoji, Metallurgical Transactions, **22A**, 2097 (1991).

[2] K. M. Yu, S. H. Nahm, and Y. I. Kim, JMSL, **18**, 1175 (1999).

[3] K. S. Ryu, S. H. Nahm, Y. B. Kim, K. M. Yu, and D. Son, Intermag 99, DP-26, Kyongju, Korea.

[4] A. M. Abdel-Latif, J. M. Corbert, and D. M. R. Taplin, Metal Science, **16**, 90 (1982).

[5] Garcia-Arribas, J. M. Barandiaran, and G. Herzer, J. Appl. Phys., **71**, 3047 (1992).

[6] H. Negishi, H. Takahashi, and M. Inoue, J. Magn. Magn. Mater., **68**, 271 (1987).

[7] K. S. Ryu, J. S. Park, C. G. Kim, and D. Son, Intermag 2000, BS-09, Toronto, Canada.

[8] T. Goto, J. Soc. Mater. Sci. Japan, **32**, 103 (1983).

[9] R. Viswanathan, *Damage Mechanism and Life Assessment of High-Temperature Components*, ASM International (1972), pp. 289-292.