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Amorphous soft magnetic composite-cores with various orientations of the powder-flakes

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ABSTRACT

$Fe_{78}Si_9B_{13}$ amorphous powder cores were prepared by cold pressing the amorphous powders crushed from amorphous ribbons and orientated with an external magnetic field. Three orientations of magnetic powder cores were obtained: (i) the disorderedly orientated amorphous magnetic powder core (DOAMP), (ii) the circularly orientated amorphous magnetic powder core (COAMP), and (iii) the radially orientated amorphous magnetic powder core (ROAMP). The effect of the shape anisotropy of the flake powders on the magnetic properties of the powder cores was investigated. The powders parallel to external magnetic field is beneficial for achieving the excellent performance of the cores. Below 100 kHz the product of the effective permeability and the quality factor of COAMP core increases by 9.1% and 21.2% compared to that of the DOAMP and the ROAMP cores, respectively, while the coercive field and the magnetic induction intensity keep almost the same. Pressing magnetic powders under a magnetic field to form preferred orientation is suitable for optimal design of soft magnetic cores toward practical applications.

1. Introduction

The soft magnetic materials of powder cores have been widely used as electromagnetic components to meet the specialized requirements for practical applications [1–3]. Fe-based nanocrystalline and amorphous alloys are with excellent soft magnetic properties and appropriate for magnetic cores. The fabrication of soft magnetic powder cores using Fe-based nanocrystalline and amorphous powders prepared by crushing ribbons have recently attracted much attention [4–6]. It was found that consolidation conditions, the powder size, characteristics of the binding materials, and the shape of the core, all affect the magnetic properties of the final cores [7–8]. But the products manufactured with them are still in development because there are applications which need the soft magnetic powder cores striking a balance between the high effective permeability and the high quality factor. Before the emergence of materials with much excellent soft magnetic properties it is very difficult to improve magnetic properties of the cores using traditional methods and it is inevitable to develop other methods to improve magnetic properties of the cores. Properties of magnetic materials depend strongly on their shapes and applying an external magnetic field is proved to be a kind of effective method for preparation of composite with ordered structure [9]. Saravanana found that $Sm(Co,Fe,Cu)_5$ nanopowders prepared by magnetic field exhibited interesting characteristics such as, flake-like morphology, reduction in particle size and anisotropy. Besides, magnetic field-induced alignment of the powder particles during epoxy curing was strongly evidenced in the SEM and XRD analysis [10]. In fact, not only magnetic metals, but also magnetic metal oxides can grow into wires, chains, and tubes in the presence of an external magnetic field [11]. Such facile routes to fabricate one-dimensional structures could be extended to other materials such as composites and the only requirement of the materials is that the materials should be ferromagnetic or ferromagnetic. The powders made by crushing $Fe_{78}Si_9B_{13}$ amorphous ribbons are naturally in the form of flakes with notable shape anisotropy which makes them a promising candidate for two-dimensional soft magnetic composites. Previous studies have shown that the magnetic properties of cores formed from flake powders is different from those formed from equiaxed atomized amorphous powder [12]. Walser et al. have theoretically proposed that the permeability of particles can be enhanced by transforming the spherical shape into flakes [13]. There are many methods to obtain desired orientations of magnetic particles such as an electric field, a magnetic field and a mechanical stress field [14–16]. The powders will be orientated to form ordered structure along the magnetic lines under an external magnetic field and the flaky powders will lie parallel to each other and form a layered microstructure in the core which may be ideal for achieving the excellent magnetic properties of the cores [17].

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In the present work, $Fe_{78}Si_9B_{13}$ amorphous powder cores are produced using methods of orientating compression and two possible stacking arrangements of flakes are taken into account. The magnetic properties of cores prepared under various external magnetic fields were discussed with a view to find a preferential orientation of flaky powders in the cores.

2. Experimental

The sieved $Fe_{78}Si_9B_{13}$ amorphous powders with sizes of 50–150 μm were passivated by phosphoric acid and uniformly mixed with 1.5 wt% of organic binders (methyl silicone) and 0.5 wt% of zinc stearate. The loose filled powder particles were then circularly or radially orientated with an external magnetic field. Toroidal powder cores with both disordered orientation and ordered orientation were formed by using the press molding process under a compaction pressure of 1000 MPa. The cores were finally annealed at 673 K in an argon atmosphere for 1 h. The dimensions of the obtained amorphous powder cores are shown in Table 1 with the outer diameter, the internal diameters and the height named as OD, ID and H, respectively. After forming, the $Fe_{78}Si_9B_{13}$ amorphous powder cores were demagnetized. For convenience, the disorderedly orientated amorphous magnetic powder core, the circularly orientated amorphous magnetic powder core and the radially orientated amorphous magnetic powder core are named as DOAMP, COAMP and ROAMP, respectively, as shown in Fig. 1.

The density of the powder cores was measured by the Archimedes method. Scanning electron microscopy (SEM) images were obtained by using a FEI Quanta650 scanning electron microscope. The static magnetic properties for the samples were carried out at room temperature with a B–H loop tracer with the maximum magnetic field of 8000 A/m. The frequency dependence of the effective permeability (μ_e) and quality factor (Q) were measured using an LCR meter (GWINSTEK 819 LCR).

3. Results and discussion

Fig. 2 shows the morphology of the $Fe_{78}Si_9B_{13}$ crushed amorphous powders observed by SEM. One can see that the powders have the irregular morphology of either sharp or round edged plates or elongated flakes. Differed from the spherical powders, the flake powders are anisometric and their thickness is much smaller than dimensions in two remaining directions. The flake powders used here possess a high aspect ratio of diameter (83 μm averagely) to thickness (28 μm averagely). Because of the morphology of powders, the static magnetic force is much larger than the friction force between powders under an external magnetic field and therefore the induced magnetic dipole will aligned along the long axis of powder. As depicted in Fig. 3, the long axis, and thus the magnetic dipole of the powders align parallel to the external magnetic field during press molding.

Three types of orientations of amorphous magnetic powder cores have been designed as illustrated schematically in Fig. 1. The horizontal and vertical cross-sectional SEM images of the cores are shown in Fig. 4, in which the red solid arrows represent the

Table 1
Physical properties of $Fe_{78}Si_9B_{13}$ amorphous powder cores.

Samples	W (g)	OD (mm)	ID (mm)	H (mm)	Density (g/cm^3)	Porosity
DOAMP	21.86	29.00	17.00	10.06	5.02	13.84%
COAMP	21.95	29.00	17.00	10.02	5.06	13.15%
ROAMP	21.87	29.00	17.00	10.00	5.05	13.32%

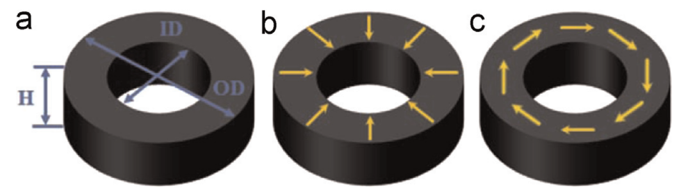

Fig. 1. Schematic diagrams of amorphous magnetic powder cores. (a) DOAMP; (b) ROAMP; (c) COAMP.

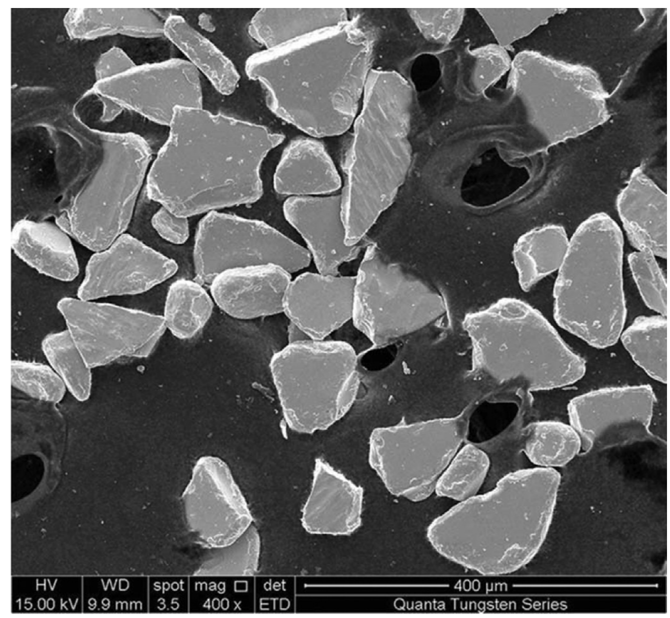

Fig. 2. Morphology of $Fe_{78}Si_9B_{13}$ crushed amorphous powders.

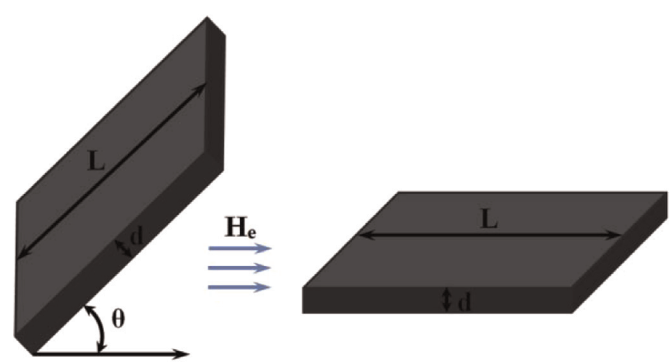

Fig. 3. Schematic illustrations of orientation process of powder particles induced by external magnetic field.

direction of external magnetic field in application and the blue dashed ones represent the direction of magnetic field applied for powder alignment before press molding. It can be seen from Fig. 4 (a) and (b) that the DOAMP core presents a disordered distribution of flake powders, the edges of which lie against each other. The magnetic powders in DOAMP have a certain angle with the external magnetic field in application. The horizontal cross-section of ROAMP core presents a orientation arrangement of powders as shown in Fig.4(c) and the long axis of powders is about perpendicular to the direction of external magnetic field in application. The vertical cross-section of ROAMP core presented in Fig. 4 (d) shows also disordered distribution similar to that in DOAMP. Both horizontal and vertical cross-sections of COAMP core shown in Fig. 4(e) and (f) exhibits a layered structure and the powders lie parallel to one another separated by an insulating layer with the