# A Permanent Magnet Device for Measuring the Coercive Force

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**Abstract**

An attached magnetic device comprising two permanent magnets for magnetizing and demagnetizing is considered. The angular displacement of one magnet, with the other being set at a preset angle, is the test parameter proportional to the coercive force of the articles.

**Keywords:** Coercive force, Permanent magnets, Testing, Metal structures

The nondestructive testing of the physico-mechanical properties of steel articles by coercive force is currently applied to estimate the in-service damage of operating fabricated metals and to predict their service life. Coercimeters comprising attached electromagnets test the demagnetizing current measured when the magnetic flux passes through zero in some portion of an “electromagnet-article” magnetic circuit[1,2]. The need for lower power consumption and instrument weight when operating under field, high-altitude and flammable conditions has prompted the development of a coercimeter with two permanent magnets to magnetize and demagnetize articles. In this case, the rotation angle of one of the magnets is the test parameter[3, 4].

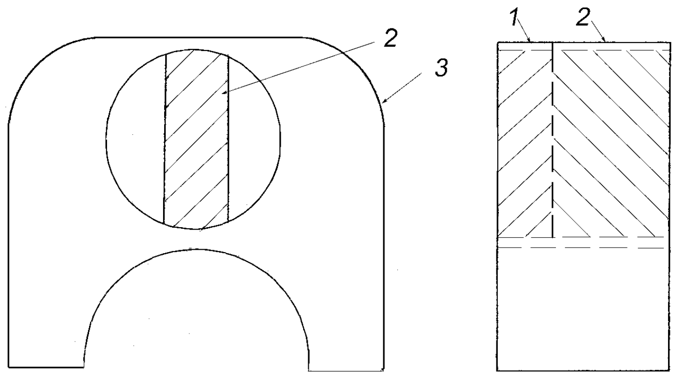


Fig.1. The magnetic circuit of the coercimeter: magnets (*1, 2*) and yoke (*3*).

Figure 1 shows the magnetic circuit of a coercimeter comprising a yoke with a laminated magnet placed in its cylindrical aperture, the magnet being made of the Nd-Fe-B alloy and divided into two parts.

The magnetomotive force $M$ of the magnet required to magnetize the article and then demagnetize it along the hysteresis loop close to major can be defined by eqn (1) obtained according to the analytical circuit (fig. 2) as

$$M = U_a\left\{b\left(1+\frac{r_\delta}{r_a}\right)+\frac{ar_y+r_m}{r_a}\right\}+c\Phi_{ra}-d\,, \qquad (1)$$

where $a = 1 + \frac{r_m}{r_{F_2}}$; $b = a(1 + \frac{r_y}{r_{F_1}}) + \frac{r_m}{r_{F_1}}$; $c = br_\delta + ar_y + r_m$; $d = a\Phi_{ry}\Phi_y$;

$\Phi = \Phi_{ra} + \frac{U_a}{r_a}$; $\Phi_y = \Phi_{ry} + \frac{U_y}{r_y}$.

Here, $\Phi_a$ , $U_a$ and $\Phi_y$, $U_y$ are the flux and potential drop in the article and the yoke, respectively; $r_a$ and $r_y$ are the magnetic resistances of the article and the yoke; $r_m$ is the total resistance of the magnet and the yoke portion magnetized by the magnet leakage flux; $r_{F_1}$ and $r_{F_2}$ are resistances to the leakage fluxes $F_1$ and $F_2$ shunting, respectively, the article and the magnet; $r_\delta$ is gap reluctance between the yoke and the article; $\Phi_a$ , $\Phi_y$ , $\Phi_m$ are the article, yoke and magnet fluxes, respectively.

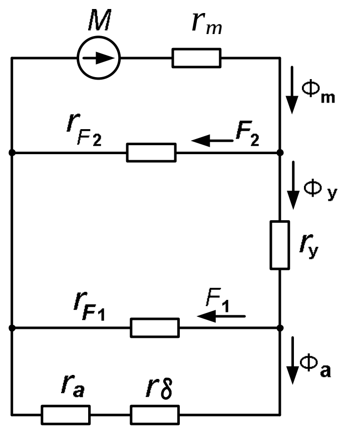


Fig.2. Analytical circuit: magnetization.

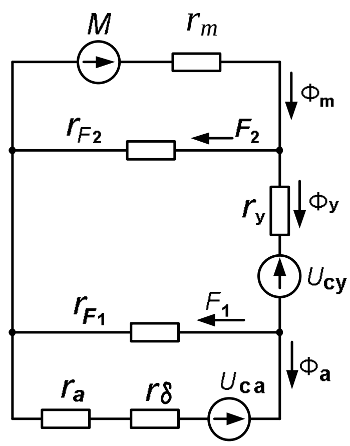


Fig.3. Analytical circuit: demagnetization.

During demagnetization, the flux is changed in the article by the rotation of the magnet from its initial position corresponding to the magnetization mode and angle α=0. The article is demagnetized along the descending branch of the hysteresis loop, and, when α=90°, it passes the area of residual magnetization. When the magnet is rotated by 180°, the article becomes magnetized oppositely [5]. The value of the magnetomotive force $M_{dc}$ corresponding to the coercive force $H_c$ of the article can be found from the expression

$$M_{dc} = \frac{r_m}{R_1}\left[(1 + \frac{R_1 + r_y}{r_{F_1}})U_{ca} + U_{cy}\right], \qquad R_1 = \frac{r_m r_{F_2}}{r_m + r_{F_2}} \qquad (2)$$

obtained from the analytical circuit shown in fig. 3 when $\Phi_a = 0$. The magnetic potential drops on the article and the yoke ($U_{ca}$ and $U_{cy}$, respectively) correspond to the magnetic fields equal to their coercive forces. The magnetomotive force $M_d$ can be assumed to vary according to the cosine law $M_d = M\cos\alpha$ as the magnet rotates. In this case, when the flux $\Phi_a$ in the article passes through zero, angle $\alpha_0$ is the test parameter for articles inspected with respect to the coercive force. Note that it is not only the mmf $M_d$ that varies as the magnet rotates, but also the resistances $r_m$ and $r_{F_2}$ .

An experiment was performed with plates imitating articles 3.5 × 39 mm$^2$ in the cross section. Figure 4 shows the induction in the central section of the article as dependent on the magnet rotation angle $\alpha_0$ for three plates with $H_c$ : 0.5 A/cm (cold-rolled transformer steel); 8.7 A/cm (steel ShKh15, with C ~ 1.5 % and Cr ~ 1 %, as delivered); 41.6 A/cm (steel

ShKh15 hardened from 850°). Angle $\alpha_0$ corresponding to zero induction is seen to vary between 98° and 120°, i. e., the range of variations in $\alpha_0$ is $\Delta\alpha_0$ = 22°.

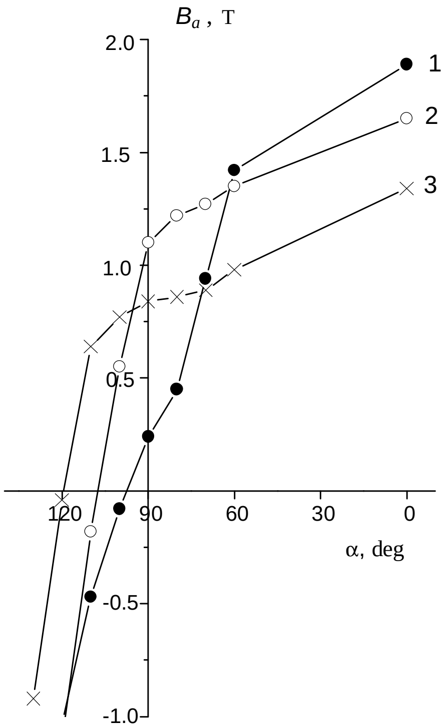


Fig.4. Induction $B_a$ as a function of the rotation angle $\alpha$ of combined magnets *1 и 2* (see Fig. 1). For three plates: $H_c \cong 0.5$ A/cm (1), 8.7A/cm (2), 41.6 A/cm (3).

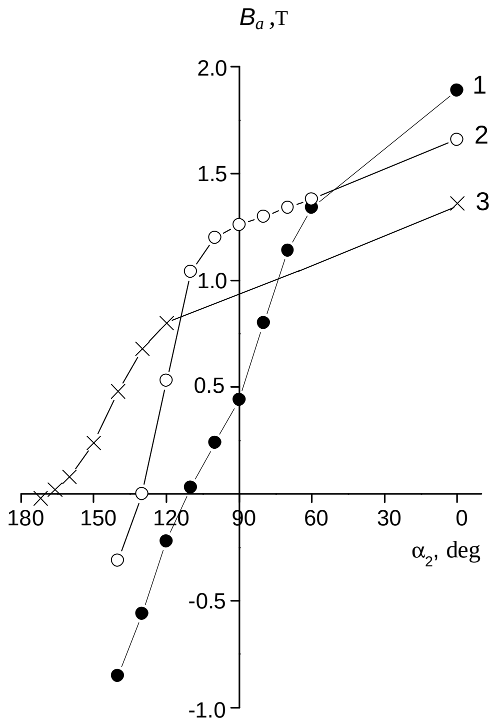


Fig.5. Induction $B_a$ as a function of the angle of rotation of the second magnet ($\alpha_2$) at fixed angle $\alpha_1$=60° of the first magnet. 1, 2 and 3 are the same as in fig. 4.

To increase the sensitivity of the test procedure, the magnet was divided into two parts. After the both magnets had been zeroed, one of them (No.1) was rotated by the angle $\alpha_1$ < 90°. The article is further demagnetized by the other magnet. In this case, $M_d = M_2\cos\alpha_2 - M_1\cos\alpha_1$ . Figure 5 shows the descending branches of the hysteresis loops for the same plates as in fig. 4. The range of variations $\Delta\alpha_{20}$ is seen to exceed $\Delta\alpha_0$ by a factor of 2.6. To increase the technological effectiveness of testing, angles $\alpha_0$ and $\alpha_{20}$ were further measured at zero voltage at the output of a Hall device mounted in the nonferromagnetic gap between the yoke pole and the article. For two plates with $H_c$ = 8.7 and 41.6 A/cm $\alpha_{20}$ was measured at $\alpha_1$=*const* in the range between 0° and 90°. The measurement results, as well as the values of $\alpha_0$ for $H_c$ = 8.7 and 41.6 A/cm, are shown in fig. 6. As is seen, $\Delta\alpha_{20}$ exceeds $\Delta\alpha_0$ by a factor of 2.6 when $\alpha_1$= 60°, and this was found when the flux $\Phi_a$ was measured in the central section of the article in the absence of a gap between the article and the coercimeter yoke.

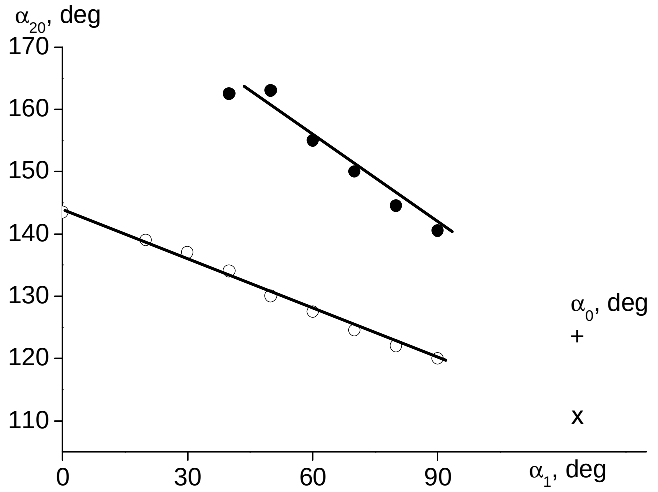


Fig.6. The dependences $\alpha_{20}$ ($\alpha_1$) for $H_c$ = 8.7 A/cm (○); 41.6 A/cm (●).
The values of $\alpha_0$ for $H_c$ = 8.7 A/cm (×) and 41.6 A/cm (+).

In conclusion, fig. 7 shows the dependence of $\alpha_{20}$ at $\alpha_1$= 60° for ten plates with the coercive force ranging between 1.4 and 48 A/cm; for comparison, the values of $\alpha_0$ are given for two plates with $H_c$ = 8.7 and 41.6 A/cm. Thus, for the coercive force ranging between 5 and 50 A/cm, the sensitivity of the test method is about 1 A/cm per one degree of the $\alpha_2$ scale.

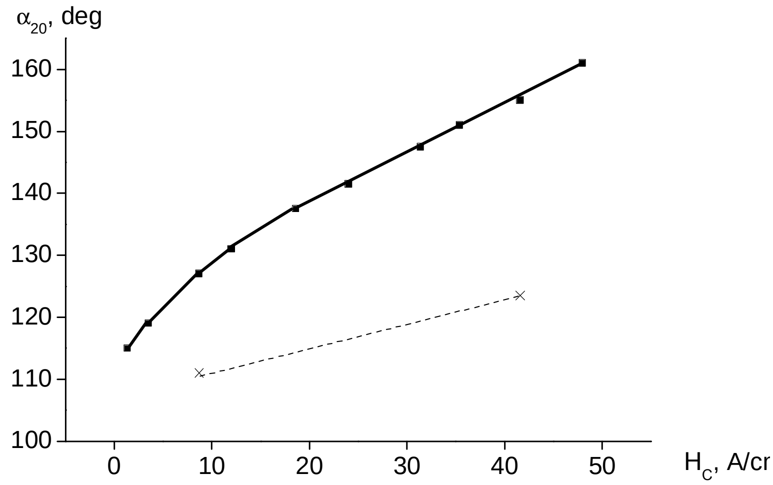


Fig.7. The $H_c$-dependences of rotation angles $\alpha_{20}$ (■) of the second magnet at $\alpha_1$ = 60° and of angles $\alpha_0$ (×) at simultaneous rotation of two magnets.

We have demonstrated the advantage of using two independently rotated magnets and testing by the rotation angle of one of them, the other being set at a fixed angle, less than 90°. Expressions have been obtained that enable the values of the magnetomotive forces of the magnets required for magnetizing and demagnetizing an article, $M$ and $M_{dc}$, respectively, to be evaluated. Small and light, the coercimeter is intended for prompt testing when power supply is hindered or limited by safety requirements.

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