STUDY OF MAGNETIC PROPERTIES OF ISOTOPICALLY ENRICHED ^{56}FE AT DIFFERENT MAGNETIC FIELD STRENGTH VALUES

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Abstract

The magnetic properties of polycrystalline samples of isotopically enriched iron with the content of isotope ^{56}Fe 99.945±0.002 at. % were investigated at different magnetic field strength values. The samples of monoisotopic iron were melted in the environment of argon and annealed in hydrogen. The same measurements were carried out on the samples of iron with natural isotopic composition. The quantity and composition of impurities in the samples of natural and monoisotopic iron were equal. The magnetic properties were measured using an automatic induction vibro-magnetometer MagEq MNMS 216 and an automatic measuring complex MK-3E in accordance with GOST 8.377-80 and GOST 12119.1-98. It was found that the value of the saturation magnetization J_s of ^{56}Fe is higher by 10.87% than that of ^{nat}Fe at room temperature, and by 11.35% at 100 K. The values of saturation induction B_s and residual magnetic induction B_r for ^{56}Fe are higher than for ^{nat}Fe. The difference in the values of the coercive force H_c for the ^{nat}Fe and ^{56}Fe samples is due to the difference in the grain size of the samples and in the purity of the materials.

Keywords: Monoisotopic ^{56}Fe, natural iron, impurities, magnetic properties

1. INTRODUCTION

Authors [1] found that the fundamental magnetic properties of natural (^{nat}Fe) and monoisotopic (^{56}Fe) iron are almost the same. The excess of saturation magnetization (J_s) for ^{56}Fe in comparison with ^{nat}Fe is 4.6%, the differences in the values of the coercive force (H_c), residual magnetic induction (B_r) and maximum magnetic permeability (μ_{max}) are explained by the difference in the content of impurities. This work is a continuation of work [1]. When carrying out it, the same objects of research were used as in [1], but they additionally annealed in high-purity dried hydrogen. The quasi-static and dynamic magnetic properties of the studied samples of natural (^{nat}Fe) and monoisotopic (^{56}Fe) iron were measured in this work at different values of the magnetic field strength and at different frequencies of the alternating magnetic field. The results obtained were compared with each other.

The aim of this work is to obtain new data on the fundamental and structure-sensitive magnetic properties of ^{nat}Fe and ^{56}Fe with decreased concentration of impurities in the samples and at increased values of the magnetic field strength.

2. MATERIALS AND METHODS

For the study, we used previously prepared [56]Fe and [nat]Fe samples [1], the isotopic composition of which is shown in **Table 1.**

Table 1 Isotopic composition of monoisotopic and natural iron, at.% [1].

Isotope / Sample	[54]Fe	[56]Fe	[57]Fe	[58]Fe
[nat]Fe	5.843±0.027	91.758±0.062	2.118±0.013	0.281±0.026
[56]Fe	0.004±0.001	99.945±0.002	0.040±0.001	0.011±0.004

Two types of samples were made, differing in shape and geometric dimensions. The first type of samples had the shape of a parallelepiped and was intended to measure the magnetic properties by the method of vibration magnetometry [2-4]. The second type of samples had the shape of a ring with an outer diameter D = 15 mm, an inner diameter d = 11.5 mm, and a height h = 4.0 mm and is intended for determining the magnetic properties by the induction-pulse method in quasi-static and dynamic modes in accordance with GOST 8.377-80 and GOST 12119.1-96 [5,6]. All samples were additionally annealed in a stream of dry hydrogen of grade "B" (purity 99.9999%) at a temperature of 1100°C for 6 hours, after which they were analyzed for impurities.

Before determining the impurity composition, in order to exclude the influence of possible surface contamination, the surface of the samples was etched for 2 hours at 30^0C in a 15% solution of hydrochloric acid of the high purity grade, further purified using a Savillex DST-1000 sub-boiling distillation system.

The analysis of the impurity composition of iron samples was carried out by laser mass spectroscopy using an EMAL-2 device (USSR).

The magnetic properties on parallelepiped samples with dimensions of 1.5x1.5x3.5 mm were measured using an automatic induction vibromagnetometer MagEq MNMS 216 (Russia) with a control program based on the LabVIEW8 package. The measurements were carried out at various temperatures in the range of 100-350K with a step of 50K. The maximum magnetic field strength was 1.79 T. Using the constructed hysteresis curves we judged the the saturation magnetization (J_s) of the measured sample.

Measurements of magnetic properties in quasi-static and dynamic modes were carried out on ring samples with an outer diameter D = 15 mm, an inner diameter d = 13.5 mm, and a height of h = 4.0 mm using an automatic measuring complex MK-3E (Russia) in accordance with GOST 8.377-80 and GOST 12119.1-98. The magnetic field strength varied from 108 to 10810 A/m. The frequency of alternating magnetic field during measurements in the dynamic mode was 50, 60, and 400 Hz. The values of the coercive force (H_c), residual magnetic induction (B_r), saturation induction (B_s), rectangularity coefficient of the hysteresis loop (K_r) and losses during magnetization reversal (P) were determined. The relative error of measurments for a confidence coefficient of 0.95 was ± 2% for H_c, ± 2% for B_r, and ± 2% for B_s. The relative measurement error the points of the magnetic hysteresis loop and the main magnetization curve by induction is ± 1.5%, by the magnetic field strength is ± 2%.

3. RESULTS AND DISCUSSION

The results of the analysis of the impurity composition of the [nat]Fe and [56]Fe samples before and after their annealing in hydrogen, determined by mass spectrometry on the EMAL-2 device, are shown in **Table 2.**

Comparing the results from **Table 2**, with the purity of the samples used for measurements in [1], it can be noted that additional annealing led to a significant (by 3 orders of magnitude) decrease in the oxygen content, the carbon content decreased by 8-10 times, and etching of the samples removed most of surface

contamination. After annealing, the content of impurities in ^{nat}Fe and ^{56}Fe for most of the impurity elements is within the same limits and leveled off.

Table 2 Results of analysis of the impurity composition of ^{nat}Fe and ^{56}Fe samples before and after their annealing in hydrogen.

Element	Concentration in ^{nat}Fe (wt%)		Concentration in ^{56}Fe (wt%)	
	Before annealing	After annealing	Before annealing	After annealing
C	$4 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	$1 \cdot 10^{-3}$
O	$1 \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$1 \cdot 10^{-3}$	$6 \cdot 10^{-4}$
Na	$<2 \cdot 10^{-4}$	$<2 \cdot 10^{-4}$	$<2 \cdot 10^{-4}$	$<2 \cdot 10^{-4}$
Mg	$<3 \cdot 10^{-4}$	$<3 \cdot 10^{-4}$	$<3 \cdot 10^{-4}$	$<3 \cdot 10^{-4}$
Al	$<5 \cdot 10^{-4}$	n/a	$<5 \cdot 10^{-4}$	n/a
Si	$9 \cdot 10^{-2}$	n/a	$1 \cdot 10^{-2}$	n/a
P	$6 \cdot 10^{-3}$	$6 \cdot 10^{-3}$	$4 \cdot 10^{-4}$	$7 \cdot 10^{-4}$
S	$4 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
Cl	$<8 \cdot 10^{-4}$	$<8 \cdot 10^{-4}$	$<8 \cdot 10^{-4}$	$<8 \cdot 10^{-4}$
K	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$
Ca	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$
Ti	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$
Cr	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$<8 \cdot 10^{-4}$	$<8 \cdot 10^{-4}$
Mn	$<7 \cdot 10^{-4}$	$<7 \cdot 10^{-4}$	$<7 \cdot 10^{-4}$	$3 \cdot 10^{-4}$
Co	$<8 \cdot 10^{-4}$	$<8 \cdot 10^{-4}$	$<8 \cdot 10^{-4}$	$<8 \cdot 10^{-4}$
Ni	$3 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$3 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
Zn	$<1 \cdot 10^{-3}$	$<1 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$7 \cdot 10^{-4}$
Ag	$<4 \cdot 10^{-3}$	$<4 \cdot 10^{-3}$	$<4 \cdot 10^{-3}$	$<4 \cdot 10^{-3}$

Table 3 shows the values of the saturation specific magnetization (σ_s) obtained on ^{nat}Fe and ^{56}Fe samples at various temperatures in the range 100-350K using a MagEq MNMS 216 vibromagnetometer. In **Table 3** Δ is the difference, % in σ_s values for these samples (Δ,%).

Table 3 Values of specific saturation magnetization (σ_s) obtained on ^{nat}Fe and ^{56}Fe samples at different temperatures in the range of 100-350 K.

| Temperature (K)		100	150	200	250	300	350
Saturation specific magnetization, σ_s ($G \cdot cm^3/g$)	^{nat}Fe	169.1	167.6	166.7	166.7	166.3	165.6
	^{56}Fe	188.3	186	184.8	184.1	183.9	183.6
Δ (%)		11.35	10.98	10.86	10.44	10.58	10.87

It can be seen from **Table 3** that the values of the saturation specific magnetization, σ_s, for ^{nat}Fe at all measurement temperatures are lower than for ^{56}Fe. The difference in values depending on the measurement temperature is 10.87-11.35%. Accordingly, the saturation magnetization defined as $J_s = \sigma_s \cdot q$, where q is the density of the material of the measured sample (for both samples, the value q = 7.78 g/cm^3), for ^{nat}Fe at all measurement temperatures will be lower than for ^{56}Fe [7-10]. Moreover, the difference in J_s values depending on the measurement temperature will also be 10.87-11.35%. It should be noted that in [1] this difference for room temperature was 4.6%.

The magnetic properties of ring-shaped ^{nat}Fe and ^{56}Fe samples after their annealing in hydrogen, measured in the quasi-static mode at various values of the magnetic field strength, are given in **Table 4**.

Table 4 Quasi-static magnetic properties of ring samples of ^{nat}Fe and ^{56}Fe after annealing in hydrogen.

| Sample	Magnetic field strength, H (A/m)	Coercive force, H_c (A/m)	Saturation induction, B_s (T)	Residual magnetic induction, B_r (T)	Rectangularity coefficient of hysteresis loop K_r
^{nat}Fe	500	92.3	1.37	1.23	0.9
	1000	96.9	1.44	1.27	0.88
	4000	98.2	1.62	1.28	0.8
	8000	101.7	1.74	1.28	0.74
^{56}Fe	500	102.7	1.42	1.3	0.92
	1000	106.6	1.5	1.35	0.9
	4000	108.5	1.65	1.37	0.83
	8000	110.6	1.77	1.37	0.77

It can be seen from **Table 4**, that an increase in the magnetic field strength (H) leads to an increase in all magnetic properties for both ^{nat}Fe and ^{56}Fe. At any values of H, the magnetic properties of ^{nat}Fe are lower than those of ^{56}Fe. The differences in the values with increasing magnetic field strength decreases for H_c and B_s and increases for B_r and K_r.
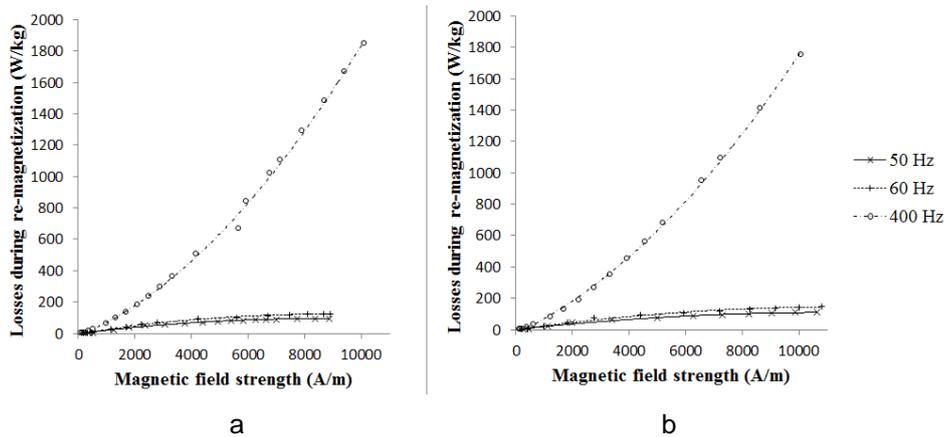

a   b
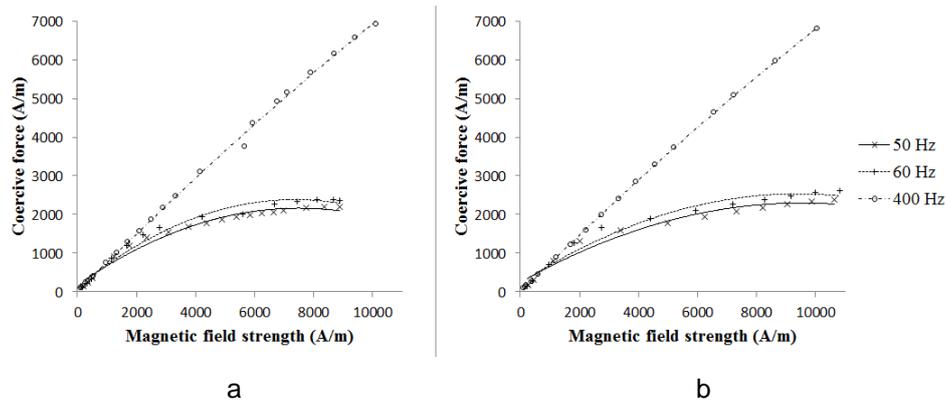
Figure 1 Field dependences of the coercive force (H_c) of the ring samples of ^{nat}Fe (a) and ^{56}Fe (b), measured at a frequency of alternating the magnetic field f = 50, 60, and 400 Hz.

a   b
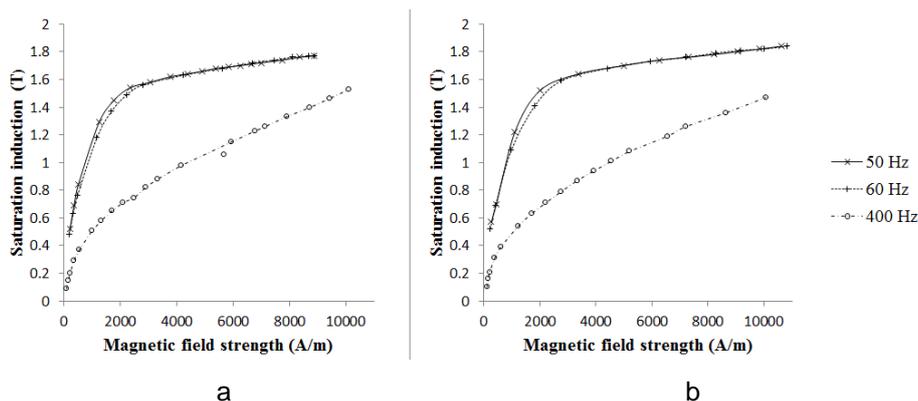
Figure 2 Field dependences of the saturation induction (B_s) of the ring samples of ^{nat}Fe (a) and ^{56}Fe (b), measured at a frequency of alternating the magnetic field f = 50, 60, and 400 Hz.

a

b
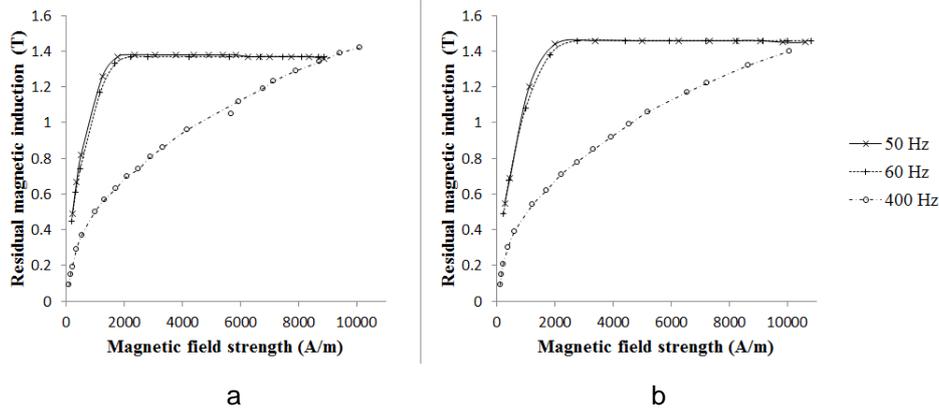
Figure 3 Field dependences of the value of the residual magnetic induction (B_r) of the ring samples of ^{nat}Fe (a) and ^{56}Fe (b), measured at a frequency of alternating the magnetic field f = 50, 60, and 400 Hz.

a

b

Figure 4 Field dependences of the magnitude of losses during re-magnetization (P) of the ring samples of ^{nat}Fe (a) and ^{56}Fe (b), measured at a frequency of alternating the magnetic field f = 50, 60, and 400 Hz.

Figures 1-4 show the results of measuring the magnetic properties for the ring samples of ^{nat}Fe and ^{56}Fe annealed in hydrogen in a dynamic mode at a frequency of an alternating magnetic field f = 50, 60, and 400 Hz, depending on the magnitude of the magnetic field H.

It can be seen that as the magnetic field strength increases, the change in H_c, B_s, B_r, P and K_r is the same at any value of the magnetic field frequency. In all cases, the values of H_c, B_s, B_r, P increase but it occurs with different intensities for different values of f. Thus, the values of H_c with an increase in the magnetic field strength from 0 to about 2 kA/m increase with the same intensity both at f = 400 Hz and at f = 50 Hz and 60 Hz. With a further increase in the magnetic field strength, the intensity of change in H_c at f = 50 Hz and 60 Hz strongly decreases, and at f = 400 Hz it remains practically unchanged (i.e., remains the same high).

The intensity of change in B_s and B_r values with an increase in H from 0 to 2 kA/m at f = 50 Hz and 60 Hz, significantly exceeds that at f = 400 Hz, but with a further increase in H at f = 50 Hz and 60 Hz, there is a strong decrease in the intensity of change in B_s and B_r, in while at f = 400 Hz it remains very high in the entire range of increasing H.

It can be seen from Figure 4 that the losses during re-magnetization of samples (P) of both ^{nat}Fe and ^{56}Fe at f = 50 Hz and 60 Hz less dependent on the magnetic field strength than at f = 400 Hz: when magnetic field strength increases from 210 to 8884 A/m, the losses during re-magnetization increase by about 52.5 times at f=50 Hz and about 275 times at 400 Hz. The same is observed for the ^{56}Fe sample as well.

As we see, the changes in the magnetic properties of the ^{nat}Fe and ^{56}Fe samples with an increase in the strength H and frequency f of the alternating magnetic field are identical. The difference is only in the values of these magnetic properties.

4. CONCLUSION

1) The saturation magnetization J_s of ^{56}Fe is higher than that of ^{nat}Fe in the temperature range from 100 to 350 K. At room temperature, this excess (Δ) is 10.87%. When the temperature changes to 100K, Δ increases to 11.35%.

2) The values of saturation induction B_s and residual magnetic induction B_r for ^{56}Fe are higher than for ^{nat}Fe. This excess Δ depends on the strength of the magnetic field H. With an increase in H from 500 to 8000A / m, the value of Δ for B_s decreases from 3.65 to 1.72%, and for B_r, increases from 5.69 to 7.03%.

3) The magnitude of the specific losses during re-magnetization P, for ^{nat}Fe and ^{56}Fe samples at any value of the strength of the alternating magnetic field H, strongly depends on its frequency f. An increase in f with a simultaneous increase in H leads to a strong increase in P.

4) The difference in the values of the coercive force H_c for the ^{nat}Fe and ^{56}Fe samples is due to the difference in the grain size of the samples and in the purity of the materials with respect to impurities and, first of all, with respect to carbon.

5) The dependence of the value of P on H and f correlates with the dependence of H_c on H and f. A decrease in H_c should lead to a decrease in P and can be achieved by further increasing the purity of the material of the samples in terms of soluble (mainly interstitial) and insoluble impurities.

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