Original Article

Properties of manganese ferrite-paraffin composites

Ronaldo Sergio de Biasi a,∗, Gabriel Burlandy Mota de Melo a, André Ben-Hur da Silva Figueiredo a, Mariella Alzamora Camarena b, José Brant de Campos c

a Seção de Engenharia Mecânica e de Materiais, Instituto Militar de Engenharia, 22290-270 Rio de Janeiro, RJ, Brazil
b Universidade Federal do Rio de Janeiro, Duque de Caxias, RJ, Brazil
c Universidade do Estado do Rio de Janeiro, São Cristóvão, RJ, Brazil

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ABSTRACT

Manganese ferrite (MnFe 2 O 4 ) nanoparticles were dispersed in paraffin and the physical properties of this composite were investigated by X-ray diffraction (XRD), ferromagnetic resonance (FMR), vibrating sample magnetometry (VSM), field cooled (FC) and zero field cooled (ZFC) curves and Mössbauer spectroscopy. The results showed that dispersion in moderate quantities of paraffin significantly increases the crystallite size, the absolute value of the anisotropy field, the saturation magnetization and the blocking temperature of the nanoparticles, a result that may be of interest for practical applications of the composite.

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1. Introduction

Nanometric manganese ferrite is a much-studied material for industrial and medical applications, such as microwave absorption, catalysis, magnetohyperthermia and drug delivery [1–4], due to its high saturation magnetization and good chemical stability [5]. However, due to magnetic attraction, ferrite nanoparticles tend to form agglomerates, which may compromise their performance for certain applications. One of the proposed solutions has been to disperse the nanoparticles in nonmagnetic materials [4–14]. A convenient nonmagnetic material is paraffin, a relatively cheap material with a low melting point.

The purpose of this work is to investigate the influence of dispersion in paraffin on the magnetic anisotropy of manganese ferrite. To achieve this end, we made samples with different dilutions of ferrite in paraffin.

2. Methods and results

2.1. Sample preparation

Manganese ferrite nanoparticles were synthesized by the combustion method [15]. Stoichiometric amounts of manganese nitrate, Mn(NO 3 ) 2 ·4H 2 O, Aldrich, 98%, and iron nitrate, Fe(NO 3 ) 3 ·9H 2 O, Aldrich, 98%, were dissolved in deionized...
water to obtain the starting solution. To this was added a solution of glycine, C2H4NO2, Aldrich, 98.5%, with a glycine-nitrate molar ratio (G/N) of 0.5. The resulting solution was stirred for 20 min at room temperature and heated to 100 °C so that auto-combustion would take place. The resulting ferrite powder was dispersed in molten paraffin with paraffin/ferrite weight (P/F) ratios of 5, 10, 15 and 20 using a 40 kHz ultrasonic bath.

2.2. XRD measurements

X-ray diffractograms were recorded at room temperature in a PANalytical X'Pert PRO diffractometer using Cu Kα radiation (0.15418 nm). Fig. 1 shows a diffractogram of undispersed ferrite powder, a diffractogram of paraffin, and diffractograms of P/F = 5, 10, 15 and 20 composites. A Rietveld refinement, performed using the HighScore plus 3.0 application, revealed that the sample of undispersed ferrite powder consists of 90% manganese ferrite (MnFe2O4), with an average crystallite size of 7 nm and a lattice constant of 0.85 nm, and 10% hematite (Fe2O3). The peaks labeled as (220), (311) and (440) are attributed to manganese ferrite, while the (401) peak is attributed to hematite. The files used in the analysis were ICSD-250539 for manganese ferrite and ICSD-415251 for hematite. The paraffin peaks (110) and (200) were identified using the file JCPDS 00-040-1995.

Since no ICSD file was available for paraffin, we could not perform a Rietveld refinement for the composites and thus, in this case, the lattice constant of the manganese ferrite nanoparticles was determined using, for the (311) peak, the equation [16]

\[ a = \frac{\lambda}{2 \sin \theta} \sqrt{h^2 + k^2 + l^2} \]  

(1)

where \( \lambda \) is the X-ray wavelength, \( \theta \) is the diffraction angle and \( h, k \) and \( l \) are the Miller indices of the diffracting plane, and the average crystallite size was determined using, for the (311) peak, the Debye–Scherrer equation [16]

\[ d = \frac{0.91}{B \cos \theta} \]  

(2)

where \( B \) is the peak width at half maximum. The results are shown in Table 1, where P/F = 0 means pure magnesium ferrite powder. Note that for pure manganese ferrite, the results were identical to those obtained using the Rietveld refinement.

An expanded view of the diffractograms is displayed in Fig. 2. The (311) peak of manganese ferrite, shown by an

Table 1 – Diffraction angle 2θ of the (311) line, lattice constant a and average crystallite size d of undispersed powder (P/F = 0) and of manganese ferrite-paraffin composites.

<table>
<thead>
<tr>
<th>P/F</th>
<th>2θ (degrees)</th>
<th>a (nm)</th>
<th>d (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>35.12</td>
<td>0.848</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>35.22</td>
<td>0.845</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>35.82</td>
<td>0.831</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>35.69</td>
<td>0.834</td>
<td>9</td>
</tr>
<tr>
<td>20</td>
<td>35.67</td>
<td>0.835</td>
<td>8</td>
</tr>
</tbody>
</table>

Fig. 1 – X-ray diffractograms of undiluted manganese ferrite, paraffin and manganese ferrite-paraffin composites.

Fig. 2 – Expanded view of the (311) peak of manganese ferrite in the diffractograms of manganese ferrite-paraffin composites.
Fig. 3 – FMR spectrum of a manganese ferrite-paraffin composite with a paraffin-manganese ferrite weight ratio P/F = 5.

Fig. 4 – Dependence of the absolute value of the magnetic anisotropy of manganese ferrite-paraffin composites on the P/F ratio. The lines are only guides to the eye.

Table 2 – Magnetic resonance parameters of undispersed powder (P/F = 0) and of manganese ferrite-paraffin composites.

<table>
<thead>
<tr>
<th>P/F</th>
<th>g</th>
<th>H_a (mT)</th>
<th>σ (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.10</td>
<td>-29.0</td>
<td>78.5</td>
</tr>
<tr>
<td>5</td>
<td>2.10</td>
<td>-41.5</td>
<td>90.3</td>
</tr>
<tr>
<td>10</td>
<td>2.10</td>
<td>-47.0</td>
<td>103.3</td>
</tr>
<tr>
<td>15</td>
<td>2.10</td>
<td>-42.0</td>
<td>97.9</td>
</tr>
<tr>
<td>20</td>
<td>2.10</td>
<td>-37.0</td>
<td>86.8</td>
</tr>
</tbody>
</table>

Fig. 5 – Hysteresis loops of all samples.

Table 3 – Saturation magnetization and blocking temperature of undispersed powder (P/F = 0) and of manganese ferrite-paraffin composites.

<table>
<thead>
<tr>
<th>P/F</th>
<th>M (emu/g)</th>
<th>T_b (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>28.8</td>
<td>&lt;50</td>
</tr>
<tr>
<td>5</td>
<td>21.9</td>
<td>260</td>
</tr>
<tr>
<td>10</td>
<td>31.0</td>
<td>280</td>
</tr>
<tr>
<td>15</td>
<td>30.7</td>
<td>265</td>
</tr>
<tr>
<td>20</td>
<td>20.8</td>
<td>260</td>
</tr>
</tbody>
</table>

arrow, is shifted to the right in the composites and the maximum shift occurs for P/F = 10, while the peak of paraffin at 2θ = 36.4° is shifted to the left in the composites up to 2θ = 36.8° for P/F = 20. The reason for this behavior is discussed in Section 3.

2.3. FMR measurements

Ferromagnetic resonance measurements were performed at room temperature and 9.50 GHz using a Varian E-12 spectrometer with 100 kHz field modulation. The microwave power was 5 mW and the modulation amplitude was 1 mT. The magnetic field was calibrated with an NMR gaussmeter. Measurement of undiluted manganese ferrite powder was performed loading the powder in a quartz tube.

The experimental results were fitted to theoretical spectra using a computer program developed by Taylor and Bray [17] for paramagnetic resonance spectra and adapted by Griscom [18] for ferromagnetic resonance spectra. A typical spectrum is shown in Fig. 3 for a sample with P/F = 5. The fitting was generally good, except for the low field part of the spectra, where the slope of the amplitude rise is much steeper in the experimental curves. This mismatch is attributed [19] to superparamagnetic effects. The fitting parameters are shown in Table 2 and the dependence of the absolute value of the anisotropy field H_a on the P/F ratio is shown in Fig. 4.

2.4. Magnetization measurements

Magnetization measurements were performed in an MPMS Quantum Design equipment using a Quantum Design VSM. The hysteresis loop at 300 K is shown in Fig. 5 and the FC and ZFC curves are shown in Fig. 6. The values of the saturation magnetization M at 300 K, obtained from the hysteresis loop, and of the blocking temperature T_b, obtained from the ZFC curves, are shown in Table 3. The blocking temperature of undiluted manganese ferrite could not be measured because the maximum of the ZFC curve is below 50 K and thus is out of the range of our equipment.
The Mössbauer spectra were recorded at room temperature in a homemade equipment of the Centro Brasileiro de Pesquisas Físicas (CBPF). Fig. 7 shows the Mössbauer spectra (a) of undispersed ferrite powder, (b) of the composite with \( P/F = 10 \) and (c) of the composite with \( P/F = 20 \). As shown in the figure, the spectra consist of three lines: a high amplitude sextet, a low amplitude sextet and a doublet. The low amplitude sextet is attributed to hematite, the high amplitude sextet to blocked ferrite particles in tetrahedral and octahedral sites (at room temperature, the sextets due to iron atoms in tetrahedral and octahedral sites are so wide that they cannot be separated) and the doublet is attributed to unblocked ferrite particles, i.e., particles in the superparamagnetic state. Table 4 shows the relative areas of the low intensity sextet \( (S_1) \), of the high intensity sextet \( (S_2) \) and of the doublet \( (D) \).

### Table 4 – Relative areas of the components of the Mössbauer spectra of undispersed ferrite powder \( (P/F=0) \) and of manganese ferrite-paraffin composites.

<table>
<thead>
<tr>
<th>P/F</th>
<th>( S_1 ) (%)</th>
<th>( S_2 ) (%)</th>
<th>( D ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
<td>72</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>79</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>11</td>
<td>78</td>
<td>11</td>
</tr>
</tbody>
</table>

3. **Discussion**

The fact that parameters of the ferrite nanoparticles such as the anisotropy field (Table 2), the blocking temperature of superparamagnetism (Table 3) and the relative area of the Mössbauer sextet (Table 4) go through a maximum for \( P/F = 10 \) is coherent with the fact that the average size of the nanoparticles increases with increasing dilution for \( P/F < 10 \) and decreases with increasing dilution for \( P/F > 10 \) (Table 1).

A faster saturation of the magnetization of manganese ferrite nanoparticles diluted with paraffin as compared with undiluted nanoparticles was observed by Aslibeiki and Kameli [5] and attributed to the interaction of paraffin with a disordered layer in the surface of the nanoparticles, making it more ordered and thus increasing the effective particle size. This is consistent with the fact that the (311) peak of the diffraction pattern of manganese ferrite is shifted to the right in all composites (Table 1 and Fig. 2), indicating a compressive tension exerted by the paraffin. On the other hand, the shift to the right of the paraffin peak suggests a tractive force, possibly due to the ultrasonic bath.

The decrease of the particle size for values of \( P/F \) larger than 10 appears to be related to the fact that the compressive tension exerted by the paraffin molecules decreases at high dilutions, as suggested by the increase in the lattice...
constant (see Table 1). The decrease of saturation magnetization for P/F > 10 is attributed to superparamagnetic effects, as evidenced by a decrease of the blocking temperature (see Table 3) and an increase of the relative number of unblocked particles observed in the Mössbauer spectra (see Table 4).

4. Conclusions

In this work, the properties of manganese ferrite nanoparticle-paraffin composites were investigated. The results showed that many measured parameters go through an extremum for P/F = 10. In particular, the saturation magnetization, the absolute value of the anisotropy field and the blocking temperature are maximum for this value of P/F, a finding that could be of interest for technological applications such as microwave absorption and drug delivery.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

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References