Research Article

Synthesis and Properties of MPEG-Coated Superparamagnetic Magnetite Nanoparticles

Xueli Cao,¹ Baolin Zhang,² Fangyuan Zhao,² and Lingyun Feng²

¹ College of Science, Guilin University of Technology, Guilin 541004, China

² State Key Laboratory Breeding Base of Nonferrous Metals and Specific Materials Processing, School of Materials Science and Engineering, Guilin University of Technology, Guilin 541004, China

Correspondence should be addressed to Baolin Zhang, baolinzhang@ymail.com

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The magnetite nanoparticles were synthesized by the thermal decomposition of iron(III) acetylacetonate in methoxy polyethylene glycol, which was used as solvent, reducing agent, and modifying agent in the reaction. The morphologies and phase compositions of the nanoparticles were determined by transmission electron microscopy and X-ray diffraction, respectively. The surface coating of the nanoparticles was recognized using Fourier transform infrared spectroscopy. Magnetic properties were measured using superconducting quantum interference device. The zeta potential and hydrodynamic size of the nanoparticles was determined using nanoparticle and zeta potential analyzer. The magnetite nanoparticles show superparamagnetic behavior in 300 K. The negatively charged methoxy polyethylene glycol-coated magnetite nanoparticles in water exhibited longer-time dispersion with small hydrodynamic size than the magnetite nanoparticles synthesized by the thermal decomposition of iron(III) acetylacetonate in polyethylene glycol. The less conjunction between methoxy polyethylene glycol-coated magnetite nanoparticles due to the inert $-\text{CH}_3$ terminal group may cause their higher stability in water dispersion.

1. Introduction

Magnetite (Fe_3O_4) nanoparticles (MNPs) with appropriate surface modifications are promising as contrast agents with long blood half-life in magnetic resonance imaging (MRI) such as MR angiography, or cerebral blood pool imaging for fMRI (functional MRI) [1–14]. Monodisperse MNPs with high crystallinity and narrow size distribution have been synthesized by high-temperature organic phase decomposition methods [15–19]. However, those magnetite nanocrystals are only well dispersible in nonpolar solvents because they have been capped by hydrophobic surfactant ligands, which limits their applications in the biomedical field unless a further surface modification is employed. PEG (polyethylene glycol) or MPEG (methoxy polyethylene glycol)-coated MNPs as useful contrast agents show a long blood circulation time because of the protein rejecting ability of PEG [3, 6, 8, 20–22], but their preparation processes reported in the literatures are complex. MNPs with small sizes and good magnetization were synthesized by the polyol process [23, 24]. Because

the aggregations of the MNPs in water take place with time due to the interaction of the nanoparticles, extra treatments have to be exploited to prevent the aggregation [25, 26]. In this work, we synthesized the MNPs in a simple way by the thermal decomposition of iron(III) acetylacetonate ($\text{Fe}(\text{acac})_3$) in MPEG and investigated their properties.

2. Experimental

All the chemicals were analytical purity and used without further purification. MNPs were synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in MPEG (MPEG-1200, $M_w = 1200$, 99%) at elevated temperature. In general, 2 mmol of $\text{Fe}(\text{acac})_3$ (98%) was dissolved in 15 mL MPEG-1200 during magnetically stirring under a flow of argon. The solution was dehydrated at 120°C for 1 h, then quickly heated to 200°C and kept at this temperature for 30 min. Then the temperature was elevated to 320°C and kept for another 30 min. The black solutions were cooled at room temperature and then

FIGURE 1: XRD patterns of the magnetite nanoparticles synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in MPEG-1200.

FIGURE 2: TEM images of the magnetite nanoparticles synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in (a) MPEG-1200; (b) PEG-1000.

were mixed with 60 mL of toluene. After ultrasonic stirring, the particles were precipitated by the adsorption of magnet and washed two times with acetone to remove the excess organics. The black powders were obtained by drying the precipitates in vacuum and then dispersed in water. For comparison, MNPs were also synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in PEG (PEG-1000, Mw = 1000, 99%) according to the procedure introduced in the literature [24].

Size and morphology of the nanoparticles were determined by transmission electron microscopy (TEM, JEOL-2010) and the crystal structure was identified using X-ray diffraction (XRD, X'Pert PRO, PANalytical). Surface coating and surface charge of the nanoparticles were recognized using Fourier transform infrared spectroscopy (FTIR, Nicolet Nexus 470, Thermo Electron) and zeta potential measurements (Nano ZS900, Malvern). Magnetic properties were determined using superconducting quantum interference device (SQUID, MPMS XL-7, Quantum Design) measurements.

3. Results and Discussion

Figure 1 shows the XRD pattern of the particles synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in MPEG-1200, which matches well with the standard XRD patterns of bulk magnetite (JCPDS File no. 01-085-1436) indicating that the particles contain Fe_3O_4 phase. The peaks with 2θ values of 30.09° , 35.44° , 43.07° , 53.43° , 56.96° , and 62.54° correspond to the crystal planes (220), (311), (400), (422), (511), and (440) of crystalline Fe_3O_4 , respectively. The widths of these peaks obviously are broaden and the average crystallite size calculated using Scherrer's equation gives 9.3 nm for (311) peak, which is consistent with the size measured in the TEM image (Figure 2(a)), indicating the single crystal nature of the particles. Figure 2 shows the TEM morphologies of MNPs synthesized in MPEG and in PEG, TEM samples were made by dropping the water dispersion onto carbon-coated copper grids and drying them under room temperature. The average sizes of the particle are 9.5 ± 1.7 nm and 10.1 ± 2 nm for MPEG-1200 and PEG-1000 as reactants, respectively.

FIGURE 3: FT-IR spectra of (a) the magnetite nanoparticles coated with MPEG-1200; (b) MPEG-1200.

Figure 3 shows the FTIR spectra for the MNPs synthesized in MPEG-1200 and pure MPEG-1200. New peaks can be found at about 1602 cm^{-1} , 1442 cm^{-1} , and 588 cm^{-1} by comparing curve (a) and curve (b). The peaks at 1602 cm^{-1} , 1442 cm^{-1} can be assigned to the COO^- vibrations [23, 24], the strong absorption band at about 580 cm^{-1} is due to Fe–O stretching vibration for the Fe_3O_4 nanoparticles [23, 24]. This suggests that $-\text{CH}_2-\text{OH}$ group has been oxidized to COO^- group during the reaction. The reaction at the $-\text{OH}$ sites [24], the subsequently Fe_3O_4 nucleation, and grain growth could be the mechanism of the formation of Fe_3O_4 nanoparticles.

Figure 4 shows the zeta potential measurement of the MPEG-coated MNPs dissolved in deionized water. The zeta potential is about -21 mV that provides electrostatic repulsion forces between nanoparticles. Figure 5 shows the images of the MNPs modified by MPEG-1200 and by PEG-1000 in water with the concentration at about 5 mg/mL . The MPEG-coated MNPs had been dispersed well in water for more than 3 months and no flocculates or precipitates were observed. However, the MNPs modified by PEG started to precipitate in water for several days, which surely would impair their application. It did not produce much difference to the results when we tried to wash the nanoparticles with acetone or ethyl acetate according to the experiment procedure or to vary the synthesis temperature between $240\text{--}320^\circ\text{C}$. Therefore, although synthesized in and modified by polyols, the dispersion stabilities of the nanoparticles in water are quite different. MPEG-1200 molecular can provide much steric hindrance because of its inactive methyl terminal groups [27] and size effect, and with the static repulsion [2–4], to stabilize the dispersion of the nanoparticles in water. MPEG-coated MNPs can avoid forming network structure due to the inert

FIGURE 4: The zeta potential measurement of the magnetite nanoparticles modified by MPEG-1200 dispersed in deionized water.

FIGURE 5: Colloidal stability tests of the magnetite nanoparticles modified by MPEG-1200 and by PEG-1000 in water.

terminal groups; however, PEG-coated MNPs form network structure easily (Scheme 1) [27].

The MPEG-coated MNPs were stable in water with small hydrodynamic size (Figure 6), which almost did not change for 3 months (Figure 7). This is an essential property that MNPs should have in order to meet the requirement in applications. On the contrary, the hydrodynamic size of the as-prepared MNPs modified by PEG-1000 was quite large (Figure 8), they precipitated in water for several days. This might be due to the possible formation of hydrogen bonding between adjacent PEGs coated on MNPs [25, 27]. It indicates that rather than the dissolution of PEGs from the surface of nanoparticles into water, which can cause aggregations of nanoparticles, the conjunction between surface molecular results in the poor water dispersion stability of the nanoparticles.

SCHEME 1: Illustration of the magnetite nanoparticles synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in PEG and in MPEG.

FIGURE 6: The hydrodynamic size of the magnetite nanoparticles synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in MPEG-1200.

Figure 9 shows the hysteretic M-H curve of the MPEG-coated MNPs at 300 K. Zero coercivity and zero remanence on the magnetization curves indicate superparamagnetic behavior of the MNPs, the saturation magnetization of the MNPs was 48 emu/g. Thermogravimetric analysis of the MNPs synthesized in MPEG-1200 shows the presence of 19% of polymer, so the saturation magnetization of Fe_3O_4 can be adjusted to 59 emu/g.

Choosing MPEG as the modification agent is also based on the purpose that we expect the MNPs can be used as the fMRI contrast agents. Longer time circulation in blood and more stable concentration in blood over time are critical requirement in that application [1, 3, 4, 6]. MPEG-coated MNPs that have no reactive $-\text{OH}$ terminal group as compared to PEG-coated MNPs on their surfaces may meet the requirement.

4. Conclusions

The MNPs were synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in MPEG-1200. The nanoparticles show superparamagnetic behavior in 300 K. The negatively charged nanoparticles with small hydrodynamic size exhibited longer time dispersion in water than the MNPs synthesized by

FIGURE 7: The hydrodynamic size of the magnetite nanoparticles synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in MPEG-1200 after being dispersed in water for 3 months.

FIGURE 8: The hydrodynamic size of the magnetite nanoparticles synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in PEG-1000.

FIGURE 9: M-H curve of the magnetite nanoparticles (with the modification layer) synthesized by the thermal decomposition of $\text{Fe}(\text{acac})_3$ in MPEG-1200.

the thermal decomposition of $\text{Fe}(\text{acac})_3$ in PEG-1000. The reduced conjunction between nanoparticles due to the inert $-\text{CH}_3$ terminal group, the steric hindrance and the electrostatic repulsion forces between the MPEG-coated nanoparticles altogether could cause the higher stability in water dispersion. Future work can be done on the testing of the nanoparticles after treatments strictly according to medical procedures as contrast agents in magnetic resonance imaging such as MR angiography and cerebral blood pool imaging for fMRI.

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