Advantages and applications of nanocrystalline magnetic materials

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This paper presents current stage and future trends of magnetic properties, advantages and applications of nanocrystalline magnetic materials in electronics. The advanced magnetic properties of the material are discussed and compared with properties of other magnetic materials. Typical relations of initial permeability, saturation induction and operating frequency are depicted to prove the advantages of these alloys. The ability to control their B-H loop, to operate at high temperatures and their low losses are shown to prove the corresponding dominant applications. Novel grades of nanocrystaline alloys are addressed to focus on the further improved characteristics. Typical and new applications of nanocrystalline materials in Electronics and Power Electronics are discussed. It is concluded that because of their advanced magnetic and operating properties the nanocrystalline materials are very prospective in future electronic equipment.

Предимства и приложения на нанокристалните магнитни материали (Венцислав Ц. Вълчев). *Статията представя текущото състояние и бъдещите тенденции относно магнитните свойства, предимствата и приложенията на нанокристалните магнитни материали в електрониката. Основните магнитни свойства на материала са представени и сравнени с тези на други магнитни материали. Типични зависимости на магнитната проницаемост, индукцията на насищане и работната честота са представени графично. Показани са специфични предимства: контролирана B-H крива, малки загуби, приложимост при високи температури. Представени са и нови разновидности на материала, фокусиращи върху подобрени свойства. Описани са типични и нови приложения на нанокристалните материали в електрониката и силовата електроника.*

I. Introduction

Fast development and further improvement of operating parameters of power semiconductor switches reflect to new challenges to power electronic equipment as high operating frequency, low volume and losses. Magnetic components are the other most important elements that define total parameters of the power systems. The research towards better soft magnetic materials for power electronics yielded the use of nanocrystalline alloys in that area. The results of nanocrystalline manufacturing processes suggest that these materials are an alternative of ferrites in power electronics applications [1], [2].

The nanocrystalline alloy structure (FeSiBCuNb) is close to the amorphous soft magnetic materials. The initial amorphous FeSiB alloy, containing small additions of Nb and Cu, is elaborated by very rapid solidification on ribbons 20µm thick ("Finemet"– HITACHI, "Vitoperm" – VACUUMSCHMELZE, "NanoPhY" – IMPHY). The material is annealed at medium temperature (500-550°C) to obtain optimum crystallization and the remarkable magnetic properties of the nanocrystalline structure discovered at the end of the 80's. First nanocrystalline cores are offered by Hitachi Metals FINEMET® [3] and VACUUMSCHMELZE, Vitroperm in 1992.

Anyhow the high prices at that time did not allow wide applications of the material. In the last 10 years some manufacturers in China started their own production and the prices came down. Nowadays about 70% of the nanocrystalline cores (about 9000 t/a) are supposed to be made in China - mostly low grade [4]. The initial standard alloy $Fe_{73,5}Cu_1Nb_3Si_{15,5}B_7$ was modified in many other structures adding mainly Nickel and Cobalt. For example, a new alloy ($Fe_{42}Co_{42}Nb_7B_8Cu_1$) with improved soft-magnetic properties: high Curie temperature and low losses are addressed in [5].

The purpose of this paper is to presents the current stage and future trends of properties and applications of nanocrystalline soft magnetic materials in Electronics and in Power Electronics.

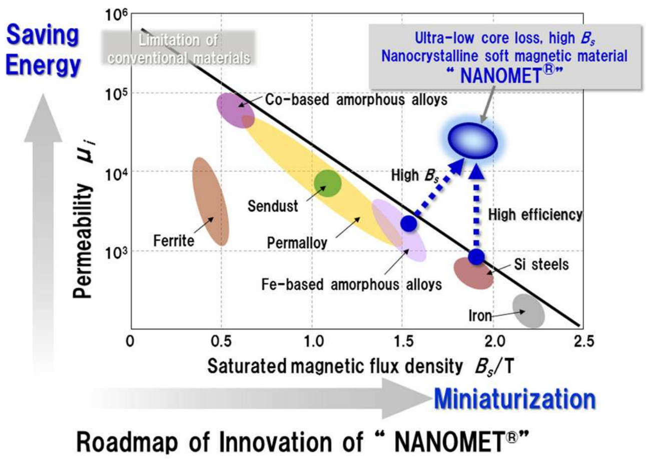

Fig.1. Development road map of ultra low loss nanocrystalline alloy "NANOMET®"[6].

II. Advantages of nanocrystalline alloys

The advanced magnetic properties of nanocrystalline alloys could be grouped as follows:

1. High values of saturation induction

Nanocrystalline alloys indicate saturation induction B_{sat} about 1,2-1,4 T. Some new materials reach even higher values. Figure 1 presents the parameters of "NANOMET®", a material with high iron-content, developed by Tohoku Innovative Materials Technology Initiatives for Reconstruction [6]. The material shows values of B_{sat} close to 2T.

2. High values of initial permeability

Typical dependencies of initial permeability on saturation induction and on operating frequency of some Soft Magnetic Materials for Power Electronics are shown in Fig. 2 [3] and in Fig. 3.

It is seen that the nanorystalline material reveals both high saturation magnetic flux density and high permeability.

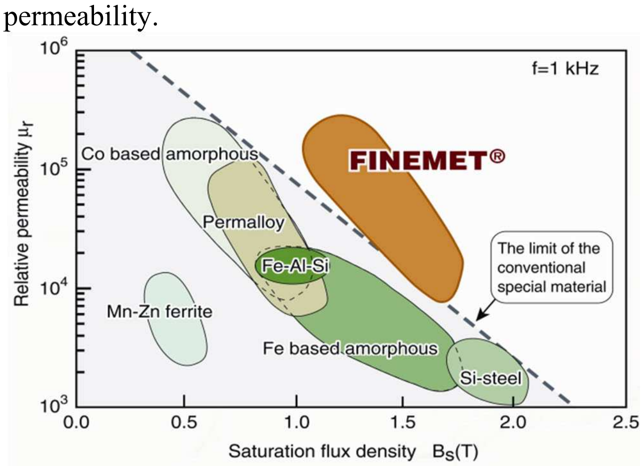

Fig. 2. Initial permeability versus saturation induction for soft magnetic materials [3].

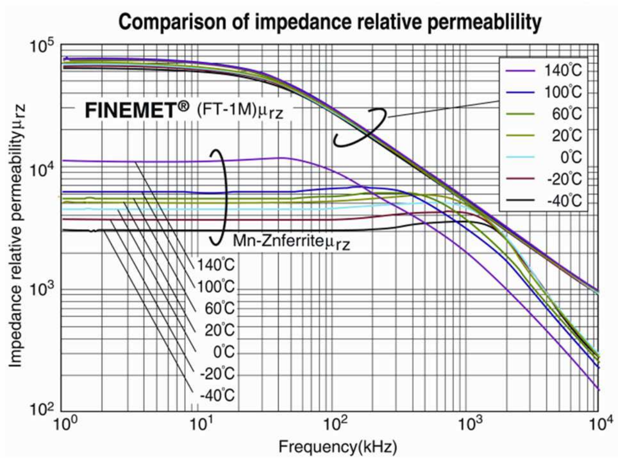

Fig. 3. Relative permeability μ_r versus operating frequency of nanocristalline material FINEMET and Mn-Zn ferrites [3].

3. Control of B-H loops

Important advantage of nanocrystalline magnetic materials is the ability to control their B-H curve. This is obtained by applying a magnetic field during annealing. Figure 4 presents three typical curves for FINEMET (Hitachi), high, middle and low remanence ratio, corresponding to various applications:

- H type: a magnetic field is applied in a circumferential direction of the core plane during annealing.
- M type: no magnetic field is applied during annealing.
- L type: a magnetic field is applied vertically.

4. Low high frequency losses

Next important advantage is low high frequency loss of nanocrystalline magnetic materials. Comparison of losses under sine wave of typical magnetic materials is given in Fig.4 [6], [7].

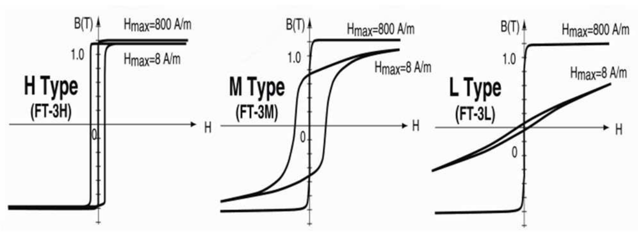

Fig. 4. Typical B-H loops for FINEMET [3].

Integral magnetic properties are to be considered as conclusion when analyzing and assessing magnetic materials. The features of the nanocrystalline materials and the corresponding applications are summarized in Fig. 6.

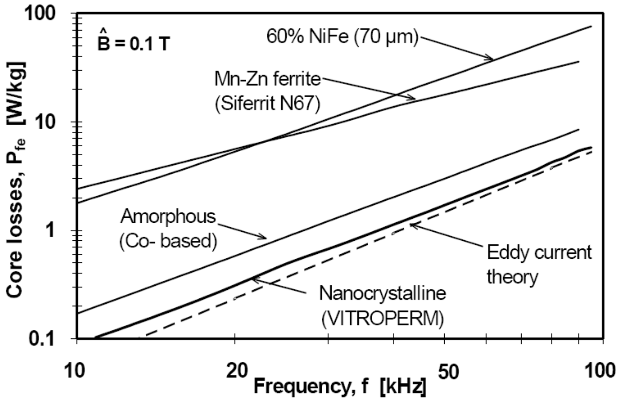

Fig. 5. Specific core losses of magnetic materials under sine wave, [7],[8].

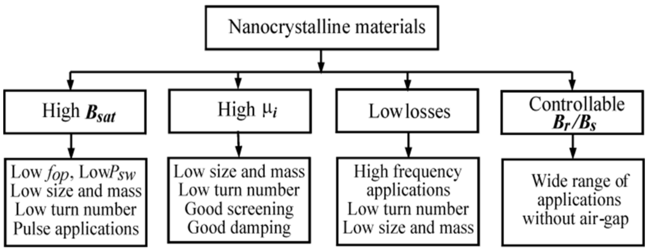

Fig. 6. Features and proper applications of nanocrystalline materials.

III. Novel grades and features of nanocrystalline alloys

1. Very high frequency applications

Nanocrystalline alloys of $(Fe_{81}Co_{19})_{84}M_9B_7$ where M = (Hf, HfTa,Ta) are presented in [9] and intended to operate at very high frequencies, up to 2 MHz. These alloys are also suitable for high temperature applications due to the Co content, which contributes to increasing the Curie temperature of the nanocrystalline alloys.

Nanocrystalline powder prepared by mechanical alloying was obtained by covering the Supermalloy particles with a polymer binder [10]. By increasing of the compacting pressure from 600 MPa to 800 MPa permeability of the material is increased by more than 8%.

2. High temperature applications

The high temperature properties of nanocrystalline soft magnetic materials are discussed in details in [11]. Several considerations are proposed to meet the challenges of using these materials at high temperatures. FeCo-based amorphous and nanocrystalline alloys have been reported in [12] that have high Curie temperatures and saturation inductions.

3. Lower core losses

The nanocrystalline alloy $Fe_{80.5}Cu_{1.5}Si_4B_{14}$ proposed in [13] exhibits high Bs of more than 1.8 T and coercivity less than $7Am^{-1}$. The core losses at 50 Hz and 1.6 T for a toroidal shape are $0.46Wkg^{-1}$, which is about 2/3 of that of grain-oriented Si steel. The losses at 10 kHz and 0.2 T are $7.5Wkg^{-1}$, which is about 25% of that of non-grain-oriented Si steel and about 60% of that of a Fe-based amorphous alloy.

The losses of nanocrystalline materials are presented by wide frequency model curves in [14] using wide frequency complex permeability μ_w.

IV. Applications of nanocrystalline magnetic materials

Proper combination of favourable magnetic properties of nanocrystalline cores make them well established in a wide field of applications.

Nowadays applications of nanocrystalline materials are in the following areas:

1. Communications equipment (telephone exchange, power supplies, inductors)

Miniaturization is a requirement for devices in communications. Thus, high-permeability FeHfN magnetic films are used to enhance the inductance of power inductors [15]. Such planar sandwiched power inductors containing have a higher inductance than air-core power inductors.

2. Railways technology, mechanical handling equipment technology

3. Switched mode converters and SMPS (Switching Mode Power Supplies)

Transformers and inductors made on nanocrystalline cores have smaller size, weight and losses, compared to these made of ferrites.

4. Electric vehicles (battery charging devices, motor inverters)

Improved parameters of the nanocrystalline magnetic components lead to including in e-Vehicle industry. Example: Inverter mass: 8kg, volume: 5 liters [16]. Similar solutions are used at Volkswagen's and BMW's eCars.

5. Common mode chokes

Common mode chokes in the EMI/EMC filters are dominant application, because due to higher permeability and more than three times higher Bsat nanocrystalline cores reduce weight, size and total power loss by up to 80% compared to ferrites.

6. Renewable energy conversion, solar and wind technologies

7. Electromechanical earth leakage circuit breakers

In the recent years, those devices were almost completely based on nanocrystalline cores replacing

Permalloy cores (e.g. Ni80Fe20) [17].

8. Induction heating

9. Smart metering systems

Because of high linearity and very low power losses the cores are one of the best solutions for high precision current transformers.

10. Applications in power converters [18], [19]

V. Conclusion

In this paper magnetic properties, operating parameters and applications of nanocrystalline magnetic materials are presented. The advantages of the nanocrystalline materials can be summarized as:

- combine both high saturation magnetic flux density and high permeability;
- combine high permeability of amorphous materials and low losses of ferrite materials.
- reduced size and weight of the components;
- wide range of permeability, up to 800 000;
- increased operational and Currie temperature;
- high aging stability and reliability;
- various hysteresis loops (from Z to flat).

Nowadays main applications of nanocrystalline materials are in the following areas and devices:

- Communications equipment;
- Mechanical handling equipment technology;
- Switched mode converters and SMPS;
- Railway equipment and devices for electric vehicles;
- Common mode chokes;
- Solar and wind technologies;
- Smart metering systems.

Summarizing the advanced magnetic and operating properties of the nanocrystalline materials leads to their are very prospective applications in future electronic equipment.

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