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Tuning microwave permittivity coefficients for enhancing electromagnetic wave absorption properties of FeCo alloy particles by means of sodium stearate surfactant

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ABSTRACT

FeCo is well known as one of the most important Fe base alloys due to its unique properties. In this research FeCo were prepared by a wet chemical reduction method. Sodium stearate (SS) surfactant was used in different amounts as a modifier. XRD and FE-SEM were used to study phase and morphology characteristics of the products. Paraffin matrix composite samples containing 80%wt FeCo were prepared to measure the frequency dependence of the permeability and the permittivity utilizing Vector Network Analyzer (VNA). The results showed that by an increase in SS amounts, the permittivity was decreased. Reflection loss (RL) plots in the frequency range of 1–18 GHz demonstrated that the most wideband RL plots were for the sample with 0.004 mol SS because of its good impedance matching characteristics. For this sample, the RL bandwidth (−10 dB) by a thickness of 2.7 mm occurred 2.2 GHz in C band. Also, it covered the whole range of X and Ku bands having thicknesses of 1.5 mm and 1.1 mm, respectively. The maximum RL of −44 dB was obtained in the frequency of 5 GHz. The results of the research indicate that the composites containing FeCo particles are suitable candidates applicable as thin and wideband microwave absorbers.

1. Introduction

Microwave absorbers have attracted a lot of attention [1–4]. The reason could be attributed to rising demands for decreasing the electromagnetic pollution and the stealth of military platforms. The scientists aim at designing wideband absorber in the form of thin and lightweight layer having strong absorption property [5–8]. Although the metamaterials are the most lightweight and thinnest absorbing structures, they are narrowband absorbers [9,10]. The composite microwave absorbing materials are usually used in cases where wideband properties are required. Wave energy is attenuated by both dielectric and magnetic losses mechanisms in materials. Greater losses don't increase absorption rate, rather, the higher performance of an absorber occurs when there is a matching impedance between the absorber layer and free space [11]. Magnetic materials are the best candidates for creating matching conditions [12–18]. Among the magnetic materials, Fe base alloys with high permeability have been studied extensively as absorbers [19–23]. High performance of these materials can be understood via the Snoek law [24]:

$$(\mu_s - 1)f_r = 4\pi\gamma M_s \quad (1)$$

where M_s is the saturation magnetization, f_r the resonance frequency, μ_s the static permeability and $\gamma = 2.8\frac{MHz}{Oe}$ is the gyromagnetic factor. According to this formula, soft magnetic materials with high M_s and low static permeability have high permeability in GHz range due to f_r shifts toward higher frequencies.

Large permittivity is a big limitation for metals as an ideal absorber. In metals, due to high conductivity and the eddy currents induced by electromagnetic waves, the permittivity increases [25]. Numerous attempts have made to control and tune the permittivity of metals. For example, some works have concentrated on creating an insulate shell on metallic particles as a core-shell structure [26–31]. Some other conventional ways are mixing metallic phase and a dielectric phase [32–36] as well as using some of special alloys [37–41].

FeCo is attractive because of its unique properties. It possesses lower static permeability and higher saturation magnetization

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compared with pure Fe and its other alloys [42]. So, this compound has the capability of being used as a microwave absorber. For example, Hualing LV et al. reported $RL_{max} = -22$ dB and bandwidth (RL < −10 dB) from 10.5 to 17.6 GHz, for the composites containing $Fe_{50}Co_{50}$ alloys [43]. Yong Yang and et al. synthesized $Fe_{50}Co_{50}$ nano plates with $RL_{max} = -43$ dB and 8.5–12 GHz bandwidth [44]. S. J. Yan could achieve to $RL_{max} = -32$ dB and 8.0–13.5 GHz bandwidth for flowerlike $Fe_{1-x}Co_x$ (x = 40, 50, 60) [45]. For $(Fe_{60}Co_{40})_{95}Al_5$ prepared with arc-discharge technique, RL_{max} was observed to be −30 dB and 10.0–13.0 GHz bandwidth [46].

In the present work, FeCo alloy was synthesized by wet chemical reduction using hydrazine. This method is well-known for the synthesis of many metals and their alloys. The main advantages of the procedure, one can refer to the Simplicity and controllability properties of the products by tuning the synthesis parameters [47–51]. Surfactant as an additive can affect the growth mechanism of the primary particles during the reduction process [52,53].

The effect of sodium stearate surfactant amounts on permittivity for modifying matching impedance dispersion was investigated. As mentioned before, different methods have been applied to control permittivity of metallic fillers. But, to the best knowledge of the authors, controlling microwave permittivity coefficients of metallic fillers by sodium stearate was not reported previously. The impressive results show promise for introducing the synthesized FeCo with sodium stearate as a high performance absorbing material for many applications, which is rarely mentioned in literature.

2. Experimental

The FeCo powders were synthesized using a self-catalyzed reduction method. 0.01 mol $FeCl_2{\cdot}4H_2O$, 0.01 mol $CoSO_4{\cdot}7H_2O$ and a suitable amount of sodium stearate surfactant were dissolved in 200 ml distilled water within three-necked round-bottomed flask under vigorous stirring. Reaction atmosphere was controlled by nitrogen flow and its temperature was kept at 70 °C in a water bath. 32 ml $N_2H_4{\cdot}H_2O$ (50% v/v) and 0.25 mol NaOH were mixed and then added to the primary solution. After 0.5 h, FeCo particles were obtained, which were magnetically washed with distilled water and acetone. The products were dried in an oven at 60 °C in air. Three samples were prepared with 0 mol, 0.002 mol and 0.004 mol sodium stearate. A Schematic of the synthesis set-up is shown in Fig. 1.

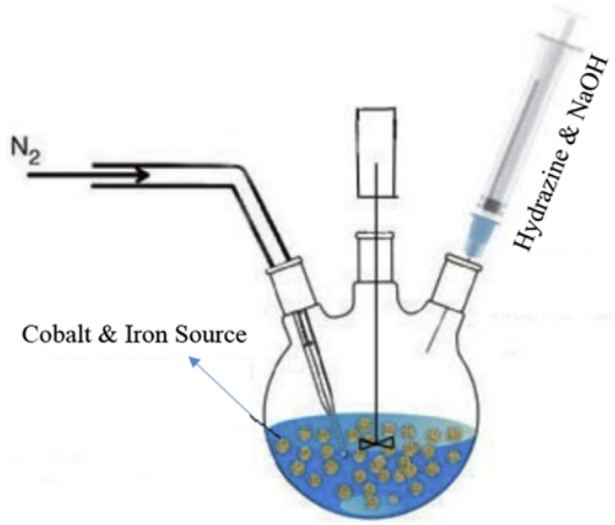

Fig. 1. A schematic of the synthesis set-up.

Field Emission Scanning Electron Microscopy (FE-SEM) was used to characterize the morphology of the powders.

The structure of the fillers was characterized by X-ray diffraction (XRD) utilizing CuK_α radiation.

For intrinsic electromagnetic properties, complex permittivity and permeability, the paraffin composites of the samples were pressed into annular disk with 7 mm and 3 mm for outer and inner diameter, respectively. For the preparation of the composites, the FeCo particles were added into a solution of toluene and paraffin, which were mixed. Subsequently the homogenously prepared solution was placed in an oven at 60 °C for 3 h to evaporate toluene. Afterwards the composite was solidified. The composites were prepared with 80% wt FeCo particles in a paraffin matrix. The composites containing synthesized fillers with 0 mol, 0.002 mol and 0.004 mol of sodium stearate were coded as S1, S2 and S3, respectively. Using transmission-reflecting method, Measurements were carried out over 1–18 GHz by means of an Agilent Vector Network Analyzer (VNA).

3. Results and discussion

Fig. 2 shows XRD patterns of the samples with different amounts of the surfactant. The peaks are related to FeCo phase in all patterns. FE-SEM images are shown in Fig. 3. Fig. 3(a) and (b) clearly show the two ranges for particle size distribution for the FeCo synthesized with no surfactant. Indeed, it contains the larger micrometer and the smaller flake-like particles. Flaky nanoparticles with a thickness of ~50 nm and a diameter of 50–100 nm were dispersed between the 1–2 μm particles with irregular shape. However, in the synthesized samples having surfactant, only the micrometer particles are seen (Fig. 3(c)–3(f)). On the other hand, Crystallites size was estimated from the full width at half maximum of the peak intensity of XRD's patterns using the Scherrer formula [54]:

$$D_m = \frac{0.89\lambda}{B\cos\theta} \quad (2)$$

where $\lambda = 1.5406$ 6 Å is the wavelength of X-ray, B is the full width at half maximum intensity in radians and θ is the Bragg angle. So, the mean crystallite size of fillers in S1, S2 and S3 was calculated 23,

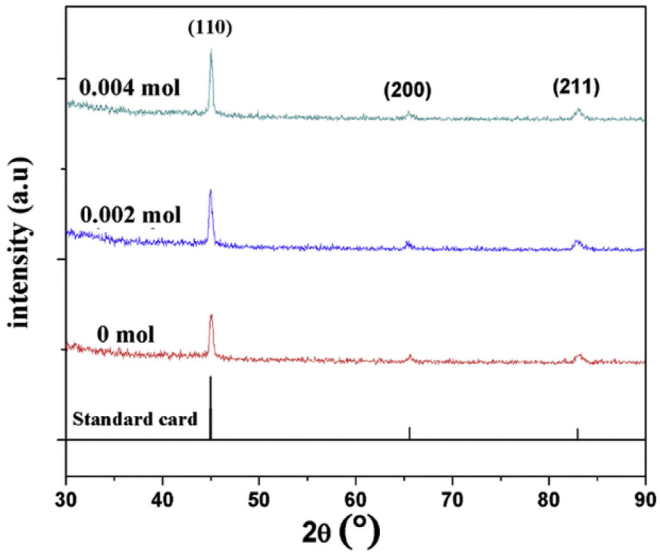

Fig. 2. The XRD patterns of the synthesized FeCo fillers with 0 mol, 0.002 mol and 0.004 mol of sodium stearate.