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Layered alloys for effective magnetic flux concentration in induction heating

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Fundamental requirements for an efficient transformer core material are that it should have a high saturation magnetic polarization and high magnetic permeability as well as low coercivity to minimize hysteresis losses, preferably in combination with high electrical resistivity, so as to minimize eddy current losses. We report on the magnetic and electrical properties of new soft magnetic materials with respect to their application in the induction heating process. The investigation focuses on a composite layered material. The offered materials properties such as saturation of magnetization, remanence, coercive field and coefficients of efficiency of transformation in the flux controllers were defined. These materials are anticipated as magnetic flux concentration materials for very severe induction heating processes because they possess high permeability and saturation flux density, and stable mechanical properties at elevated temperatures.

Key words: *soft magnetic material; composite layered material; saturation magnetic polarization; high magnetic permeability*

1. Introduction

Future power conversion technologies will require high frequency operation of electrical and magnetic components for specialized applications operating at elevated temperatures such as application of magnetic flux field intensifiers (concentrators) in induction heating systems. Magnetic components are widely used in electrical power conversion and management systems, both as energy-storage and energy-transfer elements. The continuing development of better materials for magnetic flux controllers provides the user with benefits such as improvements in heat treatment quality, production rate increase, cost reduction due to energy saving, etc. [1]. Magnetic flux intensifi-

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er enable effective concentration of magnetic field at the work piece, creating consistently reproducible heating patterns. Magnetic flux intensifier materials are characterized by high stability to magnetic shock, low magnetic loss, wide frequency range (50–100 kHz), magnetically non-saturating high heat resistance (up to 500–600 °C), high power loadings (greater than 40–80 kW), easy machining, etc.

Soft magnetic materials such as laminations, composites based on amorphous or nanocrystalline ribbons as well as metal powder and polymer binder (insulator) are applied for magnetic flux field intensifiers. The amorphous and nanocrystalline ribbons were the objects of extensive research in the last three decades of the last century [2]. The reason for broad studies of these materials are their very good soft magnetic properties, to which, first of all, belong high magnetic saturation B_S, low coercion value H_C, high magnetic permeability μ, very low, close to zero magnetostriction λ_S, and finally, low remagnetising losses. Some of these alloys are characterized by relatively high resistivity [2].

Due to melt spinning manufacturing method, these materials are available only in the form of very thin ribbons, and their commercial use is limited. The composite with the polymer matrix reinforced with the amorphous or nanocrystalline particles obtained in the process of the high-energy milling of the amorphous ribbons or mechanical synthesis constitutes an alternative for those materials. Investigation of composite materials obtained by solidification of the metallic powder using various methods has been carried out in many research centres [1, 2].

The best soft magnetic properties are still found around the originally proposed compositions, i.e. $Fe_4Cu_1Nb_3Si_{13–16}B_{6–9}$ [3]. They are comparable with the excellent properties possessed by established materials such as Permalloys or Co-based amorphous alloys. The advantages, however, are a higher saturation induction of 1.2–1.3 T and a significantly better thermal stability of the soft magnetic properties. The combination of high saturation magnetization and high permeability together with good high frequency behaviour, low losses and the good thermal stability allows reductions in the size and weight of magnetic components used in, e.g., switched mode power supplies or telecommunication [3]. Apart from its technical performance, the material is based on inexpensive iron and silicon raw materials. Furthermore, the amorphous precursor material for the Fe–Cu–Nb–Si–B alloys, , is easily accessible by rapid solidification from the melt spinning technique for large-scale production of amorphous metals.

The combination of the above factors has rendered the nanocrystalline solution competitive, not only with amorphous Co-based alloys, but also with classical crystalline alloys and ferrites.

Inhomogeneous layered magnetic materials that may be used in devices operating in medium- and high-frequency range are largely diffused and composed of grains with variable size bounded by a layer whose electrical and magnetic characteristics are sensibly different. Cross-sections of such materials can be approximated by succession of identical elementary cells. This structure influences the macroscopic eddy current circulation, affecting the Joule losses, under an imposed magnetic flux [4].

The schematic cross-section of such structures is shown in Fig. 1. Two parameters of layered structure have to be controlled: thickness of grain and its resistivity. An inherent feature of layered structures is that they work well only in plane-parallel fields, when magnetic field passes along the sheets [1]. This feature has to be taken into account when designing the flux concentrators.

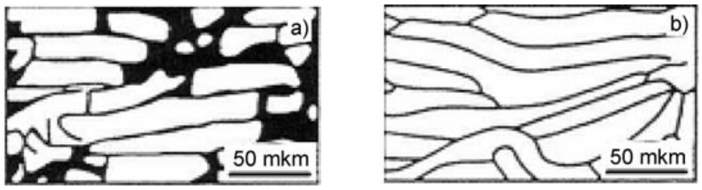
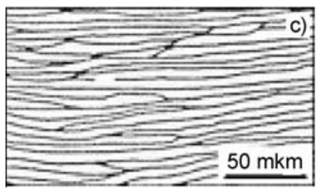


Fig. 1. Schematic cross-section of two phase layered soft magnetic composites based on melt-spun ribbon flake and polymer binder-insulator (a), compacted flakes of two types (b), and two-phase alloy rolled with high strains (c)



However, little work has been done yet in the direction of development of two-phase layered composites. The aim of this work is to examine the magnetic properties of new ferrous-based, two-phase layered composites as candidate materials for flux concentrators.

2. Experimental procedure

A ferrous alloy was melted in alumina crucible at 1700 °C for 10 min (in resistance furnace with heating of coal resistor), and then was cast and rolled into plates 5 mm thick. The samples were cut and subsequently annealed at 800 °C for 3 h. The resistivity of the samples amounted to 83 μΩ·cm. Static hysteresis loops were recorded at room temperature with various magnetic fields using an ADE model 4HF vibrating-sample magnetometer with short samples, 5–8 mm long. The samples were oriented with the long axis in the direction of the applied magnetic field. A Walker AHM-401 automatic hysteresigraph was used to measure the core losses of the samples between 0.1 and 1000 kHz. All measurements were in accordance with AST Standard [5]. The evaluation of the magnetic flux concentrator effectiveness was made for rod (diameter of 30 mm) heated by two wind coils with frequency of 3 kHz. The heating pattern was evaluated visually.

3. Results and discussion

A typical static hysteresis loop of layered alloy is shown in Fig. 2. Its main parameters are following: coercivity $H_C \approx 1.6$ Oe, remanence Br 0.015 T and magnetization of saturation B_S = 2 T. The data reveal that the selected technology parameters allow us to achieve the advantageous soft magnetic properties because of getting grain lamellas with the thickness of about 5–10 μm and separation of grains by high resistivity phase, as shown in Fig. 1c.

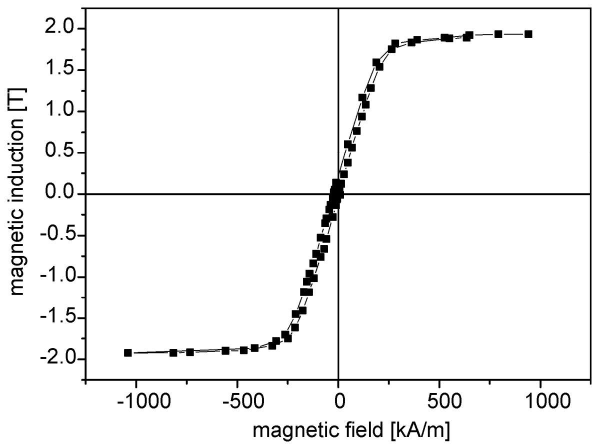


Fig. 2. Static hysteresis loop of two phase ferrous alloy after rolling and heat treatment

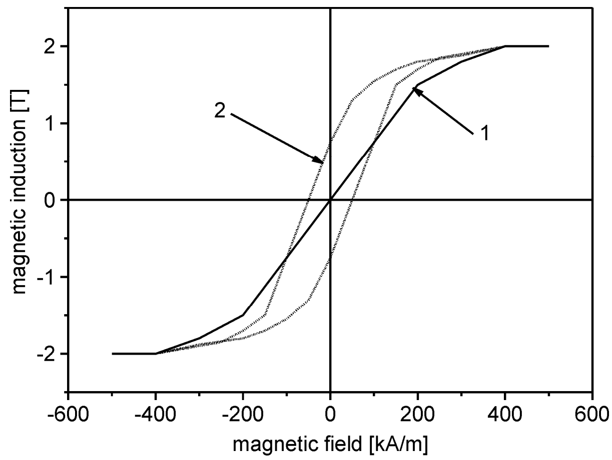


Fig. 3. Static hysteresis loops: 1 – layered two-phase alloy, 2 – polymer composite reinforced with $Co_{68}Fe_4Mo_1Si_{13.5}B_{13.5}$ ribbons [2]

A comparison of static hysteresis loops for the studied layered alloy and a composite with the polymer matrix reinforced with an amorphous or nanocrystalline particles [2] (Fig. 3), clearly demonstrates that the alloy possess lower both the coercivity and remanence. A segment of a static hysteresis loop in low magnetic fields for the studied alloy is presented in Fig. 4 pointing to low losses in the material.

Core loss analysis is of great importance for materials for magnetic flux intensifiers in processes of heat induction. Magnetic material core losses are a direct consequence of Joule heating from electric currents induced in the material by fluctuating magnetization.

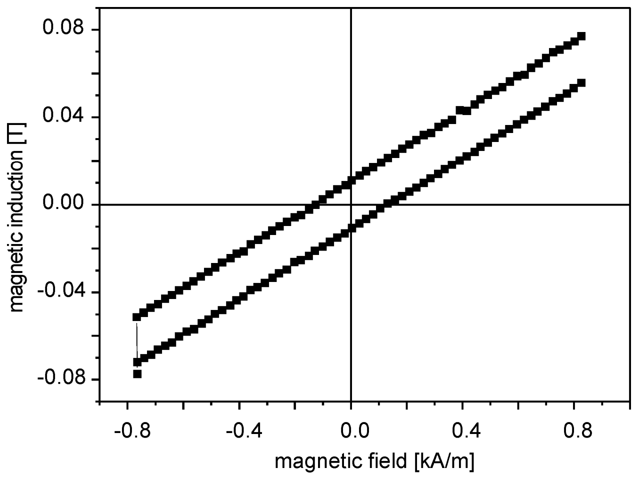


Fig. 4. A segment of a static hysteresis loop in low magnetic fields for the studied alloy

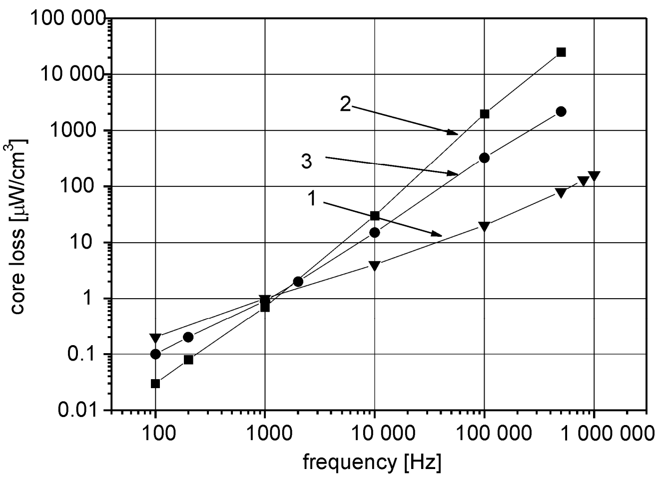


Fig. 5. Core losses of soft magnetic materials: 1– layered two-phase alloy, 2 – classical laminated steel [7], 3 – soft magnetic powder material [7]

Usually, total core losses are divided into three components: static hysteretic losses, classical eddy current losses, and excess eddy current losses (referred to as anomalous or dynamic losses) [6]. Static hysteretic losses are determined by quasi-static loop measurements. Classical eddy current losses are calculated from measurements in a sinusoidal applied field. Excess eddy current losses have contribution from magnetic domain-wall dynamics with scales on the order of microstructure features [6]. The results of eddy current loss measurement compared with the results obtained for classical laminated steels and soft magnetic powder materials are shown in Fig. 5 as dependences of core losses on frequency.

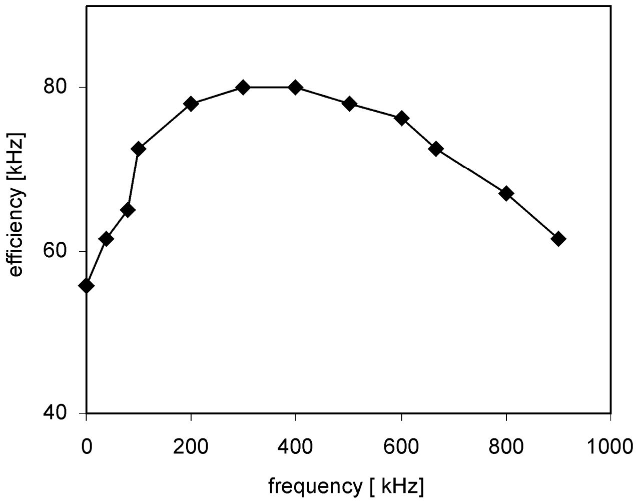


Fig. 6. The efficiency coefficient of transforming for toroidal transformer with core made of the layered two-phase alloy

The effect of decrease of core losses for layered two-phase alloy is greater for higher frequencies. The data demonstrate that core losses may be diminished by 2–10 times in the frequency range of 2–50 kHz. This effect has to be deeper studied in future.

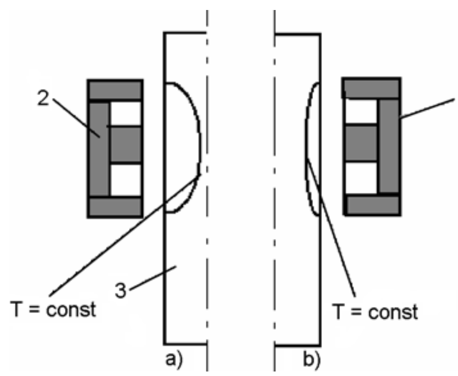


Fig. 7. A scheme of induction heating test: 1 – coil with laminated steel concentrator; 2 – coil with layered alloy concentrator; 3 – bar; induction heating with layered alloy (a) and laminated steel (b) concentrators

The effectiveness of the layered alloy was estimated as a ratio of power in secondary circuit to power brought to primary circuit. The results (Fig. 6) reveal the optimum of frequency depending on the alloy structure parameters. The exploitation tests were performed by comparing of uniformity of induction heating bars by coil with classical laminated steel concentrator (Fig. 7) and concentrator made of the alloy under study. The depth of heating zone for the former case was twice higher than for standard case (heating time – 7 s, T = 950 °C). The comparison of the main magnetic flux concentrator materials is given in Table 1.

Table 1. Main parameters of magnetic flux concentrator materials

Parameter	FLUXTROL B	FERROTRON 559H	Layered alloy
Density, g/cm^3	5.5–5.7	5.8–6.0	7.68–7.8
Maximum permeability	40	20	
Saturation, B_s, T	1.4	1.2	1.8
Exploitation temperature, T, °C	500		1000
Major range of application frequency, kHz	10–100	15–50	50–500

4. Conclusion

The investigated layered two phase Fe- based alloy is characterized by good magnetically soft properties. Improvement of its magnetic properties may be attained by a strict control of structure parameters such as grain lamellas size and resistivity of both phases. The offered alloy may be effective as the material for magnetic flux concentrators for induction heating.

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