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Microwave Heating of Oxidized Iron Powders in Ferromagnetic Resonance Mode

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Abstract—By the example of α-Fe_2O_3 hematite, $5Fe_2O_3{\cdot}9H_2O$ ferrihydrite, and γ-Fe_2O_3 maghemite powders, a microwave-radiation-induced powder system temperature growth $\Delta T_{\max}$ of several degrees has been measured in the ferromagnetic resonance mode at a frequency of 8.9 GHz. The powders heat up the most in the external field H coinciding with the ferromagnetic resonance field. The value of the $\Delta T_{\max}$ effect depends on the magnetization of a powder material. The results obtained allow us to propose a new magnetic hyperthermia method for biomedical applications.

Keywords: ferromagnetic resonance, hematite, ferrihydrite, maghemite, magnetic hyperthermia

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INTRODUCTION

The field of possible applications of magic nanoparticles is continuously expanding. In addition to the well-known and actively developing physical ideas for use of magnetic nanoparticles in biomedicine and microelectronics (spintronic devices and nonvolatile magnetic memory) [1, 2], new areas appear, including ecology (removal of heavy metal ions) [3, 4] and magnetic catalysis [5]. In biomedicine, there are already approved and established approaches to application of magnetic nanoparticles. Under magnetic hyperthermia [6], an ac magnetic field is induced in a certain area of the body where magnetic nanoparticles were previously purposefully introduced. The heat generated during the particle magnetization switching processes leads to local heating of biological tissues and, ultimately, to the destruction of unwanted (for example, malignant) cells. In our opinion, the possibilities of transforming the external effect (in the case of hyperthermia, this is an external low-frequency ac magnetic field) into local thermal heating has been fully studied to date. Expanding the frequency range, one can point to another possible method of hyperthermia: its implementation through ferromagnetic resonance (FMR) [7]. This effect occurs when frequencies of an applied microwave field and the magnetization vector precession coincide. Note that, in the physical materials science of ferromagnets, FMR is widely used as a simple and reliable technique for determining the magnetic parameters: magnetization, anisotropy of various types, exchange coupling constant, etc. [8–12]. Experimentally, the use of FMR is a well-developed area; therefore, the possibility of modifying this technique to solve practical problems does not cause difficulties.

Various approaches to measuring the thermal effect value were proposed in the literature: these are the temperature determination by resistance changes [13], by thermal radiation [14–17], etc.

This work is aimed at studying the static and dynamic magnetic properties of oxidized iron (hematite α-Fe_2O_3, ferrihydrite $5Fe_2O_3{\cdot}9H_2O$, and maghemite γ-Fe_2O_3) powders in order to establish the regularities and identify the parameters that determine heating of these powders at under FMR. To measure the heating value, a simple method of the direct temperature measurement with a thermocouple is used.

EXPERIMENTAL

Antiferromagnetic ferrihydrite $5Fe_2O_3{\cdot}9H_2O$ and hematite α-Fe_2O_3 powders were chosen as objects of study owing to the availability of these materials and previous studies on features of their structure and magnetic properties [8, 18, 19]. As an object with higher magnetization values, ferrimagnetic maghemite γ-Fe_2O_3 powder obtained by chemical deposition was chosen. Average particle size d of the ferrihydrite, hematite, and maghemite powders used was 3, 40, and 16 nm, respectively.

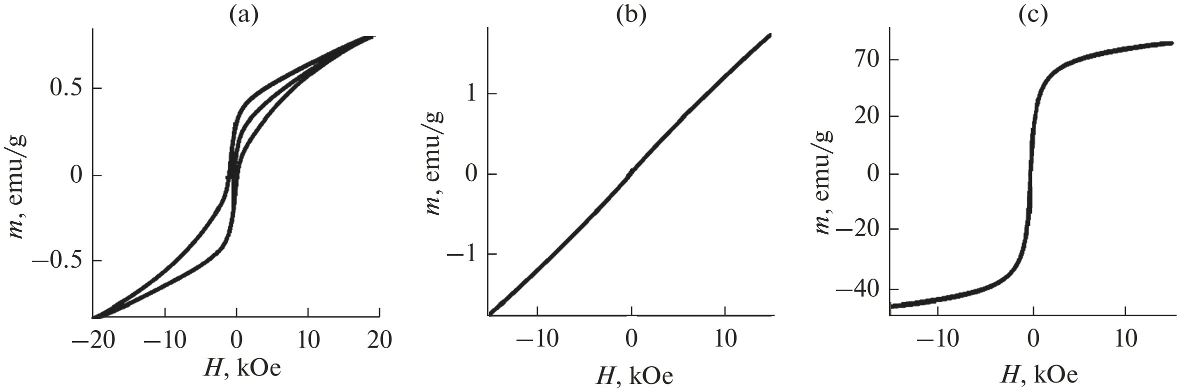

Fig. 1. Hysteresis loops of the (a) hematite, (b) ferrihydrite, and (c) maghemite powders recorded at room temperature.

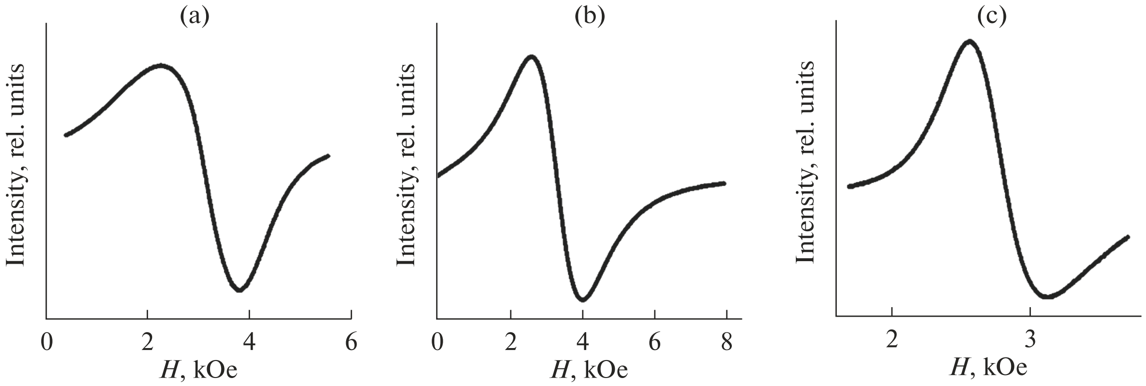

Fig. 2. Ferromagnetic resonance spectra of (a) hematite, (b) ferrihydrite, and (c) maghemite recorded at room temperature.

The static magnetic properties of particles were studied on a LakeShore VSM 8604 vibrating sample magnetometer (the measurements were carried out at the Krasnoyarsk Regional Center for Collective Use, Krasnoyarsk Scientific Center, Siberian Branch of the Russian Academy of Sciences). The FMR was observed on a Radiopan SE/X-2544 X-band EPR spectrometer at a frequency of 8.9 GHz.

RESULTS AND DISCUSSION

The hysteresis loops of hematite, ferrihydrite, and maghemite were recorded at room temperature (Figs. 1a–1c). The coercivity H_c, remanent magnetization M_r, and saturation magnetization M_s values are given in Table 1 together with the tabulated densities ρ of the powders used and their sizes *d*.

Figures 2a–2c show the FMR curves for hematite, ferrihydrite, and maghemite nanoparticles recorded at room temperature. The parameters of the resonance absorption curves—resonance field H_R and linewidth ΔH—are given in Table 1.

We studied the temperature changes ΔT of the powder systems used upon time variation in different dc magnetic fields and the microwave field (f = 8.9 GHz) of an electron spin resonance (ESR) spectrometer. The temperature measurements of nanoparticles were carried out with a T-type thermocouple with copper and constantan electrodes, and the signal was recorded with an

Table 1. Properties of the powders

Sample	ρ, g/cm^3	*d*, nm	H_c, Oe	M_r, emu/g	M_s, G	H_R, kOe	ΔH, kOe	ΔT_{max}, K	$(dT/dt)_{max}$ K/s
α-Fe_2O_3	5.3	40	575	0.21	4.3	3.1	1.5	0.8	0.016
$5Fe_2O_3{\cdot}9H_2O$	3.8	3	0	0	6.7	3.3	1.4	4.5	0.19
γ-Fe_2O_3	4.9	16	14	1.3	225	2.8	0.56	10	1.07

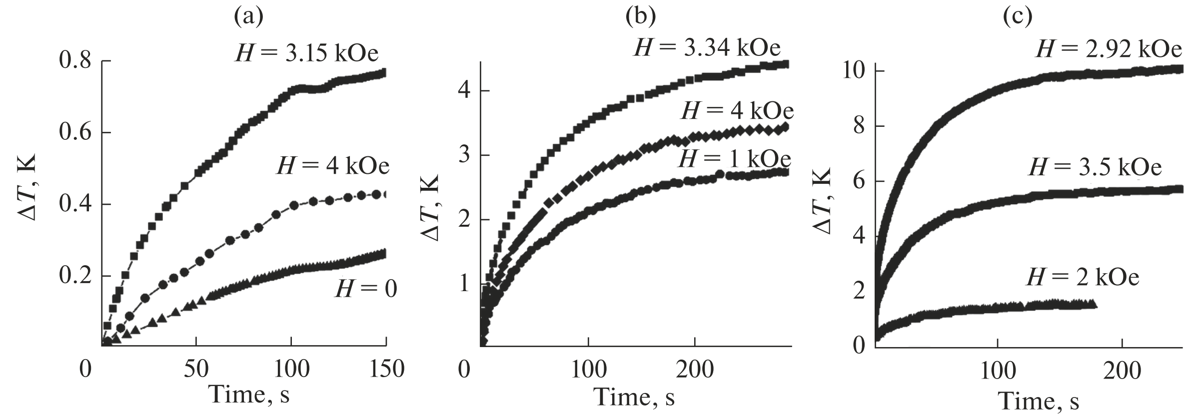

Fig. 3. Change in temperature of the (a) hematite, (b) ferrihydrite, and (c) maghemite powders in different magnetic fields under microwave pumping.

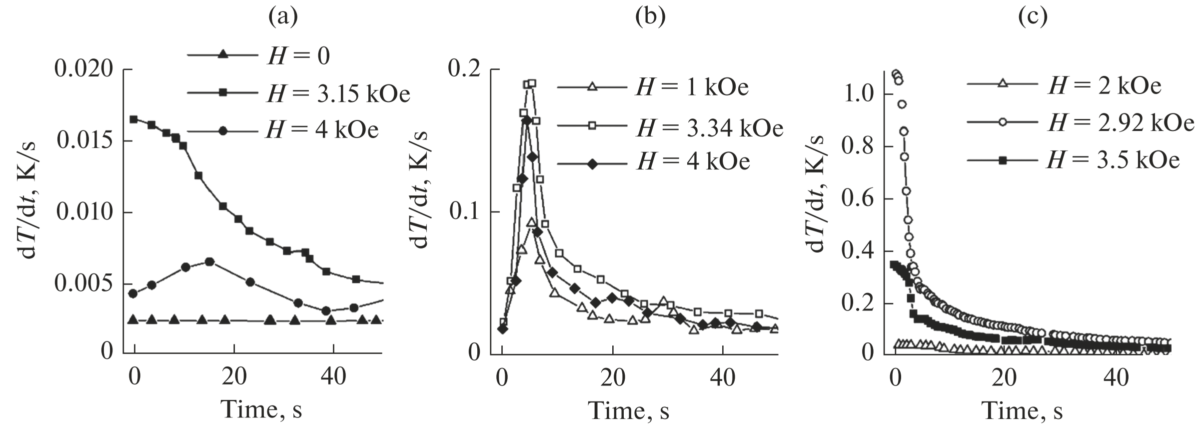

Fig. 4. Heating rate of the (a) hematite, (b) ferrihydrite, and (c) maghemite powders in various magnetic fields under microwave pumping.

N307/1 two-coordinate curve plotter. Figure 3 shows the results of the examination. In all the cases, we observe a sharp increase in temperature at the initial instant of time followed by a decrease in the temperature growth rate upon reaching the $\Delta T_{\max}$ saturation. The amount of particle heating depends, as can be seen in Fig. 3, on the applied dc field strength. Figure 4 shows the time dependence of the heating rate of the powder systems at different magnetic field strengths. In the resonance field, the greatest growth of the temperature of the powders and the highest heating rate are observed. The maximum temperature growths $\Delta T_{\max}$ and heating rates are given in Table 1. The strongest effect of heating of the powders in the FMR mode at ~10 K at a heating rate of 1 K/s is observed for the γ-Fe_2O_3 maghemite powders.

In addition, this γ-Fe_2O_3 powder system is characterized by the maximum saturation magnetization (273 G) at room temperature among the powder systems used. If we compare the heating effect on the antiferromagnetic ferrihydrite $5Fe_2O_3{\cdot}9H_2O$ and hematite α-Fe_2O_3 powders, we can conclude that the value of the $\Delta T_{\max}$ effect is determined by magnetization M: the higher the M value, the higher the powder heating temperature. However, it is still difficult to establish the functional dependence of $\Delta T_{\max}(M_s)$ using the experimental data obtained.

CONCLUSIONS

In this study, the heat release of the hematite, ferrihydrite, and maghemite magnetic powders was measured in the FMR mode at different dc magnetic fields H. It was shown that the greatest heating of the particle system is obtained at a FMR field of $H = H_R$ and the heating value $\Delta T_{\max}$ increases with the M value. The heating rates dT/dt of the investigated powders were determined. The ferrihydrite and hematite powders characterized by antiferromagnetic order have similar room-temperature magnetizations (6.7 and 4.3 G), similar resonance fields H_R (3.3 and 3.1 kOe), and similar FMR linewidths (1.4 and 1.5 kOe); however, their heating rates differ by an order of magnitude: 0.19 and 0.016 K/s, respectively. Comparing the characteristics (size d, coercivity H_c) of ferrihydrite $5Fe_2O_3 \cdot 9H_2O$ and hematite α-Fe_2O_3 powders, we can conclude that the powder heating rate in the ferromagnetic resonance mode is $dT/dt \sim 1/d$ and $dT/dt \sim 1/H_c$.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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