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THE EFFECT OF γ-RAY IRRADIATION ON MAGNETIC PROPERTIES OF ELECTROMAGNETIC Fe-Si (97%-3%) SHEETS

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The effect of γ-ray irradiation on magnetic properties of electromagnetic steel sheets has been investigated. The measurements were carried out by using transformer Fe-Si (97%-3%) sheets. The energy losses and dependence of the relative permeability as well as of the differential permeability on strength of the magnetizing field before and after irradiation were measured. The measurements show that, after irradiation, the energy losses in the electromagnetic sheets for a maximum field of 1.0 Tesla at the frequency of 50 Hz decreased to less than 10% of energy losses before irradiation. The value of the saturation magnetic field after irradiation also decreased by about 10%. The relative permeabitity values in the region of rotation of magnetization domains after irradiation decreased on the average by 5%, whereas the value of their differential permeability around each working point remained unchanged.

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1. Introduction

The change of physical properties of magnetic materials caused by irradiation with energetic particles have been the subject of several investigations [1–3]. Many authors have reported decrease of remanence, the magnetization above the knee and maximum permeability of 2% silicon iron samples after proton or electron irradiation [4,5]. Also the changes of the shape of hysteresis loop in several soft magnetic materials after neutron irradiation have been reported [6,7]. However, a limited amount of work has been done to elucidate the effect of γ-ray irradiation on the magnetic properties and nominal energy loss of electromagnetic sheets [8].

The electromagnetic Fe-Si (97%-3%) sheets have been used in fabrication of magnetic and electromagnetic instruments such as motors, transformers, smoothing chokes, etc. Sometimes these instruments are used in severe environmental conditions such as in irradiation facilities, where they are exposed to γ-radiation. Present work was made with the aim to determine the effects of γ-radiation on the nominal energy loss of electromagnetic sheets and their relative and differential magnetic permeabilities. We present the experimental results which demonstrate the change of energy losses and of magnetic properties of the sheets caused by irradiation of 4 and 8 Mrad using ^{60}Co γ-rays.

2. *Experimental technique*

Transformer sheets were cut to the standard E and I forms and four small identical-yoke magnetic circuits were made. Each magnetic circuit has cross-sections of the central leg of 25 cm^2 and the lateral legs of 12.5 cm^2. The central leg carries the primary and secondary windings of 400 turns each. The dimensions and the mean length of the magnetic lines of force in the circuit are shown in Fig. 1.

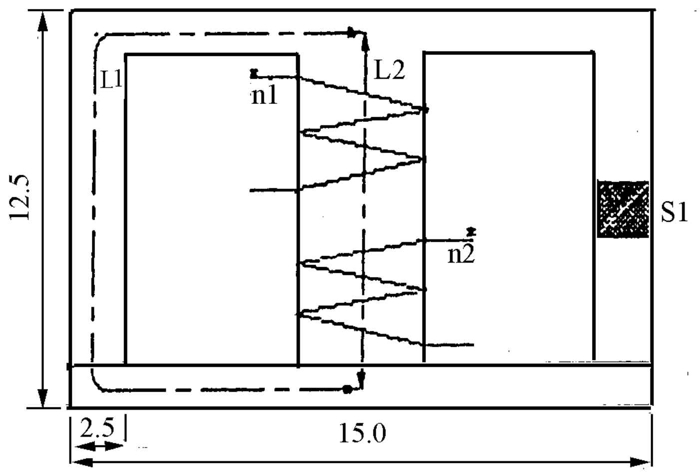

Fig. 1. Shell-type magnetic circuit used in the measurements. Cross-sections of the lateral legs are 12.5 cm^2 *and of the central leg 25* cm^2. *The dimensions are* $L_1 = 22.5$ cm *and* $L_2 = 10$ cm. *The number of windings in the two coils was* $n_1 = n_2 = 400$ *turns.*

All experimets were carried out using the four small magnetic circuits. Their energy losses as a function of maximum magnetic field values at the frequency of 50 Hz were measured. Their first magnetization curves and hysteresis loops were obtained using the direct current in one of the magnetic circuit windings [9,10]. The relative permeability curves as a function of magnetic field were derived from the data on the first magnetization curves.

In order to determine the differential permeability values as a function of the magnetic field [11,12], we proceeded as follows:

The primary windings of two magnetic circuits were connected in series and an AC voltage of pulsation ω and rms value V was applied to the windings, and the rms value of the current I circulating in the two primary windings was measured. The impedance of each winding is then given by

$$Z = \frac{V}{2I}.$$

To take the real part of this impedance into consideration, the value of inductance of each winding was calculated from the relation

$$L = \frac{1}{\omega} \times \frac{V}{2I} \cos\delta,$$

where δ is the phase angle.

To determine the phase angle δ, an oscilloscope was used in the $x - y$ mode. A voltage proportional to the current i and a voltage proportional to $\int v\mathrm{d}t$ (obtained using an integrating RC circuit) were applied to the x and y inputs, respectively. Analysis of the ellipse on the oscilloscope screen permited the determination of the phase angle δ between i and $\int v\mathrm{d}t$. The inductance was obtained from the relation:

$$L = \frac{\phi}{I} = \frac{n_1^2 S}{L}\frac{B}{H},$$

where n_1 is the number of turns in the primary winding, L the mean length of magnetic field lines in the magnetic circuit, B the magnetic field, H the magnetizing field and S the cross-section of the center leg.

The differential permeability is obtained from the relation:

$$\mu_d = \frac{L}{n_1^2 S}\frac{V}{2\omega I}\cos\delta.$$

To change the average working point, we used two secondary windings which were connected with opposite phase, as shown in Fig. 2, to make initially the sum of the alternative voltages induced on the secondary windings equal to zero. Then we applied a continuous current (DC) I_0 to the second winding and changed the average working point of magnetic circuits

$$H_0 = n_2\frac{I_0}{L}.$$

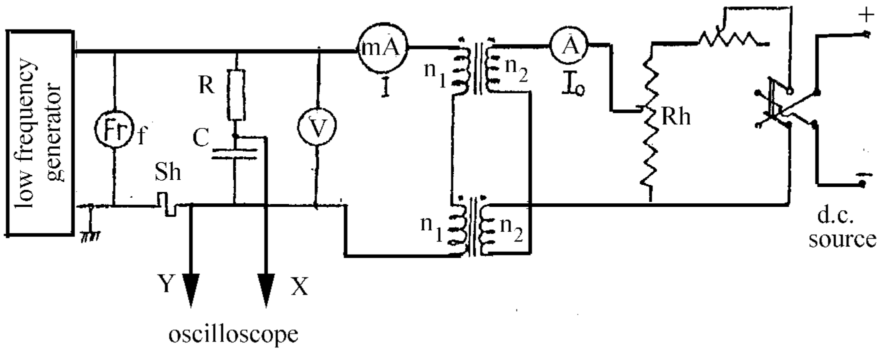

Fig.2. The electric circuit used to determine μ_d as a function of magnetic field.

The variation of differential permeability as a function of magnetizing field was obtained by a superimposing 5 volts AC signal of 50 and of 100 Hz onto the continuous current. The AC voltage was maintained constant during all experiments while the value of the continuous current applied in the secondary side was changed from 0 to 500 mA and from 500 mA back to 0.

To study the effects of γ-ray irradiation on the magnetic properties of the sheets, the four magnetic circuits were demagnetized [13] and dismantled. Their sheets were exposed to ^{60}Co γ-rays at the dose rate of 2020 rad per minute [14,15] at room temperature. Two were exposed to a 4 Mrad dose whereas the other two were exposed to a 8 Mrad dose (twice the exposition time). After irradiation, the sheets of the four magnetic circuits were assembled exactly as before irradiation and their energy losses and all mentioned magnetic properties were measured under identical conditions as before irradiation.

3. Results and discussion

Figure 3 shows the results obtained for the energy losses as a function of maximum magnetic field of the magnetic circuits before and after irradiation. Main causes of the losses are due to eddy currents and the hysteresis [16].

For maximum magnetic fields up to 0.4 T, the change of the energy losses due to irradiation are very small, but for higher maximum fields, a gradual decrease of the losses in irradiated sheets has been observed. The energy losses of electromagnetic sheets for a maximum magnetic field of 1.0 T, at the frequency of 50 Hz, are reduced by irradiation by about 10%. The decrease of energy losses caused by irradiation is probably due to the γ-ray annealing effect of the solid state defects, which are present in the sheets. The energy losses of the sheets after irradiation by 4 and 8 Mrad doses, for any value of magnetic field, are the same. The most appropriate explanation for this is that saturation of effects of irradiation is achieved at some dose below 4 Mrad.

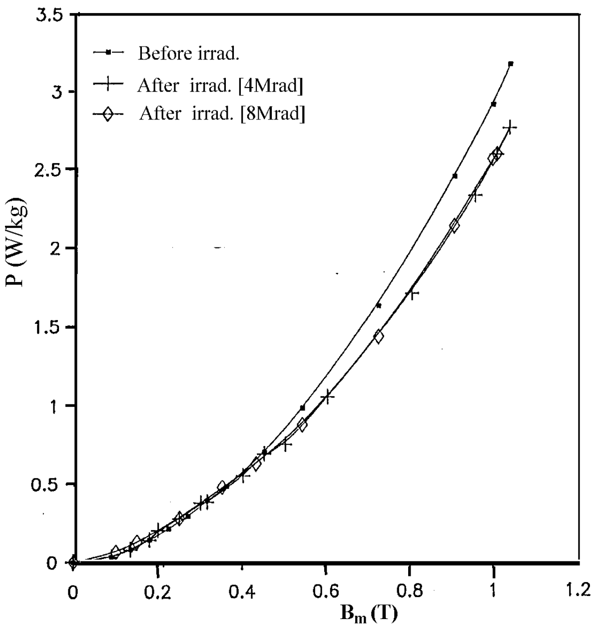

Fig. 3. Energy losses as a function of maximum magnetic field.

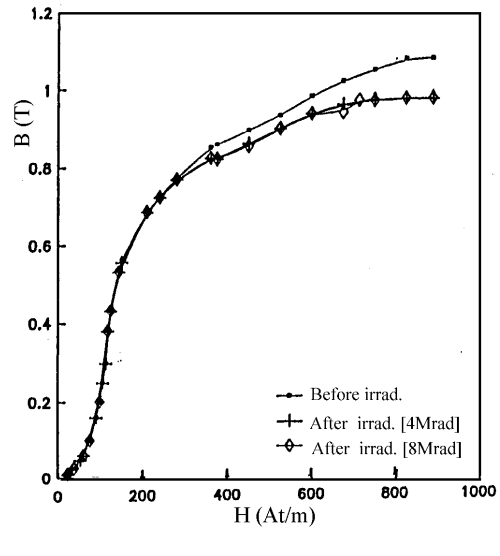

Fig. 4. The first magnetization curves.

Figure 4 shows the results for the first magnetization curves of the magnetic circuits, for a 500 mA DC current, before and after irradiation. Explanation of these curves is as follows:

The first magnetization curves before and after γ-irradiation are similar in the region of reversible and irreversible boundary domains. However, when the value of the applied magnetizing field increases to reach the rotation of magnetization domains [17], the values of the magnetic field and of the saturation magnetic field of the circuits after irradiation decrease up to 10%, i.e., up to the value that was found for the maximum magnetizing field.

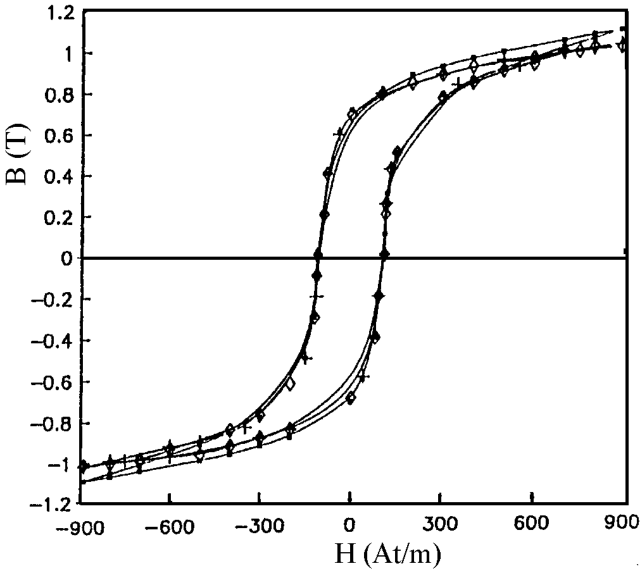

Fig. 5. The hysteresis loops.

Figure 5 shows the results for the hysteresis loops of the magnetic circuits, for a 500 mA DC current, before and after irradiation. An analogous result was obtained as in the case of the first magnetization curves. This may be due to the changes in the magnetic ordering and to the creation of magnetization of antiferromagnetic domains by γ-ray irradiation [18,19]. The γ-ray irradiation may also change the domain structures by affecting the velocity of the domain wall motion. That makes the walls move after irradiation. The change of the area of the hysteresis loops gives an explanation to the smaller energy losses of the magnetic circuits after irradiation.

The value of the remanence of the hysteresis loops of the magnetic circuits after irradiation is slightly lower than before irradiation.

Figure 6 shows the relative permeability curves as a function of magnetizing field of the magnetic circuits before and after irradiation. One can notice an average decrease of 5% of the relative permeability values after irradiation in the region of rotation of magnetization domains.

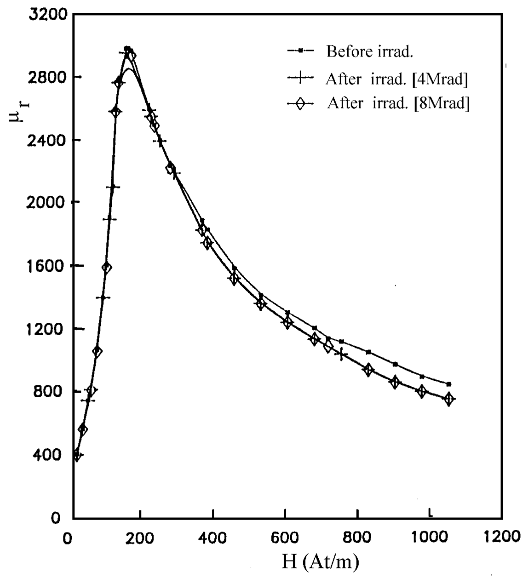

Fig. 6. Relative permeability curves.

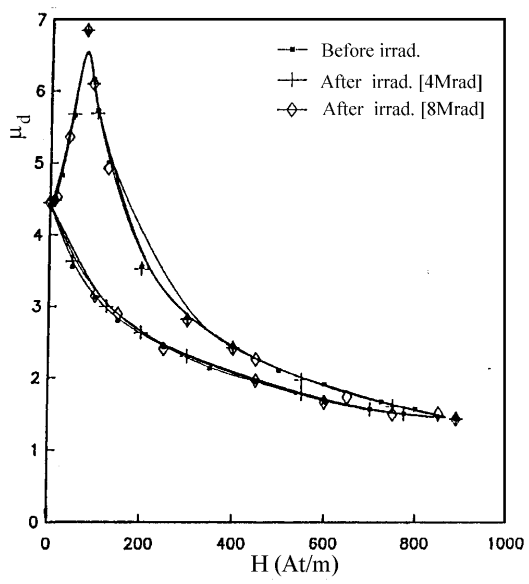

Fig. 7. The differential permeability.

Figures 7 and 8 show the measured results on differential permeability as a function of magnetic field before and after irradiation, for the frequencies of 50 and 100 Hz, respectively. The curves show that the values of the differential permeability μ_d for each working point imposed by the magnetizing field H_0, after irradiation, are still unchanged. That reflects the observed unchanged form and mean value of the slope of the small AC hysteresis loops around each working point.

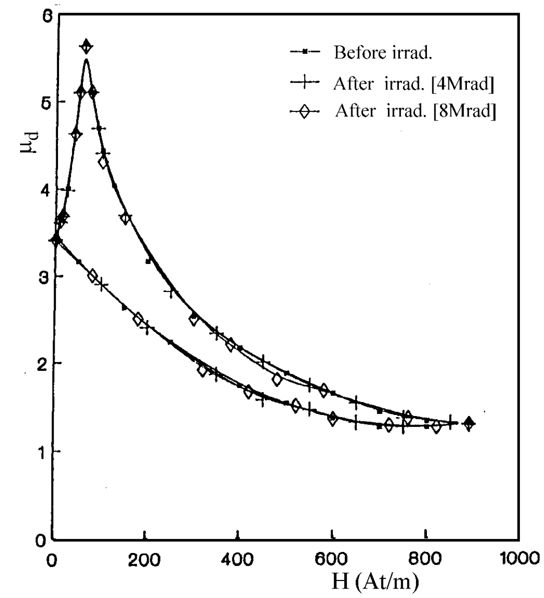

Fig. 8. The differential permeability curves at 50 Hz and at 100 Hz.

4. Conclusion

The reported results reveal the decrease of the energy losses of the saturation magnetic field and of the remanence of the magnetic circuits after high-dose γ-ray irradiation of the electromagnetic steel (97% Fe - 3% Si). The values of the relative permeability, corresponding to the rotation of magnetization domains, also decrease after γ-ray irradiation, whereas the differential permeability values at all working points that were measured have been found to remain unchanged by irradiation. The results for 4 Mrad and for 8 Mrad irradiation are almost the same. Further work is expected to give more details about the changes of the magnetic properties and their relation to γ-ray energy and dose.

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UČINAK OZRAČIVANJA γ-ZRAČENJEM NA MAGNETSKA SVOJSTVA TRANSFORMATORSKOG Fe-Si (97%–3%) ŽELJEZA

Istraživao se učinak ozračivanja γ-zračenjem na magnetska svojstva transformatorskog Fe-Si (97%–3%) željeza. Mjerili su se gubici energije, te ovisnost relativne permeabilnosti i diferencijalna permeabilnost o jakosti magnetizirajućeg polja prije i nakon ozračivanja. Mjerenja pokazuju da se za maksimalno polje od 1.0 Tesla i frekvenciju 5o Hz ozračivanjem smanjuju energijski gubici za oko 10%. Smanjuje se također za 10% vrijednost polja zasićenja. Vrijednosti relativne permeabilnosti u području rotacije magnetskih domena smanjuju se ozračivanjem u prosjeku za oko 5%, dok se vrijednosti diferencijalne permeabilnosti oko svake radne točke ne mijenjaju.