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Microstructure and magnetic properties of soft magnetic powder cores of amorphous and nanocrystalline alloys

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ABSTRACT

With the development of modern ferromagnetic technology, soft magnetic powder cores (MPCs) of amorphous and nanocrystalline alloys have been intensively studied for their excellent soft magnetic properties such as high flux density, low coercivity and reduced core loss due to amorphous state and nanocrystalline grains of 10–20 nm dispersed in a residual amorphous matrix. In this paper, the microstructures and soft magnetic properties, i.e., maximum magnetic induction B_m, effective permeability μ_e, DC-bias properties and volume power losses P_{CV} of MPCs made from amorphous powder of gas atomization and nanocrystalline powder of pulverized melt-spun ribbon were investigated and also compared on the basis of the same level of μ_e. It is found that μ_e of both kinds of MPC keeps unchanged up to 1 MHz. The amorphous MPC has lower P_{CV} at lower frequency range, while the nanocrystalline MPC has lower P_{CV} at high frequency range instead. Also, the nanocrystalline MPC has better DC-bias property. Moreover, the *DC* magnetic properties and the changes of P_{CV} of both MPCs with frequency and flux density are also studied. Furthermore, the electromagnetic characteristics, the microstructures and the mechanisms accounting for these phenomena of both MPCs are also discussed.

1. Introduction

Magnetic powder cores (MPCs), also known as soft magnetic composites (SMCs), are components made of ferromagnetic powder particles that initially are insulated electrically from each other by an organic and/or inorganic insulation layer at the powder surface before powder metallurgy (P/M) process. They find growing applications in the industry and technology owing to many advantages in comparison with block magnets, such as better mechanical properties, lower cost of production and possibility to obtain different shapes with very high accuracy which enables production of a variety of complex shapes. Moreover, the unique properties of soft MPC include three-dimensional (3D) magnetic and thermal isotropy, very low eddy current loss P_e and relatively low total core loss P_c at low to medium and/or high frequencies, high resistivity, reduction in size and weight, a low anisotropy constant, low coercivity and high Curie temperature, even though the worse magnetic properties (lower maximum magnetic induction B_m and magnetic permeability μ). Therefore, MPC is a very important kind of soft magnetic material widely used in the electromagnetic applications [1–7].

P/M parts have been used in magnetic applications for many years [5–7]. Magnetic applications utilizing P/M offer both economical benefits and design flexibility. Regarding the use of iron filings embedded in wax made in 1887 by Heaviside [8,9], who found that the inductance of a coil could be increased by such means without causing any appreciable dissipation of energy, the discovery of soft magnetic materials in the form of compressed powder cores (now known as magnetic powder core—MPC) has been established for some 125 years and MPCs have been widely used as electromagnetic components to meet the specialized requirements, such as electromagnetic wave absorber, noise suppressor and inductor [10]. As compressed MPCs have several advantages such as simplicity of the technology, tunable properties, flexibility, the final product shape is mostly reached without additional machining, a minimum of material loss, low labor and energy consumption, MPCs have also been widely used for reactors and choke cores of switching power supplies. Moreover, as a damper, the binder (such as epoxy resin) reduces both mechanical vibrations and audio noises if the material has nonzero magnetostriction [11,12]. Recently MPCs have been received a great attention for the future applications because they have been known to be suitable for the power conditioning systems of the hybrid vehicles, solar cell generators and so on [13].

Permeability is the most important parameter for soft magnetic materials, and is the distinguishing characteristic with respect to hard magnetic materials. Since permeability μ is the degree of

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magnetization of a material in response to a given magnetic field H, μ is defined as B/H, and has the unit of μ_0. It is customary to use instead the relative permeability μ_r, which is defined as following:

$$\mu_r = \frac{\mu}{\mu_0} = \frac{B}{\mu_0 H} \tag{1}$$

The relative permeability μ_r is dimensionless, and is numerically the same as the CGS permeability μ [14]. As far as we know that, if the relative permeability of a core is μ_r, then the inductance of a coil with the core will μ_r times larger than that of the coil without the core. But if an air gap is introduced into the magnetic path of a core, the reluctance is increased hence the inductance is decreased. The effect of an air gap is to reduce the inductance, even if the material permeability is not affected by the air gap (as it would be if the core were subjected to a steady field). Thus the core behaves as though it had a reduced permeability, referred to as the effective permeability μ_e. Effective permeability can be defined [9] as following:

$$\mu_e = \frac{1}{\mu_0}\frac{L}{N^2}\sum\frac{\ell}{A} \tag{2}$$

where L is the effective self-inductance, N is the number of turns, ℓ is the average length of magnetic path in the core, and A is the cross-sectional area of toroidal cores.

For a magnetic circuit constructed with an air gap or air gaps, μ_e is actually the permeability of a hypothetical homogeneous material having an equivalent un-gapped structure which would provide the same reluctance and same dimensions. The following simple formula is a good approximation only for small air-gaps:

$$\mu_e = \frac{\mu_{in}}{1+(G\times\mu_{in}/l_e)} \tag{3}$$

where μ_{in} is intrinsic permeability, G is the gap length, and l_e is the effective length of magnetic circuit. For longer air-gaps some flux will cross the gap outside its normal area (stray flux) causing an increase of the effective permeability. A further quantity referred to loosely as effective permeability relates only to a particular coil assembly, and is defined by the ratio L/L_0, where L is the inductance of the coil plus core, and L_0 is the inductance of the same coil with core removed. Effective permeability is dependence on intrinsic permeability of the ferromagnetic materials used and dimensions of the distributed air gap. The difference between the intrinsic permeability and μ_e is due to flux leakage.

In many applications when large amount of direct current (*DC*) must be tolerated, the core material also must exhibit a high incremental permeability (μ_Δ) (also known as reversible permeability μ_{rev} when alternating current (AC) magnetic field is very small) at a higher DC-bias magnetic field H_{DC} (the so-called DC-bias behavior) [15–19]. When *DC* flows through the winding of a ferromagnetic device, it tends to pre-magnetize the core and reduce its inductance. This permeability is referred to as the incremental permeability μ_Δ and is defined as following:

$$\mu_\Delta = \frac{1}{\mu_0}\left[\frac{\Delta B}{\Delta H}\right]H_{DC} \tag{4}$$

where ΔB is incremental flux density and ΔH is the incremental field intensity. The permeability of a material measured with superimposed *DC* might increase slightly for very low values of *DC* ampere-turns, but then it progressively decreases as the *DC* field is increased and the core approaches saturation.

Soft magnetic materials are presently required to exhibit good properties in a high frequency range because the operating frequencies of electronic equipment continue to increase. Due to the conductive nature of metallic soft magnetic alloys, including amorphous and nanocrystalline (NC) alloys, they are mainly used in *DC* conditions. When they are used in AC conditions, they are laminated or tape-wound to reduce the large eddy current loss P_e, as the primary way to decrease P_e is to make the core out of thin sheets, or laminations rather than from a solid piece. If these lamination sheets are electrically insulated from one another, the eddy currents are forced to circulate within each lamination, so magnetic cores used for low and medium frequency applications are usually made of strips of electrical steel. Such as, under the operation conditions of many of today's motors (drive frequency: a few hundred Hz to 1 kHz, drive flux density: 1.0 T or higher), the mainstream type of soft magnetic material presently used in these motors is electromagnetic steel sheet in view of the electromagnetic conversion characteristic of soft magnetic materials [20].

Soft ferrite has low core loss in the high frequency region, but due to its low magnetic flux density, it has the drawback of requiring a large core. Electrical steel sheets have high flux density, but they cannot be used in the high frequency region due to excessive core loss. MPCs are magnetic materials which cover the region where the former two magnetic materials cannot be used [21]. Furthermore, MPC offers several advantages over traditional laminate steel in some applications. For example, the isotropic nature of the MPC, combined with new shaping methods, opens up possibilities for 3D design solutions [22–24]. The use of MPCs allows us to create a distributed air gap leading to a lower permeability of the component, consequently, an increase of the relaxation frequency [12]. Additionally, MPCs have a significant advantage over metallic or ceramic materials because they can be produced using the established polymer processing techniques. Besides, they can be readily moulded into complex shapes to produce magnetic components for specific applications. By consolidation of powders complex-shape parts can be realized.

With MPCs, high permeability material is ground or atomized into powder. The individual powder particles are insulated from one another, allowing the cores to have inherently distributed air gaps for energy storage in an inductor. This desired property ensures that the energy is stored evenly through the core, and also makes the core have better temperature stability. MPCs have low linear permeabilities as well as a resistance to saturation at high magnetizing field levels due to distributed air gap between the insulated metal particles; this is in contrast to the discrete air gap of a ferrite or cut core. Both techniques shear the hysteresis loop and an isoperm material is obtained, that is, the material with a constant permeability whose hysteresis loop will be isoperm loop is achieved for a wide range of applied fields [25]. Through the use of insulated particles, the bulk resistivity is much higher than that of the metal itself. In addition, compared with ferrite cores, MPCs have the advantage of higher saturation magnetization, making them suitable for large current applications, while the relative permeability μ_r of the ferrite core will drastically decrease under large working current conditions.

A wide range of magnetic performance requirements can be met via P/M through the proper choice of materials and the appropriate processing of those materials. Moreover, as a result of recent advances in ferromagnetic technology, a greater choice of core materials for design optimization is now available. Several materials such as pure iron, Fe–Si, Fe–P, Fe–Si–Al, Fe–Ni–Mo, ferrite stainless steel, and other soft magnetic alloys, etc., have been studied as powder cores in many applications [1–10]. For switch mode power supplies (SMPS), inductors, chokes and filters, typical materials are MPP (MPP stands for molybdenum permalloy powder, also known as molypermalloy), High Flux (Fe–Si powder), Sendust (Fe–Si–Al powder), and Iron Powder cores. Each of the above powder core materials has individual characteristics suitable for different applications.

Now it is well known that the future direction of MPC development is aimed at those applications that have lower operating frequencies; in particular those applications at 50/60 Hz [5–7]. Soft magnetic properties of P/M parts are influenced by materials and