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Modification of Nanocrystalline Fe–Cu–Nb–Si–B Alloys and Their Applications as Magnetic Cores in Rail Power Transformers

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The microstructure and some magnetic properties of the nanocrystalline $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ ($x = 2$ or 3) alloys obtained by one-step or two-steps annealing of amorphous ribbons (at 830 K for 30 min or at 660 K for 30 min and then at 830 K for 30 min, respectively) were investigated. Using the core made of the nanocrystalline $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ alloy, the single-phase transformer of 40 kVA power for operation in the rail static converter has been designed. Until now used transformers have 3C95-type ferrite cores due to very low losses and almost noiseless operation. An application of the nanocrystalline material as a core is an alternative solution because the mass of the transformer will be significantly reduced maintaining low losses and an acceptable level of the noise around the transformer.

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1. Introduction

Nanocrystalline Fe–Cu–Nb–Si–B based soft-magnetic materials are used in a wide range of commercial products in many applications needing electrical devices operating at low, medium, or high frequencies [1]. These nanocrystalline materials exhibit excellent soft magnetic properties [2] such as low coercivity (< 100 A/m), high saturation induction (≈ 1.25 T), very low magnetostriction ($< 2 \times 10^{-6}$), and significantly better thermal stability of soft magnetic properties as compared to their amorphous equivalents. Large noise caused by the magnetostriction of amorphous alloys eliminates them from use as transformer cores in railway converters. It has been found [3, 4] that the magnetic properties of Fe-based nanocrystalline alloys depends on their composition, preparation of amorphous ribbons, and heat treatment conditions.

Transformers are very important elements of power electronic converters supplying circuits for the needs of modern passenger rail cars. Technical parameters of this type of equipment are strictly defined [5, 6] and working conditions are difficult due to mechanical stresses, vibrations and environmental conditions (low and high temperatures, humidity, pollutions). Furthermore, the dimensions and mass of the transformer are very important for static converters construction, usually precisely defined by the customer.

In order to fulfil many technical requirements 3C95 type of ferrite and nanocrystalline $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ material with low losses and low magnetostriction were used for the optimization calculations of 2TTK-40kVA transformers.

Using values of maximum induction, relative magnetic permeability and core losses, basic parameters of the transformer working in the rail static converter have been calculated.

2. Experimental procedure

Ribbons of nominal composition $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ ($x = 2$ or 3) were prepared using a planar flow casting technique on a copper wheel. The ribbons were about 25 μm thick and 10 mm wide. The amorphicity of the as-quenched material was verified by Brucker D8 Advanced X-ray diffractometer with Cu K_α radiation. The Mössbauer spectra were measured in transmission geometry using a constant acceleration driver equipped with a ^{57}Co(Rh) radioactive source. X-ray diffraction patterns and the Mössbauer spectra were recorded at room temperature. The parameters of the Mössbauer spectra (i.e. hyperfine field distributions $P(B)$ and phase composition) were analysed using a Normos package [7].

Magnetic properties i.e. magnetic permeability, maximum induction, and core losses were measured by a transformer method using a completely automated setup. The microstructure and magnetic properties was studied for the samples in the as-quenched state and after the heat treatment at 660 K for 30 min and then at 830 K for 30 min (two-steps annealing) or at 830 K for 30 min (one-step annealing). Study of these properties was aimed at obtaining optimal initial parameters for simulation process of a single phase 2TTK-40kVA type transformer working in rail static converter. The parameters were simulated using design software by RALE Engineering GmbH [8].

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3. Results and discussion

Both of investigated alloys were fully amorphous after solidification. It has been confirmed by X-ray diffractometry and the Mössbauer spectroscopy studies. No Bragg peaks have been detected in the case of the as-quenched alloys and only broad diffraction humps at about $2\Theta = 50°$ are observed. The Mössbauer spectra, presented in Fig. 1A for the samples in the as-quenched state, display a broad structure characteristic of amorphous ferromagnetic materials. In distributions of hyperfine field induction it is possible to distinguish low and high field induction components, which are connected with regions of different iron concentrations. Representative Mössbauer spectra of $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ ($x = 2$ or 3) alloys after two-steps annealing are shown in Fig. 1B. The additional sharp lines corresponding to the crystalline phase in the Mössbauer spectra of these alloys are present. From the Mössbauer spectra analysis we have found that this phase consists of α-FeSi nanograins.

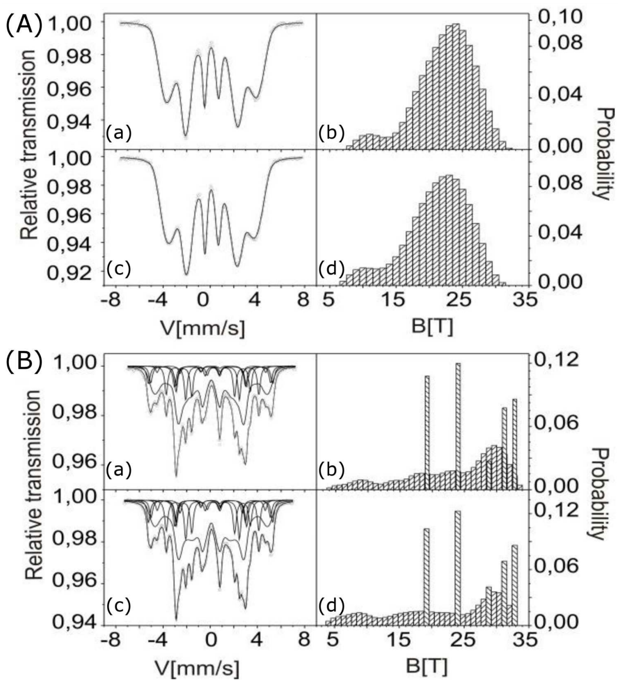

Fig. 1. Transmission Mössbauer spectra (a, c) and corresponding distributions of hyperfine field induction (b, d) for the as-quenched (A) and two-steps annealed (B) $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ alloys: $x = 2$ (a, b) and $x = 3$ (c, d).

The relative magnetic permeability versus the amplitude of the magnetizing field for the nanocrystalline $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ alloys is depicted in Fig. 2. It is seen that the maximum permeability reaches the highest value after two-step treatment for the $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ alloy.

In Fig. 3 magnetic induction versus the amplitude of the magnetizing field for the nanocrystalline $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ is shown. The maximum induction of this alloy at the amplitude of the magnetizing field

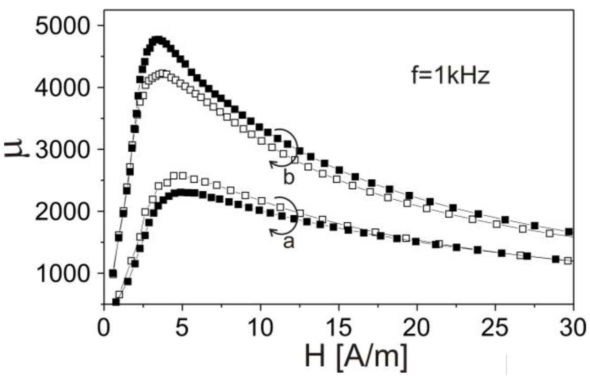

Fig. 2. Relative magnetic permeability as a function of the amplitude of the magnetizing field for the nanocrystalline $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ alloys obtained by one (open circles) or two-steps annealing (full circles): $x = 2$ (a) and $x = 3$ (b).

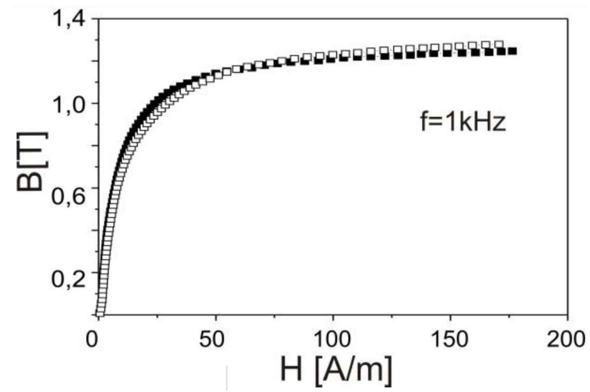

Fig. 3. Magnetic induction as a function of the amplitude of the magnetizing field for the nanocrystalline $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ alloy obtained by the different heat treatment; one-step annealing (open symbols), two-steps annealing (full symbols).

$H_m = 160$ A/m determined from Fig. 3 is equal to 1.25 T and is comparable with that observed for the nanocrystalline alloys of the similar chemical and phase composition [9]. The dependence of core losses on the maximum induction for representative frequencies for $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ ($x = 2$ or 3) alloys subjected to one- or two-steps annealing is shown in Fig. 4. The nanocrystalline $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ alloy exhibits lower core losses than the $Fe_{74}Cu_1Nb_2Si_{13}B_{10}$ one.

Because of the best soft magnetic properties of the $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ alloy, it has been applied as a material for preparation of 2TTK-40 kVA type transformer core. In Table I the transformer parameters calculated by RALE distribution and power transformer design software are listed. As can be seen in this table, the total mass of the transformer is reduced using nanocrystalline $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ alloy. Moreover, losses efficiency and level of the noise are comparable with the 3C95 type of ferrite core transformer. In the destination of lowering the weight of transformers in both aluminium windings were applied.

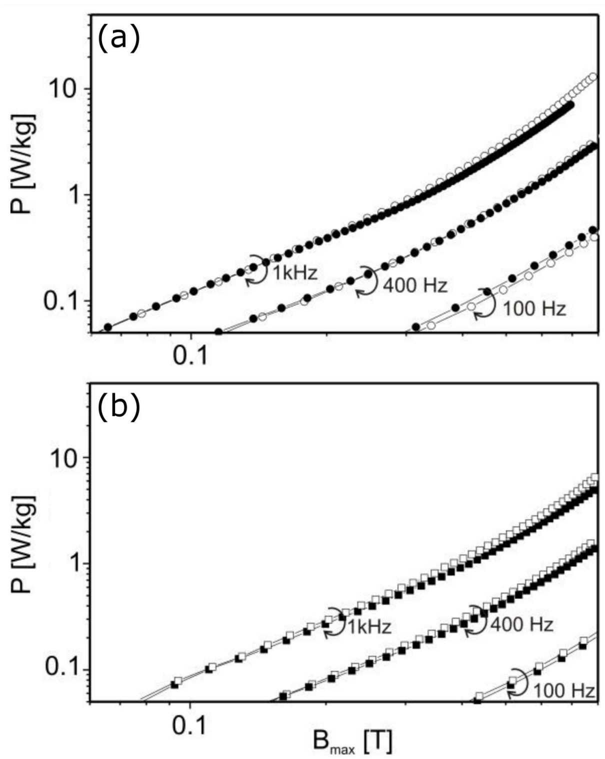

Fig. 4. Dependence of core losses on the maximum induction for the nanocrystalline $Fe_{76-x}Cu_1Nb_xSi_{13}B_{10}$ alloys: $x = 2$ (a) and $x = 3$ (b); one-step annealing (open circles), two-steps annealing (full circles).

TABLE I

Transformer parameters for $f = 1$ kHz obtained from the simulation processes. Nominal power = 40 kVA, primary voltage = 1100 V, Secondary voltage = 350/350 V

2TTF-40kVA 1100/350/350 V		
	Ferrite 3C95	Finemet $Fe_{73}Cu_1Nb_3Si_{13}B_{10}$
core losses	20 W	58 W
winding losses	194 W	156 W
efficiency	99.4%	99.4%
total mass	40.5 kg	21.7 kg
transformer dimensions ($L \times B \times H$) [mm]	270 × 220 × 320	310 × 170 × 300

The influence of environmental and other factors mentioned in paragraph 1 on the operation of railway transformers is eliminated by the appropriate technology and construction of these devices. The epoxy resins are most often used as mechanical and environmental protection of transformers (Fig. 5) but they make it difficult to transfer the heat from the transformer to environment. Because the transformer's convection cooling is difficult due to the low coefficient of thermal conductivity of epoxy resins, a technological solution was proposed that would enable heat to be transferred to the casing and a special transformer support by thermal conduction.

Fig. 5. Three-windings 2TTK-40kVA-type transformer for PD4 pollution zone.

4. Conclusions

The structure and magnetic properties of nanocrystalline materials are dependent on the composition and annealing conditions of amorphous precursors.

$Fe_{73}Cu_1Nb_3Si_{13}B_{10}$ alloy subjected to two-steps annealing exhibits the best soft magnetic properties.

Single-phase transformer of 40 kVA power for operation in the rail static converter with core made from this alloy shows the lowest total mass.

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