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Dependence of demagnetizing fields in Fe-based composite materials on magnetic particle size and the resin content

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ABSTRACT

Demagnetizing fields are in general produced by the volume and surface magnetic poles. The structure of soft magnetic composite materials, where the ferromagnetic particles are insulated from each other, causes the formation of demagnetizing fields produced by the particle surfaces. These fields depend on the amount of insulation and on the shapes, clustering and distribution of ferromagnetic particles. In this work the demagnetizing fields in iron–phenolphormaldehyde resin composite samples were investigated experimentally using the method for determining the demagnetization factor from the anhysteretic magnetization curve measurement. The initial magnetization curves were calculated for an ideal composite with 100% filler content using the values of the demagnetization factor. The results on the "ideal" permeability show differences between the samples with different resin content for each granulometric class, which tells about the internal stresses introduced into ferromagnetic material during the compaction process.

1. Introduction

In general, the sources of demagnetizing fields are the volume and surface magnetic poles with densities $\rho = -\ div\ \vec{M}$ and $\sigma = \vec{M} \cdot \vec{n}$, respectively (where $\vec{M}$ is the magnetization and $\vec{n}$ is the normal vector to the surface of magnetized body). The demagnetizing field is then calculated (integrating through the volume V and the surface S of magnetized body) [1]:

$$\vec{H}_d = \frac{1}{4\pi} grad \left(\int_V \frac{div\ \vec{M}}{r} dV - \int_S \frac{\vec{M} \cdot d\vec{S}}{r} \right) \tag{1}$$

The volume poles in bulk magnetic material arise from the inhomogeneous magnetization – at stress regions having their origin in lattice defects or chemical inhomogeneity and the surface poles arise at the surfaces of magnetized bodies – at the sample surface as well as at grain boundaries, at precipitates of different phases or at gas bubbles [2–4]. In case of closed magnetic circuits (e.g. ring-shaped samples) the "geometrical" demagnetization factor is equal to zero (closed magnetic flux path not causing any demagnetizing fields from magnetic poles on the surface of the sample) and only "inner" demagnetizing fields arise, including also the special case observed in [5] when the easy axis of magnetization of all grains is not oriented along the magnetic flux path in the ring leading to some surface magnetic poles regardless. "Inner" demagnetizing fields are present to a greater or lesser extent in every ferromagnetic material and may significantly affect its magnetic properties.

Till now several studies of demagnetizing fields in various soft magnetic materials has been performed in order to investigate their influence on some magnetic properties, e. g. in [6] for Fe–Si steels and nanocrystalline and amorphous Finemet, or in [7] the demagnetizing action of graphite inclusions in cast iron was studied.

In materials like soft magnetic composites (SMCs), which represent a relatively new kind of heterogeneous soft magnetic materials with still increasing importance and range of applications [3,8,9], the situation is much more complicated, when small, randomly oriented ferromagnetic particles are insulated from each other. This is of advantage e.g. for three-dimensional isotropic ferromagnetic behavior or eddy current loss reduction, but it also gives rise to the demagnetizing fields produced by the ferromagnetic particle surfaces of SMC. In this case these fields depend on the amount of insulation and on the shapes of particles, their clustering and distribution [3,9,10], thus lowering the permeability of SMC and resulting in locational fluctuations of magnetic field within the composite [11].

The investigation of demagnetizing fields can provide valuable information on various properties and behavior of magnetic materials [2–7,12,13]. Several methods for quantitative study of these fields in

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some soft magnetic materials were described and applied e. g. the calculations from measured permeabilities [3,9,10,14], from the hysteresis model [6], from measured remanent and saturation magnetization [7] or also from the tilt of the anhysteretic magnetization curve [1,2,4,7]. On the other hand the anhysteretic magnetization curve was mainly analyzed acoording to the Jiles–Atherton ferromagnetic hysteresis model [15,16], including SMCs [17]. The demagnetizing fields within SMC have not yet been studied by means of the anhysteretic magnetization curve measurement.

The aim of this work was to experimentally determine the demagnetization factor of iron–phenolphormaldehyde resin ring-shaped composite samples with different content of the resin and different mean magnetic particle size in order to find their relation with the properties of SMC.

2. Experimental

In order to study the influence of mean magnetic particle size and the resin content on magnetic properties of SMCs by means of the demagnetizing fields, the iron–phenolphormaldehyde resin composite samples with different content of the resin and different mean particle size (sieved granulometric classes) were prepared by conventional powder metallurgy process.

Pure iron powder ASC 100.29 from producer Höganäs AB Sweden [18] was sieved – particle size distributions showing peaks at 45 μm, 75 μm, 100 μm and 160 μm were obtained (granulometric classes labeled F45, F75, F100 and F160). In Fig. 1 particle size distribution measurement performed by laser diffraction granulometer is shown. Sieved iron powder was homogenized with 5 vol%, 10 vol% and 15 vol% (1 wt%, 2 wt% and 3 wt%) of phenolphormaldehyde resin (Bakelite ATM) and acetone. Each mixture was compacted at uniaxial pressure of 800 MPa in the form of a ring (outer diameter of about 24 mm, inner diameter 18 mm, height from 1.4 mm to 2.4 mm), followed by a heat treatment at a temperature of 165 °C for 60 min in electric furnace in air atmosphere. Structure investigations of samples were performed by light optical microscope (LOM) Olympus GX71 and by scanning electron microscope (SEM) TESLA BS 340, in Fig. 2 the view on fracture area of bulk sample F75-10 shows the iron particle coated by the resin. Porosity of samples was calculated from the mass and dimensions (density of iron: 7.851 g/cm^3 and resin: 1.39 g/cm^3). Parameters of the samples are given in Table 1.

For the investigation of magnetic properties the initial magnetization curves, the dc hysteresis loops and the anhysteretic magnetization curves were measured by the fluxmeter-based dc-hysteresisgraph. The anhysteretic magnetization curve was measured using the following method: The dc magnetic field is first set to the maximum value H_m to obtain the point $[H_m, B_m]$, Fig. 3. Then the bias dc magnetic field is set first (point “h” on hysteresis loop) followed by ac magnetic field with frequency of 6 Hz, with gradually descending amplitude (point “a” on anhysteretic curve). Each point of the anhysteretic curve was measured by the same way, making the measurement of each point independent. The method in general is described in [2,4]. The values of demagnetization factor, relative permeability and dc losses were obtained from the measured anhysteretic magnetization curves, initial magnetization curves and dc hysteresis loops, respectively.

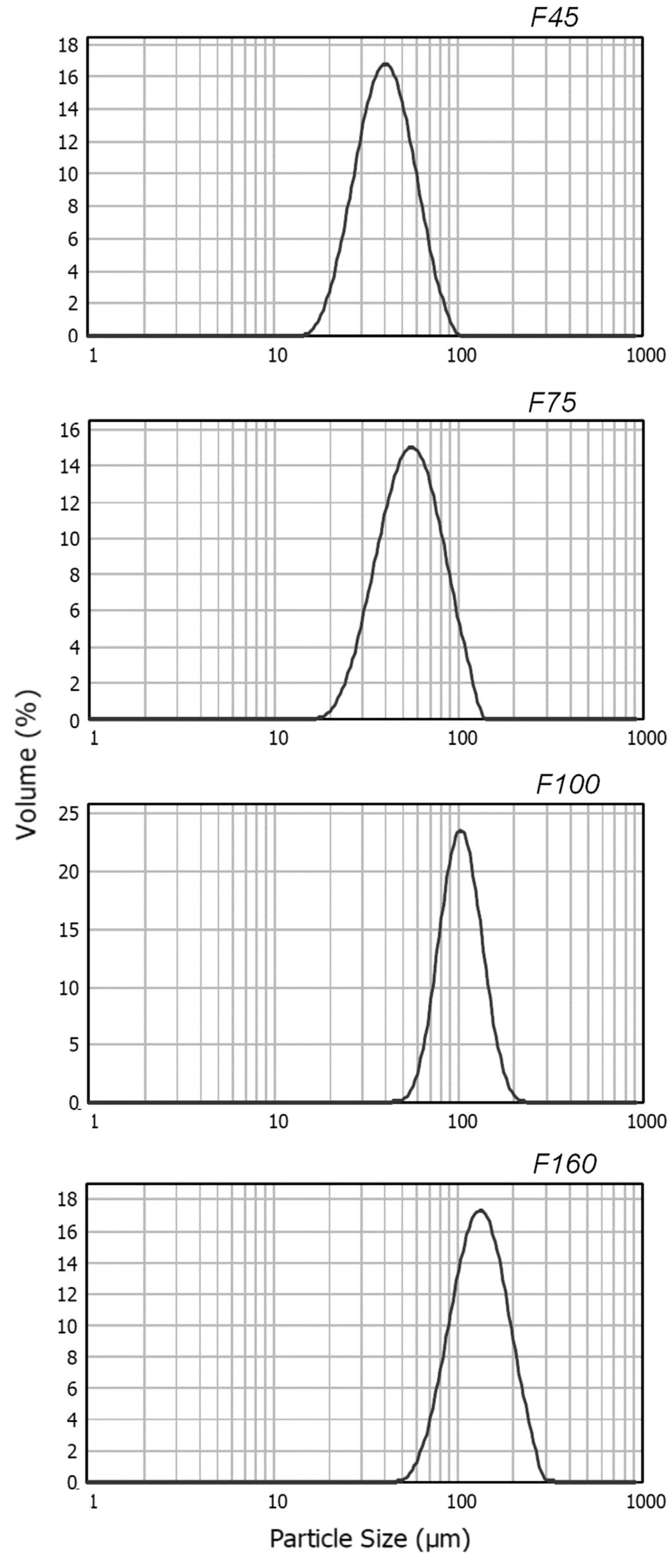

Fig. 1. Particle size distribution of granulometric classes F45, F75, F100 and F160.

3. Demagnetization factor of composite material and its determination

3.1. The “ideal” permeability of an ideal SMC with 100% of magnetic content

The quantity demagnetization factor N_d determines the intensity of demagnetizing field $\vec{H}_d$ by the proportionality:

$$\vec{H}_d = -N_d \vec{M} \tag{2}$$

N_d having values from 0 to 1. In the view of the SMC sample (ring-shaped) the demagnetizing fields are produced by magnetic poles on the surfaces of ferromagnetic particles and also by