Materials Chemistry and Physics 153 (2015) 359–364

Contents lists available at ScienceDirect

Materials Chemistry and Physics

journal homepage: www.elsevier.com/locate/matchemphys

# Fabrication and properties of iron-based soft magnetic composites coated with parylene via chemical vapor deposition polymerization

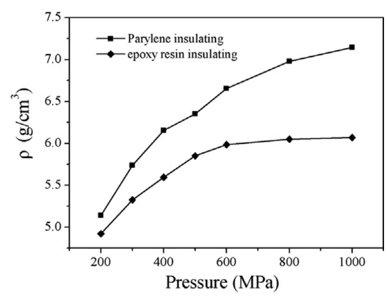
Shen Wu [a, b], Aizhi Sun [a, *], Zhenwen Lu [a], Chuan Cheng [a]

[a] School of Material Science and Engineering, University of Science and Technology Beijing, Beijing 100083, People's Republic of China
[b] Mechanical and Electrical Engineering Institute, Zhengzhou University of Light Industry, Zhengzhou 450002, People's Republic of China

## HIGHLIGHTS

- Parylene C uniformly coated the powder, increased the operating frequency of SMCs.
- Compared with epoxy coated, the density of SMCs increased by 17.02% at 800 MPa.
- The resistance of the iron particles is obviously improved with parylene film insulated.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 17 March 2014
Received in revised form
30 December 2014
Accepted 6 January 2015
Available online 8 January 2015

*Keywords:*
Magnetic materials
Chemical vapor deposition (CVD)
Electron microscopy
Magnetic properties

## ABSTRACT

This paper focuses on novel iron-based soft magnetic composites synthesis utilizing low friction factor parylene C films to coat iron powder via chemical vapor deposition polymerization. The morphology, magnetic properties, density, and chemical stability of parylene insulated iron particles were investigated. The coated parylene insulating layer was characterized by scanning electron microscopy and energy dispersive X-ray spectroscopy. The thickness of parylene C film is averagely 300 nm according to the results of transmission electron microscopy. Parylene C film uniformly coated the powder surface resulting in reducing the permeability imaginary part, increasing electrical resistivity and increasing the operating frequency of the synthesized magnets. It was shown that the parylene C coated compacts exhibited noticeably higher density compared to the epoxy resin coated compacts at the same pressure, suppress at 800 MPa increased the density by 17.02%. The result of Tafel curves indicated that the resistance of the iron particles to corrosion by NaCl solution is obviously improved after being insulated with parylene C film.



## 1. Introduction

In recent years, soft magnetic composites (SMCs) have aroused much scientific interest because these materials exhibit good overall performance with high combined magnetic induction and permeability, very low eddy current loss and 3D magnetic properties in comparison with laminated steels, which are in latent demand for the application of high-power motors and generators [1–3]. Soft magnetic composites are basically ferromagnetic powder articles surrounded by an electrical insulating film and joined by high pressure compaction. During the compaction process, some cold work is imparted in the particles and consequently increases the dislocation density, which has bad effects on the coercivity and hysteresis loss of SMCs in actual application [4]. For this reason, the

* Corresponding author.
*E-mail address:* sunaizhi@126.com (A. Sun).

http://dx.doi.org/10.1016/j.matchemphys.2015.01.026

elimination of residual stresses in the compaction step is very important.

Recently, several researchers have tried to minimize the residual stresses of SMCs, by applying suitable annealing treatments and selecting suitable powder metallurgy (PM) compaction combined with new techniques, such as two step compaction, warm compaction and multi-step compaction [5–7]. Organic coatings have been used as insulating material for the fabrication of SMCs, but the resistance temperature of conventional insulator such as phenolic resin and epoxy resin is lower than 200 °C, therefore, the stress-relief and reduction of hysteresis loss of resin coated powders cannot be completed at the typical stress-relief temperature for pure iron, which is between 570 °C and 775 °C [8]. In order to improve the annealing temperature, many studies have been focused on inorganic coatings with high thermal resistance such as phosphate, MgO and $Al_2O_3$ [4,9,10].

The above mentioned insulating coatings primarily by increasing the annealing temperature to achieve minimize the residual stresses. It is important to note that density has a significant effect on the magnetic loss and the performance of SMCs. Higher density PM parts exhibit high permeability and saturation induction without any degradation of the coercive force. Increasing the pressure can increase the density and magnetic induction, but it is easier to damage the insulating layer under greater pressure as a result of the electrical resistivity reduction. Consequently, it is an effective way to minimize the residual stresses of SMCs by reduced the compacted pressure.

Parylenes as well-known insulating material have been widely used due to their chemical inertness, low dielectric constant, low friction factor and excellent barrier properties [11,12]. Commonly available parylene variants are parylene C, N, D and parylene HT, among them, parylene C is the most widely used polymer because of its biocompatibility and its excellent barrier properties and manufacturing advantages. H.T. Pu et al. have investigated the structure, magnetic properties and chemical stability of parylene encapsulated reduced iron particles via chemical vapor deposition (CVD) polymerization. They have reported that the chemical stability of parylene encapsulated iron particle is obviously improved, which is advantageous for the application of soft magnetic particles in MR fluid [11]. However, the above-cited work was no description about the key factors such as low dielectric constant and low friction factor of parylene, which is important in SMCs application. Unlike conventional organic insulating materials, parylene C film has lower friction factor, utilize it as the insulating material can effective increase the density under the same PM pressure. On the other hand, parylene C is a high molecular weight and crystalline polymer, which is naturally stable and highly resistant to chemical attacks.

In this research work, parylene C insulation coating was applied to the surface of iron powder to increase electrical resistivity and decrease compacting pressure. The polymerization proceeds at room temperature and produces semi-crystalline, transparent conformal and pinhole-free coating thin film by a chemical vapor deposition (CVD) process known as the Gorham process [13,14]. And then the improvement of density, chemical stability and magnetic properties of the soft magnetic composite particles is mainly concerned.

## 2. Experimental details

### 2.1. Materials

High-purity iron powders with an average size <150 μm and a large size distribution was supplied by Licheng Co., Ltd. were used as the raw material. The purity of Fe was above 98% containing 0.02 wt% C, 0.01 wt% Cu, 0.01 wt% Zn and some oxides. To create a uniform parylene coating on iron particles, 3-aminopropyltriethoxy silane (APTS, A1100) was employed for iron powders surface modification by the wet chemistry method. The parylene C purchased from Specialty Coating Systems (Indianapolis, USA) was chosen as the insulating material.

### 2.2. Preparation of parylene insulated powders by CVD polymerization

Iron particle powders were first cleaned by acetone, and then the iron powders were surface treated in a dilute solution of APTS including 5 vol% distilled water and 95 vol% alcohol. In surface treated process the iron powders to APTS mass ratio was adjusted to 100:1. For removing additional coupling agent from the surface, the powders were washed three times in ethanol and then dried at 75 °C. The modified iron powders were coated by mixing with 3 wt % parylene C, and the diagram of the reaction system used for polymer CVD is shown in Fig. 1. The system consists of evaporation zone, pyrolysis zone and deposition zone. The starting parylene C was first sublimated at 150 °C and then transported through a pyrolysis stage where it is cracked into a monomer at 670 °C. The reactive monomer finally condenses and polymerises on the

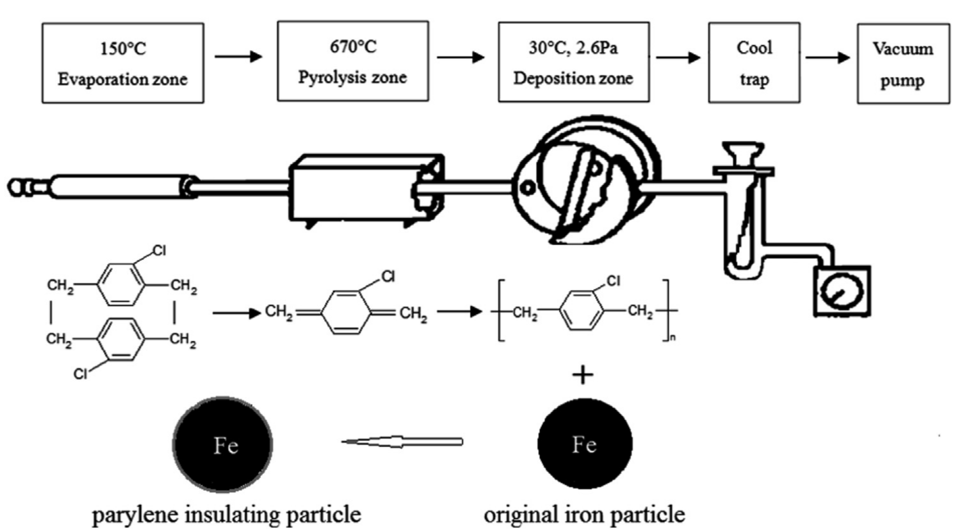



**Fig. 1.** Diagram of chemical vapor deposition polymerization of parylene C.