Heat generation efficiency of non-spherical magnetic particles synthesized with a supercritical fluid

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Abstract

We synthesize non-spherical magnetic particles and evaluate their heat generation efficiency under an ac magnetic field. Ferrocene is dissolved in ethanol and the solution is heated up to reach a supercritical state. Spherical, dendritic and flower-shaped magnetic particles are synthesized under the supercritical condition and their production rates change depending on the heating time. We show that the non-spherical magnetic particles exhibit higher heat generation efficiency under an ac magnetic field as compared to the spherical ones.

1 Introduction

It is well known that magnetic particles dissipate heat under an alternating magnetic field due to magnetic hysteresis and eddy currents. By using magnetic particles, tiny objects can be selectively heated up since magnetic particles can also be manipulated by an external magnetic field. The heat generation of magnetic particles has been widely applied in biomedical studies. For instance, the hyperthermia treatment of cancer cells [1] and the encouragement of enzyme reaction [2] using magnetic particles have been demonstrated. Recently, it has been reported that non-spherical magnetic particles exhibit better heat generation efficiency than that of spherical ones [3]. In this study, we synthesize non-spherical magnetic particles using ferrocene and supercritical ethanol and investigate their heat generation efficiency.

2 Experimental details

We dissolved ferrocene in ethanol at the concentration of 4.8 mg/mL and the solution was enclosed in a cylindrical chamber of 44.4 mL volume. Note that the amount of the solution in the chamber was set at 4.4 mL, in which case if the temperature is increased to 350 °C, the pressure becomes 6.2 MPa and therefore the solvent reaches a supercritical state according to the van der Waals equation of state. We heat up the solution by an electric heating wire installed around the chamber and maintain its temperature at 350 °C for t_h = 0-120 min. After cooling to room temperature, magnetic particles produced in the solution were collected using a magnet and were washed with ethanol. We evaluated the shape and size of magnetic particles synthesized with a scanning electron microscope (SEM, SU6600, manufactured by Hitachi High-Technologies) and analyzed the effect of the heating time, t_h, on the particles' shape.

We evaluated the heat generation efficiency of the synthesized particles under a radio frequency alternating magnetic field. The particles were dispersed in water with 10% v/v of surfactant (US0010, US Research Nanomaterials Inc.). The volume fraction of particles was set at 0.02%. A cylindrical cell containing 300 µL of the solution was placed inside a coil generating a radio frequency alternating magnetic field. The temperature increase of the solution subjected to an alternating magnetic field (0.3 MHz, 20 kA/m) was measured using an optical fiber thermometer

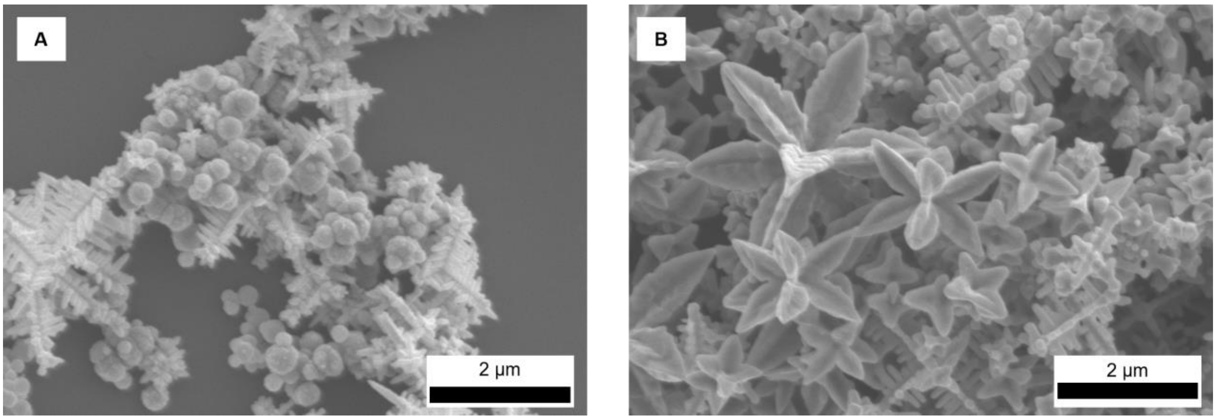

Figure 1: SEM images of magnetic particles. (A) t_h = 0 min. (B) t_h = 120 min.

(Reflex, Neoptix Inc.) and the specific absorption rate (SAR) was calculated by the following equation:

$$\mathrm{SAR}\left[\mathrm{W/g}\right] = \frac{c\left(m_p + m_s\right)}{m_p} \cdot \frac{\Delta T}{\Delta t}, \tag{1}$$

where, c, m_p and m_s are the specific heat of the solvent, the total mass of the particles in the solution and the mass of the solvent, respectively. ΔT represents the temperature increase during the time interval $\Delta t = 300$ s.

3 Results and discussion

SEM images of magnetic particles synthesized in the present study are shown in Fig. 1. Spherical, flower-shaped, and dendritic magnetic particles were synthesized under the supercritical condition and their production rates changed depending on the heating time, t_h. As the heating time increased, the production rate of the non-spherical particles increased. We believe that small spherical particles were initially produced under the high temperature condition and they grew during heating. As the size of the particles increased, their shape may have become non-spherical. In fact, the average size of the particles increased with an increase in the heating time. As the heating time in the production process of the particles increased from 0 to 120 min, the SAR value of the particles increased from 25 to 107 W/g. This suggests that the heat generation efficiency of non-spherical particles was higher than that of the spherical ones since the production rate of the non-spherical particles also increased with an increase in the heating time as mentioned above.

4 Conclusions

We synthesized magnetic particles with ferrocene-ethanol solution. When the solution was heated above the critical temperature of the solvent, spherical, flower-shaped, and dendritic magnetic particles were produced. As the heating time in the particle production process increased, both the production rate of the non-spherical particles and the heat generation efficiency of the particles increased.

References

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