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THE IMPACT OF ADDITIONAL LOSSES IN AMORPHOUS TRANSFORMER CORES ON VIBRATIONS - IN THE CONTEXT OF PROTECTION AND CONSERVATION OF EXHIBITS AND HISTORICAL OBJECTS

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Abstract

Modern materials are increasingly used, directly or indirectly, in the protection of monuments. Electrical equipment is used in all laboratories, where monuments are subjected to conservation or restoration. Transformers are included in most of these electrical devices; and, in museums and laboratories, there are also distribution transformers. In these transformers, idling losses (also known as 'transformer core losses'), play a major role in relation to significant changes in load. Materials in which magnetostriction occurs are commonly used to manufacture transformer cores. During the magnetization of the magnetic core of the transformer, there is a change in its dimensions, resulting in the formation of mechanical waves; these waves propagate, both in the air (giving the characteristic sound of a transformer in operation - with significant intensity for large installations), and also in the building structure - through fixtures installed in the ground and walls. High magnetostriction of the core material also creates significant releases of heat - which should be removed, so as not to damage the stored exhibits. Electrical devices usually work at low frequencies of 50 Hz - which causes the formation of waves of considerable wavelengths in the building structure. The suppression of these waves is problematic, and even at low amplitudes, in the long-term such waves can cause plastic deformation or fatigue of the materials from which exhibits are made, hence resulting in their gradual degeneration. Using a carefully selected chemical composition and an amorphous structure, material properties can be modeled in such a way as to obtain a material with almost zero magnetostriction. In addition, changes in chemical composition can lead to the reduction of losses on remagnetization; i.e. the reduction of energy consumption and the associated release of adverse heat. One of the components of losses due to magnetization is that of 'additional losses'. As part of this work, amorphous samples of two alloys, $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ and $Fe_{60}Co_{10}Y_7Ni_3B_{20}$, were produced using injection casting method. Dynamic performance tests were carried out on the manufactured materials using a Ferrometer. Based on the loss measurements, additional losses were determined in relation to the maximum induction. The relationship between the percentage share of additional losses and the maximum induction was found for both of the examined alloys.

***Keywords**: X-ray diffractions; Low-frequency mechanical waves core losses; Additional losses*

Introduction

The harmful effect of low-frequency mechanical waves, produced by the working cores of transformers, and the excessive heat emission in the process of their magnetization, are common phenomena. In the case of priceless museum objects or exhibits, hardly anyone takes

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into account the destructive influence of these factors. Low frequency mechanical waves, propagating through a building structure, are difficult to suppress and, despite their low amplitude, they affect the exhibits continuously. This can cause fatigue or permanent plastic deformations and, in the long run, also damage the materials that make up priceless exhibits. There are various methods of suppressing mechanical waves and eliminating excessive heat [1, 2]. The harmful effects of low-frequency mechanical wave propagation can be partially eliminated by limiting the additional losses in the cores of magnetic transformers made from amorphous materials. Amorphous alloy material has a liquid-like structure but is in the form of a solid. An amorphous alloy structure has a much higher internal energy than a crystalline material with the same chemical composition. The lack of periodicity exhibit by the crystalline systems and their angular translations reduces the phenomena of magnetostriction and loss of magnetization [3]. Amorphous materials can be classified into two groups: 'classical' and 'bulk' amorphous materials. Classical materials include those made in the form of thin strips (with a maximum thickness of 100 μm and a cooling speed within the range of 10^3-10^6K/s) [4, 5], and in the form of solid materials (with thicknesses of more than 100 μm and a cooling speed within the range of 10^{-1}-10^3K/s) [6, 7]. In the case of samples in the form of strips, their limited thickness (resulting from their high cooling rates) slightly limits their range of applications. Therefore, a better solution is to use magnetic cores made from bulk Fe-based amorphous alloys, which are much more difficult to obtain. In 1989, A. Inoue (from Tohoku University) developed empirical criteria for the production of bulk amorphous alloys [8, 9]. Makino *et al.* made a significant contribution to the development of low-loss iron-based amorphous alloys [10].

They stated that the basic criteria for the suitability of the material for transformer cores [11] are the losses due to magnetization, which include: hysteresis losses P_{his}, eddy current losses P_{cl} and additional losses P_{exc}:

$$P_t = P_{his} + P_{cl} + P_{exc} \tag{1}$$

Losses from hysteresis and eddy currents are quite well described. The measure of losses due to hysteresis is the area of the dynamic magnetic hysteresis loop. Eddy current losses arise due to the induction of a magnetic field opposite to the magnetizing field. The last, and least described and explained element of losses is 'additional losses'. These losses can be determined approximately by the formula [12]:

$$P_{exc} = 8{,}76\sqrt{\sigma G S V_0}\, B_{peak}^{3/2} f^{\,3/2} \tag{2}$$

Where:
G –Dimensionless factor;
S –Cross-section of the sample;
V_0–Constant associated with the impact of inhibitory centres on domain walls;
σ - Electrical conductivity;
f – Frequency;
B_{peak} - Maximum induction value.

The occurrence of additional losses is associated with migratory relaxation and so-called fluctuation viscosity. Theoretically, magnetization losses are a linear function of the frequency-squared. In practice, however, losses as a function of f^2 are not a linear relationship, as shown in many papers [13]. The differences between the linear relationship and the actual course of losses are the additional losses.

This paper presents test results for two amorphous alloys: $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ and $Fe_{60}Co_{10}Y_7Ni_3B_{20}$, samples of which were produced by a rapid-cooling technique. Their structure was investigated and losses due to magnetization to 1000 Hz were measured. The aim of the work was to determine the share of additional losses in the total losses on remagnetization, and to determine their dependence on the maximum induction value. This approach to the subject may indicate the need, when renovating or storing monuments, to take into account a degradation factor such as ‘additional heat’ and ‘low-frequency mechanical waves’ propagating from transformers.

Experimental

Ingots of the $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ and $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloys were produced in an arc furnace. Elements with a purity ~~of~~ greater than 99.9 at % were used. The ingot production process was carried out on a water-cooled copper plate under a protective argon atmosphere. The charge was melted by plasma arc, using a non-fusible tungsten electrode, working in the operating current range of 180 - 380A. The charge was re-melted several times, physically inverting it each time. A titanium ‘getter’ was also melted. These treatments were designed to provide high purity and homogeneity of the resulting ingots. The resulting 10 gram ingots were divided into smaller pieces and cleaned - both mechanically and using an ultrasonic cleaner. Rapidly-cooled alloys were prepared by injecting the melt into a copper mould (Fig. 1).

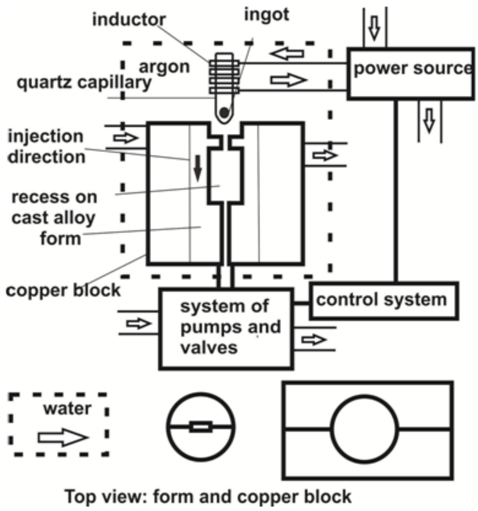

Fig. 1. Diagram of the apparatus for production rapidly-cooled alloys, using a liquid alloy injection method.

Each polycrystalline ingot was placed in the quartz crucible and melted using eddy current heating. The liquid charge was forced, under argon pressure, into a water-cooled copper mould. The charge was melted at 10A. The production process of rapidly-cooled alloys was carried out under a protective atmosphere of argon. The alloys were made in the form of rods with a diameter of 0.5 mm and a length of 20 mm.

The structure of the produced materials was examined using a Bruker Advance D8 X-ray machine. The test was conducted over the two-theta angle range of 30-100°, on samples that were in the form of powder.

Dynamic ferrous hysteresis loops and losses as a function of maximum induction were measured using a Ferrometer (the transformer method).The measurements were carried out over the range of 50 - 1000 Hz. The measurements were carried out at room temperature. The samples of the tested alloys were mounted in yokes made from super permalloy.

Results and discussion

Figure 2 contains X-ray diffraction images for the tested alloys.

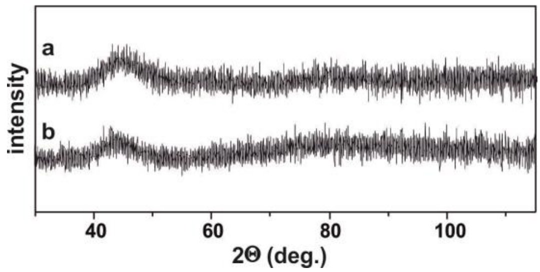

Fig. 2. X-ray diffraction images, measured for the alloys: a) $Fe_{60}Co_{10}Y_8Ni_2B_{20}$, b) $Fe_{60}Co_{10}Y_7Ni_3B_{20}$.

The resulting X-ray diffraction images are typical for materials with an amorphous structure. The occurrence of a wide maximum is associated with the chaotic arrangement of atoms within the volume of the tested samples. Figure 3 presents a list of losses due to magnetization, and dynamic magnetic hysteresis loops for selected frequencies.

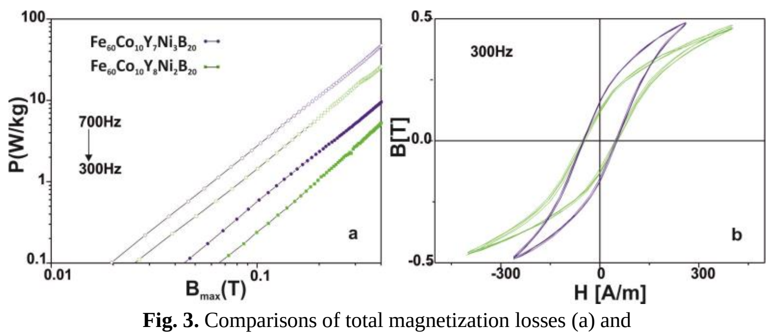

Fig. 3. Comparisons of total magnetization losses (a) and dynamic magnetic hysteresis loops (b) for the manufactured alloys.

The $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ alloy has a lower value of 'magnetization losses'. Interestingly, the areas of the dynamic magnetic hysteresis loops are almost identical. It is also worth noting that the $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloy achieves a higher induction value with the same magnetizing field as the $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ alloy. Figure 4 shows the losses due to magnetization, as a function of frequency, for the tested alloys.

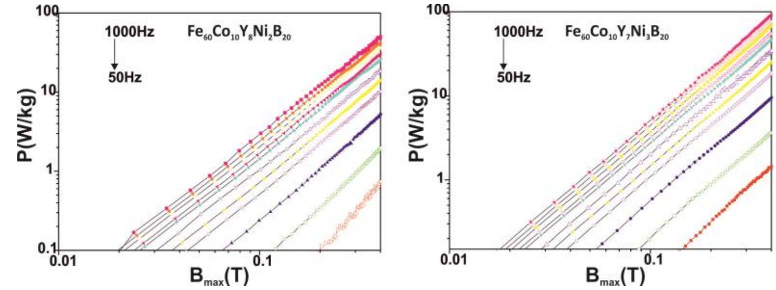

Fig. 4. Core losses on remagnetizationas a function of maximum induction for the produced alloys, over the magnetizing field frequency range of: 50 - 1000 Hz

The core losses on remagnetization for the $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloy reach higher values than for the $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ alloy - at each frequency. Considering the dynamic magnetic hysteresis loops, it can be concluded that the higher level of losses for the $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloy is associated with higher eddy current losses. Figure 5 shows the core losses, as a function of the frequency-squared, for different maximum induction values.

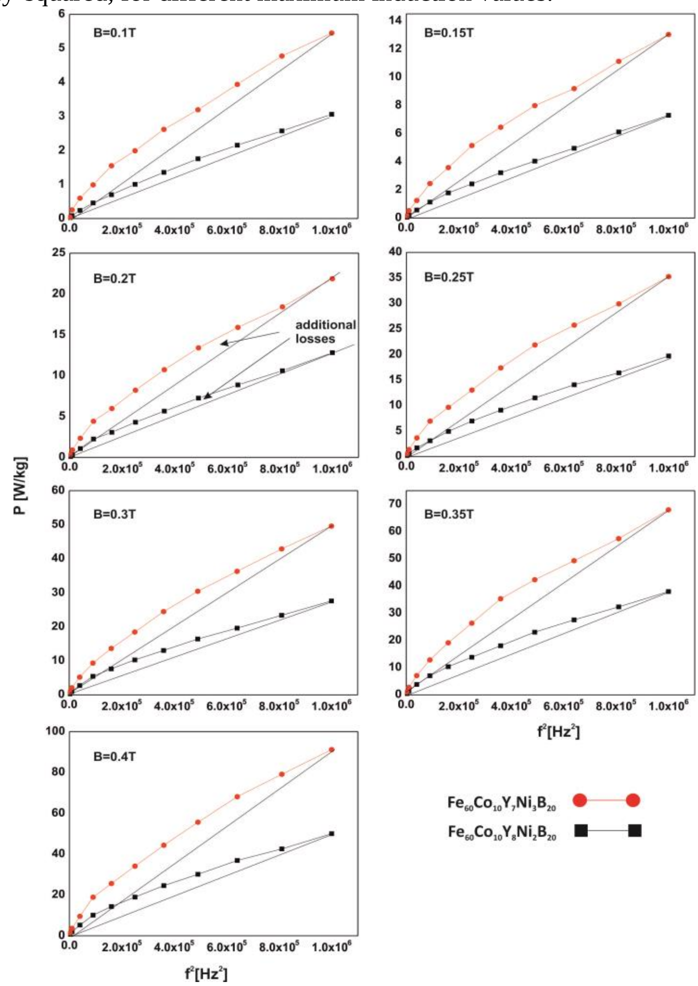

Fig. 5. Loss of magnetization, as a function of the square of the frequency of the magnetizing field, for the tested alloys, for different maximum induction values.

Figure 6 shows the dependence of the share of additional core losses on the maximum induction value for the tested alloys.

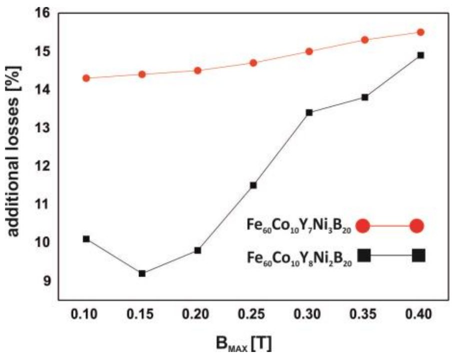

Fig. 6. Share of additional core losses as a function of the maximum induction value

For both of the examined alloys, a correlation was found between the share of additional losses and the value of maximum induction. The $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloy is generally characterized by higher magnetization losses (Fig. 4) and a greater proportion of additional losses. This is probably associated with a greater degree of heterogeneity of this alloy. In the case of the $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloy, the share of additional losses increases linearly as the maximum induction increases.

Conclusions

Many very valuable exhibits are located in modern or old historic buildings that have been converted into museums. Each of these museums uses electrical devices that are connected to large transformer switchboards. Typically, these transformers are installed underground and, during use, they become a source of noise, heat and vibration. While noise and heat is almost completely absorbed by building foundations and ceilings, vibrations are transmitted to the entire building structure. It should be added that, during micro-vibrations, valuable exhibits are exposed to plastic deformation and excessive surface interference of bacteria and fungi.

The effect of additional vibration is usually overlooked by conservators. One of the sources of these vibrations is core losses, generated during the magnetization process. Therefore, from the point of view of the protection and conservation of monuments, it is important to limit the core losses.

In this work, additional losses were tested for the rapidly-cooled alloys, $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ and $Fe_{60}Co_{10}Y_7Ni_3B_{20}$. For the tested alloys, core losses due to magnetization were not a linear relationship for any of the considered maximum induction values. Test results show that additional losses are a significant component of total losses on remagnetization. In the case of the $Fe_{60}Co_{10}Y_8Ni_2B_{20}$ alloy, the percentage share of additional losses is from 9.2% to 14.9%, while for the $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloy the range is from 14.3% to 15.5%. Such a large share of these losses cannot be ignored during theoretical calculations of core losses for designed transformer cores. An increase in the share of additional losses was found, depending on the maximum induction. For the $Fe_{60}Co_{10}Y_7Ni_3B_{20}$ alloy, the increase in the share of additional losses increases linearly with increasing maximum induction. For the

$Fe_{60}Co_{10}Y_8Ni_2B_{20}$ alloy, the share of additional losses is also dependent on the value of the maximum induction, although this relationship is not linear.

Additional losses associated with composition fluctuations and magnetic delays are the least described loss component. However, as shown in this work, their impact on core losses is significant and also related to the chemical composition of the alloy and maximum induction. In view of the above, it should be noted that the reduction of additional losses, by optimizing the chemical composition of the alloy (amongst other techniques), can reduce the core losses and thus reduce the level of generated vibrations.

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