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Magnetic Properties of Nanocrystalline Powder Cores Using Mechanically Crushed Powders

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Abstract: Toroidal shape FeCuNbSiB nanocrystalline alloy powder cores were prepared by cold pressing using mechanically crushed and ball-milled powders, respectively. The morphologies and their effects on the magnetic properties of the compacted cores were investigated. Compared with ball-milled powders, mechanically crushed ones have more regular shapes and rounder edges, which lead to better inter-particle insulation. FeCuNbSiB nanocrystalline alloy powder cores fabricated from mechanically crushed powders exhibit remarkably lower core loss of about 248.2 kW/m^3 at 100 kHz for maximum flux density $B_m = 0.1$ T, and more stable permeability up to 10 MHz. Moreover, the dc-bias property could be improved significantly using mechanically crushed powders.

Key words: nanocrystalline powder core; morphology; core loss; high-frequency property

Fe-based nanocrystalline magnetic materials exhibit excellent soft magnetic properties including high permeability and low coercivity[1,2], as exemplified for Fe-Cu-Nb-Si-B alloys, commercially known as FINEMET. It was found that doping the Fe-Si-B alloys with optimal Cu and Nb elements enables to improve their soft magnetic properties due to the ultrafine nanocrystalline α-Fe(Si) grains embedded in an amorphous matrix after suitable annealing of amorphous precursor. Fe-Cu-Nb-Si-B alloy amorphous ribbons prepared by roller melt spinning method are used for many applications such as sensors and pulse generators. However, the core shapes have been restricted to toroidally wound or stacked types. And amorphous alloys in powdered form are suitable for compaction and densification in a variety of shapes for using in high frequency range. Accordingly, a large number of researches on soft magnetic powder cores using Fe-Cu-Nb-Si-B nanocrystalline alloys have been carried out[3-8]. In the fabrication of soft magnetic powder cores, an appropriate electrical insulation is essential for obtaining superior high frequency magnetic properties. Acid-treatment is considered to be effective to synthesize an oxide layer on the particle's surface and exhibits wonderful intergranular insulation for the powders. However, conventional ball-milled powders have sharp-angled shapes[9], which are unfavorable to inter-particle insulation. There is a requirement to change the powder edge to be as round as possible.

In this paper, FeCuNbSiB amorphous flakes were mechanically crushed to round-edged powders effectively. FeCuNbSiB nanocrystalline alloy powder cores prepared from crushed powders exhibit significantly lower core losses, more excellent frequency characteristics and dc-bias properties, compared with those from the ball-milled. These characteristics were respectively investigated in detail.

1 Experimental Details

Melt-spun $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ amorphous ribbons were pre-crushed into flaky powders after pre-annealing at 350 ℃ and then mechanically crushed and ball-milled to a size range below 100 μm, respectively. The morphologies of the powders were examined by scanning electron microscopy (SEM).

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Both types of powders of about 10 kg were identically mixed with organic and mineral binders after acid-treatment and were cold pressed into ring cores under 2100 MPa respectively. Then the cores were annealed at 550 ℃ for 1 h in air. The cores thus formed had inside and outside diameters of about 14.1 and 22.9 mm, respectively, and a height of about 7.6 mm. Magnetic core loss was measured using an Iwatsu SY-8232 B-H analyzer. The effective permeability and the dc-bias field performance of the nanocrystalline alloy powder cores were measured using an impedance analyzer.

2 Results and Discussion

Fig. 1 shows the morphologies of the mechanically crushed and ball-milled powders observed by SEM. Mechanically crushed powders in Fig. 1(a) appear relatively regular and round. While the ball-milled powders in Fig. 1(b) have sharp-angled shapes which are not beneficial to inter-particle insulation.

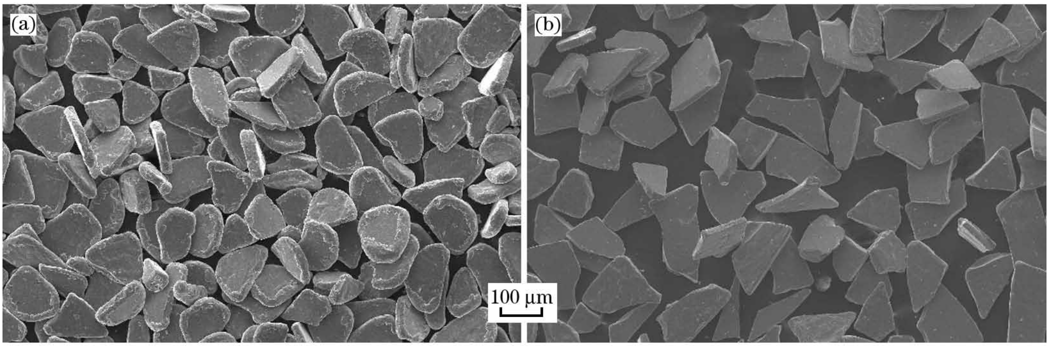

Fig. 1 SEM images of mechanically crushed (a) and ball-milled (b) powders

Core loss as a function of frequency at maximum flux density $B_m=0.1$ T is presented in Fig. 2. In both cases the cores were identically treated. A notable result was found that samples fabricated from mechanically crushed powders showed conspicuously lower value of about 248.2 kW/m^3 at 100 kHz, compared with that of the ball-milled ones of about 2701.8 kW/m^3. For various frequencies and magnetic induction amplitudes, the measured total core loss P (energy loss density) can be subdivided into hysteresis loss P_h and eddy current loss P_e:

$$P=P_h+P_e \quad (1)$$

Among these, eddy current loss is dominant in high frequency[10] and can be effectively reduced by appropriate insulation of the powders. Moreover, hysteresis loss is correlated with defects leading to an enhanced domain wall pinning[11]. According to the cross-sectional SEM images of FeCuNbSiB nanocrystalline alloy powder cores, ball-milled powders in Fig. 3(a) are prone to breakage due to the sharp-angled shapes, which induces defects such as cracks in the powder compacts. In addition, it is seen that the distribution of nanocrystalline powders differs significantly. Powder core fabricated from ball-milled powders shows more complex distribution of magnetic particles and more irregular entangled binders between the powders, which degrade the electrical insulation. However, mechanically crushed powders in Fig. 3 (b) are regularly aligned with insulated coatings. Consequently, relatively more defects and worse inter-particle insulation result in higher hysteresis loss and significant increase of the eddy current loss in high frequency, respectively, which can be confirmed from the values measured using an Iwatsu SY-8232 B-H analyzer, as shown in Table 1.

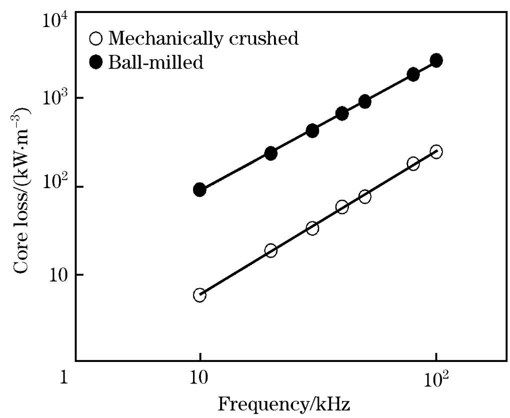

Fig. 2 Frequency dependence of the core loss for FeCuNbSiB nanocrystalline powder cores

Frequency dependence of the effective permeability for the FeCuNbSiB nanocrystalline powder cores is plotted in Fig. 4. The cores fabricated from mechanically crushed powders exhibit percent permeability of 89.1% up to high frequency range over 10 MHz. While the value of 68.1% is obtained from