Hysteresis Properties of the Soft Magnetic Nanocrystalline Alloy

Tsepelev V. S.
Boris Yeltsin Ural Federal University, Ural Technical Institute of Communication and Informatics Yekaterinburg,
Email: Russia v.s.tsepelev@urfu.ru

Starodubtsev Yu. N.
Boris Yeltsin Ural Federal University, Gammamet Research and Production Enterprise, Yekaterinburg, Russia
Email: yunstar@mail.ru

***Abstract*—The scaling law of minor loops was studied on an soft magnetic nanocrystalline alloy $Fe_{72.5}Cu_1Nb_2Mo_{1.5}Si_{14}B_9$. An analytical expression for the coercive force in the Rayleigh region was derived. The coercive force is connected with the maximal magnetic field H_{max} via the reversibility coefficient $\mu_i/\eta H_{max}$. Reversibility coefficient shows the relationship between reversible and irreversible magnetization processes. A universal dependence of magnetic losses for hysteresis W_h on the remanence B_r with a power factor of 1.35 is confirmed for a wide range of magnetic fields strengths.**

***Index Terms*—soft magnetic nanocrystalline alloy, minor hysteresis loop, Rayleigh law, remanence, coercive force.**

I. INTRODUCTION

Regularities of changes of minor magnetic hysteresis loops depending on the amplitude of magnetic field or frequency can provide useful information on the magnetization processes in a magnetic material. Therefore, the scaling law of minor loops is intensively applied for the investigation of different magnetic materials [1–7].

In the work, the interrelation of parameters of minor magnetic hysteresis loops (W_h is the area of static hysteresis loop, i.e., magnetic losses for hysteresis, B_r is the remanence, H_c is the coercivity, B_{max} is the maximal induction, and H_{max} is the maximal magnetic field) was investigated on the soft magnetic nanocrystalline alloy $Fe_{72.5}Cu_1Nb_2Mo_{1.5}Si_{14}B_9$ [8] in a wide range of magnetic fields. Regions that present the logarithmic-scaled dependences of the parameters were distinguished; they correspond to the power function of the form

$$Y = rX^s \tag{1}$$

Such a representation was for the first time used by Steinmetz for the dependence of magnetic losses for hysteresis on maximal induction [9]. Numerical changes in the power factor s in formula (1) are controlled by different types of the magnetization reversal process [1, 2, and 10].

II. EXPERIMENT

The alloy $Fe_{72.5}Cu_1Nb_2Mo_{1.5}Si_{14}B_9$ was melt in a vacuum induction furnace. A 25 μm thick and 10 mm wide ribbon with amorphous structure was produced by the planar flow casting process. The ribbon was wound up onto ring-type cores with the 32 mm outer diameter and 20 mm inner diameter. The cores were subjected to optimum annealing at a temperature of 820 K for 1 h. Parameters of the DC hysteresis loop were determined by means of the point-by-point DC testing on the measuring and computing system MMKC-100-05 in the range of maximal magnetic induction B_{max} from 0.003 T to magnetic saturation [11]. Before measuring each minor loop, the sample was demagnetized by a decaying alternating magnetic field.

III. RESULTS AND DISCUSSION

In Fig. 1, the static minor loops of magnetic hysteresis are shown from which it is seen that the loop shape regularly changes from lens-like in the range of weak fields to elongated along the magnetic induction axis in the range of medium fields (in the range of maximal permeability). The measured parameters of minor loops are given in Table I. The results of measurements are placed in columns: B_{max} is the maximal induction, H_{max} is the maximal magnetic field, B_r is the remanence, H_c is the coercive force, W_h is the area of the static hysteresis loop (magnetic losses for hysteresis). The calculated parameters of minor loops are given in Table II.

In a weak magnetic field, the permeability

$$\mu = \frac{B}{\mu_0 H} \tag{2}$$

changes insignificantly and therefore, can be expand in a Maclaurin series in the vicinity of $H = 0$. With only two first terms, we obtain

$$\mu = \mu(0) + \left(\frac{\partial \mu}{\partial H}\right)_{H=0} H \tag{3}$$

Manuscript received May 3, 2018; revised January 5, 2019.

doi: 10.18178/ijmerr.8.2.173-176

Equation (3) is the Rayleigh law of magnetization expressed in the form [12]

$$\mu = \mu_i + \frac{1}{2}\eta H . \tag{4}$$

The first term in formula (4) represents the initial permeability μ_i, which is related to the contribution of reversible magnetization processes, and η is the Rayleigh constant related to irreversible magnetization processes.

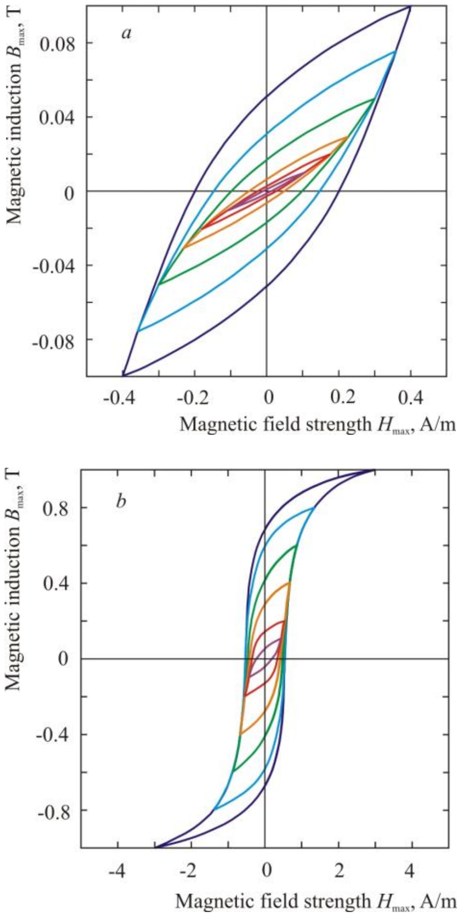

Figure 1. Minor hysteresis loops for different maximal magnetic induction Bmax (a, b).

Using the Rayleigh law, one can write out equations for the ascending and descending branches of magnetic hysteresis in the form

$$B = \left(\mu_i + \eta H_{\max}\right)\mu_0 H - \frac{1}{2}\eta\mu_0\left(H_{\max}^2 - H^2\right), \tag{5}$$

$$B = \left(\mu_i + \eta H_{\max}\right)\mu_0 H + \frac{1}{2}\eta\mu_0\left(H_{\max}^2 - H^2\right). \tag{6}$$

After substitution of $H = H_{\max}$ into (5) obtain

$$B_{\max} = \mu_i \mu_0 H_{\max} + \eta\mu_0 H_{\max}^2 . \tag{7}$$

In equations (5) and (6) with $H = 0$ the remanence is

$$B_r = \frac{1}{2}\eta\mu_0 H_{\max}^2 , \tag{8}$$

and specifying $B = 0$, we determine the coercive force

$$\frac{H_c}{H_{\max}} = -\left(\frac{\mu_i}{\eta H_{\max}} + 1\right) + \sqrt{\left(\frac{\mu_i}{\eta H_{\max}} + 1\right)^2 + 1} \cdot \tag{9}$$

The dimensionless value $\mu_i/\eta H_{\max}$ characterizes the interrelation of reversible and irreversible magnetization processes and, therefore it can be called reversibility coefficient. The area of the magnetic hysteresis loop is determined as

$$W_h = \frac{4\eta\mu_0 H_{\max}^3}{3} = \frac{8}{3} B_r H_{\max} . \tag{10}$$

TABLE I. MEASURED PARAMETERS OF MINOR HYSTERESIS LOOPS OF THE NANOCRYSTALLINE ALLOY FE72.5CU1NB2MO1.5SI14B9

$B_{\max}$, T	$H_{\max}$, A/m	B_r, T	H_c, A/m	W_h, J/m^3	μ
0.003	0.033	$1.3 \cdot 10^{-4}$	0.0010	$1.02 \cdot 10^{-5}$	72000
0.005	0.054	$3.2 \cdot 10^{-4}$	0.0024	$3.60 \cdot 10^{-5}$	74000
0.0075	0.075	$6.0 \cdot 10^{-4}$	0.0045	$9.0 \cdot 10^{-5}$	80000
0.01	0.094	0.0010	0.0070	$2.18 \cdot 10^{-4}$	84000
0.02	0.176	0.0035	0.022	0.00112	90000
0.03	0.22	0.0075	0.050	0.0037	109000
0.05	0.29	0.018	0.10	0.0117	137000
0.075	0.36	0.035	0.14	0.029	166000
0.1	0.40	0.060	0.20	0.055	199000
0.2	0.48	0.126	0.30	0.170	332000
0.4	0.70	0.30	0.40	0.49	455000
0.6	0.88	0.45	0.47	0.86	543000
0.8	1.33	0.59	0.49	1.30	479000
1.0	3.0	0.68	0.52	1.85	265000

TABLE II. CALCULATED PARAMETERS OF MINOR HYSTERESIS LOOPS OF THE NANOCRYSTALLINE ALLOY $FE_{72.5}CU_1NB_2MO_{1.5}SI_{14}B_9$

$B_{\max}$, T	$B_r/B_{\max}$	$\frac{W_h}{B_r \cdot H_{\max}}$	$\frac{W_h}{B_r \cdot H_c}$	$\eta \cdot 10^{-6}$, (A/m)$^{-1}$	$\frac{\mu_i}{\eta \cdot H_{\max}}$
0.003	0.04	2.4	79	0.17	12.5
0.005	0.06	2.2	47	0.14	9.5
0.0075	0.08	2.0	33	0.13	7.3
0.01	0.10	2.2	31	0.16	4.8
0.02	0.18	1.8	15	0.12	3.2
0.03	0.25	2.2	10	0.21	1.5
0.05	0.36	2.2	6.5	0.29	0.8
0.075	0.47	2.3	5.9	0.37	0.5
0.1	0.60	2.3	4.6	0.51	0.3
0.2	0.63	2.0	3.2	0.92	0.2
0.4	0.75	2.3	4.1	0.85	0.1
0.6	0.75	2.2	4.1	0.75	0.1
0.8	0.74	1.7	4.5	–	–
1.0	0.68	0.9	5.2	–	–

The Rayleigh constant was calculated using numerical values of W_h and $H_{\max}$ by formula (10) for $\mu_i = 70000$. As follows from Table II, in the nanocrystalline alloy $Fe_{72.5}Cu_1Nb_2Mo_{1.5}Si_{14}B_9$ for $B_{\max} < 0.05$ T calculated values η vary slightly near the mean value $0.15 \cdot 10^6$ (A/m)$^{-1}$. In this region, there prevail reversible processes with the reversibility coefficient $\mu_i/\eta H_{\max} > 1$, and the hysteresis loops have a lens-like shape with a low remanence ratio $B_r/B_{\max} < 0.2$. The reversible magnetization process in the region of weak fields can be connected with the 180 ° domain wall bulging under the action of a magnetic field at the points where the wall is unpinned without tearing off the place of pinning [13]. The bulging of the wall without tearing-off and, consequently, the magnetization process would proceed until the magnetic field pressure becomes equal to the surface tension of the domain wall.

In Fig. 2, the dependences of $B_{\max}$, B_r, and H_c on the maximal magnetic field $H_{\max}$ are shown. It is seen that on the logarithmic scale, all the dependences are linear only in the Rayleigh region. The power factors *s* are close to the calculated values. For $B_{\max,}$ the factor *s* is equal to 1 for the region in which the quadratic term in formula (7) can be neglected, i.e., provided that $\mu_i/\eta H_{\max}$ is by far larger than 1. For B_r and H_c, the factor *s* is equal to 2 in accordance with formulas (8) and (9). Note that quadratic dependence of H_c obviously does not follow from formula (9), however, it can be ascertained from a graphic representation of the functional dependence (9) in the Rayleigh region.

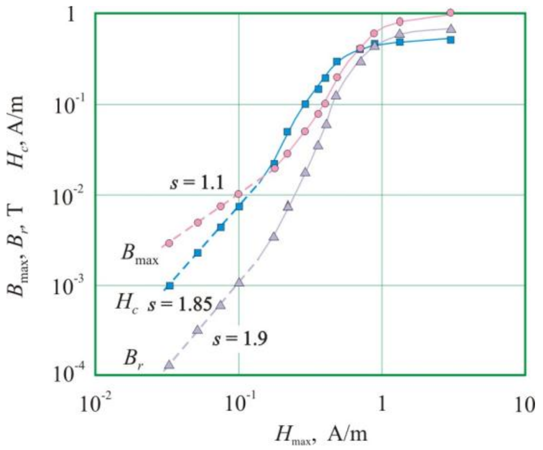

Figure 2. Dependences of maximal induction Bmax, remanence Br, and coercive force Hc on the maximal magnetic field Hmax for nanocrystalline alloy Fe72.5Cu1Nb2Mo1.5Si14B9.

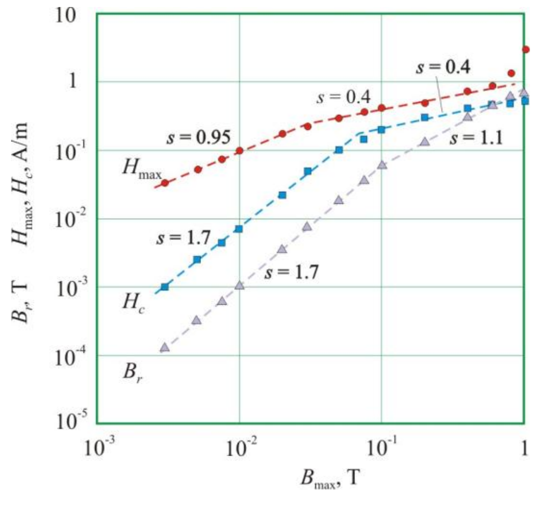

Figure 3. Dependences of maximal magnetic field Hmax, coercive force Hc, and remanence Br on the maximal magnetic induction Bmax for the nanocrystalline alloy Fe72.5Cu1Nb2Mo1.5Si14B9.

In the dependences of the parameters of minor hysteresis loops on the maximal induction $B_{\max}$ on the logarithmic scale, one can find linear portions in both the region of weak magnetic field and where the permeability displays maximal growth (Fig. 3). Note that in the $H_{\max}$ curve there are two points in the region of decreasing permeability at $B_{\max} > 1.0$ T that fall noticeably beyond the linear plot. At the same time, no decline of the B_r and H_c curves from linearity is observed. It is also seen from Fig. 3 that in the region of maximal permeability, the power factors *s* are significantly lower than in weak fields. In this region of the easiest magnetization reversal, the irreversible jump-wise motion of domain walls occurs, which results from sequential overcoming by the domain walls of local potential barriers.

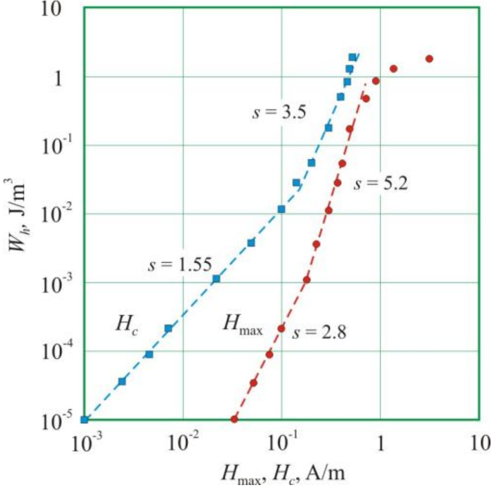

Figure 4. Dependence of magnetic losses for hysteresis Wh on the maximal magnetic field Hmax and coercive force Hc for the nanocrystalline alloy Fe72.5Cu1Nb2Mo1.5Si14B9.

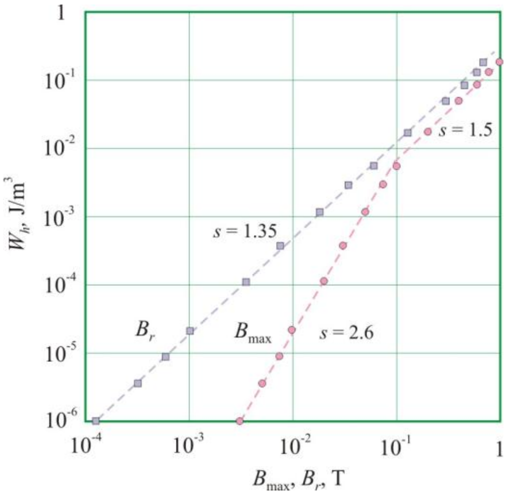

Figure 5. Dependence of magnetic losses for hysteresis Wh on the maximal induction Bmax and remanence Br for the nanocrystalline alloy Fe72.5Cu1Nb2Mo1.5Si14B9.

The dependences of the magnetic losses for hysteresis W_h on the parameters of magnetic hysteresis loops are shown on the logarithmic scale in Fig. 4 and 5. As is seen, all the dependences change their slope at the boundary of the Rayleigh region except for the remanence B_r. In the Rayleigh region, the power factor for the dependences of

W_h on $B_{\max}$ and $H_{\max}$ is close to 3, which corresponds to formula (10). The dependence of W_h on H_c with the factor 1.55 becomes evident if to substitute in formula (10) an empiric expression $H_c \sim H_{\max}^{1.85}$ shown in Fig. 2.

In the region of the maximal permeability growth, the power factor for the dependence of W_h on $B_{\max}$ on the logarithmic scale is equal to 1.5, which is close to the classical value 1.6 obtained by Steinmetz.

The power factor s for the dependence of the hysteresis losses on the remanence on the logarithmic scale is equal to 1.35 and remains constant up to the point of bending of the magnetization curve where the displacement of 180 ° domain walls starts prevailing. The same dependence of W_h on B_r was earlier discovered in other magnetic materials [3–6]. As follows from Table II, the hysteresis losses in the Rayleigh region are proportional to the product $B_r \cdot H_{\max}$, whereas in the region of the maximal permeability growth, to the product $B_r \cdot H_c$, i.e., to the remanence in both cases. The ground for this is the shape of the hysteresis loop. From the geometrical point of view, up to the bend of the magnetization curve (to the appearance of the beak in the loop), the height of the loop is remanence B_r, and the width, either $H_{\max}$ in the Rayleigh region or H_c in the region of the maximal permeability growth.

IV. CONCLUSION

In the work, an interrelation of the parameters of minor hysteresis loops was investigated for the case of the soft magnetic nanocrystalline alloy $Fe_{72.5}Cu_1Nb_2Mo_{1.5}Si_{14}B_9$. An analytical expression for the coercive force in the Rayleigh region is derived. The coercive force is connected with the maximal magnetic field $H_{\max}$ via the reversibility coefficient $\mu_i/\eta H_{\max}$. Reversibility coefficient shows the relationship between reversible and irreversible magnetization processes. If the reversibility coefficient exceeds 1, the reversible magnetization processes are predominant and vice versa. The linear curves of the interrelation of the hysteresis loop parameters are plotted on the logarithmic scale for the Rayleigh region and region of the maximal permeability growth. The universality of the dependence of the magnetic losses for hysteresis W_h on the remanence B_r with the power factor 1.35 is confirmed. It is shown that the magnetic losses for hysteresis in nanocrystalline alloy $Fe_{72.5}Cu_1Nb_2Mo_{1.5}Si_{14}B_9$ are proportional to the product $B_r \cdot H_{\max}$ in the Rayleigh region and to $B_r \cdot H_c$ in the region of the maximal permeability growth, i.e., to the remanence in a wide range of magnetic fields.

ACKNOWLEDGMENT

This work was supported by the Scientific researches of higher education institutions within the State task of the Russian Federation No. 4.9541.2017/8.9.

REFERENCES

[1] Y. Sakaki, and T. Matsuoka, "Hysteresis losses in Mn-Zn ferrite cores," *IEEE Trans. Magn.*, vol. 22, pp. 623–625, 1986.

[2] Y. L. He and G. C. Wang, "Observation of dynamic scaling of magnetic hysteresis in ultrathin ferromagnetic Fe/Au (001) films," *Phys. Rev. Lett.*, vol. 70, pp. 2336–2339, 1993.

[3] S. Takahashi, S. Kobayashi, Y. Kamada, H. Kikuchi, L. Zhang, and K. Ara, "Analysis of minor hysteresis loops and dislocations in Fe", Phys. B, vol. 372, pp. 190–193, 2006.

[4] S. Kobayashi, T. Fujiwara, S. Takahashi, H. Kikuchi, Y. Kamada, K. Ara, and T. Shishido, "The effect of temperature on laws of hysteresis loops in nickel single crystals with compressive deformation", Phil. Mag., vol. 89, pp. 651–664, 2009.

[5] S. Kobayashi, S. Takahashi, T. Shishido, Y. Kamada, and H. Kikuchi, "Low-field magnetic characterization of ferromagnets using a minor-loop scaling law", J. Appl.Phys., vol. 107, 023908, 2010.

[6] S. Kobayashi, S. Takahashi, H. Kikuchi, and Y. Kamada, "Domain-wall pinning in Er and Dy studied by minor-loop scaling laws", J. Phys.: Conf. Ser., vol. 266, 012015, 2011.

[7] L. Varga, and J. Kováč, "Minor loop scaling rules for Finemet type soft magnetic cores", Acta Phys. Pol. A, vol. 126, pp. 156–157, 2013.

[8] V. Tsepelev, V. Konashkov, Y. Starodubtsev, V. Belozerov, and D. Gaipishevarov, "Optimum regime of heat treatment of soft magnetic amorphous materials", IEEE Trans. Magn., vol. 48, pp. 1327–1330, 2012.

[9] C. P. Steinmetz, "On therelationship between magnetic losses and domain structurelaw of hysteresis", Proc. IEEE **72**, 197–221 (1989), preprinted from the Amer. Inst. Electr. Eng. Trans. **9**, 3–64 (1892).

[10] Y. N. Starodubtsev and V. A. Kataev "On the relationship between magnetic losses and behavior of domain structure in monocrystals of silicon iron", Phys. Met. Metallogr. **64**, 1076–1083 (1987).

[11] S. Tumanski, Handbook of magnetic measurements, CRC Press, Taylor&Francis Group (2011).

[12] S. Chikazumi, Physics of ferromagnetism, Oxford University Press, New York (1997).

[13] M. Kersten, "Die Wölbung der Blochwand als Elementarvorgang reversibler Magnetisierungsänderungen (Anfangapermeabilität und ΔE-Effekt)", Z. angew. Phys. **8**, 313–322 (1956).

Vladimir Tsepelev was born in Yekaterinburg, Russia on 01.10.1949. Received Doctor Degree in Metallurgy of Ferrous and non-ferrous metals from Boris Yeltsin Ural Federal University on 1998.

In 1998, as director he headed Research Center of Liquid Metal Physics. In 2000 he was Full Professor of Chair Health and Safety Department of Fundamental Education Boris Yeltsin Ural Federal University. In 2002 he was elected an Academician of the Engineering Academy named after A.M. Prokhorov. His research interests cover subjects such as, study the physical properties of liquid metal, the development of technologies for the production of amorphous and nanocrystalline soft magnetic materials, the preparation of amorphous high-entropy solders.

He has a Diplom of the winner of the international exhibitions and scientific competitions, the title of the Veteran of Labour, Diploma of the Ministry of Education of the Russian Federation, Honorary Worker of higher school Russian Federation.

Yuri N. Starodubtsev was born in Verkhnyaya Salda in Sverdlovsk Oblast, Russia on 22.08.1951. Received Candidate of Physico-mathematical Sciences from Institute of Metal Physics of Russian Academy of Sciences on 1980.

Since 1973, engineer researcher at the Central laboratory of the Verkh-Isetsky Metallurgical Plant, Yekaterinburg. Since 1991 up to now the Chief technologist of Gammamet Research and Production Enterprise, Yekaterinburg. The field of scientific interests is the physics and technology of magnetic materials. Among the publications the book "Soft Magnetic Materials", Moscow, Technosphera, 2011, "Glossary of Physical Terms", Moscow, Hot Line – Telecom, 2017.