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ANALYTIC METHOD FOR DETERMINING THE COERCIVE FORCE OF FERROMAGNETIC MATERIALS

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Abstract. An analytical method is proposed for determining the coercive force for some magnetically soft materials. The comparison of experimental and calculated values of the coercive force depending on B_m for different steel grades shows that offered here analytic method is in good accordance with the experimental result. For a hysteresis case, the binding force was found experimentally with the most accurate calculations, and the conductance value is determined. Using the limiting hysteresis circuit, the values of Bs (maximum induction of the limiting hysteresis loop) are also found.

Keywords: *magnetic methods, coercive force, hysteresis curves, ferromagnetic materials.*

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1. Introduction

The synthesis of materials with new functions and the study of their physicochemical properties are among the main areas of research in materials science, electronics, and spintronics. A special place among these materials is occupied by semiconductors, ferroelectrics and ferromagnets. Therefore, their structure and physical properties are widely studied (Bayramova *et al.*, 2022; Hossain *et al.*, 2021; Vishwanathan, 2021; Ordin, 2018; Mursakulov *et al.*, 2022).

Recently, the study of physical properties of ferromagnetic alloys is considered the most promising field in the physics of metals. The distinguishing features of soft magnetic materials include maximum magnetic penetration, low temperature dependence of the material's electrical resistance, small coercive force, small magnetic anisotropy constant, and near-zero magnetostriction. Thus, all of this makes it possible to study and calculate various physical effects and parameters. As we know, magnetic methods are widely used to study the structure and mechanical properties of ferromagnetic alloys. Coercive force (Hc) determination is one of the most important methods of magnetic structure analysis

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(Sandomirskii, 2011; Gobov *et al*., 2017; Bida & Nichipuruk, 2000; Sandomirskii *et al*., 1996). Since the permeability increases as the coercive force decreases, this force is mainly used to determine the magnetic quality of the components. Vibrating Sample Magnetometer (VSM) is used to measure saturation magnetization of hysteresis curves of magnetic materials (Sandomirskii, 2006; Pesch, 1983; Foner, 1959; Cullity, 1972). In this regard, the coercive force of soft magnetic materials was also measured using VSM, and the values obtained from these measurements were in full agreement with the hysteresis graph measurements performed on toroids. In general, the study of magnetic properties has an important role in the study of magnetic materials (Ismayilova & Asadullayeva, 2022; Asadullayeva *et al*., 2022). In the paper an analytical method is introduced for determining the coercive force of ferromagnetic materials.

2. Methods

Before determining the magnetic parameters, the samples were subjected to demagnetization. The demagnetization was carried out by a switched constant field with an amplitude decreasing practically to zero. The initial amplitude of the demagnetizing field was chosen on the basis of a 50-fold excess of the coercive force of the material. The minimum field at which the current circuit was broken was no more than 0.03 A/m. The demagnetization time lasted about 1.5-2 minutes. A ballistic galvanometer of the M 197 type was used as a flux meter. To determine the magnetic induction and magnetic field strength on the test samples with a PETV wire (0.49-0.51 mm in diameter), magnetizing and measuring windings are found to determine the magnetic induction and magnetic field strength by the ballistic method.

3. Results and discussion

The study of hysteresis phenomena in ferromagnetic materials allows us to put forward the assumption that there is a dependence between the base of the magnetization curve and the hysteresis curves of the same ferromagnetic material. Based on this assumption, analytical expressions are obtained that describe any outgoing (or ascending) branch of the family of hysteresis loops in the B_m function. These formulas do not yet meet the desired requirements, but careful studies have shown that they can be used with sufficient accuracy, in particular, to determine the coercive force of some magnetically soft materials.

The formula has the following form:

$$H_c = \frac{B_k B_m}{B_k + B_m} \frac{1}{\mu_H \left[7 \pm (1 - \frac{B_m}{B_s})^2\right]} , \quad (1)$$

where B_k is the induction corresponding to the point of contact of the main magnetization curve with line emanating from the beginning of coordinate; B_m is the maximum induction of a given hysteresis cycle; μ_H is the initial magnetic permeability: is found from the experimental curve ($\mu_H = \frac{dB}{dH}|_{H=0}$); B_s is the maximum induction of the limiting hysteresis loop; H_c is the coercive force (Fig.1).

The plus sign in the formula is taken at $B_s/B_k > 2$, minus at $B_s/B_k \leq 2$. Using the data of the experimentally taken magnetization curve, first we build a curve of internal permeability, then, by extrapolating this curve, we determine the saturation induction, which can be used instead of B_s for practical calculations. With the most accurate calculations for one hysteresis cycle, the coercive force is experimentally found using the above formula, the permeability value is specified: it is known that the exact determination of the derivative of the experimental curve is associated with certain difficulties. It is desirable to use the limiting hysteresis loop in this case, then at the same time it is possible to find the values of B_s.

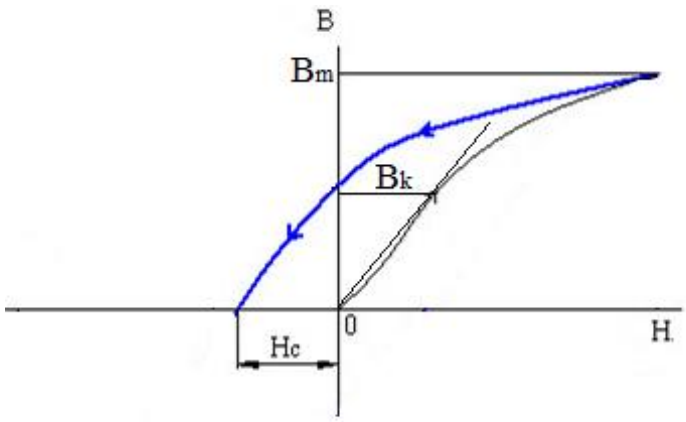

Fig. 1. Hysteresis loop, B_m is the maximum induction of a given hysteresis cycle, B_k - is the induction corresponding to the point of contact of the main magnetization curve with line emanating from the beginning of coordinate, H_c is the coercive force

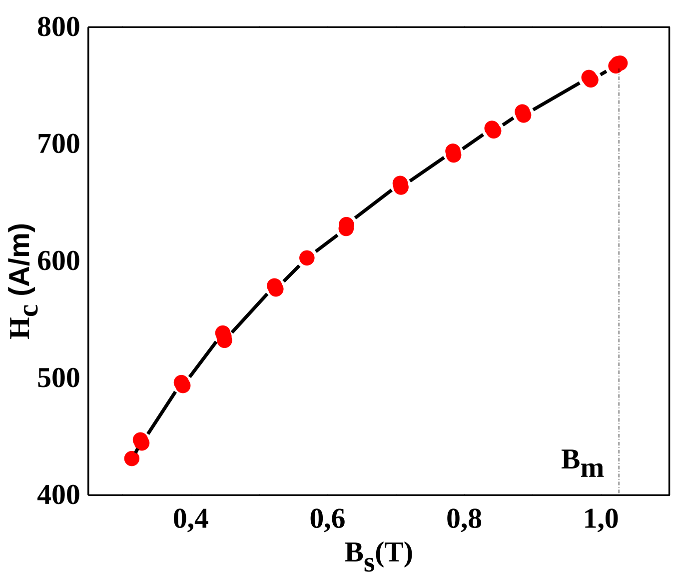

Fig. 2. Graphically comparison for the experimental and, accordingly, calculated values of the coercive force depending on B_m for one of the steel grades

To confirm the reliability of the formula obtained, experiments were performed on cylindrical steel samples having different sizes. Fig. 2 shows this comparison graphically for the one of the of steel grade. Further development of work in this direction may lead to the determination of other parameters or a complete analytical description of the magnetic characteristics during cyclic demagnetization.

The table 1 shows the experimental and, accordingly, calculated values of the coercive force depending on B_m for different steel grades.

Table 1. Calculated values of the coercive force depending on B_m for different steel grades with experimental results

St. 40Kh			St. 5			St.6			St.40		
B_m, T	H_c Cal.	H_c Exp.	B_m, T	H_c Cal.	H_c Exp.	B_m, T	H_c Cal.	H_c Exp.	B_m, T	H_c Cal.	H_c Exp.
1.078	743.789	743.550	1.532	324.124	323.965	1.312	290.366	290.207	1.08	777.94	777.78
0.957	712.420	714.570	1.340	312.022	303.742	1.039	266.003	266.719	0.93	740.36	731.28
0.765	656.050	667.038	1.093	290.525	283.519	0.773	231.528	213.375	0.60	632.0	644.82
0.696	632.006	627.468	0.750	246.656	236.226	0.625	206.210	187.369	0.168	308.28	351.03
0.609	598.089	596.656	0.518	203.343	189.012	0.351	143.312	-	-	-	-
0.493	543.471	543.869	0.375	167.515	155.254	-	-	-	-	-	-
0.342	448.487	448.805	-	-	-	-	-	-	-	-	-
μ_H=0.747*10^{-4} H/m			μ_H=1.3499*10^{-4} H/m			μ_H=1.6866*10^{-4} H/m			μ_H=0.6929*10^{-4} H/m		
B_s=1.0788 T			B_s=1.5322 T			B_s=1.3125 T			B_s=1.0800 T		
B_k=0.6090 T			B_k=0.3828 T			B_k=0.4640 T			B_k=0.5800 T		

4. Conclusions

Using the data of the experimentally obtained magnetization curve, the internal permeability curve was first constructed. Then by extrapolating this curve, the saturation inductance is determined, which can be used instead of B_s for practical calculations. The coercive force was found experimentally using the above formula with the most accurate calculations for one hysteresis period, the conductivity value was determined: it is known that the exact determination of the derivative of the experimental curve is associated with certain difficulties. In this case, it was possible to find the values of B_s at the same time by using the limiting hysteresis circuit.

From analytic method was calculated values of the coercive force depending on B_m for different steel grades. The correctness of our results is confirmed by comparisons with experiments carried out on steel cylindrical samples of different sizes. Further development of work in this direction may lead to the determination of other parameters or a complete analytical description of the magnetic characteristics during cyclic demagnetization.

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