COMPARATIVE STUDIES OF SOFT MAGNETIC MATERIALS

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Abstract. Devices using soft magnetic materials are used extensively throughout the electronics and power-distribution industries. Selecting the right material and core type for a given application can be difficult and confusing. In this discussion, we will focus on the similarities and differences of the various material groups and their applications. It's necessary to choose the adequate static and dynamic parameters describing the appropriate magnetic materials for particular application.

Keywords: soft magnetic materials, studies.

INTRODUCTION

Soft magnetic materials play a fundamental role in many of the electrical and electronic systems that characterize modern society. They play a key role in power distribution, make possible the conversion between electrical and mechanical energy, underlie microwave communication, and provide both the transducers and the active storage material for data storage in information systems [1].

For many decades the crystalline soft magnetic metals dominated this field, however, more recent development work in the field of rapid solidification technology led to the discovery of the new material group of amorphous soft magnetic metals around 1970 followed by the nanocrystalline materials around 1988 [2], [3].

In the last few years attention has been focused on the similarities and differences of the various material groups and on pure material development and processing technology. This has resulted in a wide ranging spectrum of soft magnetic materials [4].

SOFT MAGNETIC MATERIALS

Static and Dynamic Parameters of Soft Magnetic Materials

Technical applications place widely varying requirements on material. When it comes to characterizing and categorizing soft magnetic materials in the spectrum of magnetic materials it's necessary to choose the appropriate static and dynamic parameters. Static or quasistatic magnetization takes place so slowly that characteristic magnetic curve and data are reproduced without being affected by eddy currents and other time dependent factors. With dynamic magnetization like ac magnetization or pulse magnetization the eddy currents exert a great influence. The frequency dependency of permeability is mostly described by the complex permeability.

The most important characteristic curve of a magnetic material, which also offers the most information, is the hysteresis loop [3]. There are three most important shapes of the hysteresis loop:

R: Round loop where the remanence is approximately 50 % of the saturation.

Z: Square or rectangular loop with high remanence, which may be over 95% of the saturation. Materials with these loops are called rectangular materials.

F: Flat loop with very low remanence e.g. below 10% of the saturation.

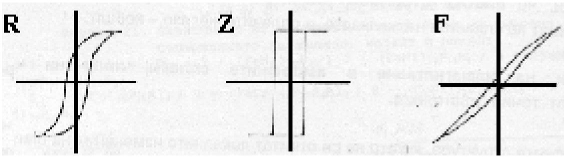

Figure 1. Shapes of the hysteresis loop.

A number of important static characteristic parameters of soft magnetic material can be read off the hysteresis loop and the virgin curve and these parameters are:

1) initial permeability μi;

2) maximum permeability μmax;

3) coercivity Hc;

4) remanence Br;

5)saturation magnetization Bs;

6) losses (loop area);

The saturation Bs, the coercivity Hc and the permeability are the most suitable parameters when it comes to characterizing and categorizing soft magnetic materials in the spectrum of magnetic materials. In the case of permeability either the initial permeability μi or the permeability μ4 (at 4mA/cm), is used as a characteristic material parameter, occasionally maximum permeability μmax is taken.

The most important dynamic characteristic parameters are:

1) total losses;

2) complex permeability;

There is also a characteristic parameter called limiting frequency of eddy currents above which the magnetic field no longer penetrates the specimen. The "anomaly factor" is another dynamic parameter, which depends on the domain structure.

Some Applications of Soft Magnetic Materials

Technical applications place widely varying requirements on material. They involve the saturation polarization and Curie temperature, which are primarily dependent on alloy composition and should, as a rule, be high. High permeability, low coercivity or other terms, which affect the magnetic softness are important. The requirements also include certain hysteresis loop shapes and, particular, dynamic properties like low total losses, minor dependence of permeability on frequency etc. There are two important cases, the emphasis being on static properties:

1) special hysteresis loop shape;

2) high permeability, low coercivity;

Selecting the right material and core type for a given application can be difficult and confusing. It's necessary to choose the adequate static and dynamic parameters describing the appropriate magnetic materials for particular application [4], [5], [6].

Power Transformers. The majority of power transformers fall into two categories: Low-Frequency power transformers used at frequencies less than 1000 Hertz and High-Frequency power transformers used at frequencies above 1000 Hertz. These definitions are not universal, and 1000 Hz was chosen only as an arbitrary reference point. Variations of power transformers include:

- Wide (frequency) band transformers.
- Impedance matching transformers.
- Pulse transformers

Requirements to the material: high saturation flux density, low losses at high frequency, high permeability.

RF Transformers. RF (radio frequency) transformers usually operate at low power levels above 500 кHz. **Requirements to the material:** high permeability, low losses at high frequency.

Precision Transformers. Precision transformers are special devices used in “sensing” and instrumentation applications. Low Permeability is useful in sensing applications where high frequency, small-signals is superposed on high-current conductors. One very common type of precision transformer is the Current Transformers. Another precision transformer is called the **Flux Gate Magnetometer**. This transformer is used to detect very low-level magnetic fields or very small changes in a magnetic field. A third type of precision transformer is the Hall Effect Transducer. **Requirements to the material:** high permeability, low losses at high frequency.

Saturable Reactors. Saturable reactors are used for voltage and current control and are very effective at high power levels. A variation of the saturable reactor is called the MAG AMP, which operates on the same control winding concept as the saturable reactor. Mag amps are used as variable series impedance in squarewave and pulse applications, being driven into and out of saturation within a single cycle. One popular application for a mag amp is as a post regulation technique on the output stage of Switch mode Power Supplies. **Requirements to the material:** To work effectively, saturable reactors and mag amps require magnetic material with a very square loop to allow for a sharp transition into and out of saturation.

Pure Inductors. Pure inductors are used at all frequencies to provide an electronic circuit with inductive reactance. **Requirements to the material:** high permeability, low losses at high frequency.

EMI Filters. Electromagnetic interference (EMI) is produced by a multitude of electronic and electrical devices including motors, light dimmers, digital computing devices, switch mode power supplies, and motor speed controls. **Requirements to the material:** high saturation flux density, low losses at high frequency.

Energy Storage Inductors. Energy storage inductors release the energy stored in them when the voltage across the device is switched.

The Flyback Transformer is a special type of energy storage device that performs both energy transfer and energy storage functions. It is used in low cost high-frequency power conversion. The type of core used in this device must have moderately high permeability for good flux transfer and, at the same time, high saturation flux density for better energy storage capacity.

Classification of Soft Magnetic Materials

In this classification the materials are indirectly grouped according to their structure, certain magnetic properties, such as high saturation magnetization, high permeability etc. Another subdivision could be made within the different alloy groups according to loop shapes: round (R), rectangular (Z) or flat (F).

- Crystalline materials
- Powder Core Materials
- Thin Soft Magnetic Films
- Amorphous Alloys
- Nanocrystalline Iron Base Alloys

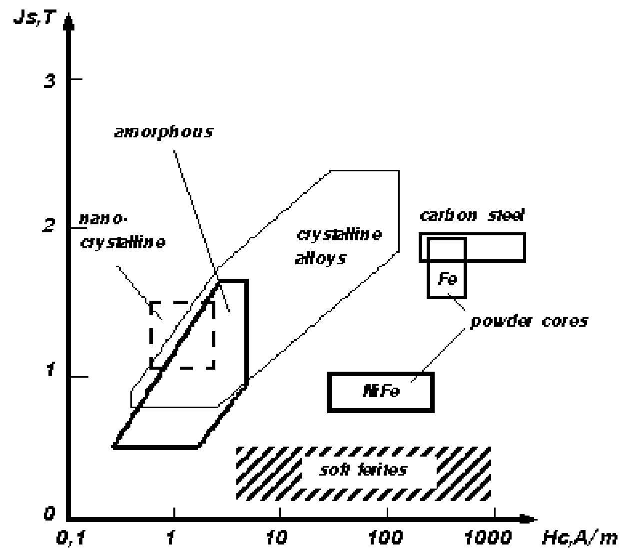

Figure 2. Survey of soft magnetic materials.

Manganese-Zinc **soft ferrites** typically have high permeability and low eddy current losses; Nickel-Zinc ferrites have lower permeabilities with very low eddy current losses. A variety of materials spans the frequency range form 10 KHz to 1 GHz and up. Soft ferrites have low saturation flux densities, in the range of 2500 to 4000 gauss. Because of their very low core loss at high frequency, ferrites are used extensively in switch mode power supplies as power transformers, filter inductors, current transformers, and mag amps (a variation of the saturable reactor). Ferrites are available in a wide variety of shapes and sizes with volumes up to about 500 cm. Some other common applications for ferrites are rod antennas, common mode filters, RF transformers, and pure inductors. Ferrites were plagued for many years by their extremely wide physical and magnetic tolerances. Additionally, ferrites are hindered by rather large temperature dependence. Extensive research and development has improved, but not eliminated, all of the soft ferrite shortcomings. Because of their widespread manufacture and readily available technical information, soft ferrites are the most widely used magnetic material at High-Frequency.

Scrapless laminations are usually in the shape of E-E ’s, U-I ’s, or E-I ’s. They are punched from a continuous roll of thin-gauge magnetic material —most commonly silicon-iron, either low grade non-oriented or high-grade oriented types. Nickel-iron or cobalt-iron thin-gauge materials are also available as laminations. The advantage of scrapless laminations is that, in high-volume applications, it is the least expensive choice for low-frequency high-permeability requirements. Silicon-iron scrapless laminations and shearings are the most widely used soft magnetic cores for 60 Hz applications.

Powdered iron cores are made from basically 99+% pure iron in the form of extremely small particles. Because the particles ideally are separated by an air gap (occupied by insulating and bonding material, as well as air), a distributed air gap system is created. The finished powdered iron core has a maximum effective permeability of about 90. Powdered iron cores can be divided into three permeability categories: high, medium, and low. The high permeability category, 60 to 90, is used primarily for EMI and energy storage filters. Effective frequency range is up to about 75 kHz. Medium-permeability powdered iron cores, with permeabilities from 20 to 50, are used as RF transformers, pure inductors, and energy storage inductors. These materials are used at frequencies from 50 kHz to 2 MHz. They can handle higher flux densities and higher power levels without saturating than can their ferrite counterparts. This powdered iron family will become more attractive to switch mode power supply manufacturers as nominal frequencies of operation fall into the range of 250 kHz to 1 MHz. Low-permeability powdered iron cores, with permeabilities of 7 to 20, are used almost exclusively in the RF range. Typical applications are RF transformers and pure inductors in the frequency range from 2 MHz to 500 MHz. Some radar applications use powdered iron cores at frequencies in excess of 1 GHz. Good flux characteristics combined with low loss and good temperature stability make this type of core material popular for applications in the communications industry.

Another type of powder is the MPP core, pressed from powder made of 81%nicke l,2% molybdenum and 17%iron. They are almost always used for inductors and other energy storage applications. The lower-permeability MPP cores can be used at frequencies that exceed 500 kHz. As the permeability of the core increases, stability tends to decrease. The most popular MPP permeabilities are in the 60 to 173 range, where all the advantages of the MPP product are most apparent [4]. HI-FLUX cores are a variation of the standard MPP cores. They are produced with permeabilities of 14 to 160 and are designed to operate up to about 6500 gauss, as opposed to the 3500-gauss limit of standard MPP.

Amorphous and Nanocrystalline Alloys

The amorphous materials on a metal-metalloid base are usually classified into three groups according to their technical significance:

- Fe-base alloy;
- Co- base alloy;
- NiFe base alloys;

Iron Base amorphous alloys have the highest saturation polarization, 1,5-1,8T, of all amorphous alloys. However, the soft magnetic behavior is limited by the relatively high saturation magnetostriction of typically 30x106. They have lower coercivity and in comparison to the crystalline 3%SiFe alloys, which means low hysteresis losses. The amorphous Fe-rich alloys are of special interest for transformers operating at mains and medium frequency.

Cobalt Base Alloys there are zero passages of magnetostriction. This is a good prerequisite for high permeability and low coercivity as the magnetoelastic or stress anisotropies are negligible. The Co-rich alloys achieve the highest permeabilities of all the amorphous alloys, comparable with those of the high permeability crystalline NiFe alloys of Permalloy type (μi~100 000). The saturation polarization is 0,6-1,0T. The losses of the Co-rich alloys are extremely low so that this material is highly suitable for transformers operating in the medium frequency range (20kHz-500kHz) and is even superior to the ferrites.

Nickel-Iron base amorphous alloys have saturation polarization approximately 0,8T. Due to the excellent elastic properties these alloys can be used for magnetoelastic sensors. After annealing leading to R loop the initial permeability reaches values around 20 000 and is thus higher by a factor of 2-3 than crystalline 50%Ni.

Nanocrystalline Iron Base alloys fill the gap between amorphous metals and conventional polycrystalline alloys. Magnetic field annealing allows the shape of the hysteresis loop to be varied according to the demands of the application. Nanocrystalline materials reveals relatively high electrical resistivity and low eddy current losses up to frequencies of 100kHz. These soft magnetic properties are similar to those of amorphous Co-rich alloys. But nanocrystalline materials moreover shows a much better thermal stability of its magnetic properties than its amorphous counterparts.

The best static and dynamic soft magnetic properties are presently achieved as well in amorphous Co-base as in nanocrystalline Fe-base alloys. Due to their unique combination of soft magnetic properties and a high thermal stability nanocrystalline alloys comply with the fundamental requirements for high performance inductors for a wide range of modern electronic devices in a unique manner. The major benefit of this class of hightech materials is a miniaturization of the inductors in volume combined with a high degree of universality in shape and electric properties. This allows a reduction in size for the complete device and in many cases solutions being impossible with conventional magnetic alloys. On the other side the reliability and cost optimization of the production process brought the price of the product in a range being highly competitive with classical crystalline alloys and ferrites [6].

CONCLUSIONS

In general, the choice of magnetic material is the result of a trade-off between saturation flux density, energy loss, cost of the material and size for the complete device.

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