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ON THE TRANSITION BETWEEN FERROMAGNETIC AND PARAMAGNETIC STATES IN MESOPOROUS MATERIALS WITH FRACTAL MORPHOLOGY

Shishulin A.V.[1,*], Potapov A.A.[2,3], Shishulina A.V.[4,5]

[1]G.A. Razuvaev institute of organometallic chemistry, Russian Academy of sciences, Nizhny Novgorod, Russia, chichouline_alex@live.ru
[2]V.A. Kotel'nikov institute of radio engineering and electronics, Russian Academy of sciences, Moscow, Russia
[3]JNU-IREE RAS Joint Laboratory of Information Technology and Fractal Processing of Signals, Jinan University, Guangzhou, China
[4]R.E. Alekseev Nizhny Novgorod State technical University, Nizhny Novgorod, Russia
[5]N.I. Lobachevsky Nizhny Novgorod State University, Nizhny Novgorod, Russia

In this paper, we have shown how the presence of pores and pore morphology influence on magnetic phase transition temperatures in mesoporous ferromagnetic materials. Model calculations have demonstrated the possibility to obtain macroscopic mesoporous samples with notably reduced Curie temperatures which is also further depressed in the case the pore morphology is more complicated. The results have been obtained on the basis of the experimentally verified correlation between the Curie temperature and cohesive energy of the material and illustrated using the examples of pure mesoporous iron, nickel and cobalt while pore morphology has been determined by the methods of fractal geometry. Several practical applications of mesoporous materials with tuned values of the Curie temperature have also been discussed in the final section.

Keywords: mesoporous materials, second-order phase transition, ferromagnetism, Curie temperature, cohesive energy.

Introduction

Nanostructured ferromagnetic materials are objects of a considerable interest among researchers [1]. Tremendous attention is being attracted to such materials in recent years due to a wide range of their technological applications including high-density information storage devices [2], magneto-optical sensors [3], spintronics devices [4], biomedical technologies [5] etc, as well as a set of phenomena of fundamental interest such as superparamagnetism [6], giant magnetoresistance [7, 8], complicated dynamics of magnetic skyrmions [9] or magnetic catalysis [10]. One of the main and vital parameters which determine the behavior of ferromagnetic materials is the Curie temperature (temperature of a second-order phase transition when magnetic ordering disappears and ferromagnetic materials become paramagnetic). It is well-known that nanoscale particles or grains of a ferromagnetic material exhibit a lower Curie temperature [11-20] which is (as well as some other parameters, e.g. the saturation magnetization [16], characteristics of hysteresis loops [20] or magnetic anisotropy constants [21]) size- [11-20] and shape-dependent [14,15,20]. Such size- and shape effects in nanoparticles are commonly related to an increase in the surface-to-volume ratio with decreasing the size of a nanoparticle and "complicating" its shape which causes an increase in the fraction of lower coordinated atoms near the surface edge with magnetic characteristics (e.g. magnetic moments, exchange integrals etc. [19]) different from the bulk ones. Such regularities could be described using various approaches including models based on the spin-spin correlation length mechanism [11], on the bond order-length-strength correlation combined with the Ising preposition [12],on Monte-Carlo [19,20] and molecular-statics simulations on the Ising model [20] or on the size- and shape-dependent cohesive energy of nanostructures [14-16].

Note that high surface-to-volume ratios and fractions of surface atoms could be obtained not only in nanopowders or in nanocomposites containing nanoparticles distributed in a matrix, but also in microporous and mesoporous materials, while porous samples of such materials can be macroscopic-sized [22-24]. Formation of such structures is possible, for example, during the early stages of spark plasma sintering [25], laser sintering [26] of nanopowders (a review of synthesis methods of nanosized powders has been presented by M.K. Berner *et al* [27]) as well as using a variety of other techniques, e.g. [28].

1. A cohesive energy-based model for magnetic phase transitions in mesoporous media.

The object of simulation is a mesoporous material with the given volume fraction of pores, α .In order to take into account possible irregular and complicated pore shapes [28], let us introduce two parameters for their description. The first one is the effective diameter of the pore, d_{eff}, which is equal to the diameter of a spherical pore of the same volume, and the second one could be, for example, the pore shape coefficient, k. The shape coefficient is the ratio between the surface area of the pore under consideration, A , and the surface area of the sphere of the same volume, A_0 : $k = A/A_0$ (in details, such approach and its variants have been described in [29-32], being applied to porous structures. In [33], some other geometry considerations could be found). The number of pores in 1 g of a material, N_{por}, could be calculated as $N_{por} = 6\alpha \cdot 1\ \mathrm{g}/\left(\pi\rho d_{eff}^3\right)$ where ρ is the material density. Factor 1 g has been introduced to match the units. The specific surface area, A_{sp} , could be expressed as $A_{sp} = N_{por} \cdot \pi k d_{eff}^2 = 6\alpha k \cdot 1\ \mathrm{g}/\left(\rho d_{eff}\right)$. To estimate the influence of the pore morphology on the Curie temperature of a mesoporous material, let us use a simple expression describing the relation between the Curie temperature of a material and its cohesive energy:

$$\frac{T_c^{por}}{T_c^{bulk}} = \frac{E_{coh}^{por}}{E_{coh}^{bulk}}. \tag{1}$$

Here, E_{coh}^{por} and E_{coh}^{bulk} are the cohesive energies of porous and continuous materials, respectively; T_c^{por} and T_c^{bulk} are the Curie temperatures of a porous material and a material in the absence of pores, respectively.

This expression has been retrieved in Refs. [13-16] and experimentally justified by the authors of [16]. This expression is similar to the one used by G. Guisbiers, *et al* to describe different size-and shape-dependent material properties [34-36] and also found to be in a good agreement with experimental data. 1g of a porous material contains N atoms, where $N = 6\omega \cdot 1\ \mathrm{g}/\left(\pi d_{at}^3 \cdot \rho\right)$. Here, d_{at} is the atomic diameter and ω is the lattice packing parameter in the crystal structure. N_s atoms are located on the pore walls: $N_s = \eta A_{sp}/\pi d_{at}^2 = 6\alpha\eta k \cdot 1\ \mathrm{g}/\left(\pi\rho d_{at}^2 d_{eff}\right)$ where η is the surface packing parameter. So, the number of atoms at the surface is given by

$$N_s = \left(\frac{6 \cdot 1\ \mathrm{g}}{\pi\rho}\right)^{1/3} \cdot \frac{\alpha\eta k}{\omega^{2/3} d_{eff}} N^{2/3}. \tag{2}$$

The estimates for the cohesive energy of a porous material could be obtained using the relations suggested by F. Aqra and A. Ayyad [37]:

$$\begin{aligned} E_{coh}^{bulk} &= \frac{1}{2}\beta N \varepsilon_b, \\ E_{coh}^{por} &= \frac{1}{2}\beta\varepsilon_b\left(\frac{1}{4}N_s + \left(N - N_s\right)\right), \end{aligned} \tag{3}$$

where β is the number of bonds per one atom in the structure and ε_b is the bond energy.

Therefore, from Eqs. (1-3) we have

$$E_{coh}^{por} = \frac{1}{2}\beta\varepsilon_b N\left(1 - \frac{3}{4}\left(\frac{6 \cdot 1\ \mathrm{g}}{\pi\rho}\right)^{1/3} \frac{\alpha\eta k}{\omega^{2/3} d_{eff}} N^{-1/3}\right), \tag{4}$$

$$T_c^{por} = T_c^{bulk}\left(1 - \frac{3}{4}\left(\frac{6 \cdot 1\ \mathrm{g}}{\pi\rho}\right)^{1/3} \frac{\alpha\eta k}{\omega^{2/3} d_{eff}} N^{-1/3}\right). \tag{5}$$

Below, the Curie temperatures of mesoporous materials have been estimated by using Eq. 5. High values of shape coefficient k could be obtained, for example, in the case of porous materials where the pores have the shapes similar to simple non-spherical geometric structures (for example, k=1.49 for a tetrahedron, k=1.52 for a cone, k=3.20 for a star icosahedron (an icosahedron with a tetrahedron at each face)) or structures extended in

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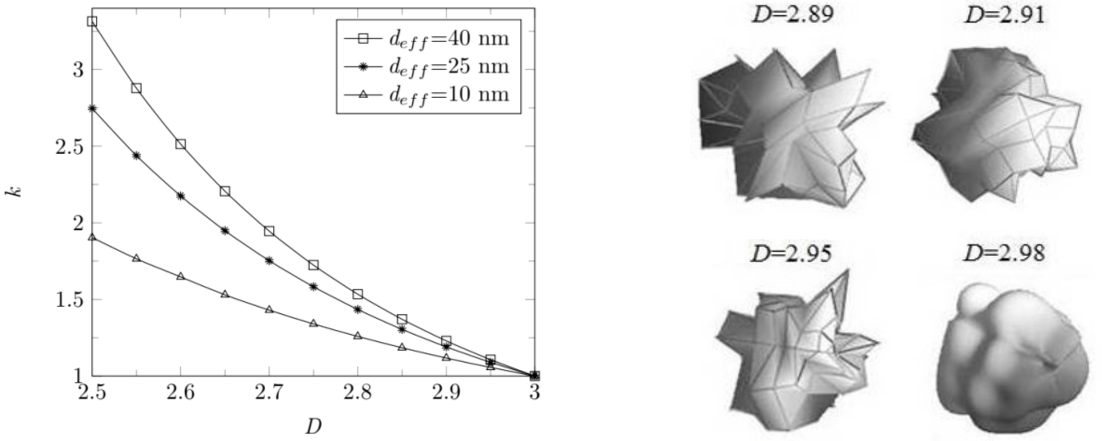
one direction (for example, values $k>2.00$ correspond to oblate spheroids with aspect ratio $a/b>5$ or to prolate spheroids with $a/b>3$). Moreover, high surface-to-volume ratios are also characteristic for pores of complicated and irregular shapes, in order to take into account their morphology, the notion of fractal geometry is often used [29,30,38-42]. According to the approach suggested by us in [30, 40-42], the shape of a pore can be characterized by its fractal dimension D which correlates its volume V and surface area A: $A = CV^{2/D}$, where C is a numerical coefficient.

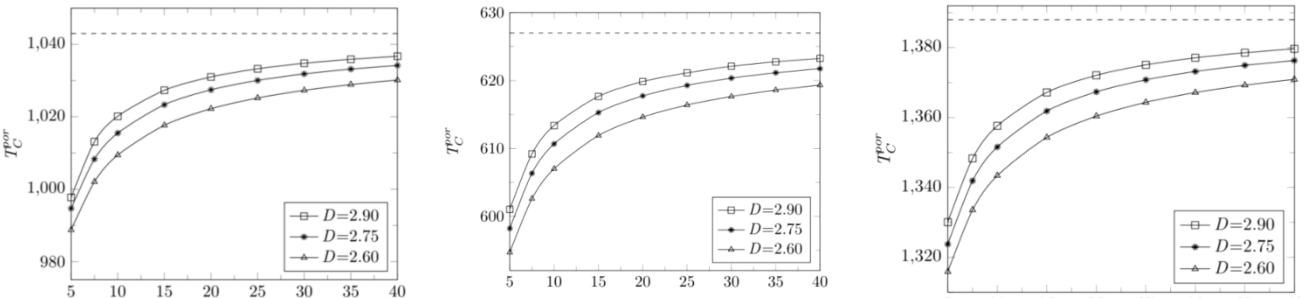
Without any losses of generality, coefficient C, which also matches dimensions, is accepted below to be 4π for the sake of convenience. For real irregular morphologies of materials structure elements, $D<3$ and is typically non-integer. The most classic examples of fractal structures are *worm-like*, *amoeba-like,* and *porcupine-like* ones [30, 40-43].



a *b*

Fig. 1. a) shape coefficient k of a pore versus its effective diameter d_{eff} and fractal dimension D; b) examples of "amoeba-like" and "porcupine-like" fractal structures with various D.

The correlation between shape coefficient k (the ratio between the surface areas of the pore under consideration and the spherical pore of the same volume), pore volume $V = \pi d_{eff}^3/6$ and its fractal dimension D is determined as follows: $k(V,D) = V^{2/D}/(3V/4\pi)^{2/3}$ (see Fig. 1a). Several examples of *amoeba-like* and *porcupine-like* structures with various fractal dimensions are presented in Fig. 2b.



a *b* *c*

Fig. 2. The dependences of the Curie temperatures for mesoporous Fe (a), Ni (b), Co (c) on pore geometric characteristics (fractal dimensions D and effective diameters d_{eff} of pores). The Curie temperatures for continuous macroscopic samples are 1043 for Fe, 627 K for Ni,1388 K for Co.

It is necessary to note that such parameters as shape coefficients or fractal dimensions generalize different but equivalent variants of materials morphology: the structures which differ in their geometric outlook but share the same values of k or D (see Fig. 1b in [41], for example) have the same fraction of surface atoms and demonstrate the same behavior in the case considered in the present paper.

Specific surface areas in micro- and mesoporous materials can reach extremely high values (from 500m^3/g [22] to 1000 m^3/g [23] or even several thousands of m^3/g [24]). In the present paper, however, we limit ourselves to considering materials with not very high specific surface areas (in comparison with the values obtained in [22-24]), mostly below 200-300 m^3/g (α=0.85). The dependences of the Curie temperature on pore size and shape for mesoporous iron (*a*), nickel (*b*) and cobalt (*c*) are plotted in Fig. 2. For these metals, material densities and atomic diameters are accepted in our estimates to be 7.874 g/cm^3 and 252 pm, respectively, for Fe; 8.902 g/cm^3 and 248 pm, respectively, for Ni; 8.900 g/cm^3 and 250 pm, respectively, for Co. The structure of nickel is *fcc* within the entire temperature range up to the melting point. At the same time, cobalt has two stable polymorphic modifications: β-Co with a *fcc* crystal lattice which is equilibrium in the considered temperature range and low-temperature hexagonal α-Co (the temperature of the $\alpha \leftrightarrow \beta$ polymorph transition is about 700 K). At the temperatures under consideration, the structure of Fe is *bcc* (α-Fe), iron exhibits the $\alpha \leftrightarrow \gamma$ polymorph transition between *bcc* and *fcc* modifications at about 1190 K. Packing parameters are ω=0.74, η = 0.91 for *fcc* structures [37,44] and ω=0.68, η = 0.83 for *bcc* ones [44].

Fig. 2 shows that reducing the effective pore diameter, d_{eff}, and increase the shape coefficient, *k*, (an increase in the specific surface area of a material) are accompanied with a decrease in the Curie temperature. Note that in the case of pores filled with a substance, such estimates are to be corrected, for example, by modifying the approach suggested by C. Ling-fei *et al.* [14] for embedded nanoparticles. Increasing the specific surface area of porous materials up to the values obtained experimentally by the authors of [22-24] allows expecting much more significant shifts of the magnetic transition temperatures similar to the ones obtained in [19] for free-standing nanoparticles.

Conclusion

It is also worth noting that micro- and mesoporous materials (with functionalized pore walls [45], maybe) have a wide range of technological applications e.g. nanoreactor matrices [46]. For multiple applications, a great interest is attracted by magnetocaloric effects in ferromagnetic nanostructures, for example, heating ferromagnetic nanoparticles - invasive agents in alternating magnetic fields (magnetic hyperthermia treatment for cancer) due to hysteresis losses, losses for re-orientation of the magnetization vector etc. and maintaining their temperature near the Curie point [5, 47]. In the case considered in this paper, the possibility to tune the Curie temperature of materials by preparing the samples with different pore morphologies and specific surface areas shows possibilities to obtain mesoporous materials/nanoreactors with self-imposed limits of raising the temperature in alternating magnetic fields and the possibility of autonomous temperature control. The considered ferromagnetic materials have also high catalytic activity in a variety of commonly used chemical reactions [36]; meanwhile, materials with a higher specific surface area of pores (up to the ones from [24]) allow expecting a more significant decrease in the Curie temperatures down to the values demonstrated in [19].

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