Published in final edited form as:

Carbon N Y. 2017 November ; 124: 170–179. doi:10.1016/j.carbon.2017.08.043.

Synthesis and Characterization of Graphite-Encapsulated Iron Nanoparticles from Ball Milling-Assisted Low-Pressure Chemical Vapor Deposition

Duygu A. A. Ullari^{1,2,*}, Steven J. Madsen^{2,*}, Burcu Ögüt², Ai Leen Koh³, and Robert Sinclair²

¹Particulate Materials Laboratories (PML), Department of Metallurgical and Materials Engineering, Faculty of Chemical and Metallurgical Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey

²Department of Materials Science and Engineering, Stanford University, 496 Lomita Mall, Stanford, CA 94305-4034, USA

³Stanford Nano Shared Facilities, Stanford University, Stanford, CA 94305-4045, USA

Abstract

Graphite-encapsulated Fe nanoparticles were synthesized using a combined method of high-energy ball milling and low-pressure chemical vapor deposition (LPCVD). Fe₂O₃ and graphite powders were milled to increase their surface areas and obtain a more homogeneous distribution. LPCVD was performed at a pressure of ~0.57 Torr in a tube furnace under a CH₄/H₂ atmosphere at 1050°C for 1 and 3 h. As-synthesized samples were purified in a 2 M HF solution. Characterization was performed using X-ray diffractometry (XRD), scanning and transmission electron microscopy (SEM and TEM) and alternating gradient magnetometry (AGM). XRD revealed the presence of body centered cubic (BCC) and face centered cubic (FCC) Fe phases without residual iron oxides. SEM confirmed the powders were better mixed and smaller after ball milling compared to mortar and pestle milled powders. High resolution TEM showed all nanoparticles had at least four and on average 16 graphitic layers, around an Fe core ranging from 20–300 nm. Magnetic measurements indicated that nanoparticles exhibit soft ferromagnetic behavior with low saturation magnetization (17–21 emu/g) and coercivity (110 Oe). A chemical stability test performed in a 2 M HCl solution showed that graphitic shells did not degrade, nor was there evidence of core dissolution or shell discontinuity.

1. Introduction

There is considerable interest in metallic magnetic nanoparticles owing to their potential applications such as magnetic carriers for biomedicine, malignant cancer detection and therapy, drug and gene delivery, drug targeting, magnetic resonance imaging (MRI), magnetic data storage, magnetic sifting and xerography [1–8]. In particular, Fe, Ni and Co-based magnetic nanoparticles are preferred candidates for medical applications because of

*Corresponding authors. Tel: +90(212) 285 68 58; bozkurtdurdu@itu.edu.tr (Duygu A. A. Ullari); Tel: +1(248) 990 4846; smadsen1@stanford.edu (Steven Madsen).

their high magnetization and catalyzing abilities [4,6,9,10]. However, they oxidize readily and the strategy has been to encapsulate them with a protective layer to prevent them from being oxidized or corroded [4,11–14]. Materials such as silica, boron nitride, noble metals and organic polymers have been used for such coating [15–22]. Carbon has also been considered to be a good option to form core/shell type nanostructures because it is light-weight, biocompatible, thermally stable, chemically inert and easily functionalized [1,4,8,15–19].

Several studies on the preparation of carbon-encapsulated magnetic nanoparticles (CEMNPs) have been reported since their discovery during growth of single or double-walled carbon nanotubes (S/DWCNTs) [23]. Methods such as carbon arc discharge [9,24–26], solid-state synthesis from iron chelates under $H_2/N_2/O_2$ flows [15], flame spray synthesis [27], pulsed Nd:YAG laser irradiation [4], mechanically activated annealing [10], radio frequency (RF) thermal plasma jet method [18,19,28], solid-state carbothermal reduction [29], spray pyrolysis [30], arc plasma and combustion synthesis/explosion [31,32], microwave-arcing-induced synthesis [33], autoclave synthesis [34], ion-beam sputtering [35] and hydrothermal reaction [36] have been used starting from various raw materials. The carbon encapsulant could be in the amorphous or graphitic form, depending on the source, reaction temperature and interaction of carbon and core starting materials [24–36]. The major drawback of these syntheses approaches is the formation of non-encapsulated particles, or carbon encapsulants with defects such as uneven coating due to edges and steps in the graphitic layer, which can affect the long-term stability of the CEMNPs [17–36]. Moreover, non-encapsulated nanoparticles contribute to the magnetic behavior of the resulting product. Thus, a mandatory purification step containing leaching (e.g. in hot HCl solution), filtering, washing (with distilled water and/or ethanol) and drying treatments is conducted to remove the non-encapsulated particles [17–19,28,29,32,36].

Chemical vapor deposition (CVD) has also been employed for the synthesis of CEMNPs under different pressure conditions such as high vacuum (10^{-4} – 10^{-6} Torr), atmospheric pressure and low pressure (0.1–1 Torr) originating from metallic salts or metallic salt-loaded silica powders, metallocene precursors and ferrofluid-loaded silicon wafers [6,11–14,16,37–40]. The formation of non-encapsulated particles encountered in the above-mentioned methods can be avoided using CVD processes by increasing the interaction area and reaction kinetics through the introduction of a gaseous carbon source. However, utilizing a metal precursor which is in the gaseous form or has a low boiling temperature during CVD processes conducted at relatively high temperatures can be a disadvantage for reaction yield and hence for scalability. Thus, using a solid metal precursor and a gaseous source of carbon in a CVD system could be more efficient to produce fully encapsulated particles.

In the present study, we applied a combined method of high-energy ball milling and low-pressure chemical vapor deposition (LPCVD) to synthesize graphite-encapsulated Fe nanoparticles from an inexpensive solid precursor containing hematite (Fe_2O_3) and graphite powders. We prefer graphite to embed Fe_2O_3 in order to prevent possible spinel reaction between metallic source and support material which was encountered in the growth of CNTs (in which Fe precursors were loaded into the oxides). The application of ball milling prior to LPCVD process assists to prepare a well-dispersed reactants with active surfaces ready to be

encapsulated by decomposed gaseous carbon source. Compositional and microstructural analyses by X-ray diffractometry and transmission electron microscopy indicate that this method produces iron nanoparticles with multiple layers of graphitic encapsulation. Additionally, there is no evidence of undesired iron oxides or unencapsulated particles. Finally, we investigated the chemical stability and room-temperature magnetic properties of the synthesized nanoparticles to evaluate their possible usage as a resource for medical applications.

2. Experimental procedure

2.1. Starting materials

Hematite (α -Fe₂O₃, Acros Organics, 99.999 % purity, < 150 μ m particle size) and graphite (C, Sigma-Aldrich, 99.99 % purity, < 150 μ m) powders were used as starting materials. In these experiments, the latter served as a support/substrate in which Fe₂O₃ particles were embedded so as to form a high surface area medium. The graphite can act as a partial reducing agent to obtain Fe nanoparticles as well as a partial graphitization source for the reduced Fe nanoparticles. Stoichiometric powder batches were prepared according to the ideal reduction reaction given in Eq.(1).

For each run, powder batches of 2 g containing 81.6 wt.% Fe₂O₃ and 18.4 wt.% C (a 1:3 molar ratio of Fe₂O₃ to C) were blended by hand in the laboratory atmosphere using an agate mortar and pestle. They are hereinafter referred to as “as-blended” Fe₂O₃-C powders.

2.2. Precursor preparation by high-energy ball milling

As-blended Fe₂O₃-C powders were subjected to a high-energy ball milling process in order to increase the active contact surfaces of the Fe₂O₃ and C particles by reducing their initial sizes, and to mix them more homogeneously. Milling was carried out using a Retsch PM 100 planetary ball mill at a speed of 600 rpm. As-blended Fe₂O₃-C powders were loaded in a stainless steel milling vial (50 ml capacity) with stainless steel balls (4 mm diameter) using a ball-to-powder weight ratio of 10:1. Sample handling was conducted in a Vacuum Atmospheres glove box which was evacuated to about 10⁻³ Pa and back-filled with Ar gas (Praxair, > 99.998 % purity). Milling was continuously performed for 5 h, the product of which is hereinafter referred to as “ball milled” Fe₂O₃-C powders.

2.3. Sample synthesis by low-pressure chemical vapor deposition

500 mg of the ball milled Fe₂O₃-C powders was placed into a quartz boat which was subsequently inserted into a quartz tube (2.54 cm in diameter and 60 cm in length) in a single-zone horizontal tube furnace (Atomate), for a low-pressure chemical vapor deposition (LPCVD) process. Two different gases, hydrogen (H₂, Praxair, 99.999 % purity) and methane (CH₄, Praxair, 99.97 % purity) were employed. Hydrogen gas was utilized for both the reduction of Fe₂O₃ and the acceleration of methane decomposition. Methane gas was used both as a reducing agent for full reduction of Fe₂O₃ and as a main contributor for

formation of graphitic shells around the reduced Fe nanoparticles. A gas mixture of CH₄ and H₂ was delivered together into the quartz tube for 2 min to purge residual air and water vapor in the tube. The furnace temperature was ramped up from room temperature to 1050°C in about 1 h, with H₂ gas flowing through the tube at a rate of 100 ml/min. The temperature and gas flow rates were chosen to ensure complete reduction of Fe₂O₃ to metallic Fe. Once the furnace had been heated to 1050°C, a 1:1 molar ratio of H₂:CH₄ gas mixture was introduced at 200 ml/min. The flow rates were controlled by a vacuum gauge measurement and control system (MKS Type 146 C). Samples were held at 1050°C for either 1 h or 3 h, after which cooling was performed under the same gas mixture for about 1 h. The heating element was not powered during this step and therefore the cooling rate was not directly controlled. The pressure in the CVD system was maintained using a dry scroll vacuum pump (Varian 600 DS, 0.6 kW, 50–60 Hz) connected to the outlet stream of the quartz tube. The total pressure of the LPCVD system was continuously measured and checked by a capacitance manometer (MKS Baratron) and pressure controller (MKS 600 series). The maximum pressure was about 0.57 Torr (76 Pa) while CH₄ and H₂ gases were flowed through the quartz tube during the holding and cooling reaction steps. After LPCVD reaction, as-synthesized products were taken out from the quartz tube for further purification treatments. The LPCVD experiments were carried out several times to ensure reproducibility.

2.4. Purification

After the LPCVD process, as-synthesized products were subjected to a purification treatment to obtain predominantly graphite-encapsulated Fe nanoparticles. In the reported literature, the utilized steps for obtaining only CEMNPs free of non-encapsulated ones contained a conventional method of overnight HCl leaching (which dissolves Fe and Fe oxides) and removal of leaching solution by sonication, centrifugation, decantation, washing and drying [17–19,28,29,32,36,39]. In the present study, purification was conducted primarily to remove possible stoichiometric or non-stoichiometric iron oxides which were not completely reduced during LPCVD. Based on this, 2 M aqueous HF solution (J.T. Baker, 50:1 solution), which dissolves Fe oxides and does not dissolve reduced Fe, was selected as the leaching media. Leaching was performed for 12 h under sonication (Fisher Scientific FS20 ultrasonic cleaner) with a solid-to-liquid ratio of 2.5 mg/ml. Following this, the solutions containing insoluble solids were centrifuged (Hettich EBA 21) using a rotation speed of 4500 rpm for 15 min. The leaching solution was decanted and residual solids were resuspended in distilled water. Centrifugation and washing was repeated for a total of 4 times. The pH value of the solution obtained after each washing step was tested by a pH-indicator strip (MColorpHast) in order to reduce the presence of remnant fluorine. After all washing steps were completed, pH values in the range of 6.0–7.0 were achieved. Finally, the residual solid was dried in air using a hot plate (Thermo Scientific Super-Nuova) at 90°C for 2 h. Approximately 93–95 wt.% of the as-synthesized product was obtained after leaching. The decrease in mass likely results from a combination of the dissolution of Fe oxides, loss during decanting, and adherence of nanoparticles into the internal walls of the glass beaker and tubes during purification steps.

2.5. Chemical stability test

The chemical performance of the graphite-encapsulated Fe nanoparticles was tested using 2 M aqueous HCl solution (EMD Millipore, 37 % concentration) in order to detect any penetration of acid into the core through the graphite layers and hence any dissolution of Fe nanoparticles. This chemical stability test was performed under sonication for 12 h with a solid-to-liquid ratio of 1 mg/1 ml. Subsequent centrifugation, decantation, washing and drying steps were carried out in the same way as for purification.

2.6. Characterization

X-ray diffraction (XRD) investigations were performed using a PANalytical X'Pert PRO diffractometer with CuK_α radiation ($\lambda=0.154$ nm, 45 kV and 40 mA) in the 2θ range of 10° – 100° with a step size of 0.02° and at a rate of $2^\circ/\text{min}$. The International Center for Diffraction Data® (ICDD) powder diffraction files were utilized for identification of the crystalline phases. Microstructural characterization was carried out using a FEI Magellan 400 XHR scanning electron microscope (SEM) operated at 10 kV. Specimens were dispersed onto a carbon conductive tab (Ted Pella PELCO, double coated) for SEM analyses. Transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDS) analyses of the samples were performed using a FEI Tecnai G2 F20 X-TWIN TEM operated at 200 kV and a FEI Titan Environmental TEM (C_s image aberration corrected) operated at 300 kV in high vacuum. Specimens for TEM were prepared by suspending the samples in a solution of distilled water and ethanol ($\text{C}_2\text{H}_5\text{OH}$, Fisher Scientific, 99.5 % purity) via sonication for 30 min. The suspension was dropcast onto a copper TEM grid coated with lacey carbon (Ted Pella Inc.) and allowed to dry in air. Magnetic measurements were carried out by an alternating gradient magnetometer (AGM, PMC MicroMag 2900 Series) using a silica parallel probe at room temperature. Specimens for AGM were prepared by transferring the same suspension used for TEM onto $3\times 3\times 1$ mm Si chips which had been cleaned with isopropanol ($\text{C}_3\text{H}_7\text{OH}$, J.T. Baker, 99.5 % purity) and then air dried.

3. Results and discussion

3.1. XRD and SEM analyses

LPCVD experiments were carried out on three different precursors to understand the effect of the high energy ball milling: Fe_2O_3 raw material, as-blended Fe_2O_3 -C powders and ball milled Fe_2O_3 -C powders. XRD measurements were performed on the three sets of samples before (Figure 1) and after (Figure 2) the LPCVD process. Figures 1a–c and 2a–c are photographs illustrating their general appearance. The corresponding XRD data are displayed in Figures 1d–f and 2d–f. The XRD diffraction pattern acquired from Fe_2O_3 raw material before the LPCVD experiment (Figure 1d) shows the characteristic peaks of hematite (ICDD Card No: 15-6943, Bravais lattice: primitive rhombohedral, with trigonal unit cell dimensions $a=b=0.5035$, $c=1.3753$ nm).

XRD analysis of the Fe_2O_3 powder after the CH_4/H_2 LPCVD process shows that the powder has been reduced to Fe (ICDD Card No: 06-0696, Bravais lattice: body-centered cubic, $a=b=c=0.2866$ nm) (Figure 2d). X-ray reflections for the BCC Fe phase comprise four peaks

at 2θ values of 44.7° , 65.0° , 82.3° and 99.0° . These are indexed as the standard {110}, {200}, {211} and {220} families of planes, respectively, which yields a consistent calculated lattice parameter of 0.287 nm. There are no peaks for unreacted Fe_2O_3 or other remaining oxides.

It had been previously reported that several Fe-containing phases including BCC Fe, Fe_3O_4 , FeO and $\text{Fe}_{0.96}\text{O}$ (non-stoichiometric FeO) were found as reaction products of $\alpha\text{-Fe}_2\text{O}_3$ (70 wt.% of the overall sample) and carbon black/carbon nanoparticles/graphite powders (30 wt.% of the overall sample) at 1000°C for 3 h in N_2 gas [29]. Since the LPCVD reaction in our experiments was not interrupted at shorter time intervals, it is unclear whether the reduction mechanism of Fe_2O_3 includes magnetite (Fe_3O_4) and wüstite (FeO) transition phases prior to fully reduced BCC Fe. Previous studies on carbothermal reduction have suggested that the reaction mechanism depends on several reaction parameters such as particle size, duration, temperature, heating rate, pressure and type of reducing atmosphere, and presence of impurities or additives [29,41–43]. A study in which 30 min of grinded $\text{Fe}_2\text{O}_3\text{-C}$ powders were utilized as the precursors reported that full reduction was achieved after annealing at 1200°C for 3 h under N_2 flow [29]. We opted to use a mixture of H_2 and CH_4 gases as the reducing atmosphere for our LPCVD experiments in order to increase reaction kinetics. This is different from other reports, in which dry or moisturized ($\sim 3\% \text{ H}_2\text{O}$) H_2/Ar gas mixtures or CO/Ar gas mixtures were used for the reduction [41–43]. As demonstrated by Wimmers et al. and by Jozwiak et al., introducing H_2 gas positively contributes by initiating reduction of Fe_2O_3 [41,43]. In our study, thermal decomposition of CH_4 gas, which is known as a mild endothermic reaction above about 600°C [44,45], provides both hydrogen and carbon for the complete reduction of Fe_2O_3 powders in addition to the delivered H_2 gas at a rate of 100 ml/min during the LPCVD process. Once metallic Fe is present, the decomposition temperature of CH_4 gas is expected to be reduced to $400\text{--}500^\circ\text{C}$, because Fe particles are known to catalyze the methane reaction [44]. Thus, the parameters of the LPCVD process chosen in our experiments are sufficient to ensure complete reduction of Fe_2O_3 to the elemental Fe.

However, the high-temperature reduction process can lead to sintering of the powders (Figure 2a). Hence, there is a need to utilize a suitable support/substrate to increase the surface area of the Fe_2O_3 precursor and reduce interparticle contact. The Fe_2O_3 powder was blended with graphite in an agate mortar for this purpose. A backscattered scanning electron micrograph (BSE-SEM) of as-blended powders is shown in Figure 3a, with large dark graphite flakes (approximately 20 to 100 μm) and bright Fe_2O_3 particles (forming clusters from around 10 to 150 μm). Figures 1e and 2e display the XRD spectra of the as-blended $\text{Fe}_2\text{O}_3\text{-C}$ powders before and after LPCVD for 3 h, respectively. As-blended powders (without ball milling) have the characteristic peaks of Fe_2O_3 and graphite (ICDD Card No: 56-0159, Bravais lattice: primitive hexagonal, $a=b=0.2462$, $c=0.6711$ nm) phases (Figure 1e). The as-synthesized product after the LPCVD process contains BCC Fe in addition to unreacted graphite (Figure 2e) and has a similar appearance (Figure 2b) to that of the sample run without graphite, consisting of several mm-scale pieces of iron.

As hand mortar and pestle mixing resulted in poor blending of the two precursors, ball milling for 5 h was conducted on the as-blended $\text{Fe}_2\text{O}_3\text{-C}$ powders both to reduce their

particle sizes and yield a more homogeneous precursor distribution. An XRD pattern of the ball milled $\text{Fe}_2\text{O}_3\text{-C}$ powder is illustrated in Figure 1f. No new peaks appear after milling the hand-blended mixture (Figure 1e–f), indicating there is no reaction between Fe_2O_3 and C during the milling process. Milling for 5 h results in a decrease in the intensities and broadening of Fe_2O_3 peaks, which correspond to a decrease in the average crystallite sizes. Additionally, graphite peaks at values of 26.5° , 54.7° and 87.1° completely disappear. Previous studies have found that graphitic carbon can be amorphized after extended milling times [46,47].

BSE-SEM images depict the change in microstructure after milling of as-blended powders. The large graphite flakes found in Figure 3a are not observed after milling in Figure 3b. Fe_2O_3 particles (bright) appear smaller (generally $<1\ \mu\text{m}$) and better separated after milling (Figure 3b). After LPCVD of the ball milled powders, some amount of FCC iron is detected (Figure 2f). This is in contrast to the bulk as-blended sample where only BCC iron and unreacted graphite were observed (Figure 2e). Although BCC is the stable phase of bulk iron at room temperature, prior work has found that a fraction of nanoparticles rich in carbon remain in the FCC phase after cooling from elevated temperatures such 900°C , where the FCC phase is stable in the Fe-C system [14]. Therefore, the partial suppression of the FCC to BCC phase transition after synthesis using the ball milled sample suggests that the milling process promotes the formation of nanoscale iron particles.

Ball milling of Fe_2O_3 powder without the graphite substrate was also tested. While reduction to metallic iron was again successful, the iron particles in direct contact led to mm-scale iron fragments, shown in Supplementary Figure 1. This demonstrates that ball milling alone is insufficient to produce nanoscale encapsulated particles.

The emergence of the cementite (Fe_3C) phase which was generally reported in the XRD patterns of carbon-encapsulated Fe nanoparticles [14,19,28], was not observed in the XRD patterns of the as-blended nor of the ball milled powders after LPCVD (Figure 2e–f), within the detection limit of the diffractometer ($<1\ \text{wt.}\%$). Moreover, no carbon or graphite peaks were present in the as-synthesized product of the ball milled powders even though encapsulation was found in the TEM results in the following section.

Based on the XRD and SEM analyses (Figure 1–3), it can be stated that ball milling process conducted in the presence of graphite support reduced the interparticle contact of the Fe_2O_3 powders and allowed them to yield a powder after the LPCVD process.

3.2. TEM analyses

Figure 4a shows a representative TEM image of the ball milled $\text{Fe}_2\text{O}_3\text{-C}$ powders. The particles have a variety of shapes and sizes owing to the repeated fracturing and welding which occurs during the milling process. A dark field image generated by selecting the amorphous carbon ring in the diffraction pattern (Figure 4b) shows C distributed between and around the Fe_2O_3 nanoparticles, consistent with the XRD data (Figure 1f) and BSE-SEM image (Figure 3b). Figure 4c is a histogram showing the particle size distribution of the ball milled $\text{Fe}_2\text{O}_3\text{-C}$ powders, based on the random measurements of 250 particles, fitted

to a log-normal distribution. The nanoparticles have diameters varying from 20 to 220 nm, with a mean of 90 nm and standard deviation 40 nm.

Figure 5a shows a TEM micrograph of the ball milled $\text{Fe}_2\text{O}_3\text{-C}$ powders after LPCVD (with a holding time of 3 h) and purification (2 M HF) processes. The image shows that all individual nanoparticles have graphitic shells with different thicknesses. Random measurements of 100 nanoparticle cores reveal a similar size distribution to that of the precursors, with a mean of 105 nm and standard deviation 60 nm (Figure 5b). The slight increase in the diameter range of the nanoparticles after LPCVD could be due to the effect of high temperature and hence particle growth.

Figure 5c is a TEM micrograph of an individual nanoparticle with a diameter of about 50 nm and 11 layers of graphitic shell. There is another nanoparticle (upper left) with 40 layers of encapsulation, illustrating the variations observed in shell thickness. The inset shows a higher magnification view of individual layers of graphitic carbon with a spacing of 0.34 nm.

Figure 5d shows another example of an individual nanoparticle (36 nm in diameter). The 4-layer graphitic shell is less clear due to the amorphous carbon support film. A magnified high resolution transmission electron micrograph (HR-TEM) (Figure 5e) has been taken from the indicated region, illustrating that the particle is FCC Fe in the [110] zone axis orientation. The utility of the high resolution image to identify the iron phase has been described previously [14].

An EDS spectrum (Figure 5f) acquired from the nanoparticle in Figure 5c shows the existence of Fe (L line at 0.7 keV, K_α line at 6.4 keV and K_β line at 7 keV), C and Cu (from the TEM grid). Peaks of oxygen and any other elements were not detected in the EDS spectrum suggesting low amounts of any oxide-based iron compounds or contamination in the composition of this graphite-encapsulation and the Fe nanoparticle. A total of 25 nanoparticles were tested with EDS, with similar results.

Although XRD analysis shows the majority of the iron in the BCC structure, HR-TEM analysis of several sufficiently electron transparent particles (< 100 nm) do show only the FCC phase. It is possible that larger particles, which have much greater volume, are more likely to transform to BCC, the stable bulk phase upon cooling; however, this was not confirmed as HR-TEM images cannot be obtained on larger particles (cores > 100 nm) because of their thickness.

In a study of 55 nanoparticles, all were found to have graphitic shell encapsulation, ranging from 4–42 layers, with a mean of 16. It was recently reported that carbon-encapsulated Fe nanoparticles including an amount of non-encapsulated Fe nanoparticles result in higher toxicity in glioma cells than that of fully encapsulated ones [8]. The absence of non-encapsulated particles in our observation can thus be considered to be an important contribution of the current synthesis method and an advantage for possible medical applications. Unlike previous related investigations in the literature in which a maximum of 15 layers of graphitic carbon were reported [4,6,11–14,18,28,29,32,37–40], this study finds over 40 layers on some particles. The formation of multi-layered graphitic shells without

observation of non-encapsulated nanoparticles could be the combined effect of homogeneous distribution of Fe_2O_3 powders in graphite by ball milling prior to the LPCVD process and gas interaction with these reactants during a relatively long reaction time (3 h).

In order to monitor the effect of the synthesis process duration, the holding time at 1050°C was decreased to 1 h during the LPCVD process. Figure 6a shows a low magnification TEM image of the product after HF leaching. Encapsulation around all individual nanoparticles can be seen, along with the amorphous carbon substrate and several hollow graphitic structures. The presence of these hollow structures can be due to carbon originating from decomposition of CH_4 and/or amorphous carbon originating from the support which transformed into the graphitic carbon form due to metal induced graphitization or CNT growth [48–52].

The diameters of 180 randomly selected nanoparticles from images such as Figure 6a were measured and found to have a mean of 90 nm and a standard deviation 50 nm (Figure 6b), slightly lower than those of the purified product synthesized with a holding time of 3 h. A cumulative percentage plot comparison of the size distributions of the three samples can be found in Supplementary Figure 2. This is a convenient way to compare the particle size distributions, as described earlier [53]. Figure 6c is a TEM image of an individual nanoparticle with a diameter of about 35 nm and with 42 layers of graphitic shell with interplanar spacing 0.34 nm. Also, Figure 6d shows an image of a nanoparticle near the FCC [110] zone axis orientation (with high magnification image in Figure 6e). The corresponding EDS analysis of this particle shows peaks for Fe, C and Cu (Figure 6f), suggesting the shorter holding time is still sufficient to fully reduce the precursors. Between 5 and 42 layers of graphitization were observed in a study of 25 nanoparticles, indicating that the degree of graphitization is not highly sensitive to reaction time.

3.3. Magnetic measurements

The magnetic properties of the nanoparticles were investigated using alternating gradient magnetometry. For both 1 h and 3 h LPCVD reaction times, the hysteresis loops of the purified products demonstrate soft ferromagnetic behavior (Figure 7, Table 1). The remanent magnetization, M_r , is quite low (0.8–1.5 emu/g), which is required to minimize the mutual attraction and agglomeration of the particles in solution. The coercivities of both products were measured to be 110 Oe, similar to those of previous high pressure CVD studies [6].

The saturation magnetization, M_s , at 17–21 emu/g, is not as high as some previously reported iron core-shell structures, which find values ranging from 20–120 emu/g (as compared to the bulk value of 218 emu/g for metallic Fe) [6,14,28,32]. We attribute this to two main factors. First, it has been shown that the magnetization of similarly encapsulated particles strongly correlates with the iron content of the sample [28]. The current method results in a large fraction of carbon in the final product due to the graphite precursor. Second, some particles were observed to remain in the FCC phase after cooling in both XRD and TEM investigations. Based on the XRD data, we estimate the fraction of iron remaining in the FCC phase to be <10% of the total Fe volume. These particles do not contribute substantially to the magnetic properties due to their low susceptibility. While the M_s values of the current synthesis product are not yet sufficient to replace iron oxide for

medical applications, there are unique advantages to the ball milling-assisted CVD synthesis method, as described below.

3.4. Advantages of ball milling-assisted LPCVD Process

The synthesis technique described in this work has several strengths. Traditional CVD techniques make use of metal-organic precursors in order to deposit both iron and carbon, which are collected from the reaction vessel walls. In the current method, iron oxide is used, with the reaction temperature held below the melting point of Fe_2O_3 as well as metallic iron. Thus, the precursors (500 mg sample containing 408 mg Fe_2O_3 and 92 mg C based on the reaction in Eq.(1)) are loaded into the furnace in a quartz boat, and the products are collected from the same location, simplifying the synthesis. The use of a solid precursor also results in little material loss during LPCVD. Complete reduction of all iron oxide, as observed in this work, is calculated to cause an expected mass decrease of 25 % (i.e. 125 mg). The measured change after LPCVD was only 10–15 % (i.e. 50–75 mg), suggesting a net increase in the mass of other components in the sample. We attribute this to the deposition of carbon during the encapsulation process. It can be said that ball-milled Fe_2O_3 -C powders were reduced to Fe and encapsulated in a single process step under the flow of CH_4/H_2 gas during LPCVD. As compared to the literature reporting the reduction and encapsulation temperature as 1200°C [29], fully reduced and graphite-encapsulated Fe nanoparticles free from the non-encapsulated ones were obtained at a lower reaction temperature. Additionally, the initial precursors are low cost. Importantly, the particle size distribution remains similar before and after the LPCVD processes, which suggests that the final nanoparticle size can be controlled by the changing the ball milling conditions, a topic of further study.

3.5. Chemical stability

One of the important properties of the encapsulated nanoparticles is their chemical stability under corrosive conditions. The latter was tested in a 2 M HCl solution ($\text{pH} = -0.3$) in order to monitor possible degradation which might arise from discontinuities in the encapsulation or dissolution of the Fe core from penetration of acid through the graphite layers. According to the test results (Figure 8), the composition, structure and graphitic layers exhibit no degradation from those of the initial particles, without any evidence of core dissolution or shell discontinuity. Nanoparticles were leached in a 2 M HF solution as a purification step to remove oxide-based materials before the chemical stability test. Thus, the graphite-encapsulated Fe nanoparticles show no evidence of degradation in strong acidic conditions, either HCl or HF.

4. Summary and Conclusions

In this study, graphite-encapsulated Fe nanoparticles ranging in size between 20 and 300 nm were successfully synthesized from a solid precursor containing Fe_2O_3 and graphite powders by a combined method of high-energy ball milling and low pressure chemical vapor deposition. XRD analysis indicates the presence of the major BCC Fe and FCC (Fe,C) phases, without any signs of partially reduced or unreduced iron oxides. Transmission electron microscopy was used to determine the particle size distribution, deduce the crystal structures of several smaller nanoparticles and observe the presence and degree of graphite-

encapsulation. The number of graphitic shells around the particles was found to range from 4 to 42 layers, with an average of 16. Magnetic measurements of these nanoparticles show that they are soft ferromagnetic materials with low remanent magnetization and coercivity values. An important output of this work is to establish a method of synthesizing graphite-encapsulated magnetic Fe nanoparticles without the presence of non-encapsulated ones using an economical and easy-to-handle solid precursor. The current particles show no signs of degradation under environments more acidic than those found in human physiology, a promising sign for their potential to move toward biological applications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Dr. Duygu A. A. Öllari would like to express her appreciation to The Scientific and Technological Research Council of Turkey (TUBITAK) for financial support from the 2219 International Post Doctoral Research Fellowship Programme during her stay in the Department of Materials Science and Engineering at Stanford University. Part of this work was performed at the Stanford Nano Shared Facilities (SNSF). This research was supported by the Center for Cancer Nanotechnology Excellence and Translation (CCNE-T) grants funded by NCI-NIH to Stanford University U54CA151459 and U54CA199075. We appreciate the support and encouragement of Professor Sanjiv (Sam) Gambhir. We also thank Professors William Chueh and Shan Wang for access to their equipment for ball milling and magnetic measurements respectively, and Will Gent and Amal El-Ghazaly for their assistance.

References

1. Ferrari M. Cancer nanotechnology: opportunities and challenges. *Nat Rev Cancer*. 2005; 5(3):161–71. [PubMed: 15738981]
2. Cuenca AG, Jiang H, Hochwald SN, Delano M, Cance WG, Grobmyer SR. Emerging implications of nanotechnology on cancer diagnostics and therapeutics. *Cancer*. 2006; 107:459–66. [PubMed: 16795065]
3. Nie S, Xing Y, Kim GJ, Simons JW. Nanotechnology applications in cancer. *Annu Rev Biomed Eng*. 2007; 9:257–88. [PubMed: 17439359]
4. Park JB, Jeong SH, Jeong MS, Kim JY, Cho BK. Synthesis of carbon-encapsulated magnetic nanoparticles by pulsed laser irradiation of solution. *Carbon*. 2008; 46(11):1369–77.
5. Earhart CM, Wilson RJ, White RL, Pourmand N, Wang SX. Microfabricated magnetic sifter for high-throughput and high-gradient magnetic separation. *J Magn Magn Mater*. 2009; 321(10):1436–9. [PubMed: 20161248]
6. El-Gendy AA, Ibrahim EMM, Khavrus VO, Krupskaya Y, Hampel S, Leonhardt A, et al. The synthesis of carbon coated Fe, Co and Ni nanoparticles and an examination of their magnetic properties. *Carbon*. 2009; 47(12):2821–8.
7. Farrell D, Alper J, Ptak K, Panaro NJ, Grodzinski P, Barker AD. Recent advances from the National Cancer Institute Alliance for nanotechnology in cancer. *ACS Nano*. 2010; 4(2):589–94. [PubMed: 20175564]
8. Grudzinski IP, Bystrzejewski M, Cywinska MA, Kosmider A, Poplawska M, Cieszanowski A, et al. Comparative cytotoxicity studies of carbon-encapsulated iron nanoparticles in murine glioma cells. *Colloid Surface B*. 2014; 117:135–43.
9. Seshadri R, Sen R, Subbanna GN, Kannan KR, Rao CNR. Iron, cobalt and nickel nanoparticles encapsulated in carbon obtained by the arc-evaporation of graphite with the metals. *Chem Phys Lett*. 1994; 231(2):308–13.

10. Bokhonov B, Korchagin M. The formation of graphite encapsulated metal nanoparticles during mechanical activation and annealing of soot with iron and nickel. *J Alloys Compd.* 2002; 333:308–20.
11. Li H, Dai H, Sinclair R. Synthesis and characterization of Fe-C core-shell nanoparticles. *Microsc Microanal.* 2005; 11:1902–3.
12. Li H, Dai H, Xing L, Sinclair R. Characterization of AuFe-C core-shell nanoparticles. *Microsc Microanal.* 2006; 12:524–5.
13. Li, H. PhD thesis. 2008. Synthesis characterization of metal-carbon core-shell nanoparticles Stanford CA USA, Stanford University (Materials Science and Engineering Department).
14. Sinclair R, Li H, Madsen SJ, Dai H. HREM analysis of graphite-encapsulated metallic nanoparticles for possible medical applications. *Ultramicroscopy.* 2013; 134:167–74. [PubMed: 23809196]
15. Kopelev NS, Chechersky V, Nath A, Wang ZL, Kuzmann E, Zhang B, et al. Encapsulation of iron carbide in carbon nanocapsules. *Chem Mater.* 1995; 7:1419–21.
16. Wang ZH, Zhang ZD, Choi CJ, Kim BK. Structure and magnetic properties of Fe(C) and Co(C) nanocapsules prepared by chemical vapor condensation. *J Alloys Compd.* 2003; 361:289–93.
17. Oku T, Narita I, Tokoro H. Synthesis and magnetic property of boron nitride nanocapsules encaging iron and cobalt nanoparticles. *J Phys Chem Solids.* 2006; 67(5-6):1152–6.
18. Bystrzejewski M, Károly Z, Szépvölgyi J, Kaszuwara W, Huczko A, Lange H. Continuous synthesis of carbon-encapsulated magnetic nanoparticles with a minimum production of amorphous carbon. *Carbon.* 2009; 47:2040–8.
19. Bystrzejewski M, Grabias A. Tailoring phase composition in carbon-encapsulated iron nanoparticles. *Mater Charact.* 2011; 62:152–6.
20. Thakor AS, Luong R, Paulmurugan R, Lin FI, Kempen P, Zavaleta C, et al. The fate and toxicity of Raman-active silica-gold nanoparticles in mice. *Sci Transl Med.* 2011; 3(79):79ra33.
21. Thakor AS, Paulmurugan R, Kempen P, Zavaleta C, Sinclair R, Massoud TF, et al. Oxidative stress mediates the effects of Raman-active gold nanoparticles in human cells. *Small.* 2011; 7(1):126–36. [PubMed: 21104804]
22. Jokerst JV, Thangaraj M, Kempen PJ, Sinclair R, Gambhir SS. Photoacoustic imaging of mesenchymal stem cells in living mice via silica-coated gold nanorods. *ACS Nano.* 2012; 6(7): 5920–30. [PubMed: 22681633]
23. Ruoff RS, Lorents DC, Chan B, Malhotra R, Subramoney S. Single crystal metals encapsulated in carbon nanoparticles. *Science.* 1993; 259:346–8. [PubMed: 17832348]
24. Guerret-Piecourt C, Lebouar Y, Loiseau A, Pascard H. Relation between metal electronic structure and morphology of metal compounds inside carbon nanotubes. *Nature.* 1994; 372:761–5.
25. Saito Y. Nanoparticles and filled nanocapsules. *Carbon.* 1995; 33(7):979–88.
26. Host JJ, Teng MH, Elliott BR, Hwang JH, Mason TO, Johnson DL, et al. Graphite encapsulated nanocrystals produced using a low carbon: metal ratio. *J Mater Res.* 1997; 12(5):1268–73.
27. Herrmann IK, Grass RN, Mazunin D, Stark WJ. Synthesis and covalent surface functionalization of nonoxidic iron core-shell nanomagnets. *Chem Mater.* 2009; 21(14):3275–81.
28. Bystrzejewski M, Károly Z, Szépvölgyi J, Huczko A, Lange H. Continuous synthesis of controlled size carbon-encapsulated iron nanoparticles. *Mater Res Bull.* 2011; 46:2408–17.
29. Bystrzejewski M. Synthesis of carbon-encapsulated iron nanoparticles via solid state reduction of iron oxide nanoparticles. *J Solid State Chem.* 2011; 184(6):1492–8.
30. Wang JN, Zhang L, Yu F, Sheng ZM. Synthesis of carbon encapsulated magnetic nanoparticles with giant coercivity by a spray pyrolysis approach. *J Phys Chem B.* 2007; 111(8):2119–24. [PubMed: 17269820]
31. Wu W, Zhu Z, Liu Z, Xie W, Zhang J, Hu T. Preparation of carbon-encapsulated iron carbide nanoparticles by an explosion method. *Carbon.* 2003; 41(2):317–21.
32. Borysiuk J, Grabias A, Szczytko J, Bystrzejewski M, Twardowski A, Lange H. Structure and magnetic properties of carbon encapsulated Fe nanoparticles obtained by arc plasma and combustion synthesis. *Carbon.* 2008; 46:1693–701.

33. Liang YC, Hwang KC, Lo SC. Solid-state microwave-arcing-induced formation and surface functionalization of core/shell metal/carbon nanoparticles. *Small*. 2008; 4(4):405–9. [PubMed: 18383573]
34. Huo JP, Song HH, Chen XH. Preparation of carbon-encapsulated iron nanoparticles by co-carbonization of aromatic heavy oil and ferrocene. *Carbon*. 2004; 42(15):3177–82.
35. Hayashi T, Hirono S, Tomita M, Umemura S. Magnetic thin films of cobalt nanocrystals encapsulated in graphite-like carbon. *Nature*. 1996; 381:772–4.
36. Wang Z, Xiao P, He N. Synthesis and characteristics of carbon encapsulated magnetic nanoparticles produced by a hydrothermal reaction. *Carbon*. 2006; 44:3277–84.
37. Seo WS, Kim SM, Kim YM, Sun X, Dai H. Synthesis of Ultrasmall ferromagnetic face-centered tetragonal FePt-graphite core-shell nanocrystals. *Small*. 2008; 4:1968–71. [PubMed: 18752210]
38. Wang S, Huang X, He Y, Huang H, Wu Y, Hou L, et al. Synthesis, growth mechanism and thermal stability of copper nanoparticles encapsulated by multi-layer graphene. *Carbon*. 2012; 50:2119–25.
39. Cui C, Qian W, Zheng C, Liu Y, Yun S, Yu Y, et al. Formation mechanism of carbon encapsulated Fe nanoparticles in the growth of single-/double-walled carbon nanotubes. *Chem Eng J*. 2013; 223:617–22.
40. Pilatos G, Vermisoglou EC, Perdikaki A, Devlin E, Pappas GS, Romanos GE, et al. One-step, in situ growth of unmodified graphene–magnetic nanostructured composites. *Carbon*. 2014; 66:467–75.
41. Wimmers OJ, Arnoldy P, Moulijn JA. Determination of the reduction mechanism by temperature-programmed reduction: application to small iron oxide (Fe_2O_3) particles. *J Phys Chem*. 1986; 90(7):1331–7.
42. Munteanu G, Ilieva L, Andreeva D. Kinetic parameters obtained from TPR data for $\alpha\text{-Fe}_2\text{O}_3$ and $\text{Au}\alpha\text{-Fe}_2\text{O}_3$ systems. *Thermochim Acta*. 1997; 291(1-2):171–7.
43. Jozwiak WK, Kaczmarek E, Maniecki TP, Ignaczak W, Maniukiewicz W. Reduction behavior of iron oxides in hydrogen and carbon monoxide atmospheres. *Appl Catal A-Gen*. 2007; 326(1):17–27.
44. Shah N, Panjala D, Huffman GP. Hydrogen production by catalytic decomposition of methane. *Energ Fuel*. 2001; 15(6):1528–34.
45. Dunker AM, Kumar S, Mulawa PA. Production of hydrogen by thermal decomposition of methane in a fluidized-bed reactor-effects of catalyst, temperature, and residence time. *Int J Hydrogen Energ*. 2006; 31(4):473–84.
46. Tanaka T, Nasu S, Ishihara KN, Shingu PH. Mechanical alloying of the high carbon Fe-C system. *J Less-Common Met*. 1991; 171:237–47.
47. Tang J, Zhao W, Li L, Falster AU, Simmons WB Jr, Zhou WL, Ikuhara Y, Zhang JH. Amorphization of graphite induced by mechanical milling and subsequent crystallization of the amorphous carbon upon heat treating. *J Mater Res*. 1996; 11:733–8.
48. Sinclair R, Itoh T, Chin R. In situ TEM studies of metal-carbon reactions. *Microsc Microanal*. 2002; 8(4):288–304. [PubMed: 12533226]
49. Itoh T, Sinclair R. In Situ TEM Study of Reactions in Iron/Amorphous Carbon Layered Thin Films. *Mat Res Soc Symp Proc*. 1995; 382:45–50.
50. Dai H. Carbon Nanotubes: Synthesis, Integration, and Properties. *Acc Chem Res*. 2002; 35:1035–44. [PubMed: 12484791]
51. Hofmann S, Sharma R, Ducati C, Du G, Mattevi C, Cepek C, et al. In situ Observations of Catalyst Dynamics during Surface-Bound Carbon Nanotube Nucleation. *Nano Lett*. 2007; 7(3):602–8. [PubMed: 17319731]
52. Yamada T, Namai T, Hata K, Futaba D, Mizuno K, Fan J, et al. Size-selective growth of double-walled carbon nanotube forests from engineered iron catalysts. *Nat Nanotech*. 2006; 1:131–6.
53. Park DW, Sinclair R, Lal BB, Malhotra SS, Russak MA. Grain Size Analysis of Longitudinal Thin Film Media. *J Appl Phys*. 2000; 87(9):5687–9.

Figure 1.

Appearance and XRD spectra of Fe₂O₃ powders (a, d), as-blended Fe₂O₃-C powders (b, e) and those ball milled for 5 h (c, f), respectively. While the same fraction of graphite is added to the latter two samples, it can be seen that the powder changes from brown (b) to black (c) as a result of ball milling. Additionally, the graphite peaks observed in the as-blended sample (e) no longer appear after ball milling (f).

Figure 2. Appearance and XRD spectra of post LPCVD (for 3 h) products using three precursors: Fe₂O₃ powders (a, d), as-blended Fe₂O₃-C powders (b, e) and those ball milled for 5 h (c, f). The first two processes generate mm-scale pieces (a,b) while the third produces a powder too fine to be resolved by eye (c).

Figure 3. Back-scattered SEM images of (a) as-blended Fe₂O₃-C powders and (b) ball milled Fe₂O₃-C powders. The former shows large graphite flakes (indicated by arrows) and iron oxide particles (arrowheads) which are poorly blended. The latter has smaller particle size and more homogeneous mixing (note the approximately tenfold increase in magnification for (b), with higher magnification inset). The black regions in (a) are the carbon filled acrylic substrate.

Figure 4.

(a) TEM image of the ball milled $\text{Fe}_2\text{O}_3\text{-C}$ powders. (b) A dark field image of a different region, generated by tilting the electron beam to allow a fraction the amorphous carbon diffraction ring to pass through the objective aperture. The carbon (bright contrast, indicated by arrows) is distributed around iron oxide cores. (c) Histogram of 250 particle sizes fitted to a log-normal distribution.

Figure 5.

(a) Low magnification TEM image of the products of ball milled Fe₂O₃-C powders after LPCVD for 3 h and purification. (b) Histogram showing the size distribution of the nanoparticles, with log-normal fit overlaid. (c) Higher magnification image showing graphitic carbon surrounding nanoparticle cores, with HRTEM inset showing an interplanar spacing of 0.34 nm between graphite sheets. (d) A second particle with less obvious graphitic shell due to the carbon support. (e) HR-TEM image from the indicated region in (d) with interplanar distances matching those FCC iron in the [110] zone axis orientation;

Fourier transform inset. (f) EDS spectrum from the particle in (c) taken with the probe focused to the approximate size of the particle, showing only carbon and iron (plus copper from TEM grid).

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 6.

(a) TEM image of the ball milled $\text{Fe}_2\text{O}_3\text{-C}$ powders after LPCVD process for 1 h and HF leaching. (b) Histogram of core diameters, demonstrating a similar size distribution to that of the precursors, with log-normal fit. (c) Higher magnification of a single particle, showing many layers of encapsulation, with individual graphite planes resolved in the inset, taken from the indicated region. (d) Another particle with fewer layers of encapsulation. (e) HR-TEM image from the region indicated in (d), showing the particle is FCC Fe in the [110]

zone axis, Fourier transform inset. (f) Corresponding EDS spectrum finding only C and Fe in the particle, and Cu from the TEM grid.

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 7. Magnetic hysteresis loops from the samples after (a) 3 h and (b) 1 h of LPCVD, generated with AGM performed at room temperature. Both samples show soft ferromagnetic response with similar saturation magnetization. Note the change in Y axis scale.

Figure 8.

(a) TEM image of an iron particle after a chemical stability test in 2 M HCl. Inset: Higher magnification image showing graphitic coating remains intact. (b) EDS spectrum from a nanoparticle showing no observed change in composition.

Table 1

Magnetic measurement results of samples.

Sample	M_s (Emu/G)	M_r (Emu/G)	H_c (Oe)
Fe ₂ O ₃ Powders	74	22	1100
As-Blended Fe ₂ O ₃ -C Powders	49	11	470
Ball Milled Fe ₂ O ₃ -C Powders	40	7	190
Ball Milled Fe ₂ O ₃ -C Powders After LPCVD For 3 H And Purification (I.E. Fe Nanoparticles)	21	1.5	110
Ball Milled Fe ₂ O ₃ -C Powders After LPCVD For 1 H And Purification (I.E. Fe Nanoparticles)	17	0.86	110