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Evaluation of case depth in induction-hardened steels: Magnetic hysteresis measurements and hardness-depth profiling by differential permeability analysis

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We have studied case depth of induction-hardened steel rods using magnetic hysteresis technique. A step-like behavior of magnetization curve, a decrease of maximum flux density, and an increase of coercivity with case depth, typical for surface-hardened steels, were observed, reflecting a mixture of magnetically hard hardened layer and soft core. Differential permeability exhibited a double peak structure with high- and low-field peaks due to hardened layer and core, respectively. Analysis for the area and position of the permeability peaks, based on a simple model, demonstrated that the volume fraction of hardened layer can be quantitatively and directly inferred from the permeability data alone. Although this method is generally restricted to the case in which a double peak structure in differential permeability is observed, this analysis method can be a possible technique to non-destructively construct depth profile of Vickers hardness from magnetic measurements.

1. Introduction

Surface-hardened steels are widely used for many industrial components, such as gears, cam, and shafts of engine parts, cutting tools, etc., in which high wear resistance at the surface is required with keeping high toughness in the core [1]. Hardened surface layers can be formed by various treatments including induction hardening, carburization, nitriding, shot peening, and the depth of the hardened layers ranges from sub-millimeter to a few tens of millimeters. Evaluation of the case depth is important for controlling and maintaining quality of the components and a micro-hardness test has been commonly carried out to check the depth profile. However, the test is destructive and time-consuming. Therefore, it is not suitable for large and expensive components where the destructive tests should be avoided and also for on-line inspection which requires a short measurement time.

Various non-destructive evaluation techniques have been examined so far as an alternative method; alternating current potential drop [2], laser acoustic wave [3], ultrasonic back-scattering [4], eddy currents [5], photothermal radiometric radiometry [6], magnetic Barkhausen emission (MBE) [7,8], magnetic hysteresis [9–11], so on. Each technique gives indications of a good correlation between a measured physical parameter and hardness. By measuring many samples with different case depth, the calibration curve which relates the physical parameter with case depth is constructed and a case depth of unknown hardened steels may be inferred empirically using the curve.

In this paper, we report results of magnetic hysteresis measurements on the two types of steels, whose surfaces were induction hardened with effective case depth up to ~4 mm. Magnetic hysteresis technique utilizes the magnetoelastic interaction between Bloch wall and lattice defects and its parameters are known to be very sensitive to microstructural change due to such as deformation, precipitation, heat treatment [12]. In addition, the technique does not require a complicated measurement setup and is fast and easy to be applied for on-site inspection. Previous studies using magnetic hysteresis [9–11] revealed a correlation between hysteresis parameters and case depth. While saturation magnetic flux density and maximum permeability decrease with increasing case depth, coercivity and hysteresis loss increase. Besides these hysteresis parameters, we here focus on a profile of differential permeability obtained during magnetization process. By analyzing permeability peaks due to hardened layer and core region and by assuming a simple model, the volume fraction of hardened layer, and therefore case depth are found to be directly inferred without a calibration curve. The advantage and the limitation of this method will be discussed in detail.

2. Experiment

Two types of steels were used for the present investigation; SCM435 chromium–molybdenum and S45C carbon steels. The chemical compositions are listed in Table 1. The steel rods with

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dimensions of $\phi 10 \times 150\ \text{mm}^2$ were surface hardened by high-frequency induction heating under constant electrical power condition for induction coil. Case depth was controlled by varying traveling speed of the rod through the coil from 8 to 23 mm/s. Immediately after induction heating, the rod was water quenched for three seconds. We prepared samples with different effective case depth d_{eff} up to 4 mm; d_{eff} was defined as a depth from the surface in which Vickers hardness becomes 400 and 450 HV for SCM435 and S45C steels, respectively, based on the carbon content (JISG0559 standard). The prepared samples and their d_{eff} are listed in Table 2.

Before magnetic hysteresis measurements, case depth of each sample was characterized by measuring depth profile of Vickers hardness, microstructure, and magnetic properties. Disk samples with dimensions of $\phi 10 \times 3\ \text{mm}^2$, cut from the rods with electric discharge machine, were used. Vickers hardness was measured with load of 1 kg for 15 s on sample cross-sectional plane at 0.1–0.5 mm interval from hardened surface to core. The tests were carried out for four different directions on the plane. The disks were then chemically etched by 5% nital and their microstructure was examined with optical microscopy. Depth profile of magnetic properties was examined using a superconducting quantum interference device (SQUID) magnetometer (Quantum Design MPMS-XL), for small bars ($\sim 0.2 \times 0.2 \times 3\ \text{mm}^2$), taken at different depth positions of disk samples. Saturation magnetization and coercivity were determined from dc magnetization curve under applied fields up to 640 kA/m.

Magnetic hysteresis measurements were performed for rod samples ($\phi 10 \times 100\ \text{mm}^2$) using a fluxmeter. The setup of measurement system is shown in Fig. 1. A magnetic Fe–Si yoke with 1000-turn exciting coil was attached to rod sample to form a magnetically closed circuit. To eliminate a gap between them, magnetic spacers of annealed iron were intervened. A triangular current with a frequency of 0.05 Hz was applied to the exciting coil to generate a cyclic magnetic field and magnetize the sample. The magnetic field within the sample, H, was obtained from the voltage across a 1-Ω resistance connected to the exciting coil in series. The induced voltage due to magnetization was measured by a 175-turn pick-up coil wound around the rod. A magnetic flux density within the sample, B, was obtained by integrating the induced voltage. B–H loops were measured under applied fields up to a maximum field of 25 kA/m. For each rod sample, the measurements were repeated five times and the data were averaged.

Table 1
Chemical compositions of as-received SCM435 and S45C steels (wt.%).

	C	Mn	Cr	Mo	Si	Fe
SCM435	0.33–0.38	0.60–0.85	0.90–1.20	0.15–0.30	–	Balance
S45C	0.42–0.48	0.60–0.90	–	–	0.15–0.35	Balance

3. Characterization of hardened steels

Fig. 2(a) and (d) shows a depth profile of Vickers hardness for SCM435 and S45C with different d_{eff}, respectively. For all hardened steels, Vickers hardness exhibits a high value around the surface and then decreases with depth from the surface, indicating the formation of a hardened layer. For steels with a higher d_{eff}, the value at the core did not reach that of as-received sample and the core region was also slightly hardened. To characterize the hardened layer in more detail, the depth profile was least-squares fitted to a theoretical curve [11], given by

$$HV(r) = \frac{HV_1 - HV_c}{2}\,erfc\left(\frac{r - d_t}{w}\right) + HV_c. \qquad (1)$$

Here, $erfc$ is a complementary error function, HV_1 and HV_c are Vickers hardness at a hardened layer and core, respectively, d_t is a theoretical case depth, w is a width of transition region, and r is a depth from the surface. The results of least-squares fits are listed in Table 2. Hereafter, we will use d_t instead of d_{eff}.

Hardened layers have martensitic microstructure for both SCM435 and S45C steels, while the core is predominantly ferrite associated with fine cementite for SCM435 and a mixture of ferrite and perlite phase for S45C steel. In the transition region, microstructure is a mixture of hardened and core structures. In the case of SC-3 and SC-4 samples, the microstructure in the sample center (~5 mm from the surface) is not simple mixture of ferrite and perlite phase, but a structure similar to that of the transition region of the SC-2 sample, whereas that around the surface is martensitic microstructure.

Fig. 2(b), (c) and (e), (f) shows the depth profile of magnetic properties for SCM435 and S45C steels with different d_t, respectively. Although a systematic trend with depth was not confirmed

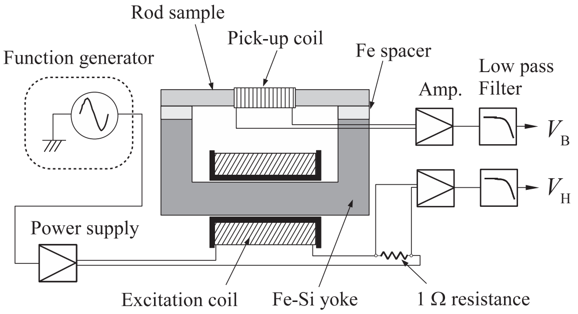

Fig. 1. Setup of magnetic measurement system.

Table 2
Prepared samples and the results of least-squares fits. d_t, HV_1, and HV_c are parameters obtained from the depth profile of Vickers hardness and V_{ratio}, d_{cal}, $HV_{\text{cal}}^{\text{layer}}$, and $HV_{\text{cal}}^{\text{core}}$ are those obtained from differential permeability data.

	Sample	d_{eff} (mm)	d_t (mm)	HV_1 (HV)	HV_c (HV)	V_{ratio}	d_{cal} (mm)	$HV_{\text{cal}}^{\text{layer}}$ (HV)	$HV_{\text{cal}}^{\text{core}}$ (HV)
SCM435	SCM-0	0	0		233 ± 1	0	0	–	233
	SCM-1	0.14	0.40	400 ± 7	238 ± 1	0.12	0.27	645	202
	SCM-2	1.37	1.45	536 ± 5	228 ± 2	1.10	1.55	595	239
	SCM-3	2.12	2.06	561 ± 2	258 ± 1	3.32	2.59	596	278
S45C	SC-0		0		267 ± 1	0	0	–	267
	SC-1	0.58	0.55	710 ± 11	285 ± 4	0.24	0.51	894	241
	SC-2	0.99	0.93	735 ± 4	268 ± 2	0.45	0.84	841	226
	SC-3	3.36	2.59	726 ± 7	388 ± 7	24.9	4.02	732	267
	SC-4	3.94	2.82	712 ± 10	434 ± 8	–	–	729	–