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Structures of organic additives modified magnetite nanoparticles

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Abstract

Magnetite (Fe_3O_4) nanoparticles and magnetite-based inorganic–organic hybrids are attracting increasing attention in biomedicine, as thermoseeds for hyperthermia and contrast media in magnetic resonance imaging. Controlling the size of Fe_3O_4 thermoseeds is important, as particle size affects their heat generation under alternative magnetic fields. Fe_3O_4 is easily synthesized via aqueous processes. We previously demonstrated that adding organic polymers during synthesis affected the size and crystallinity of the resulting Fe_3O_4. However, the relationship of the chemical structure of the low-molecular-weight organic additive of its effect on the product has not been elucidated. In this study, organic compounds containing varying functional groups and surface charges were added to the precursor solution of Fe_3O_4. Crystalline Fe_3O_4 formed in the presence of neutral acetone, cationic ethylenediamine, and anionic acetic acid. These nanoparticles had slightly smaller particle sizes than those prepared in the absence of additives. The presence of oxalic acid and tris(hydroxymethyl)aminomethane inhibited Fe_3O_4 nucleation, instead yielding lepidocrosite- or akaganeite-type FeOOH. These differences were attributed to the ability to form complexes between iron ions and the organic additives. The saturation magnetizations of the products were consistent with Fe_3O_4. This indicated that the crystal phase of the iron oxide products differed, even when prepared in the presence of organic additives of the same functional group. It is concluded that state of ion-organic molecule complex in the solutions is a key factor governing nanostructure of the resultant iron oxide.

Keywords: A. Powders: chemical preparation; D. Ferrites; E. Biomedical applications

1. Introduction

Magnetite (Fe_3O_4) is an inorganic material with applications in magnetism, electronics, and biomedicine. It shows promise for use in thermoseeds in cancer hyperthermia. Hyperthermia is a low-invasion cancer treatment, based on the lower heat resistivity of cancer cells compared with healthy cells [1]. Tumors can be heated by infrared radiation, radiofrequency ablation, and hot water treatment. However, tumors deep within the body cannot be effectively treated because these techniques require heating from outside the body. New cancer treatments using ferromagnetic ceramic particles such as Fe_3O_4 and γ-hematite (γ-Fe_2O_3) are attracting much attention. Deep tumors can be heated effectively and killed, if ferromagnetic ceramic particles are implanted around the tumors and an alternating magnetic field is applied. Various magnetic nanoparticles have been investigated as thermoseeds for this process [2,3]. Implanting 20–30 μm size ferromagnetic microspheres in blood vessels around the tumors can result in hyperthermia and embolization effects, cutting off nutrient supply to the tumors [4–6].

We previously prepared Fe_3O_4 nanoparticles by adding various water-soluble polymers. The nanoparticles size and crystal phase were controlled by the polymer structure and addition sequence [7]. Fe_3O_4 was formed by adding polystyrene sulfonate, rather than polyacrylic acid, so different iron oxides could be formed after adding the negatively charged polymer. The interaction between Fe_3O_4 and small organic molecules is important in biomedicine, as many biomolecules

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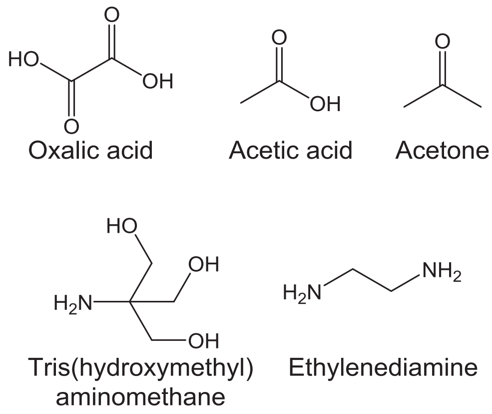

Fig. 1. Chemical structures of organic reagents.

such as amino acids and drugs are of low molecular weights. The crystal structure of iron oxide is reportedly controlled by complex formation upon adding ethylenediaminetetraacetic acid (EDTA) [8,9]. However, the effect of adding organic molecules with different functional group has not been comprehensively investigated.

In the present study, we synthesized Fe_3O_4 nanoparticles in the presence of oxalic acid, acetic acid, acetone, tris(hydroxymethyl) aminomethane, and ethylenediamine. Their chemical structures are shown in Fig. 1. We investigated the effect of the additives chemical structure on the crystalline phase, crystalline size, and magnetic properties of the resulting nanoparticles.

2. Materials and methods

Oxalic acid, acetic acid, acetone, ethylenediamine, and iron (II) chloride were purchased from Wako Pure Chemical Industries, Osaka, Japan. Tris(hydroxymethyl)aminomethane was purchased from Nacalai Tesque, Kyoto, Japan. Oxalic acid, acetic acid, acetone, tris(hydroxymethyl)aminomethane, or ethylenediamine was dissolved in 25 mL of 1.2 mM aqueous iron (II) chloride at 4 mass%. Aqueous 1 M NaOH was then added dropwise, until the pH was ~7. The resulting solution was stirred at 75 °C for 1 h to precipitate solid particles. In the case of ethylenediamine, NaOH was not added because the pH of the solution was already >7. The solution was then dialyzed by a cellulose tube for 24 h to remove excessive water-soluble by-products, and the formed precipitate was collected by filtration.

Crystalline structures were investigated using powder X-ray diffraction (XRD, MXP3V, Mac Science Ltd., Yokohama, Japan). The size and shape of the products were observed using transmission electron microscopy (TEM, JEM-3010, JEOL, Tokyo, Japan). The saturation magnetizations of the samples were measured using vibrating sample magnetometry (VSM, VSM-5, Toei, Tokyo, Japan), under an applied magnetic field (10 kOe, 80 Hz).

3. Results and discussion

Fig. 2 shows the XRD patterns of the samples. Peaks characteristic of crystalline Fe_3O_4 (JCPDS19-0629) were apparent for samples prepared with no additive, acetic acid, acetone, and ethylenediamine. Peaks characteristic of lepidocrocite-type FeOOH (JCPDS44-1415) and akaganeite-type FeOOH (JCPDS34-1266) were detected in the patterns of samples prepared with oxalic acid and tris(hydroxymethyl) aminomethane, respectively.

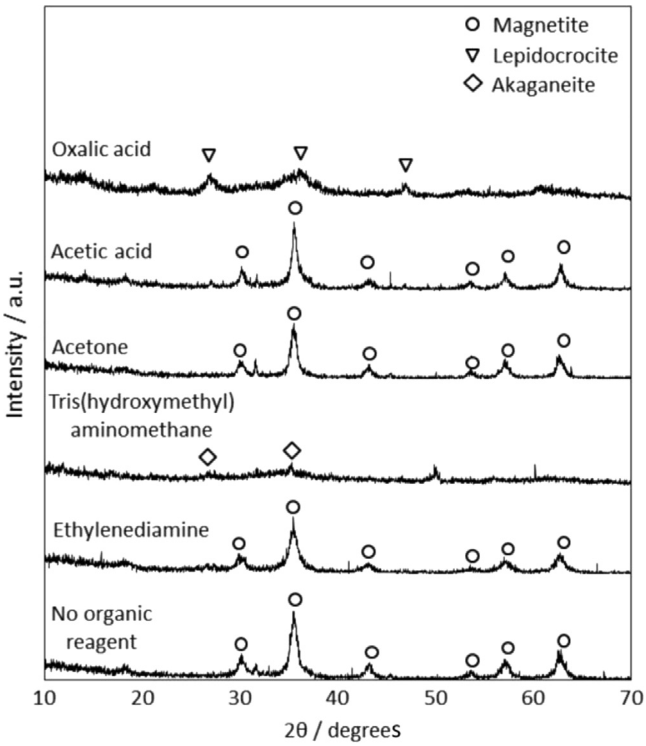

Fig. 2. XRD patterns of samples prepared in the presence of organic additives.

Fig. 3 shows TEM images and particle size histograms of the samples. Cubic particles were observed for samples prepared with no additive, acetone, ethylenediamine, and acetic acid. The average particle sizes of samples prepared in the presence of organic additives was slightly smaller than the sample prepared with no additive. Fine particles of 3 nm in size were observed for the sample prepared with oxalic acid. Needle-like particles larger than 200 nm were observed for the sample prepared with tris(hydroxymethyl)aminomethane.

Table 1 shows the saturation magnetizations of the samples, and whether or not Fe_3O_4 was formed. The samples containing crystalline Fe_3O_4 exhibited high saturation magnetizations of 40–57 emu/g, in the order: acetone > no additive > acetic acid > ethylenediamine. Samples not containing crystalline Fe_3O_4 exhibited lower saturation magnetizations.

These results indicated that the crystal phase of the prepared iron oxide nanoparticles was sensitive to the organic additive. Fe_3O_4 forms by reaction of the Fe^{2+} and Fe^{3+} precursors according to [10,11]:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \tag{1}$$

$$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3 \tag{2}$$

$$Fe(OH)_3 \rightarrow FeOOH + H_2O \tag{3}$$

$$Fe(OH)_2 + 2FeOOH \rightarrow Fe_3O_4 + 2H_2O \tag{4}$$